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CERAMIC SOUND RECEIVERS

By

A. A. Anan'yeva

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EDITED MACHINE TRANSLATION

CERAMIC SOUND RECEIVERS

By: A. A. Anan'yeva

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ABSTRACT: It is hoped that this book will be useful to accoustic engineers and experimenters in the field, as the author presents some of the results obtained by himself and his colleagues in research on piezoceramic sound receivers. The author thanks V. A. Berezin, V. A. Basov, Ye. V. Vavilov, A. N. Sapry*gin, and A. V. Sosnov for their experimental work. Thanks are expressed to Academician N. N. Andreyev and to Doctor of Technical Sciences V. S. Grigor'yev for their helpful attention to the experimental work and the preparation of the manuscript. Finally, the author acknowledges the assistance of Mechanics A. V. Prakhov and P. D. Kholin, who sometimes played a decisive role in the practical development of the sound receivers. The Chapters of this translation are as follows: Contents: ~~Chapter I.~~ Dielectric and Piezoelectric Properties of Ceramics of Barium Titanate; ~~Chapter II.~~ Methods of the Determination of Characteristics of Sound Receivers; ~~Chapter III.~~ Nondirectional Broad-Band Sound Receivers; ~~Chapter IV.~~ Broad-Band Sound Receiver with Flat Receiving Diaphragms; ~~Chapter V.~~ Spectra of Natural Frequencies of Piezoceramic Spherical and Cylindrical; ~~Chapter VI.~~ Resonance Sound Receivers with Ceramic Piezoelectric Elements. English translation; 165 pages.

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

AUTHOR'S COMMENTS

In acoustic technology there is wide application of piezoceramic electromechanical and electroacoustic transducers. Piezoceramic receivers and emitters of sound are used with success in various kinds of electroacoustic systems and in particular in systems intended for acoustic and hydroacoustic measurements and investigations. For several years the author was engaged in the study of properties and possible designs of piezoceramic converters of different assignments, including measuring acoustic and hydroacoustic sound pickups and projectors. In this work are certain results obtained by us during investigations of piezoceramic sound pickups are given. We hope that the book will be useful to acoustics-experimenters before whom there is frequently the problem of the creation of special sound pickup devices for which piezoelectric ceramics, in the opinion of the author, is an irreplaceable material.

In the experimental investigations which served as a base for the writing of the book V. A. Berezin, V. A. Basov, Ye. V. Vavilov, A. N. Saprygin and A. V. Sosnov participated, to which the author expresses her sincere gratefulness.

The author also expresses gratitude to Academician N. N. Andreyev and Doctor of Technical Sciences V. S. Grigor'yev for the constant attention given to the work and the help and valuable advice during the carrying out of investigations.

We consider it a duty also to note the skill of mechanics A. V. Prakhov and P. D. Kholin which in certain cases played a decisive role in the practical fulfillment of sound pickups.

INTRODUCTION

The beginning of the use of piezoelectric substances in the designing of acoustic sound pickups was assumed as early as in 1917 by Langevin, who at the end of the First World War first created a hydroacoustic converted emitter-receiver with a quartz crystal mosaic[1] [1]. For some time this so-called vibrator of Langevin was the only piezoelectric instrument in acoustics. Other natural piezoelectric crystals, for instance, tourmaline and zinc blende, the piezoelectric properties of which were already well-known at that time, did not find practical application mainly due to the high costs of the initial material. During the Second World War, in connection with the necessity of application of hydroacoustic sound pickups for sonic depth finders, hydroacoustic hydrophones, and other similar devices, there was an increase in interest toward the search and use in the designing of sound pickups of synthetic piezoelectric substances, in the first place Seignette salt the piezoelectric properties of which were revealed

[1]Piezoelectric properties of quartz were discovered in 1880 by the Curie brothers.

and investigated in 1880 by Pierre and Jacques Curie. Quantitative measurements of the piezoeffect in Seignette salt were first conducted as early as 1895 by Pockels. Apparently the first publications in which the technical application of Seignette salt is considered in acoustics are the articles of Nicholson [2]. Descriptions of the first constructions of loudspeakers, sound pickups, and microphones are given in them. In spite of the absence of source material it is possible to consider that at this time hydroacoustic sound pickups with a transducer from Seignette salt were already being used. Thus from American data [3] in the United States piezoelements from Seignette salt were used in hydroacoustics during 1917-1920 (development of firm Western Electric). It is possible that similar works were also conducted by the German i rm Atlas-Verke (Bremen).

Before the Second World War the use of Seignette salt in acoustic instruments was expanded gradually but slowly. Thus in 1931 the article of Sawyer [4] was published in which for the first time there was described a technically sufficiently perfect broadcast microphone and loudspeaker with a transducer of Seignette salt. In this microphone the so-called bimorph piezoelectric transducer was used; one should note that in precisely this technical form the piezoelectric transducer was proposed in the USSR by N. N. Andreyev as early as 1930 [5].

Since this time the number of works devoted strictly to microphones with pickups from Seignette salt has considerably increased [6-16 and others], and already by 1940 the piezoelectric microphone had become a serious competitor to the earlier used carbon and electrodynamic broadcast microphones. However, a number of substantial deficiencies of Seignette salt (hygroscopicity, little mechanical strength, low Curie point) impelled the search for other synthetic piezoelectric materials. The works of Valashek, Shul'vas-Sorokina, I. V. Kurchatov, Mason, Fowler, Mueller, Bush, Sherrer, and others indicated with evidence that such substances must be sought among substances similar to Seignette salt, since it possesses unusually high values of piezoelectric coefficients, which is very important for technical applications in acoustics. Also of great scientific interest is its electrical anomalies. Unique properties of Seignette salt and substances similar to it served as the base so that for this class of substances the term "Seignette-electrics" (or "ferroelectrics") was established.

In the search of new ferroelectrics there are works of Kurchatovykh, Blumenthal, Evans on the study of crystals isomorphic with Seignette salt and mixed tartrates, and also the work Bush and Scherrer (1935) on ferroelectric properties of KH_2PO_4 the piezoelectric properties of which were qualitatively revealed by Elingson and Ternstra in 1928. Also of interest is the later work of Bush (1938) on the crystal growth of phosphoric acid and arsenous salts of potassium and ammonium (phosphates and arsenates) and the investigation of their piezoelectric properties.

However, in that period not one of the new piezomaterials found a technical application in acoustic instrument-making, if we do not consider the attempts to use the KH_2PO_4 crystals for purposes of frequency stabilization.

The carrying out of extensive research in the search of new synthetic piezomaterials received a serious stimulus during the Second World War in connection with a quartz shortage appearing due to the wide use of the quartz crystal in hydroacoustic instruments and in military radio engineering (stabilization of frequency, electromechanical filters, and so forth). Pertinent publications, however, appeared in the postwar period starting from 1946. We cannot consider here all the literature pertaining to the investigation of new synthetic crystals and point out only those works which are connected with crystals having application in acoustics (for instance, [17-23]). Thus during the Second World War as a material for electromechanical transducers the piezoelectric crystal of dihydrophosphate of ammonium found wide application. As a result of these investigations there was established a broad class of synthetic piezoelectric substances of the type of ferroelectrics characterized by large values of piezoelectric and dielectric constants, which is connected with the presence in these substances of spontaneous polarization, and also substances not possessing ferroelectric properties but still having sufficiently large values of piezoelectric constants usually with comparatively small values of the dielectric constant.

Of these new piezoelectric substances in acoustics up till now only the monosubstituted phosphate of ammonium, sulfate of lithium, and dihydrophosphate of potassium have been used, and they were used in the form of mosaic packs in hydroacoustic converted emitter-receivers and so forth, i.e., essentially just as in the constructions from Seignette salt. It turned out that almost all the indicated substances has one common deficiency, little mechanical strength.

In connection with the discovery of piezoproperties for so considerable a number of synthetic materials interest was revived toward the use of various kinds of special piezoelectric sound pickups and emitters in acoustic measuring technology. Of the works in this field one should mention those which are connected with measuring sound pickups from piezoelectric crystals [24-28]. In the practice of the designing of broadcast microphones the new piezoelectric substances still did not find proper application [29].

A new stage in the development of piezoelectric acoustic technology advanced in connection with the discovery by Corresponding Member of the Academy of Sciences of the USSR B. M. Vul and colleagues of ferroelectric properties of ceramics of barium titanate and the establishment subsequently of the fact that the polarized ceramics of barium titanate possesses piezoelectric properties [30-43]. At this time a number of investigations is begun dedicated to the synthesis of different ceramic piezomaterials and questions of their practical use as electromechanical transducers in acoustics and radio engineering. Subsequently there also appeared works on the growing of single crystals of barium titanate and other similar substances, and it seemed that such single crystals possess piezoelectric properties without artificial polarization. However, till now such single crystals still have not found technical application in acoustics.

With respect to piezoelectric properties, polarized ceramics of barium titanate and other similar substances in general yield to synthetic crystals, for instance, Seignette salt yields to phosphate of potassium and to phosphate of ammonium. Therefore, one should dwell on those special properties of piezoelectric ceramics owing to which at present they have found so wide and ever expanding application in acoustic technology. These properties are basically the following: 1) the possibility of the creation of piezoelectric elements essentially of any form with the help of a simple technological procedure; 2) the possibility of the creation of the direction necessary in accordance with the selected form of axes of polarization by means of the corresponding plotting of electrodes; 3) the wide selection of methods of distribution of electrodes caused by the great magnitude of the dielectric constant. Finally the essential advantages of ceramic piezomaterials are also their great mechanical strength, small hygroscopicity, and high dielectric strength.

In the Soviet Union the piezoelectric sound receiver with the use of ceramics of barium titanate was created for the first time in the Acoustic Laboratory of the Physics Institute of the Academy of Sciences by Ana'yeva and Tsarev [44] from the idea of Andreyev and Grigor'yev. This sound receiver was developed in connection with the general problem of the creation of small-size nondirectional sound receivers for measuring purposes. This work served as the beginning of a systematic investigation of questions of the application of piezoceramics in the designing of various kinds of measuring and other sound receivers and emitters conducted in the Acoustic Laboratory of the Physics Institute of the Academy of Sciences of the USSR in the period from 1950 to 1960.

The first foreign publication on the question of the application of ceramics of barium titanate for electroacoustic purposes appeared in 1948 [45-46]. However, articles devoted strictly to sound receivers and emitters with ceramic transducers appeared later. Here one should mention the two articles pertaining to high-frequency measuring sound receivers [47-48] and articles of Koren [49], Mason [50-51], Johnston [52], Bredfield [53], and other authors [54-56] on the application of ceramics in electromechanical converters, including in acoustic generators.

A comparatively insignificant number of works published in foreign literature devoted to the given question should not, however, lead us to the conclusion concerning the fact that the use of ceramics of barium titanate and other similar substances in electroacoustics creates no interest. The large number of publications pertaining to the investigation of piezoelectric properties of ceramic materials is preferably representative [57-74]. The content of these works indicates all the more the increasing influence of the need of acoustic technology for the chemical and chemical-technological developments in the given field. In the Soviet Union starting from 1950 there have been conducted and published a large number of works devoted to the study of new ceramic piezomaterials; it is sufficient to mention at least the works of Smolenskiy and his colleagues [75-88], Roy [89-90], Bokov [91-92] Myl'nikova [93], Isupov and Kosyakov [94-95], Pasynkov and Vinogradov [96]. Certain research works concerning properly the development of piezoelectric ceramic materials and technology of manufacture of piezosubstances and piezoelements will be considered by us subsequently, but only in the part directly important for the designing of sound receivers. In the framework of this work it would be impossible and hardly necessary to analyze the whole available extensive material, since the improvement of parameters of piezoelectric ceramics does not have an essential influence on the purely constructive solutions in the creation of electroacoustic instruments.

Subsequently we consider basically the works of the author devoted to the creation of sound receivers of different types with the use in transducers of ceramics of barium titanate.

We considered it expedient to premise the introductory chapters (Chapters I and II), in which certain properties of ceramic piezomaterials are considered on the basis of barium titanate as well as questions of the method of measurements used during the study and test of ceramic piesoelements and sound receivers with piezoelements of ceramics of barium titanate, to the basic material which is discussed in Chapters III-VI.

CHAPTER I

DIELECTRIC AND PIEZOELECTRIC PROPERTIES OF CERAMICS OF BARIUM TITANATE

Up to now barium titanate has been used in electroacoustic transducers only in the form of ceramics. Ceramics of barium titanate is a polycrystalline substance consisting of chaotically located microcrystals. By subjecting the polycrystalline barium titanate to the effect of an external constant electrical field, it is possible to change the direction of spontaneous polarization in the separate microcrystals and to orient the spontaneous polarization of the latter in the direction of the external applied field. With a comparatively prolonged influence on the ceramics of a constant electrical field there is, after removal of the field, a residual polarization in the ceramics owing to which the ceramics becomes in a known degree similar to the single domain single crystal and in particular takes on properties of piezoelectric substance. The described technological process is called polarization of ceramics and the ceramics, subjected to such treatment, is said to be polarized.

Nonpolarized ceramics of barium titanate to which alternating electric fields are applied manifests only electrostrictive properties, and the corresponding ponderomotive effects in this case turn out to be quadratic. Polarization of ceramics to a considerable extent linearizes the phenomenon, and therefore when designing piezoelectric receivers with transducers of barium titanate ceramics is used polarized ceramics are used. Inasmuch as piezoelectric properties of polarized ceramics of barium titanate are ultimately determined by properties of the components of single crystals, we should consider the properties of single-crystal barium titanate of basic interest to us.

Single-crystal barium titanate belongs to the class of ferroelectrics, since it possesses in a definite temperature interval (below 123°) of spontaneous polarization. X-ray diffraction analysis shows that in the temperature range of 4° to 123°C the lattice of barium titanate has a tetragonal structure. The table of piezoelectric moduli for a single crystal of barium titanate is characterized by five piezocoefficients differing from zero.

	X_x	Y_y	Z_z	Y_z	Z_x	X_y
P_1	0	0	0	0	d_{15}	0
P_2	0.	0	0	d_{24}	0	0
P_3	$-d_{31}$	$-d_{32}$	d_{33}	0	0	0

Here $d_{31} = d_{32}$ and $d_{24} = d_{15}$. In accordance with this table the equations of the dependence of the piezoeffect of a single crystal on the voltage take the form:

$$P_1 = d_{15}Z_x; \quad P_2 = d_{24}Y_z;$$
$$P_3 = d_{33}Z_z - d_{31}X_x - d_{32}Y_y,$$

where d_{ik} (i = 1, 2, 3) are the piezoelectric moduli constituting proportionality factors between the components of piezoelectric polarization P and the components of mechanical stress giving rise to this polarization.

The first subscript of coefficients corresponds to the subscript of the corresponding component of voltage. Spontaneous polarization in barium titanate is directed along the z axis corresponding to the third index.

Above a temperature of the upper phase transition (i.e., higher than 123°) barium titanate does not possess spontaneous polarization and is consequently not ferroelectric. Megaw [97-100] conducted roentgenographic investigations of single crystals of barium titanate over a wide range of temperatures and determined the change in ratio of length of axes a, b and c of the lattice of barium titanate depending upon the temperature. According to works of Megaw the lattice of $BaTiO_3$ with 123°C passes from tetragonal, at which a = b ≠ c, into cubic (a = b = c). At a temperature of 4°C there occurs a second phase transition, at which the lattice is turned from tetragonal into orthorhombic (a ≠ b ≠ c).

At temperatures of phase transitions there occurs a jump in heat capacity and anomalous increase of the dielectric constant. These phenomena are especially sharply expressed with the high-temperature phase transition and are observed both in single crystals and in the polycrystal-line barium titanate. In single crystals of barium titanate the dielectric constant in the direction of the polar axis (ε_3) essentially differs from the dielectric constant in a direction perpendicular to the polar axis (ε_1).

The investigation of dielectric properties of a single-crystal barium titanate is the prime purpose of works [101-114] and several others in which results of the measurement of the dielectric constant and dielectric loss in a wide range of temperatures and intensity of the electric field are given. Piezoelectric properties of a single-crystal barium titanate is the subject of the work [115] in which the following values of piezoelectric moduli are given:

$$d_{33} = 9{,}5 \cdot 10^{-6}\ \text{CGSE and } d_{31} = -3{,}1 \cdot 10^{-6}\ \text{CGSE.}$$

Table 1 gives a short summary of experimentally obtained parameters of single-crystal barium titanate. The considerable scattering of values of the parameters is apparently caused by the fact that from indications of the majority of the authors the degree of chemical purity of the investigated single crystals was insufficient and in certain cases uncontrollable.

Table 1

Crystal	Upper Curie Point °C	Crystallographic shear and form of oscillations	Dielectric constant (At room temperature)	Effective piezoelectric modulus (At room temperature)	Dielectric constant in the upper Curie point	Authors
Barium Titanate	90		$\varepsilon_a = 1{,}5 \cdot 10^3$; $\varepsilon_c = 1{,}2 \cdot 10^2$		$\varepsilon_a = 6{,}5 \cdot 10^3$; $\varepsilon_c = 1{,}9 \cdot 10^3$	Matthias, Hippel' [101]
	~117		$\varepsilon_a = 170 \cdot 10^3$; $\varepsilon_c = 120 \cdot 10^3$		$\varepsilon_a = 290 \cdot 10^3$; $\varepsilon_c = 540 \cdot 10^3$	Matthias
				$d_{33} = 9{,}5 \cdot 10^{-6}$; $d_{31} = 3{,}1 \cdot 10^{-6}$		Bond, Mason Shimin [115]
			$\varepsilon_c = 200$			Merz [103]
Seignette salt	24	L-cut, longitudinal in thickness	$\varepsilon_L = 170$	$d_L = 1{,}97 \cdot 10^{-6}$		Mason [22]
		$XY_{t\ 45^0}$, longitudinal in length	$\varepsilon^T_{11} = 480$	$d'_{12} = 57{,}5 \cdot 10^{-7}$		
		$YX_{t\ 45^0}$, longitudinal in length	$\varepsilon^T_{22} = 12$	$d'_{21} = 80 \cdot 10^{-7}$		
Ethylenediamine tartrate	120	YX, longitudinal in length	$\varepsilon^T_{22} = 6{,}2$	$d_{22} = 20{,}3 \cdot 10^{-8}$		Mason [22]
		ZX, displacement in length	$\varepsilon_{33} = 6$	$d_{33} = 50 \cdot 10^{-8}$		

A comparison of the properties of single-crystal barium titanate with properties of other single-crystal ferroelectric materials utilized for the designing of piezoelectric elements is of interest. For this purpose in Table 1 parameters of two typical ferroelectrics are given, Seignette salt and ethylenediamine tartrate.

From the given data it follows that the single-crystal barium titanate is by no means the best substance in its parameters in comparison with other synthetic ferroelectric piezoelectric crystals. It possesses the most marked piezoelectric modulus approximately one order less than that of Seignette salt and ethylenediamine tartrate, while the dielectric constant of barium titanate is approximately one order higher than that for these materials, and this by far is not always an advantage. Therefore, the single-crystal barium titanate as a material for the construction of electromechanical converters, under the condition of obtaining in the future of large single-crystal blocks, can find application in converters only in virtue of other advantages: high temperature of the second phase transition, great mechanical and electrical strength, small hygroscopicity, and so forth. However, these advantages will have considerable value only with the use of single-crystal barium titanate in the construction of converter-motors for instance, for purposes of sound radiation.

As one will see further, the dielectric and piezoelectric properties of ceramics of barium titanate do not essentially differ from the corresponding properties of single-crystal barium titanate. Therefore, the predominant value of ceramic piezomaterials and, in particular, ceramics of barium titanate, in electroacoustic technology is determined in the first place not by some exceptional values of parameters of the material but by special technological and constructive possibilities obtained during the use of ceramics.

The main advantage of the ceramics of barium titanate is the possibility of its artificial polarization. A polarized sample of ceramics of barium titanate possesses a single axis of symmetry of infinite order in a direction coinciding with the direction of the polarizing field. If the vector of the polarizing field is directed along the z axis, then by cutting from the polarized ceramics of barium titanate a parallelepiped from one side along the z axis and with an arbitrary orientation of x and y axes we obtain a similarity of the piezoelectric element with a tetragonal structure. The obtained values of the piezoelectric modulus d_{33} and piezoelectric moduli d_{31} and d_{32} (by the arbitrarily selected orthogonal axes x and y) differ comparatively little from analogous moduli for the single crystal of barium titanate. However, the presence of the axis of symmetry of infinite order permits using ceramics quite differently than that of the single crystal.

Let us note another advantage of ceramics which consists in the fact that by means of simple technological methods (grinding, pressing, casting) it is possible to give to the ceramic piezoelement any necessary form, flat plate, spherical or cylindrical shell, and so forth. By creating different directions of artificial polarization, longitudinal, transverse, radial, etc., and then different directions of polarization on different sections of the same piezoelement, we obtain the possibility of practically an unlimited variation of constructive forms of ceramic elements.

The phenomenon of residual polarization in polycrystalline ceramics is similar to the well-known phenomenon of magnetization of a ferromagnetic material by external magnetic field. Therefore, in foreign literature ferroelectric properties of barium titanate are called ferroelectric properties (we subsequently will not use this terminology).

The first indications of piezoelectric properties of polarized ceramics of barium titanate are contained in works of Adler [37] and Roberts [38]. However, for the first time the piezoeffect in polarized ceramics was quantitatively measured by Rzhanov [40-43].

Polarization of ceramics can be carried out under different conditions, i.e., with a different magnitude of the field strength of the polarizing field, temperature, time of exposure, etc., which essentially influence the final result, the magnitude of the piezoele[illegible] modulus. Initially all works on the creation of piezoelectric ceramics w[illegible] conducted with use of polarization at room temperature.

We investigated the dependence of the piezoelectric modulus in a direction of the polarizing field (d_{33}) on the time of polarization and magnitude of the polarizing field at room temperature. Measurement of the piezoelectric modulus was made in a static regime by means of the determination of emf on facings of the sample with the help of a string electrometer in the force function applied in the direction of polarization. The magnitude necessary for the calculation of the piezoelectric modulus of the capacity of tested sample was measured in the direct current by the method of comparison with a standard capacitor and in alternating current with the help of a universal bridge or a Q-meter.

Figure 1 shows the influence of the time of polarization at room temperature on the value of the piezoelectric modulus d_{33} for samples of ceramics $BaTiO_3$ prepared in the laboratory of dielectrics of the Physics Institute of the Academy of Sciences. From the figure one can see that polarizations during 50-60 minutes are sufficient for the establishment of the almost limiting value of the piezoelectric modulus with the assigned polarizing field.

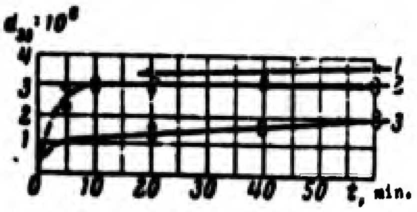


Fig. 1. Dependence of the piezoelectric modulus on the time of polarization. Field strength of the polarizing field: 1) 25 quanta/cm; 2) 15 quanta/cm; 3) 7.5 quanta/cm; polarization at room temperature.

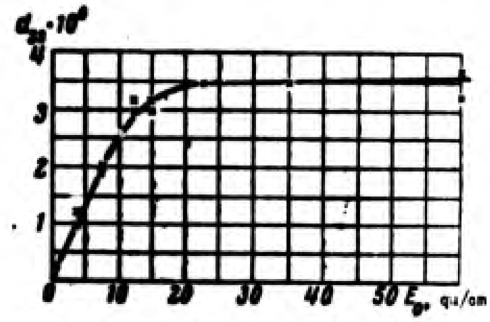


Fig. 2. Dependence of the piezoelectric modulus on intensity of the constant field. Polarization at room temperature.

Figure 2 gives for the same samples the dependence of the piezoelectric modulus d_{33} on intensity E_0 of the polarizing field (with polarization during one hour). The limiting value of the piezoelectric modulus d_{33} obtained for data of samples is equal to $3.6\cdot10^{-6}$ CGSE. The constant field with an intensity of 15-20 quanta/cm is sufficient for the obtaining in ceramics of an almost limiting value of the piezoelectric modulus with polarization at room temperature for one hour.

Experiments on the determination of the electrical strength of ceramics for breakdown showed that the field strength at which the breakdown appears by mass of the sample is changed extensively depending upon the degree of purity of the initial materials and the accuracy of the carrying out of the technological process of manufacture of the ceramics. With the field strength near 30 quanta/cm danger of breakdown becomes already essential, although for certain samples breakdown comes at 15-20 quanta/cm and for specially thoroughly prepared samples (at the Physical Institute of the Academy of Sciences of the USSR), at 40-50 quanta/cm [116]. Therefore, the use of polarization at room temperature is connected with the loss of a large number of samples, which is unacceptable.

A considerable decrease in the necessary field strength can be attained with the use of polarization at raised temperatures [117-118]. It is important to note that the breakdown voltage for the ceramics $BaTiO_3$ in limits of interest to us of the change in temperature practically does not depend on the latter.

Figure 3 gives the value of the piezoelectric modulus in the direction of polarization d_{33} depending upon the field strength of the polarizing field with polarization of ceramics of barium titanate at a temperature of the upper Curie point (123°) with subsequent cooling of the ceramics to room temperature without removal of the polarizing field. The full time of polarization, including the time of heating and cooling, consisted of not less than 3 hours. For the heating of the samples during polarization a butyric bath was used.

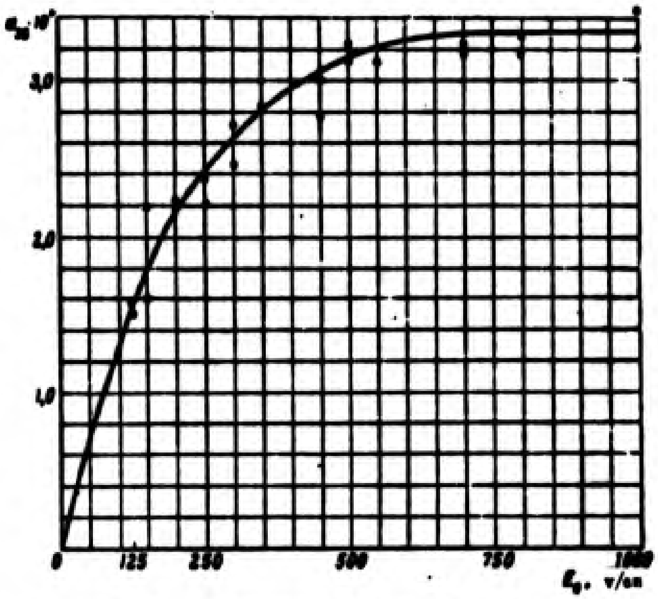


Fig. 3. Dependence of the modulus d_{33} of ceramics barium titanate on the field strength of the polarizing field for the regime of polarization at a temperature of 123°.

Thus the polarization of ceramics with an increased temperature permits considerably the decreasing of the field strength of the polarizing field (up to 0.6 quanta/cm instead of 15-20 quanta/cm) necessary for the creation in ceramics of a limiting ordered structure, i.e., for obtaining ceramic material with the piezoelectric modulus of the limiting value.

The dependence obtained by us of piezoelectric properties on the time of polarization and magnitude of the constant polarizing field [119] was subsequently confirmed by works of other authors.

It should be noted that polarization during a raised temperature is not the only way to decrease the field strength utilized during polarization. Thus in work [120] it is shown that the same result can be attained if one were to cool the sample to a temperature close to the lower Curie point (for ceramics of barium titanate, from -4° to $+4^{\circ}$) and then by applying the polarizing voltage to heat the sample to room temperature. However, this method of polarization of ceramics till now has not received wide technological application.

The piezoelectric properties of ceramics $BaTiO_3$ subjected to high-voltage polarization with small mechanical loads are approximately linear. For an illustration of this position Fig. 4 gives the dependence of the emf appearing on the facings of the sample on the mechanical stresses changing from 0 to 1800 g/cm^2. With large mechanical loads the linear dependence between mechanical stresses appearing on the facings and electrical charges is disturbed. According to works of Vul and his colleagues the linear dependence between electrical charges and mechanical stresses in polarized ceramics of barium titanate is kept under mechanical loads not higher than 100 kg/cm [121-122]. The same conclusion can be made from the work [123]. However, so high mechanical stresses can be encountered in the practice of acoustic instrument making only in special exceptional cases. As a rule even in converters and motors utilized for sound radiation the mechanical stresses are minute, and we can consider the piezoeffect of polarized ceramics of barium titanate to be linear.

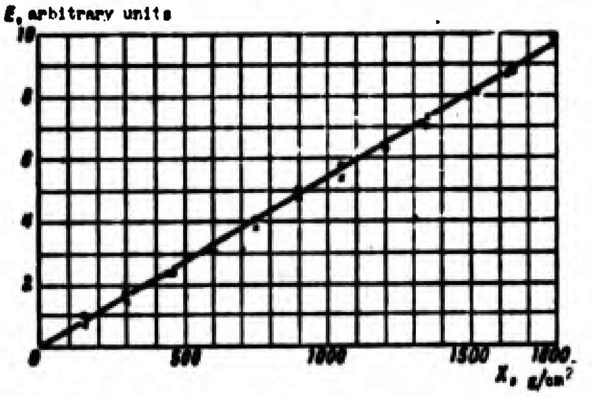


Fig. 4. Dependence of emf of the polarized sample of ceramics of barium titanate on the mechanical load on the sample.

Besides the piezoelectric modulus d_{33} we measured the static diametrical piezoelectric modulus $d_{31} = d_{32}$ at room temperature. Results of measurements for the case of polarization at room temperature are given in Table 2; results of the measurement of the compression modulus are also given there. Measurements are taken with the hydrostatic compression of the sample of cubic form in oil.

Table 2

No. of sample	$d_{33}, \times 10^{6}$	$d_{31}=d_{32}, \times 10^{6}$	$d_{3c.\,\text{сж.}} = (d_{33}+2d_{31}), \times 10^{6}$	Direct measurement $d_{3c.\,\text{сж.}}, \times 10^{6}$	d_{33}/d_{31}
1	2,32	−0,98	0,44	0,47	2,38
2	2,32	−0,98	0,44	0,54	2,38
3	2,18	−0,90	0,38	0,54	2,42
4	3,40	−1,65	0,10	—	2,10

The values obtained by us of parameters of ceramics polarized by the field with the intensity E_0 = 600 v/cm with heating to a temperature of +123° with subsequent cooling in the presence of a high-voltage field are given in Table 3. The averaged value of the dielectric constant is ε = 1200.

Table 3

No. of sample	$d_{33}, \times 10^{6}$	$d_{32}=d_{31}, \times 10^{6}$	$d_{3c.\,\text{сж}} = (d_{33}+2d_{31}), \times 10^{6}$	d_{33}/d_{31}
5	3,35	−1,39	0,57	2,41
6	3,57	−1,52	0,53	2,35
7	3,52	−1,38	0,76	2,54
8	3,83	−1,51	0,81	2,54
9	3,70	−1,41	0,88	2,59
Mean value	3,6	−1,5	0,7	2,5

In literature it is possible to encounter information on results of the measurement of either the piezoelectric modulus d_{33} or piezoelectric modulus $d_{31} = d_{32}$, but only in a small number of works is there information on values of both of these moduli for the same sample. To estimate the properties of ceramics in the presence of a value of only one piezoelectric modulus we often judge the value of another on the basis of the ratio known by some experimental data of piezoelectric moduli d_{33}/d_{32}. This ratio is given for our measurements in the last columns of Tables 2 and 3. According to Rzhanov the ratio d_{33}/d_{32} = 2.28; Mason indicates the magnitude d_{33}/d_{32} = 2.7. Analogous data are also given by Kozlabayev [124]. According to measurements of this author the ratio d_{33}/d_{32} on certain samples of ceramics exceeds 3. In the work of Berlincourt and Krueger [69] it is indicated that this ratio to a considerable degree depends on the porosity of the body of ceramics of barium titanate. With a small porosity it decreases to 2.2, and with an increase in porosity it increases to 2.5. The ratio

d_{33}/d_{31} is different for ceramics of barium titanate and for solid solutions of barium titanate with other substances isomorphic to it. For instance, for a composition of 88% $BaTiO_3$ + 12% $CaTiO_3$ this ratio is equal to 3.1. Thus the divergence of our data with results of measurements of Mason, Rzhanov, and Kozlabayev can be explained by a different quality of ceramic samples. Theoretically the ratio calculated for a single crystal of barium titanate $d_{33}/d_{31} = 2$.

It should be noted that not only the ratio d_{33}/d_{31} but also in general, piezoelectric dielectric and elastic properties of the ceramics to a considerable degree are determined by the quality of the calcined body. Consequently they depend on the cleanness of the initial materials (titanium dioxide and barium carbonate) and on the correctness of the technology of manufacture samples, i.e., on the correct selection of the regime of grinding of the mass, pressure, pressing, and temperature of the roasting of samples. As our measurements showed the parameters of technical ceramics of barium titanate (i.e., $BaTiO_3$ without specially introduced impurities) prepared by different organizations differ somewhat from each other. We find the same divergences, however, in source material.

For polarized ceramics of barium titanate, as also for any other piezosubstance, present temperature dependencies of piezoelectric moduli and the dielectric constant ε are of considerable interest.

The temperature dependence of the piezoelectric modulus d_{33} of the polarized ceramics by our measurements has the form represented in Fig. 5. The lower solid curve pertains to the ceramics polarized at room temperature with a field strength of the polarizing field at 5 quanta/cm; the upper curve pertains to the ceramics polarized up to the limiting value of the piezoelectric modulus d_{33} at room temperature ($E_0 = 15$ quanta/cm). The dotted curve gives the temperature rate of the dielectric constant ε.

It should be noted, that a sharp increase in the piezoelectric modulus d_{33} in the region close to the upper Curie point does not have any practical value from the point of view of the construction of sound receivers. Indeed the sensitivity of the piezoelectric transducer in the regime of the generator is determined not by the magnitude of the piezoelectric modulus d_{33}, but by the relation $4\pi d_{33}/\varepsilon$. This relation is usually designated as the parameter g_{33}.

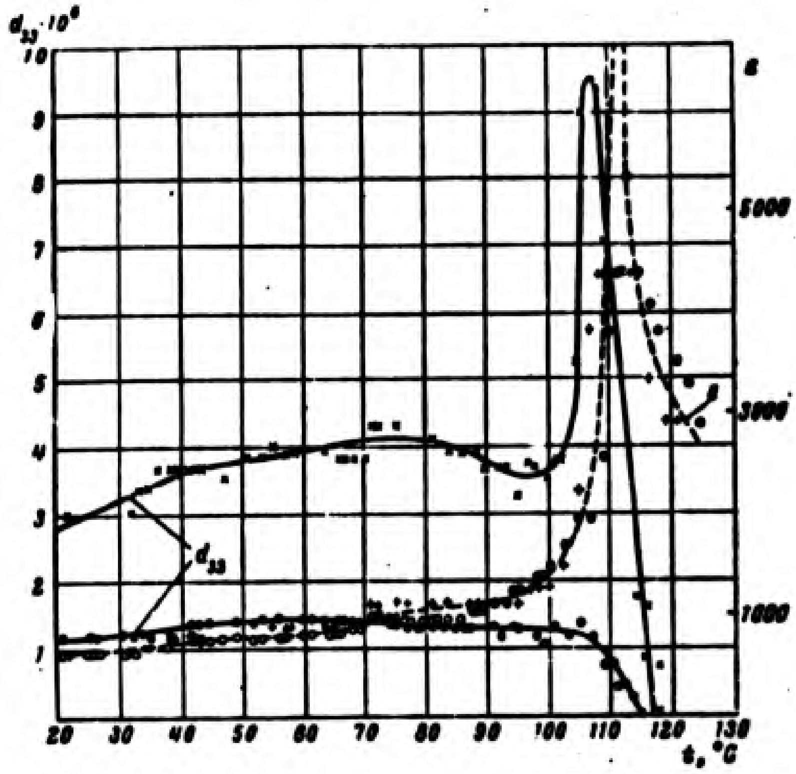


Fig. 5. Temperature dependencies of the piezo-electric modulus d_{33} and dielectric constant ε of the ceramics of barium titanate.

Figure 6 gives the temperature dependence of the consant g_{33} for a ceramics of barium titanate in relative units. In both cases represented by curves 1 and 2 polarization was produced at room temperature. It is easy to see that parameter g_{33} is changed monotonically up to the upper Curie point. Near the Curie point piezoelectric properties of the ceramics disappear completely and irreversibly, and a repeated polarization is required in order to restore again the piezoelectric properties in the sample.

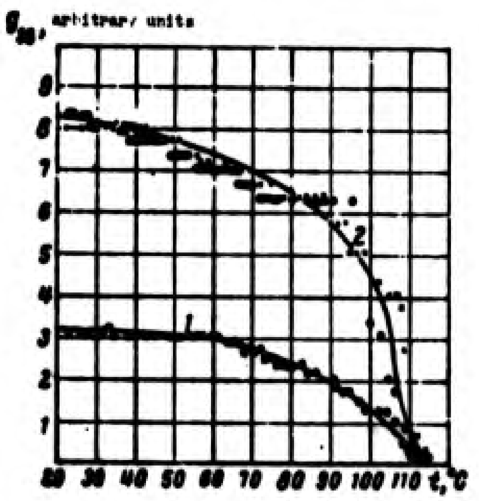


Fig. 6. Temperature dependence of the constant g_{33} of a ceramics of barium titanate 1) ceramics polarized at 5 quanta/cm; 2) ceramics polarized at 15 quanta/cm.

Results of our measurements of the temperature dependence of the longitudinal piezoelectric modulus d_{33} will agree qualitatively with that obtained by Rzhanov [42, 43, 125] of the temperature dependence of the transverse piezoelectric modulus of the ceramics d_{31} determined in the dynamic process by oscillations of rectangular rods.

To judge the conditions of the use of a certain form of piezoelectric ceramics in the designing of electromechanical transducers, besides information about piezoelectric constants, it is necessary to know the magnitudes, and temperature dependencies of such parameters as the dielectric constant, conductivity, and specific dielectric losses.

The investigation of dielectric properties of barium titanate is the subject of a large number of works containing results of measurements of the dielectric constant and dielectric losses taken in a wide temperature range both on single crystals [101-114] and on polycrystalline ceramic samples of $BaTiO_3$ [30-40, 126-144]. Results of these works can be used directly. Data on direct measurements of the conductivity of ceramics of barium titanate is small comparatively in literature. Therefore, we took measurements of the conductivity of the ceramics of barium titanate in a function of temperature. Corresponding results are shown in Fig. 7. The current of conductivity was directly measured by a microammeter with application to the sample of a constant potential difference.

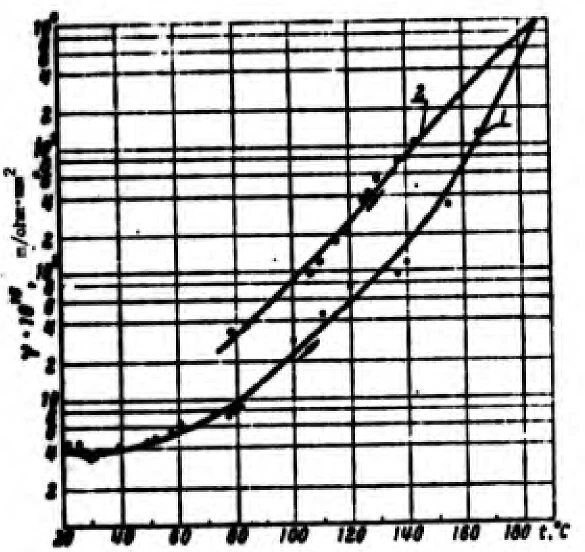
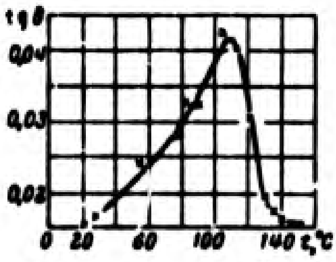


Fig. 7. Dependence of the conductivity of ceramics of barium titanate on temperature. 1) measurement with a heated sample; 2) measurement with a cooled sample.

From the figure one can see that for ceramics of barium titanate "hysteresis" of conductivity is observed, which is characteristic for imperfect dielectrics. From room temperature to 50° the conductivity of ceramics is about $4 \cdot 10^{-15}$ m/ohm·mm^2; with an increase in temperature the conductivity increases sharply. Thus with the heating of the ceramics to 150° the conductivity is increased by two orders, and with heating to 185° by more than three orders.

It is interesting to compare this value with the conductivity for such a typical ferroelectric as Seignette salt. According to Valasek [145] the conductivity of Seignette salt at room temperature is $(22.0\text{-}11.0)\cdot 10^{-14}$ mho/cm[1]. Thus from this point of view the ceramics of barium titanate is a better dielectric Seignette salt.

We also measured the dielectric losses of the polarized ceramics of barium titanate in the temperature range from room temperature to 150° at frequencies of 50 and 5 Mc. Fig. 8 gives the dependence of the loss tangent δ on the temperature with a frequency of 5 Mc. The peak of Curie is located at 123°. Measurements were taken during the small intensity of the variable field not exceeding 2.5 v/cm.



Temperature dependence of dielectric losses of ceramics of barium titanate at a frequency of 5 kilocycles.

From the given data and also on the basis of reference information [43, 111, 129, 136 and others] it is possible to conclude that the mean value tg δ for the ceramics of barium titanate at room temperature oscillates in a range from 0.01 to 0.03. The ceramics with the upper value tg δ should be considered more than ceramics of reduced quality.

For the designing of electroacoustic equipment and especially measuring sound receivers the question of the constancy of parameters of piezoelectric materials with time is considerably important, i.e., the question of their aging. Our experiment and also the data given by Kozlabayev [124, 146] permit considering the ceramics of barium titanate to be a piezomaterial sufficiently stable in time for a number of technical applications. The data cited by Mason [63, 147] show nevertheless that for the achievement of great time stability of the ceramics it is useful to take measures for the artificial aging of piezoceramic articles.

A brief summary of information about parameters of piezoelectric ceramics of barium titanate (at room temperature) from our measurements and source material is given in Table 4.

It is easy to see that the scattering of the values measured of parameters is sufficiently large, which is probably conditioned by differences in the technological methods used by the authors in the manufacture of ceramics. For a comparison Table 5 gives parameters of certain other piezomaterials utilized in in electroacoustic technology or which can find application in acoustics.

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[1]The two values are obtained by a change in the sign of the applied emf.

Table 4

Dielectric constant	Piezoelectric constants d_{33}	d_{31}	d_{15}	g_{33}	g_{31}	g_{15}	Density g/cm³	Elastic constants	Coefficients of electro-mechanical coupling	Curie point °C	Authors	Remarks	
	×10[illegible]			×10[illegible]									
1600	3,2	—1,4		2,51	—1,1		6,2	$E = 1,15 \cdot 10^{12}$ d/cm²			Rzhanov [40, 42, 125]		
	5,4	—2,25									Jaffe [57]		
	3,65	—1,4	5,35								Vul, Bogdanov, Rozbash [148]		
1420÷1565	3,2÷4,3						5,5÷5,71	$Q = 75÷164$	0,33÷0,41	125	Egartone, Koonce [65]	Ceramics of technical raw material	Different values correspond to different temperatures of roasting
	0,49÷4,45						5,37÷5,72	$Q = 80÷232$	0,034÷0,37			Chemically pure ceramics	
$\varepsilon_{33} = 900÷1500$, $\varepsilon_{11} = 1500÷1800$	3,00÷6,7	—2,35÷—1,1	5,00÷7,50	—8,1÷—7,1	+2,5÷+1,2	4,2÷6,3	5,5÷5,8				Bronnikova, Stavitskiy [149]		
1600	3,5	—1,3									Roy [89, 90]		
	5,75	—2,35	7,8								Berlincourt [66]		
	5,73	—2,37	8,1								Bechmann [67]		
	4,0	—1,5	5,5								Bogdanov, Vul, Rozbash, Timonin [150, 151]		
1800	4,2										Smolenskiy and colleagues [152]		
	5,7	—2,34					5,7				Berlincourt, Krueger [69]		Technical ceramics
	6,87	—2,84					5,85						Pure ceramics
2000	—	—2,25			—1,41				$k_{15} = 0,185$		Herber. [70]	Technically pure ceramics	

Table 4 (Continued)

Dielectric constant	Piezoelectric constants d_{33}	d_{31}	d_{15}	g_{33}	g_{31}	g_{15}	Density g/cm³	Elastic constant	Coefficients of electro-mechanical coupling	Curie point °C	Authors	Remarks
	×10[illegible]			×10[illegible]								
$\varepsilon_{11}^T = 1436$; $\varepsilon_{33}^T = 1680$; $\varepsilon_{11}^S = 1123$; $\varepsilon_{33}^S = 1256$	5,74	−2,37	8,1		−2				$k_{33} = 0{,}494$; $k_{31} = 0{,}208$; $k_{15} = 0{,}466$		Berlincourt and Jaffe [153]	
1200	2	1,5			1,47					130	Rez, Kachkasheva, Smazhevskaya [154]	
1700	5,7	−2,34		4,21	−1,76			$E = 11{,}0 \times 10^{11}$ d/cm²; $Q = 400$	$k_{33} = 0{,}52$; $k_{31} = 0{,}22$; $k_p = 0{,}22$	115	Crawford [71]	
1200		−1,4			−1,46		5,35				Serova, Slushevskiy, Strelets [155]	Parameters recommended by our industry
1700		−2,34			1,76		5,7		$k_p = 0{,}36$	113	Berlincourt [66]	
$\varepsilon_3 = 1872$; $\varepsilon_1 = 1596$	5,73	−2,35	7,8	3,84	−1,575		5,77		$k_{33} = 0{,}496$; $k_{15} = 0{,}46$			
$\varepsilon^T = 1600$; $\varepsilon^S = 1200$	5,4	−2,25		4,3	−1,8		5,5	$E = 1{,}1 \times 10^{12}$ d/cm²; $\sigma = 0{,}31$	$k_{33} = 0{,}45$; $k_p = 0{,}31$	110	[156]	
$\varepsilon = 1200$	3,6	−1,4		3,77			5,3	s = 1,1× ×10[illegible]		123	Ana'yeva [157]	Ceramics of technical raw material
1750÷3000		−2,4					5,9	$E = 1{,}25 \times 10^{12}$ d/cm²			Ana'yeva, Ugryumova, Strizhkov [158, 159]	Ceramics of high degree of purity

Table 5

Material	Chemical formula	Limiting operating temperature °C.	Density g/cm³	Crystallographic shear and form of oscillations	Effective piezoelectric modulus	Dielectric constant	Piezoelectric constant, X 10⁸	Elastic constant X 10¹²	Authors	Remarks
Tartrate of potassium (potassium tartaric acid)	$K_2C_4H_4O_6 \times \times {}^1/_2 H_2O$	80	1,987	$XY_{t\ 45°}$; longitudinal in length	$d'_{12} = d'_{13} = \frac{d_{14}}{2} = 34,5$	$\varepsilon^T_{11} = 6,40$	$g'_{12} = \frac{g_{14}}{2} = 68,3$	$s'_{22} = s'_{33} = 4,01$	Mason [22]	
Dihydrophosphate of potassium	KH_2PO_4	100		ZX_t edge shift	$d_{36} = 69,6$	$\varepsilon^T_{33} = 23,75$ $\varepsilon^S_{33} = 21,8$	$g_{36} = 39,4$	$s_{66} = 16,1 \div 16,4$	Mason [17,22]	Little applicable cut
				longitudinal in length	$d'_{31} = 34,8$	$\varepsilon^T_{33} = 21,8$	$g'_{31} = 20,2$	$s'_{11} = 4,77$		
Dihydrophosphate of ammonium (ammonium phosphoric acid)	$NH_4H_2PO_4$	100	1,803	$ZX_{t\ 45°}$; longitudinal in length	$d'_{31} = 74$	$\varepsilon^T_{33} = 15,7$	$g'_{31} = 50,2$	$s'_{11} = 5,1$	Mason [17, 22]	
				ZX_t shift along the edge	$d_{36} = 148$	$\varepsilon^T_{33} = 15,7$	$g_{36} = 118,5$	$s_{66} = 16,5$		
Triglycine sulfate	$(NH_2CH_2COOH)_3 \times \times H_2SO_4$	49	1,68	Longitudinal in length	For nonpolarized d_{32} = 76; For polarized d_{32} = 150	$\varepsilon_{22} = 43$	$g_{32} = 44,5$	$s_{22} = 23,2$	Konstantinova, Sil'vestrova, Aleksandrov, Yurin [160, 161]	
Terpinmonohydrate	$C_{10}H_{18}(OH)_2 \times \times H_2O$	116	1,11	ZX_t longitudinal in thickness	$d_{33} = 6,6$	$\varepsilon_{33} = 3,2$	$g_{33} = 25,9$	$s_{33} = 8,57$	Chumakov, Sil'vestrova, Aleksandrov [162]	
				Longitudinal in length	$d_{31} = 10,6$	$\varepsilon_{33} = 3,2$	$g_{31} = 41,6$	$s_{11} = 11,886$		
				Shift in thickness	$d_{15} = 17,3$	$\varepsilon_{11} = 2,8$	$g_{15} = 76,2$	$s_{44} = 40,9$		Cut difficult to use in constructions
Benzophenone	$(C_6H_5)_2CO$	47	1,219	$ZX_{t\ 45°}$; longitudinal in length	$d_{31} = \frac{d_{36}}{2} = 30,8$	$\varepsilon_{33} = 3,7$	$g'_{31} = 50,2$	$s'_{11} = 13,03$	Chumakov, Sil'vestrova, Aleksandrov [163]	

Table 5 (Continued)

Material	Chemical formula	Limiting operating temperature °C	Density g/cm³	Crystallographic shear and form of oscillations	Effective piezoelectric modulus	Dielectric constant	Piezoelectric constant, X 10⁸	Elastic constant X 10¹²	Authors	Remarks
Monohydrate of L rhamnose		126	1,471	YZ; longitudinal in length	$d_{33}=13,7$ $d_h=16,4$	$\varepsilon_{33}=2,9$ $\varepsilon_{33}=6$	$g_{33}=58,6$ $g_h=34,3$	$s_{33}=5,88$	Chumakov, Sil'vestrova, Aleksandrov [164]	Cut is used for realization of the regime of hydrostatic stress
Quartz	SiO_2	300	2,65	Curie or shear XY	$d_{11}=6,27$	$\varepsilon_{11}=4,49$	$g=17,52$	$s_{11}=2,649$	Curie, Vogt, Rikke,	
					$d_{11}=6,93$	$\varepsilon_{11}=4,58$	$g_{11}=19,26$	$s_{11}=1,277$	Mason [22]	
Tourmaline					$d_{33}=5,8$	$\varepsilon_{33}=6,05$	$g_{33}=15,15$		Rikke, Vogt	
					$d_{33}=5,5$	$\varepsilon_{33}=7,5$	$g_{33}=9,25$	$s_{33}=0,636$	Mason [22]	
Sulfate of lithium	$Li_2CO_4\cdot H_2O$	90	2,052	XY	$d_{22}=49$	$\varepsilon^T_{22}=6,5$	$g_{22}=94,7$	$s_{22}=2,25$	Boelman [23]	
				XY	$d=43,3$	$\varepsilon^T_{22}=6,5$	$g_{22}=6,5$	$s_{22}=2,13$	Mason [22]	
Seignette salt	$NaKC_4\times$ $\times H_4O_6 4H_2O$	24	1,775	L-cut; longitudinal in thickness	$d_L=197\div200$	$\varepsilon_L=170$	$g_L=147$	$s_L=5,6$		
				XY_t 45° longitudinal in length	$d'_{12}=57,5$	$\varepsilon^T_{11}=480$	$g'_{12}=15$	$s'_{11}\approx 6,6$		
				YX_t 45° longitudinal in length	$d'_{22}=80$	$\varepsilon^T_{22}=12$	$g'_{22}=85$	$s'_{11}\approx 8,2$		
Ethylenediamine tartrate (EDT)	$C_6H_6N_2O_6$	120	1,538	YX; longitudinal in length	$d_{22}=30,3$	$\varepsilon^T_{22}=8,2$	$g_{22}=46$	$s_{22}=3,34$		
				ZX; edge shift	$d_{33}=50$	$\varepsilon_{33}=6$	$g_{33}=1045$	$s_{11}=3,34$		

As was already stated above, from the point of view of the use of piezoceramics in an electromechanical converter-generator the most important parameter is the ratio $4\pi d_{33}/\varepsilon = g_{33}$. This ratio for the ceramics of barium titanate can be assumed equal on the average to $3.8 \cdot 10^{-8}$ CGSE. At the same time, for instance, for Seignette salt, with a 45° cut XY_{t45° the parameter g'_{21} playing the same role is equal to $85 \cdot 10^{-8}$ CGSE. Even for quartz the analogous parameter $g_{11} = 19.26 \cdot 10^{-8}$ CGSE. The small magnitude of parameter g_{33} for the ceramics of barium titanate is the consequence of a very great dielectric constant. Therefore, it is desirable to increase the ratio d_{33}/ε for the ceramics either by means of increasing the piezoelectric modulus or by means of decreasing the magnitude of the dielectric constant. One of the possible methods of decreasing the dielectric constant is introducing into the composition of the ceramics of barium titanate (before the process of its sintering) various kinds of impurities. Such impurities can serve as substances not belonging to the class of ferroelectrics. We conducted experiments on the use of the impurity of alumina (up to 10-15%), as a result of which a well sintering ceramics was obtained, and the displacement of the upper Curie point did not occur but the dielectric permeability decreased noticeably. Simultaneously there occurred a decrease in the piezoelectric modulus, but the ratio d_{33}/ε remained practically the same as for the ceramics of barium titanate [157, 165]. An attempt to create piezoelectric materials by means of grinding of the burned ferroelectric ceramics of barium titanate, molding of the obtained powder with a binding substance (for instance, methylmetacrylate), and subsequent polarization after polymerization of the filler [157, 165] leads to a sharp decrease in the piezoelectric modulus and a decrease in the parameter g_{33}. From our data it is possible to attain values $d_{33} = 0.02\text{-}0.09 \cdot 10^{-6}$ CGSE and values $g_{33} = 0.36\text{-}0.72 \cdot 10^{-8}$.

Analogous investigations were conducted by Zheludev [166, 167]. According to his data the maximum value of the modulus g_{33} for such kind of piezomaterial is on the average $2.7 \cdot 10^{-8}$, which in all exceeds our results several times.

The method of the introduction into the composition of ceramics of admixtures of other ferroelectrics of the type titanate of lead, tin, strontium, and so forth is more promising; this leads to the formation of a solid solution with new quantitative characteristics, for instance, with strongly displaced Curie point and with values of piezoelectric moduli and the dielectric constant differing from characteristics of ferroelectric components appearing in the composition of the given solid solution.

The number of works published to the present time concerning the question of dielectric, mechanical, and piezoelectric properties of ceramics complicated composition is very great. We investigated [119, 157, 165] the two-component compositions $Ba(TiSn)O_3$, $(BaSr)TiO_3$, and $(BaSr)TiO_3$ with the mixture CoO (0.5%); Roy [89, 90] investigated compositions $(BaSr)TiO_3$, $Ba(TiSn)O_3$, and $Ba(TiZr)O_3$; Smolenskiy and his colleagues [75-88] investigated broad class of compounds of type $(BaPb)TiO_3$, $(BaZr)TiO_3$, and others. In works of Mason [63, 147] double compositions of $(BaPb)TiO_3$ and triple compositions of $(BaPb)TiO_3$ + $CaTiO_3$ are investigated. Berlincourt, Krueger, Crawford, and Jaffe [66, 69, 71] investigated compositions $PbTiO_3$ + $PbZrO_3$. A large number of works [61, 74, 94] is devoted to ceramic compositions not containing titanium, for instance, niobates, tantalates, and others.

A summary of published data on parameters of piezoelectric ceramics of complicated composition on the basis of barium titanate (at room temperature) is given in Table 6.

Representing the greatest from the point of view of an increase in the piezoconstant g_{33} are solid solutions of type titanate of zirkonate of lead. Thus in work [168] for ceramics containing obvoiously 45% titanate of lead and 55% zirkonate of lead, the value of $g_{33} = 8.05 \cdot 10^{-8}$ is given, i.e., more than twice exceeding the mean value of the corresponding constant for ceramics of barium titanate; with this the value of the dielectric constant differs little from the value of the dielectric constant for ceramics of barium titanate. In the work [96] value of piezoconstant $g_{33} = 4.4 \cdot 10^{-8}$ is given for the composition of ceramics of 94% $BaTiO_3$ and 6% $CaTiO_3$, somewhat exceeding the value piezoconstant g_{33} of ceramics of barium titanate. It can be expected that such compositions will find wide application in electroacoustic technology.

Although a number of new complicated ceramic compositions do not give an increase in the parameter of g_{33}, in comparison with the ceramics of barium titanate, however, they possess properties substantial from the point of view of construction of piezoelectric converters. For instance, of great interest are compositions with an increased coercive force (solid solutions of barium titanate and titanate lead [93]) and compositions having a smaller temperature dependence of parameters than that of ceramics of $BaTiO_3$ without admixtures (for instance, 80% $BaTiO_3$ + 12% $PbTiO_3$ + 8% $CaTiO_3$ and 84% $BaTiO_3$ + 8% $PbTiO_3$ + 8% $CaTiO_3$ [63, 147]). Other solid solutions of lead titanate are known [170, 171, 173]; solid solutions of the type $(BaCa)TiO_3$ and $(BaPbCa)TiO_3$ permit obtaining a smoothed temperature dependence of parameters in the region of the low-temperature phase transition [63, 96, 174]. This is of considerable importance from the viewpoint of the making of sound receivers intended for operation at low external temperatures.

For certain applications piezoelectric ceramics possessing high temperature of the second phase transition are of interest. Here one should mention compositions of type of niobates of lead, tantalates of lead, and others [94, 95, 175]. At present solid solutions with the upper Curie point near 560° are obtained with satisfactory values of piezoelectric parameters. However, compositions with a high Curie point in most cases possess increased conductivity with high temperatures, which leads to difficulties with the polarization of piezoelements. For removal of this deficiency the introduction into the composition of admixtures of bismuth, cadmium, cerium, tungsten and so forth was used with success.

During the last few years appeared works in which the influence of technological factors (temperature of roasting, duration of endurance at maximum temperature, dispersiveness of polycrystalline powder, etc.) is considered on properties of ceramics of barium titanate [65, 176]. Works on the synthesis of barium titanate from chemically pure initial components [65, 158, 177] are also interesting. These works showed that properties of chemically pure ceramics of barium titanate exceed properties of ceramics prepared from initial materials of technical degree of purity [159].

Regardless of the fact that not all the new types of piezoceramics investigated to the present can be prepared in the form of samples whose dimensions permit using them as piezoelements for sound receivers, there is no doubt that in the near future technological difficulties will be surmounted and new piezoceramic materials will find practical application in electroacoustics. Therefore, we considered it useful to give in Table 7 combined data on dielectric and piezoelectric properties of certain new ceramic materials differing from the usual barium titanate and from its solid solutions.

On the basis of the totality of data on parameters of polarized ceramics of barium titanate we will take following values of parameters: dielectric constant

$\varepsilon = 1200$, piezoelectric modulus $d_{33} = 3.6 \cdot 10^{-6}$ CGSE and piezoelectric moduli $d_{31} = d_{32} = -1.4 \cdot 10^{-6}$ CGSE. These values of parameters correspond to that piezoceramic material which we basically used during the creation of prototypes of sound receivers. This material is obtained from technical raw material on technology described, for instance, in works [178-181].

Of course, the methods of calculation of piezoelectric elements given in following chapters are correct for ceramics of any composition; the numerical results of parameters of piezoelements and sound receivers from other ceramics can be obtained by inserting into the formulas values of piezoelectric, dielectric, and other constants corresponding to given concrete piezoceramics.

Table 6

Composition	Dielectric constant	Piezoelectric constants d_{33} ×10⁸	d_{31} ×10⁸	d_{15} ×10⁸	g_{33} ×10⁸	g_{31} ×10⁸	Density g/cm³	Elastic parameters	Coefficient of electro-mechanical coupling	Curie point, °C	Authors	Remarks
(Ba[illegible]Zn[illegible])TiO_3	ε=1500	1,8			1,5 0,5						Smolenskiy, Tarutin, Grudtsin [83]	
(Ba[illegible]Pb[illegible])TiO_3 (Ba[illegible]Pb[illegible])TiO_3 (Ba[illegible]Pb[illegible])TiO_3 (Ba[illegible]Pb[illegible])TiO_3	1000 800 700 600		—2,5 —2,4 —2,1 —1,3			3,14 3,76 3,77 3,72			0,26 0,28 0,27 0,165	180	Myl'nikova [93]	Values of k, ε and d_{13} are given when t = 20°, values of ε are taken approximately from graphs
(Ba[illegible]Ca[illegible])TiO_3 (Ba[illegible]Ca[illegible]Pb[illegible])TiO_3 (Ba[illegible]Pb[illegible])TiO_3 Pb(Zr[illegible]Ti[illegible])O_3	670 450 220 600		—0,95 —0,5 —0,4 —1,1			1,77 1,39 2,29 —2,29				130 150 250 250	Rez, Sma - zhevskaya, Kashkasheva [154]	
(Ba[illegible]Ca[illegible])TiO_3 (Ba[illegible]Ca[illegible]Pb[illegible]) TiO_3					4,4 4,65	—4,33 —1,33					Pasynkov, Vinogradov [96]	
PZT—4	$ε_1$=1300 $ε_3$=1200	7,68	—3,33	13,5	8,05	—3,46	7,5	Q=600	k_{33}=0,64 k_p=0,52 k_{31}=0,31 k_{15}=0,65	340	Berlincourt, B. Jaffe, G. Jaffe, Krueger [168]	
PZT—5	$ε_1$=1285 $ε_3$=1500	9,6	—4,2	14,7	8,05	—3,2	7,5	Q=75	k_{33}=0,675 k_p=0,53 k_{31}=0,32 k_{15}=0,655	300		
(Ba[illegible]Ca[illegible])TiO_3 (mol.%)	$ε_1$=1280 $ε_3$=1200	4,5	—1,74	7,71	4,71	—1,82	5,5	Q=500 $E_{11}=11,6\cdot10^{11}$ $E_{33}=11,1\cdot10^{11}$ d/cm² $E_{55}=4,4\cdot10^{11}$ d/cm²	k_{33}=0,49 k_p=0,325 k_{31}=0,19 k_{15}=0,495	115		

Table 6 (Continued)

Composition	Dielectric constant	Piezoelectric constants d_{33}	d_{31}	d_{15}	g_{33}	g_{31}	Density, g/cm^3	Elastic parameters	Coefficient of electro-mechanical coupling	Curie point °C	Authors	Remarks
		×10[illegible]			×10[illegible]							
$(Ba_{0,8}Pb_{0,12}Ca_{0,08})TiO_3$	400	1,8	−0,6		5,65	−1,88	5,4	$Q=1200$	$k_{33}=0,34$ $k_p=0,19$ $k_{31}=0,113$ $k_{15}=0,3$	140		
$(Ba_{0,95}Ca_{0,05})TiO_3+0,75CoCO_3$	1420			1,77			5,7		$k_p=0,31$ $k_{31}=0,182$	105	Berlincourt, B. Jaffe, G. Jaffe, Krueger [168]	
Zirconate of titanate of lead	$\varepsilon=1200$		−3,83			−1,41		$E_{11}=0,85\cdot10^{11}$ d/cm²	$k_{33}=0,355$ $k_p=0,6$	320	Crawford [71]	The composition is recommended for powerful transmitters
Zirconate of titanate of lead	$\varepsilon=1500$	9,6	−4,2		8,05	−3,51		$E_{11}=0,675\cdot10^{11}$ d/cm²	$k_{33}=0,318$- $k_p=0,54$ $k_{15}=0,675$	350		The composition is recommended for broad-and receivers
$Ba_{0,9}Pb_{0,1}TiO_3$	500	5,7	−0,69					$Q=800$ $E_1=1,2\cdot10^{11}$	$k_{31}=0,12$ $k_{33}=0,36$ $k_p=0,2$	150	Jaffe [169]	
$PbTi_{0,47}Zr_{0,53}O_3$	500	5,25	−1,68					$Q=300$ $E_1=0,75\cdot10^{11}$	$k_{31}=0,23$ $k_{33}=0,55$ $k_p=0,39$	350		
PZT—4	1200	3,9	−3,15					$Q=800$ $E_1=0,35\cdot10^{11}$	$k_{31}=0,29$ $k_{33}=0,63$ $k_p=0,5$	340		

Table 7

Composition	Dielectric constant	Piezoelectric constants d_{33}	d_{31}	d_{15}	g_{33}	g_{31}	g_{15}	Density g/cm³	Elastic parameters	Coefficient of electromechanical coupling	Curie point, °C	Authors
		$\times 10^{6}$			$\times 10^{6}$							
$(Pb_{0,6}Ba_{0,4})Nb_2O_6$	1250		−1,3			−1,31					280	Raz, Smazhevskaya [154]
$PbNb_2O_6$	ε=800	2,8			4,25						570	Goodman [61]
$Na_{1,0}Cd_{0,5}Nb_2O_6$	ε=500	5,25	−1,08						E_1=0,75·10^12	k_{31}=0,23 k_{33}=0,55 k_p=0,30	350	J. Jaffe [169]
$PbNb_2O_6$	ε=225	2,4	−0,33						E_1=0,8·10^12	k_{31}=0,045 k_{33}=0,42 k_p=0.07	570	
$Pb_{0,8}Sr_{0,2}Nb_2O_6$	440		−1,3			−3,64				k_r=0,26	450	Isupov, Kosyakov [95]
$Pb_{0,7}Sr_{0,3}Nb_2O_6$	502		−1,6			−4,02				k_r=0,31	380	
$Pb_{0,6}Sr_{0,4}Nb_2O_6$	755		−1,6			−2,64				k_r=0,26	310	
$Pb_{0,55}Sr_{0,45}Nb_2O_6$	1060		−1,5			−1,70				k_r=0,22	250	
$Pb_{0,7}Ba_{0,3}Nb_2O_6$	640		−1,1			−2,14				k_r=0,19	345	
$Pb_{0,6}Ba_{0,4}Nb_2O_6$	1190		−1,7			−1,76				k_r=0,27	290	
$Pb_{0,5}Ba_{0,5}Nb_2O_6$	1205		−1,1			−1,13				k_r=0,16	315	

CHAPTER II

METHODS OF THE DETERMINATION OF CHARACTERISTICS OF SOUND RECEIVERS

1. Basic Characteristics of Sound Receivers

Any sound receiver as an electroacoustic converter is usually characterized by the totality of the following data:

1) frequency characteristic of sensitivity; in the case considered by us of piezoelectric sound receivers the frequency response of sensitivity spreads as a rule from zero frequency to a certain limiting upper frequency, and therefore, the sensitivity at zero frequency, or the so-called static sensitivity, is one of the important parameters of sound receivers of a given type;

2) frequency-response of electrical impedance; in most cases it is necessary to know not only the modulus, but also the phase of impedance in the function of frequency;

3) totality of directional characteristics for a number of selected frequencies.

A necessity to determine the amplitude characteristics of sound receivers can appear only in special cases, for instance, if the sound receiver is intended for measurement of very large sound pressures; as a rule, measuring and other sound receivers are used within the linear section of the amplitude characteristic.

As is known, there exist different determinations of sensitivity as the basic parameter characterizing the sound receiver. We will be interested subsequently in mainly the so-called field sensitivity determined as the emf ratio developed by the sound receiver to that sound pressure which would exist in the sound field in the absence of a sound receiver. By disposing of the frequency response of the field sensitivity and frequency response of electrical impedance of the sound receiver, it is possible to calculate the actual sensitivity under any conditions of electrical load.

It is less convenient to use as a basic parameter characterizing the sound receiver such magnitudes as pressure sensitivity, since they do not characterize directly the real sensitivity of the sound receiver and require additional information about the frequency response, the so-called diffractional correction, and also about the frequency response of the mechanical or acoustic impedance of the sound receiver. The experimental obtaining of these data in a number of cases encounters considerable difficulties and requires not a smaller volume of measuring work than for the direct determination of the field sensitivity.

It is natural that the frequency response of the field sensitivity should be determined with a certain assigned location of the measuring emitter with respect to the investigated sound receiver. If the sound receiver possesses an expressed axial symmetry of the directional characteristic, it appears convenient to determine the frequency response of the sensitivity with the location of the measuring emitter on the axis of symmetry of directional characteristics of the sound receiver. With this we obtain the so-called axial sensitivity. By knowing the frequency response of the axial sensitivity it is possible to construct directional characteristics standardized with respect to the axial sensitivity, i.e., in relative units.

If the axial symmetry is absent, then nevertheless it is necessary to select some direction with respect to the sound receiver as a reference; for this direction the frequency response of the sensitivity is determined. The directional characteristics are standardized with respect to the sensitivity on the reference direction. Thus for cylindrical sound receivers as a reference direction a direction is selected perpendicular to the axis of the cylinder.

The above-mentioned determination of the sensitivity field requires an additional determination of the character of the sound field utilized during the measurement of this parameter As a rule, it is assumed that the sound receiver is in a field of a flat sinusoidal sound wave. This circumstance should be considered with the practical realization of corresponding measuring equipment.

With the use of sound receivers for the measurement of very small sound pressures the question is interesting of the minimum sound pressure which can be measured with the help of a given sound receiver in totality with a preamplifier assigned to it. However, as a rule, natural noises of the sound receiver are very small. Thus Goncharov and Krasil'nikov [182] showed that natural noises of piezoelectric elements, including those carried out from ceramics of barium titanate, are at least an order lower than those at the input of natural noises of electronic amplifier circuits. Therefore, the minimum measured sound pressure cannot be a characteristic of the sound receiver.

Finally, from the point of view of the operation of the sound receiver such technical parameters as the permissible limiting external static pressure, mechanical and vibration strength, degree of airtightness, and so forth, are of interest. Such paremeters of sound receivers, not being essentially acoustic or electroacoustic, we will not consider, since they are determined with the help of methods of technical measurements usually applied for such purposes.

2. Measurement of Static Sensitivity of Sound Receivers

As is mentioned above, the static sensitivity is the sensitivity of the sound receiver at zero frequency and its measurement logically becomes a part of the measurements having the purpose of obtaining the full frequency response of the sensitivity. However, usually the static sensitivity is measured by different methods than the sensitivity with non-zero frequencies. Indeed, with the zero frequency the diffractional corrections are equal to zero, and the field sensitivity coincides with the pressure sensitivity. Therefore, it appears possible to determine the static sensitivity of the sound receiver simply by placing the latter in a closed vessel (in which by a certain method excess pressure is created) and by measuring the constant emf appearing at the output of the converter of the sound receiver.

As a rule the static sensitivity is measured with relatively large excess pressures, which permits averting the use of dc amplifiers and using for the emf measurement at the output of the sound receiver string or other electrometers. However, it is necessary to apply excess pressures not exceeding the limit conditioned by the linear section of the amplitude characteristic of the sound receiver. For piezoceramic sensing devices nonlinearity starts to appear only with very large mechanical stresses, of the order of hundreds of kg/cm^2, and therefore, with the measurement of the static sensitivity of piezoceramic sound receivers it is possible to apply excess pressures of the order of atmospheres.

Essentially it does not matter what medium is used for the creation of the excess pressure; it is possible to use both gas and liquid. In our experiments we used a measuring device in which the tested sound receiver was placed in a vessel filled with oil or water; however, the excess pressure in the liquid was created owing to the excess air pressure above the free surface of liquid. For this purpose a common piston air pump with a manual drive was used. The excess pressure was measured with the help of a precision manometer, and the emf with the help of a one-string electrometer of the Edel'man-Lutz type. An electrometer of this type is convenient in that it permits changing the sensitivity either by a suitable selection of the potential difference between the fixed electrodes (knives) or by means of a micrometric change in the distance between them. The measured emf with our experiments is usually from a tenth of a volt to units of volts.

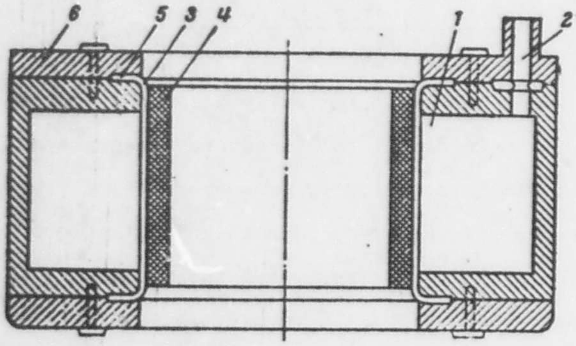

Fig. 9. Device for the creation of static pressure on the lateral surface of a cylindrical piezoelectric element
1) cylindrical chamber; 2) outlet to the pump; 3) rubber shell; 4) piezoelectric element; 5) edge of shell; 6) flange.

Not only was the measurement of the static sensitivity of sound receivers in assembled form produced by the described method, but also a preliminary check of the sensitivity of ceramic piezoelements. However, for the checking of the sensitivity of cylindrical piezoelements with different forms of polarization it turned out to be more convenient to use a device whose diagram is shown in Fig. 9. In the cylindrical chamber 1 filled by air excess pressure is created with the help of pump 2 connected to the pipe. The tested cylindrical piezoelement 4 tightly stretches the shell of thin rubber 3. The folded edges of the shell 5 are pressed to the body of the chamber with the help of flanges 6, which ensures the necessary airtightness. The described device permits creating an excess pressure on the lateral surface of the cylindrical sample without the necessity of assembly of the sound receiver as a whole.

Let us note that the equipment used for the determination of the static sensitivity of the sound receiver can be applied and was applied by us also for the test of the gathered piezoceramic sound receivers for strength and for the checking of their waterproofing. In these cases the excess pressure of the order 10 atm was used.

3. Determination of the Frequency of the Electrical Impedance of Sound Receivers

The frequency response of the electrical impedance of a sound receiver can be determined either as a totality of two frequency responses of the active and reactive components of impedance or as a totality of two frequency responses of the modulus of the impedance and its phase angle. The latter method is more convenient, since the frequency response of the modulus of impedance has an independent value, and in many cases it is possible to be limited by the determination of just this characteristic.

We determined the modulus of electrical impedance by the common method, by measuring the voltage on the sound receiver with help of a vacuum-tube voltmeter with an assigned frequency and assigned value of current in the electrical circuit of the sound receiver. Thus, the frequency response of the modulus of impedance was determined essentially either as frequency dependence of the voltage on the sound receiver with a constant (independently of the frequency) current flowing through its electrical circuit or as a frequency dependence of the current in the electrical circuit with the supporting of a constant (independently of frequency) voltage drop on the sound receiver. In order to avoid difficulties usually appearing with such kind of measurements in connection with the presence of negligible capacities of measuring instruments with respect to the earth, thermoelectric milliammeters were used for the measurement of current.

Determination of the frequency response of the phase angle of electrical impedance of the sound receiver was carried out with help of a phasemeter whose principal diagram is shown in Fig. 10.

The action of the diagram of the phasemeter is reduced to the conversion of voltages on the "potential" and "current" inputs of the phasemeter in a sequence of short pulses of identical and constant height constructed on moments of transition through the zero of corresponding voltages. Both totalities of pulses

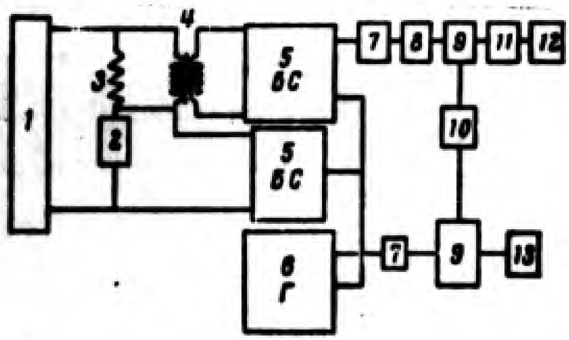

Fig. 10. Fundamental circuit of a phasemeter. 1) voltage source of audio-frequency; 2) tested sound receiver; 3) shunt resistance; 4) broad-band uniting transformer; 5) balance mixers; 6) first heterodyne; 7) filters and amplifiers of the first intermediate frequency; 8) phase inverter of the goniometric type; 9) mixers; 10) second heterodyne; 11) filters of the second intermediate frequency; 12) amplifiers and limiters with differentiation at the output; 13) cathode-ray indicator.

join the plates of the vertical beam deflection of the cathode-ray oscilloscope, the horizontal sweep of which is synchronized with the frequency of the sequence of the pulses. The process of measurement is reduced to the combination on the screen of the cathode ray oscilloscope of two pulses (one of them corresponds to the sequence of pulses of "current" circuit and second to the sequence of pulses of "potential" circuit). This combination is carried out by the rotation of the rotor of a goniometric phase inverter, and the phase angle is directly counted off on the dial of the angle of rotation of the rotor calibrated both for positive and for negative angles.[1]

The working range of frequencies of a given phasemeter is from 5 to 200 kilocycles; the accuracy of the measurement of the phase angle is 1°.

Measurement of the electrical impedance of the sound receiver can be conveniently used also for an estimate of the location of electromechanical resonances of the sound receiver by the scale of frequencies and thereby for an estimate of the working range of frequencies of the sound receiver. Of course, if resonances of the sound receiver are located very high according to the scale of frequencies, the upper limit of the working range of frequencies is determined by a fall in sensitivity due to the diffractional phenomena when dimensions of the sound receiver become comparable with the wave length. In this case the maxima of sensitivity corresponding to the resonances lie outside the limits of the working range of frequencies and are not of considerable interest. However, in many cases for aerial sound receivers we observe on the upper frequencies at first a certain fall in the sensitivity as compared to the static caused by diffractional phenomena and then again a rather sharp increase in the sensitivity caused by the first resonance. The region of the first resonance already enters

[1]The described electronic phasometer was developed by Gotsak [183] at the Acoustic Institute of the Academy of Sciences of the USSR.

into the working range of the frequencies. Finally, for hydroacoustic sound receivers for the most part resonances approach simultaneously or even earlier than the diffractional lowering of the sensitivity approaches, and the upper limit of the working range of frequencies is determined practically by the frequency of the first resonance. These considerations belong to the broad-band sound receivers; for narrow-band sound receivers resonance peaks of sensitivity have the dominating value.

The measurement of electrical impedance of the sound receiver certainly dces not permit determining the upper limit of the working range of frequencies if it is conditioned by diffractional phenomena, but at the same time permits easily the determination of the natural frequency of the sound receiver. Highly expressed resonances are easily determined by measurement of the modulus of electrical impedance in a function of frequency; weakly expressed resonances are easier to determine by means of phase measurements.

Electrical measurements directed on the determination of resonance frequencies were produced by us not only for gathered sound receivers but also for separate piezoelectric elements. Such measurements made it possible to judge to what extent the piezoelectric converter of the given form is useful for designing of a certain type of sound receivers. As a rule, even for hydroacoustic sound receivers the determination of the position of resonances by electrical means can be conducted in an air medium, since the reaction of the water medium on the sound receiver displaces the natural frequencies only insignificantly.

In general in the process of development of sound receivers it is possible to recommend taking measurement on the electric side before own acoustic, since electrical measurements are less laborious and in totality with the measurement of the static sensitiveness permit obtaining oriented information about the sensitivity of the sound receiver and its working frequency band. It is expedient to produce acoustic measurements only for finally worked variants of sound receivers.

4. Determination of Frequency Responses of the Sensitivity of Sound Receivers by the Field

To determine the frequency responses of the sensitivity of sound receivers by the field we used the known method founded on the reciprocity theorem. For spherical and cylindrical piezoceramic sound receivers the method of measurement of the sensitivity with the use of three converters [184] is convenient. We conducted such measurements in water in an unmuffled basin with pulse radiation. It is convenient to place all three converters, the tested sound receiver, reversible converter, and auxiliary converter-emitter in horizontal plane at equal distances from one another at angles of an equilateral triangle. If reversible converter and converter-emitter are nondirectional in the horizontal plane (spherical or cylindrical converters) the necessity of mutual displacement or the turning of the converters in the process of measurements is excluded.

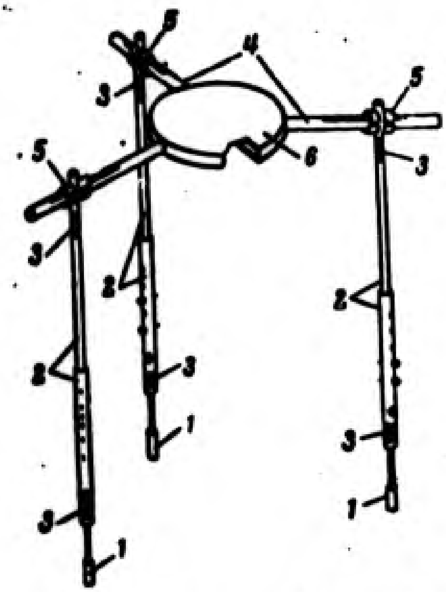

Fig. 11. Device formounting three converters with the calibration according to the method of reciprocity.

A device for mounting three converters for measurements is shown schematically in Fig. 11. Converters 1 were fastened to light duralumin tube-holders 2. In order that the converters-receivers be protected from the transmission of energy from the converter-emitter by vibration means, on the bracing frame rubber shock absorbers 3 are provided. The tube-holders are made sectional so that by means of displacement along the vertical of the lower telescopic part of tube it is possible to change depth of submersion of the converters. All three vertical tubes are fastened to the horizontal tubular crossarms 4 with the help of sliding muffs 5, which correctly permits disposing the converters at the vertexes of the equilateral triangle with the necessary length of the side. The horizontal crossarms are fastened to the cylindrical hollow body 6, which also has the role of a float since the whole device floats on the surface of water in a basin.

The block diagram of the pulse measuring system used by us is shown in Fig. 12. The pulse modulator 2 creates at the input pulses τ_1 in duration with a high-frequency filling attached to the zero reading of time. The modulator governs the timer 3 by means of forming a rectangular one-sided pulse τ_1 in duration attached moreover to the beginning of the time reading. To measure the current in the pulse the oscilloscope 5 is used and to measure the voltage in the pulse, oscilloscope 6. At distance L from the converter-emitter 7, converter-receiver 8 is located. The impulse selector 10 opens the receiving

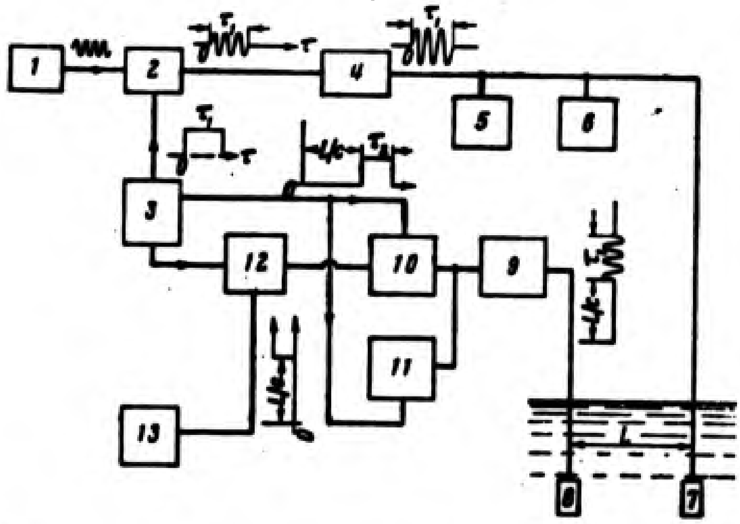

Fig. 12. Fundamental diagram of the pulse arrangement for the calibration of converters according to the method of reciprocity. 1) master oscillator; 2) pulse modulator; 3) timer; 4) terminal amplifier; 5, 6) electronic oscilloscope; 7) converter-emitter; 8) converter-receiver; 9) broad-band amplifier; 10) pulse amplifier; 11) dual-beam oscilloscope; 12) memory unit; 13) measuring instrument.

channel at the selected interval of time τ_2 with a delay in time with respect to the initial moment of the time reading. Control by the selector was carried out from timer 3 creating for this purpose a one-sided П-shaped pulse τ_2 in duration with a changed delay in time, which in our experiments was selected equal to L/c, i.e., the time of the path of the pulse from the emitter to the receiver. The duration of time of the opening of the receiving channel for the most part was selected at 0.1 millisecond; with this it was possible by changing the delay to trace the form of the pulse taken. To observe the general picture of the pulses and reverberational processes in the basin dual-beam electronic oscilloscope 11 was used on the upper line of which the amplitude-time picture of the signals was depicted and on the lower line, the position of the gating pulse indicating the time and duration of the opening of the receiving channel. To obtain the gating pulse on the oscilloscope 11 the corresponding voltage was fed from the timer 3. After the selector 10, the radio-frequency voltage of the accepted and amplified pulse was fed to the memory unit 12, which created at the output after the pulse arrival a direct-current and retaining voltage proportional to the pulse amplitude. This dc voltage was measured with help of a switch measuring instrument 13. The timer worked cyclically with a variable off-duty factor; in our experiments the frequency of the pulse sequence was changed from

1 to 50 cps and the pulse duration, from 2 to 20 milliseconds During the cyclical work readings of the memory unit 12 were cutoff directly before the beginning of the following cycle; the moment of cutoff was determined by the corresponding driving pulse proceeding from the timer. The process of the cut-off of the voltage in the memory unit and the appearance of the voltage again with the entering of the following pulse had so small a duration that this practically did not show on the accuracy of the readings of the instrument 13.

Oscilloscope 5 and 6 were calibrated with the help of a replacing voltage, measured by vacuum-tube voltmeter, obtained from auxiliary generator at the corresponding frequency. In exactly the same manner the continuous electrical calibration of the receiving channel was produced continuously by means of the introduction into the break of the circuit of a calibrating voltage from the auxiliary generator with an attenuator.

The connection of the receiving and transmitting channel of the measuring apparatus to the corresponding converters was carried out with the help of a switching circuit ensuring the possibility of carrying out three series of measurements necessary for the determination of the sensitivity according to the method of three converters:

1) The auxiliary emitter creates a sound field. The current flowing through the emitter and the voltage of open-circuit conditions V_x, developed by the tested sound receiver, are measured.

2) The receiving channel is switched to the reversible converter, and with the same current through the auxiliary emitter the voltage of no-load conditions developed by the reversible converter in conditions of the reception V is measured.

3) The transmitting channel is switched to the reversible converter which now creates a sound field; the current flowing through this converter I, is measured and with the help of the receiving channel the voltage of no-load conditions V_x' developed in this case by the tested sound receiver, is measured.

The indicated totality of the measured magnitudes permits calculating the sensitivity of the tested sound receiver by the formula

$$E_x = \sqrt{H \frac{V_x}{V} \frac{V_x'}{I}},$$

where H – the parameter of reciprocity which in this case, as usual, we took equal to

$$|H| = \frac{2R\lambda}{\rho c}, \qquad (1)$$

where R — the distance between the converters; c — the speed of propagation of sound in the water; λ — the length of the sound wave at that frequency on which the measurement is conducted; ρ — the density of the water.

To measure the sensitivity of the sound receivers possessing axial symmetry of directional characteristics, for instance, sound receivers with a flat receiving diaphragm, the method of three converters is not very convenient since it requires change during the experiment of angular orientation of at least the tested converter. Therefore, for a determination of frequency responses of the sensitivity of sound receivers with an expressed axial sensitivity, we used the pulse method of measurement with a reflection of the signal from the free surface of the water. Of course, such a method could be applied only for reversible converters, i.e., for sound receivers which could be used also as emitters.

The basin in which the experiments were conducted is supplied by a coordinate device on a rolling bridge (see Fig. 13 where in depth is seen the coordinate spacer and on the right the automated turning device for the determination of directional characteristics of the converters). With the help of the coordinate spacer the tested converter could be set at an assigned depth in such a manner so that its receiving-radiating surface would be strictly parallel to the free surface of the water.

The process of carrying out of measurements in the given case consists in the following: 1) the tested converter is used as an emitter where upon the current I flowing through the converter is measured; 2) the pulse reflected from the free surface of the water is taken by the tested sound receiver, and the end E developed by the sound receiver in conditions of reception is measured. On the basis of these measurements the axial sensitivity of the sound receiver (in no-load conditions) is determined by the formula

$$E_x = \sqrt{H\frac{E}{I}},$$

where H — the parameter of reciprocity, which in this case is equal to

$$H = \frac{4r\lambda}{\rho c}; \qquad (2)$$

where r — the distance from the sound receiver to the free surface of the water; λ — the wave length; c — the speed of sound; ρ — the density of the water.

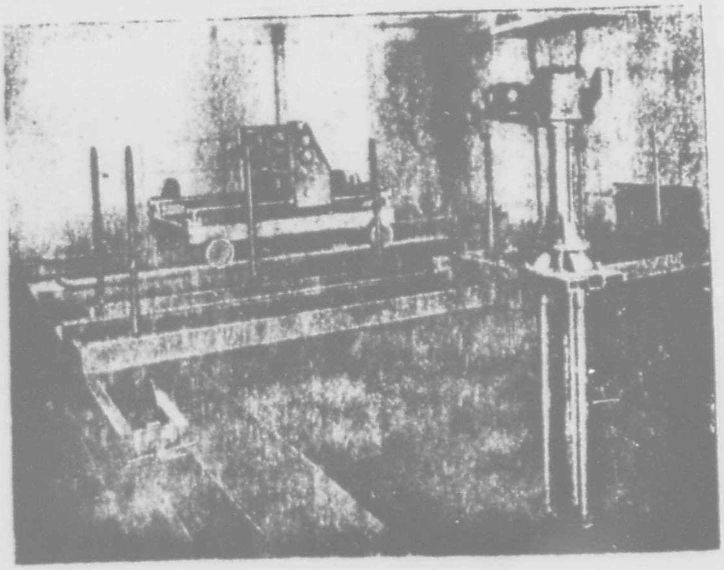

Fig. 13. Coordinate and turning device for fastening converters during measurements in a basin.

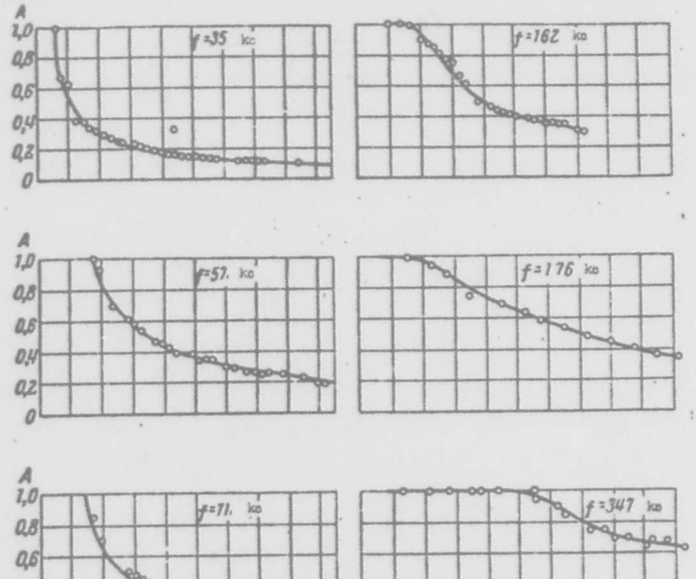

Fig. 14. Dependence of the amplitude of the receiving signal on the depth of submersion during calibration of flat converters with the use of the reflection from the free surface of the water.

Let us note that simultaneously one can determine the sensitivity of the tested converter in radiation conditions by the formula

$$R_x = \sqrt{\frac{1}{H}\frac{E}{T}}$$

(designations are the same as earlier).

It should be noted that the value of the parameter of reciprocity from formulas (1) and (2) can be used only with distances R and r considerably exceeding the axial extent of the projector zone of the converter at a given frequency. In order to judge the character of the sound field created by the tested converter in radiation conditions, we investigated the dependence of the amplitude of the taken reflected signal on the depth of submersion r of the converter. Fig. 14 gives results for one of the converters tested by us. The converter was a round plate 10 cm in diameter placed in the body ensuring the absence of radiation from the opposite side.

It is easy to see that while the distance from the radiating surface of the converter to the free surface of water less than double the extent of the projected zone of the converter at a given frequency, the taken reflected signal is constant, and only with a further increase in the distance does the decrease in the reflected signal begin gradually approaching the spherical law. At relatively low frequencies (up to 100 kilocycles) the spherical law of the decrease in amplitude of the signal is established already at relatively low depths of submersion of the converter (of the order of tens of centimeters), and consequently with the measurement of the sensitivity on such frequencies it is possible to use the parameter of reciprocity determined by the formula (2). However, in view of the limited depth of the basin, at higher frequencies it appeared impossible to select a sufficiently great depth of submersion of the converter, and it was necessary to carry out the measurement within the projected zone of the converter. In this case the radiated (and taken respectively) wave can be considered flat and determined by the parameter of reciprocity by the formula

$$H = \frac{S}{\rho c}, \qquad (3)$$

where S — the area of the radiating surface of the converter (or, what amounts to the same, the area of the cross section of the sound beam in the projected zone); c — the speed of sound; ρ — the density of the water.

With the use of formula (3) we should assume that the converter is acoustically absolutely rigid. If this condition is practically not fulfilled, then it is necessary to introduce corrections considering the acoustic impedance of the tested converter. However, this question will be considered in greater detail with a description of methods of the testing of sound receivers in tubes and on rigid delay lines.

It should be noted that with the measurement of sensitivity according to method of three converters as also with the use of the method with reflection from the surface of the water at distances exceeding the extent of the projected zone, we obtain the sensitivity of the sound receiver in a free field. During measurements with the use of the reflection within the projected zone we actually obtain the pressure sensitivity and introduce the diffractional correction equal to 2, which corresponds to the absolutely rigid converter the diameter of which exceeds several times the wave length in the medium.

5. Determination of Frequency Responses of the Pressure Sensitivity of Sound Receivers

For converters with a flat receiving-radiating surface it is convenient to use methods of determination of the sensitivity founded on the application of waveguides of limited cross section. Used most frequently for this purpose is a waveguide in the form of a pipe filled with liquid (for instance, water) pipe with metallic walls [185]. To test air sound receivers one should use a pipe with a gas (air or hygrogen) filling [186]. We used vertical pipe filled with water for the measurements; it was possible to use the same complex of measuring equipment and the same method of determination of the sensitivity that was used during the work in the basin with use of reflection from the surface. Of course, with measurements in a pipe filled with water there are a number of possible sources of errors. First of all, one should consider the influence of the pliability of the walls of the pipe and to select a thickness of the walls of the pipe so that the dispersion region of frequencies caused by the presence of the pliability of the walls lay beyond the borders of the frequency range necessary for measurement. For measurements at frequencies up to 30 kilocycles we used a brass pipe with an internal diameter of 30 mm and a thickness of the wall of 15 mm.

With measurements in the pipe only the pressure sensitivity of the sound receiver, and, consequently, in the case of the necessity to determine the diffractional corrections one should take additional measurements in the free field. However, in many cases the measuring sound receivers are used in the pipes, and therefore such a parameter as pressure sensitivity has a certain independent interest.

A second possible source of errors during measurements in a pipe filled with water consists of air bubbles remaining on the internal surface of the wall of the pipe during the filling of it with water. Therefore, it is necessary to use degassed water and to fill the pipe as slowly as possible.

The drawbacks connected with the use of a liquid waveguide can be eliminated to a considerable degree by the use of solid waveguide from a material which absorbs sound little, for instance, from aluminum, bronze, and other suitable metals. The hard waveguide applied by us, as far as we know, was used for calibration of electroacoustic converters for the first time.

We decided on a selection of the waveguide in the form of a rod of round section made of duralumin. Such a waveguide has comparatively little weight and is convenient in conversion. Moreover, duralumin easily is tooled, which permits obtaining a good mechanical contact between the flat surface of the diaphragm of the converter and the face surface of the waveguide. The surfaces indicated are subjected to grinding and before the beginning of the experiment are rubbed in oil.

The solid waveguide permits easily conducting tests of even little sensitive converters, inasmuch as in this case the acoustically solid converter turns out to be much better coordinated with the medium than with the liquid water waveguide.

We took measurements on liquid and solid waveguides by the pulse method using the signal reflected from the free end of the waveguide where the same equipment was used as during work in the basin with the reflection from the free surface of the water.

As was already said, the method of calibration of converters on the waveguide can be used only for the determination of the pressure sensitivity of the sound receiver. As is known, by pressure sensitivity of converter is implied the ratio of emf developed by the converter in conditions of reception to the pressure actually having an effect on the diaphragm of the converter. It is natural that the pressure sensitivity does not depend on parameters of the medium utilized during measurements. Therefore, for the measurement of this parameter it is possible to use different waveguides, including the solid, and in the latter case only longitudinal waves are used. The sensitivity of the converter with respect to pressure at low frequencies coincides with the static sensitivity.

We will develop relationships necessary for the calculation of the pressure sensitivity on the basis of data of the experiment performed on a liquid or solid waveguide.

Let us designate the pressure sensitivity of the receiver by $M = E/p_{\Phi}$, where p_{Φ} — actual pressure having an effect on the diaphragm of the receiver. Further we will introduce the auxiliary concept of "field sensitivity" during the work of the receiver jointly with the waveguide [187]. This sensitivity we will define as the ratio of the emf developed by the sound receiver to that sound pressure which would exist in a given section of the waveguide if it were infinite. We will designate the field sensitivity by $M' = E/p_0$, where p_0 — sound pressure of the traveling wave. Sensitivity on pressure M and sensitiveness on field M' are connected by the ratio

$$M = \frac{M'}{1+\beta},$$

where β — coefficient of reflection from the surface of the receiver.

The experiment on the determination of sensitivity of the converter on the waveguide is carried out essentially just as with measurements with the use of the reflection from the free surface of the water. At the time of sending of the pulse the effective value of the current in the pulse I_1 is measured, and at the arrival time of the reflected pulse the emf E_1 developed by sound receiver is measured. The sensitivity M_1' is calculated by the formula

$$M_1' = \sqrt{\frac{E_1}{I_1} H},$$

where H — parameter of reciprocity equal to $S/\rho_1 c_1$ (S — cross section of the waveguide equal to the area of the diaphragm; $\rho_1 c_1$ — wave impedance of the medium of the waveguide). Thus the pressure sensitivity is equal to

$$M = M_1 = \frac{1}{1+\beta}\sqrt{\frac{E_1}{I_1} H}.$$

As is known for the plane wave

$$\beta = \frac{z-1}{z+1},$$

where z – input mechanical impedance of the sound receiver.

Hence we obtain finally

$$M = M_1 = \sqrt{\frac{E_1}{I_1}\frac{z}{\rho_1 c_1}\frac{(z+1)^2}{(z-1)^2}}.$$

In the formulas obtained by us the input mechanical impedance of the tested converter is retained. Therefore, for the determination of the sensitivity it is additionally necessary to obtain experimentally frequency response of the input impedance. The latter is a complex value, and consequently it is necessary to obtain the frequency response of its active and reactive components. This is possible to carry out by measuring the modulus of reflectivity and phase shift between the reflected and incident waves (using the tested converter as a reflecting object). For this we place it on the free end of the same liquid or solid waveguide which is used for the determination of sensitivity. On other end of the waveguide an auxiliary converter is disposed for the sending and reception of the pulse signal.

As a rule, we measured the mechanical impedance of the tested converter on the waveguide of duralumin, i.e., we measured the magnitude $z/\rho_1 c_1$, where $\rho_1 c_1$ – wave impedance of duralumin. Transition to the value of impedance in water is easily carried out by the formula

$$\frac{z}{\rho c} = \frac{z}{\rho_1 c_1}\frac{\rho_1 c_1}{\rho c},$$

where ρc – wave impedance of water.

The method of measurements of the mechanical impedance is described in detail in the work of Areyeva [188]. In the experiments we used for the measurement of impedance the electronic circuit of the measuring apparatus of Ageyeva amiably given by her at our disposal.

If from the experiment the modulus of reflectivity $|\beta|$ and phase shift between the incident and reflected waves φ, then the active and reactive components of the input mechanical impedance and its modulus are calculated by the known formulas:

$$x = \frac{1-\beta^2}{1+\beta^2-2\beta\cos\varphi},$$

$$R = \frac{2\beta\sin\varphi}{1+\beta^2-2\beta\cos\varphi},$$

$$|z| = \sqrt{R^2+x^2}.$$

Results of the test of converters in a solid waveguide (in our case on a duralumin rod) were compared with results of tests in pipe filled with water; with this a satisfactory coincidence of results is obtained.

Let us note that the method of measurement of sensitivity in solid waveguides, as it seemed to us, can be especially convenient for the test of those converters which are essentially intended for work on a load in the form of solid body, for instance, with the test of sound emitters and sound receivers utilized in flaw detection.

6. Determination of Directional Characteristics of Sound Receivers

The determination of directional characteristics of developed sound receivers was conducted basically in an open reservoir with the help of automatic equipment available on barge laboratory of the Volga Scientific Station of the acoustic Institute of the Academy of Sciences of the USSR.

This equipment consisted of a lifting-turning device with an electric drive and two electronic circuits, transmitting and receiving recording.

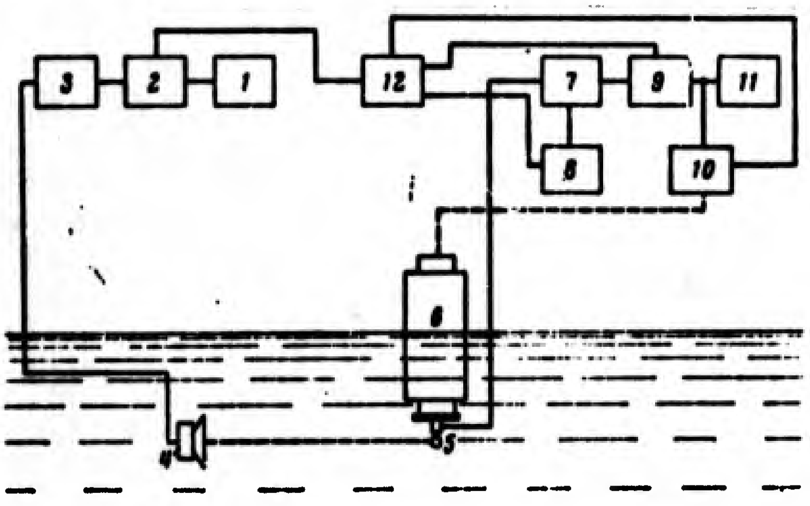

Fig. 15. Fundamental diagram of the equipment for automated registration of the form of directional characteristic of the converter. 1) master oscillator; 2) pulse modulator; 3) terminal amplifier; 4) hydroacoustic radiator; 5) tested sound receiver; 6) turning device; 7) broad-band amplifier; 8) control dual-beam cathode-ray oscilloscope; 9) electronic memory unit; 10) recorder of directional characteristics; 11) output electronic vacuum-tube voltmeter; 12) timer.

A simplified block diagram of the equipment is given in Fig. 15.

The recorder of directional characteristics 10 is a cathode-ray tube with a screen large in diameter, on which the directional characteristic of the tested sound receiver is depicted and from which it is photographed. The rotation of the sweeping system of the recorder is carried out with the help of an electrical shaft connecting the recorder with lifting and turning device 6.

The lifting-turning device 6 permits not only carrying out the automatic rotation of the tested converter 5 but also the adjusting of its position in depth. The working range of frequencies of electronic circuits of the measuring installation is from 10 to 500 kilocycles. The duration of the pulses can be changed from 0.2 to 2.0 milliseconds and the frequency of pulsing from 1 to 50 cps. The timer 12 permits opening the receiving circuit with the corresponding delay of time at an interval of time equal to or smaller than the duration of the sending and thereby avoiding the influence of undesirable reflections. The dual-beam cathode-ray oscilloscope 8 permits observing a picture of the useful signals and reverberation in the reservoir and also selecting with the help of a gate marker the necessary moment of the opening of the receiving circuit.

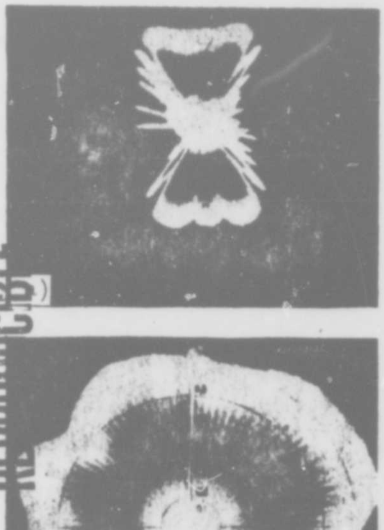

Fig. 16. Example of the directional characteristic of a converter.

The delay time can be changed from 0.2 to 20 milliseconds, which permits selecting any distance of the radiator from the tested converter within the length of the barge laboratory. The speed of rotation of the turning device 6 was selected at about one turn per minute, which permitted not only the examining of the directional characteristic on the recorder 10 visually but also the recording in sufficient detail of the directional characteristic of the converters with a high degree of directivity, for instance, possessing an apex angle of the directional characteristic of an order of units of degrees.

In our experiments the distance between the radiator 4 and the tested sound receiver 5 was changed from 0.5 to 7 m, for which the radiator was fastened with the help of a vertical rod to a carriage travelling on rails along the opening in the deck of the barge laboratory. Fig. 16 shows photographs of directional characteristics obtained with the help of described equipment.

7. General Order of the Carrying Out of Test of the Developed Sound Receiver

On the basis of our experiment we can recommend some sequence of the carrying out of measurements during a test of the developed sound receiver.

First of all a measurement is taken of the capacity and static sensitivity of the piezoelectric element which is assumed to be used in the sound receiver; the tangent of the dielectric-loss angle and resistance loss. After assembly of the sound receiver an approximate determination of operating band frequencies is produced; for this the appropriate frequency dependence of electrical impedance (in an air medium) is determined. Further on the sound receiver the static sensitivity , capacitance, tangent of the angle of dielectric losses, leakage resistance, etc., are checked; the results obtained are compared for the establishment of the quality of assembly with corresponding data for the isolated piezoelectric element.

If the assembly is performed correctly then the characteristic responses of the sound receiver are determined and its working range made more accurate. Measurements depending upon the assignment of the sound receiver are made by one of methods described above. The frequency response, of course, is determined for a certain selected reference direction (for instance, the frequency response of the axial sensitivity).

In conclusion in selected number of frequencies directional characteristics of the sound receiver standardized with respect to the sensitivity on the reference direction are determined.

Such a sequence of the carrying out of tests, as a rule, guarantees the obtaining of the necessary results with the least volume of the measuring work.

CHAPTER III

NONDIRECTIONAL BROAD-BAND SOUND RECEIVERS

1. Formulation of the Problem. First Model of a Nondirectional Sound Receiver

The problem of the creation of miniature nondirectional sound receivers was put before the Acoustic Laboratory of the Physical Institute named after P. N. Lebedev of the Academy of Sciences of the USSR in connection with the necessity of investigation of the spatial structure of sound fields. Earlier for such measurements sound receivers were used with a sensitive element of cubic form made from a piezocrystalic material. However, in 1950 due to works of a group of colleagues under the leadership of V. S. Grigor'yev it was established that the directional characteristics of such sound receivers even with dimensions of the sensing element considerably less than the length of the sound wave in the surrounding medium differ greatly in form from the spherical. The existence of the expressed directivity of miniature sound receivers was noted even with dimensions of a sound receiver 10 to 15 times less than the wave length.

For an example Fig. 17 gives the directional characteristic of "point" sound receiver with a sensing element of ethylenediamine tartrate with dimensions of 2 mm × 2 mm × 2 mm at a frequency of 50 kilocycle, i.e., with the length of the sound wave in water equal to 3 cm. To insulate the receiving element from the water medium it was included in a thin-walled cylindrical glass of plexiglas 40 mm in diameter filled with transformer oil. The directional characteristic has dips up to zero. The same was observed for this sound receiver at other frequencies.

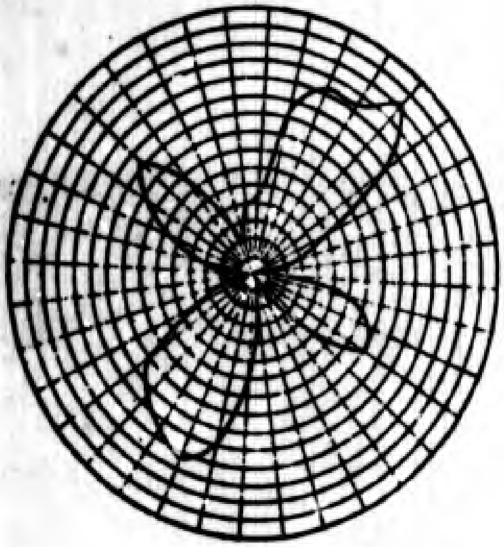

Fig. 17. "Point" directional characteristic (2 mm × 2 mm × 2 mm) sound receiver of ethylenediamine tartrate at a frequency of 50 kilocycles.

We conducted analogous experiments with miniature piezoelectric elements of polarized ceramics of barium titanate. Fig. 18 gives the directional characteristics of a piezoceramic sound receiver with a sensing device in the form of a small cube 1 cm × 1 cm × 1 cm. To eliminate the possible influence on the directional characteristic of the insulating housing the piezoelement was covered with a film of waterproof varnish, and the determination of the directional characteristics was carried out without the housing. From photographs of the directional characteristics one can see that for such a receiver the dipole and quadrupole properties are expressed brighter than the omnidirectional reception. Apparently, this is connected with the fact that the modulus of the hydrostatic stress of the ceramics of barium titanate $d_{BC.CX.} = d_{33} + 2d_{31}$ is considerably less than the piezoelectric modulus in the direction of polarization d_{33}.[1]

Almost all the piezoelectric crystals known at present (the exceptions are sulfate of lithium, tourmaline l-romnose [?]) have crystallographic axes in the direction of which at a certain angle to which the piezoelectric properties of crystal are expressed greater than the piezoelectric properties determined by the modulus of the hydrostatic stress. Therefore it is apparently difficult to make a sound receiver with a crystal sensing device the emf on the facings of which would be proportional only to the piezoelectric modulus of the hydrostatic stress.

From Fig. 18 one can see that with a decrease in the frequency the degree of directivity of the sound receiver nevertheless decreases. Therefore, in principle it would be possible to go further by way of a further decrease in dimensions of the sensing device. However, this inevitably is connected with a decrease in the sensitivity and capacity of the piezoelement, which is always

[1] d_{33} and d_{31} have opposite signs.

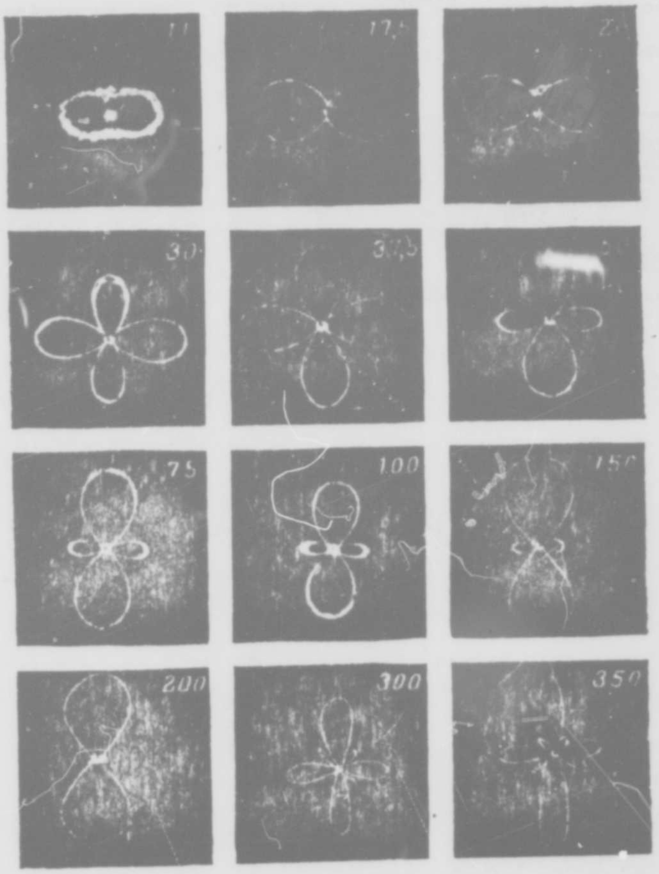

Fig. 18. Directional characteristic of the sound receiver in the form of a cube of ceramics of barium titanate 10 mm × 10 mm × 10 mm in dimension. Numbers on the figures are the frequency in kilocycles.

undesirable. It would be more correct, certainly, to go by way of the creation of sensitive piezoelements with a radial symmetry of form which appeared possible when we started to use piezoceramics.

In 1950 by the proposal of N. N. Andreyev and V. S. Grigor'yev at the Acoustic Institute of the Academy of Sciences of the USSR spherical radial-polarized elements were made from ceramics of barium titanate which allowed the making of the first dummy (model) of a nondirectional sound receiver for ultrasonic frequencies (up to 100 kilocycles) [44]. The test of this first variant of the spherical sound receiver showed promise of the selected direction of the work.

The appearance of the first dummy of nondirectional spherical sound receiver of ceramics of barium titanate is shown in Fig. 19. The receiving element constitutes two hollow hemispheres of ceramics of barium titanate with electrodes applied to the external and internal surface of the hemispheres by the method of silver brazing. The outlet of the conductor from the internal electrode is accomplished through a small hole in one of the hemispheres in which a thin ceramic tube is glued serving simultaneously for the bracing of the sensing device.

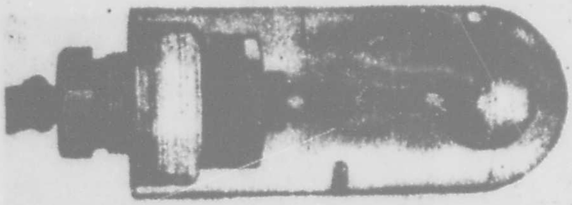

Fig. 19. The first dummy of nondirectional spherical sound receiver of ceramics of barium titanate.

The spherical radial-polarized element is placed in a plexiglas housing filled with transformer oil. The sensitivity of the first dummy sound receivers of this type, with an external diameter of the sensing device at 14 and 16 mm and thickness of the wall of the sphere at 2 mm was small. The static sensitivity was about 1.7 μv/bar, and the field sensitivity from 0.6 to 1.7 μv/bar.

The capacity of the piezoelectric elements with an external diameter of 14 and 16 mm was equal to 1000 and 1400 pf. It is possible to judge the frequency dependence of sensitivity according to data of Table 8 pertaining to one of such sound receivers.

Table 8

Frequency, kc	0 (static measurements)	25	30	45	60	75	100
Sensitivity μv/bar	1,7	0,6	0,88	1,6	1,7	1,25	1,45

Examples of directional characteristics of the first dummy of the spherical sound receiver are given in Fig. 20. The solid curve shows the directional characteristics of the receiver in a plane in which the full symmetry of the construction is retained and the dotted line represents the directional characteristics in a plane passing through the bracing elements of the spherical sensing device. Subsequently we will conditionally call these planes horizontal and vertical respectively.

Directional characteristics of even the first models of the spherical sound receivers in a horizontal plane could be recognized satisfactory as compared to

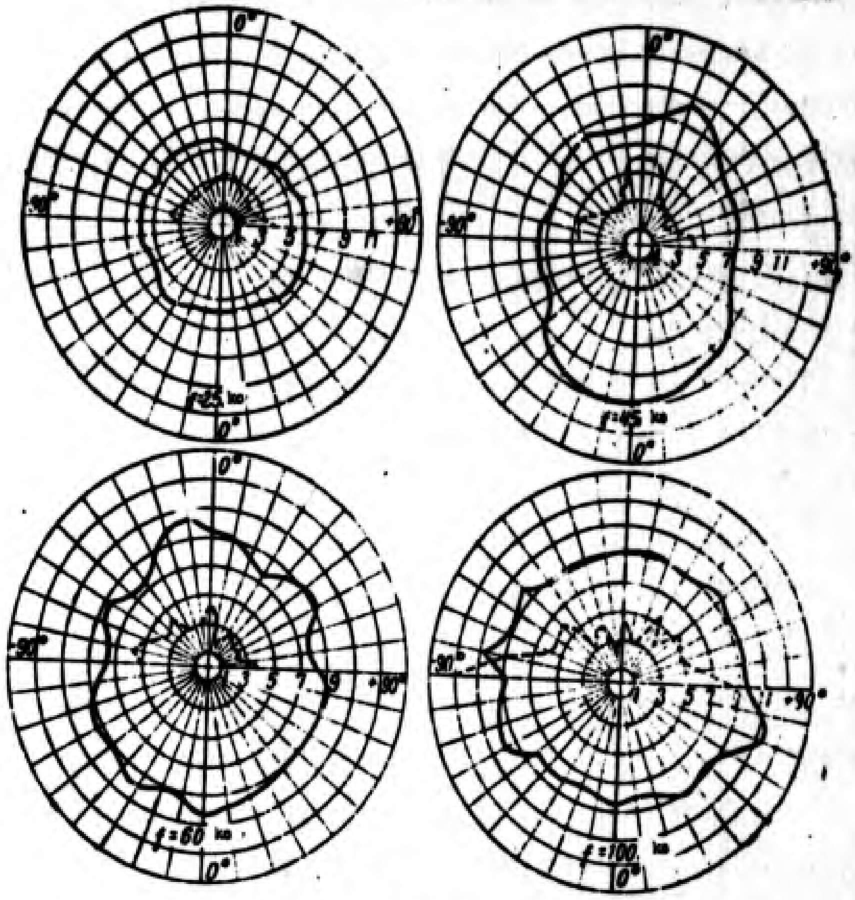

Fig. 20. Directional characteristics of the first dummy of the spherical sound receiver.

the corresponding directional characteristics for sound receivers with piezocrystalline sensing devices. In the horizontal plane in which there is no asymmetry of construction the irregularity of the directional characteristics attained at high frequencies approximately 5 decibels. In the vertical plane the directional characteristics of the first experimental sound receivers could not be considered satisfactory. The deviation from the circular directional characteristics in this plane is explained by the influence of the bracing elements of the sphere and housing.

In spite of the fact that the first samples of nondirectional sound receivers described above still did not give fully satisfactory results, they showed that the work in this direction is undoubtedly promising. We subsequently improved the data of the spherical sound receivers and also created sound receivers nondirectional only in one (horizontal) plane, i.e., sound receivers possessing not a spherical but a clearly cylindrical symmetry of the sensing device. Such cylindrical sound receivers for many regions appear not less interesting than the spherical.

In subsequent years the spherical sound receivers with a sensing device of ceramics of barium titanate have found wide application as measuring hydrophones. Thus the Soviet industry has produced standard measuring hydrophones [189] with spherical sound pickup elements of ceramics of barium titanate. This series of hydrophones covered a frequency range from 50 to 100 kc. It also follows to mention the similar measuring sound receivers released by the Rostov Institute of Technology and Machine Building by the development of the Rostov State University [190]. Cylindrical sound receivers with sensing devices of ceramics of barium titanate were applied with success for purposes of the prospecting of petroleum deposits [191].

As was already mentioned above, our initial developments appeared in connection with problems of the study of the structure of sound fields. In the beginning the main attention was given to the relatively miniature sound receivers with a high upper boundary of the working range and comparatively low sensitivity, and subsequently for the purpose of increasing the sensitivity of the sound receivers intended for different investigations at lower frequencies sound receivers of even greater dimensions were created, up to spherical sound receivers to 5 cm in diameter and cylindrical receivers, to 12 cm in diameter. However, recently there appeared the necessity to create subminiature sound receivers. We developed spherical sound receivers with a diameter of the sensing device at 2 mm and cylindrical sound receivers 2-3 mm in diameter. Such sound receivers are used in the study of the structure of high-frequency sound fields in liquid media. As a particular case we developed a cylindrical sensing device for the sound receiver introduced into the cardiovascular system for the purpose of medical diagnostics.

It should be noted that the exclusively miniature spherical sound receivers 0.2-0.3 mm in diameter were developed by Romanenko [192] in connection with the problem of the study of the distribution of pressure in front of the shock wave [193].

Information on the use of piezoelectric ceramics for the creation of measuring sound receivers available in foreign literature is very scanty. It is possible to refer only to the article of Ackermann and Holak [48] in which subminiature sound receivers 0.5 mm in diameter are described with a sensing device of ceramics of barium titanate at a range of frequencies 10 kilocycle — 1 Mc. A very large part of the foreign publications on ceramic converters is devoted to the consideration of radiating devices. Pertinent literary information can be found, for instance, in the survey article of Bredfield [53] and also in works of Johnston and Wertz [52] and others.

2. Calculation of the Static Sensitivity of a Sound Receiver with a Thin-Walled Spherical or Cylindrical Shell

As is known, the sensitiveness of sound receivers of simplest construction with a rod or pack converting element is determined in no-load conditions by the piezoelectric constant g proportional to the ratio of the piezoelectric modulus d to the dielectric constant ε. For the case of polarized ceramics we have three possible variants (Fig. 21). In case (a) the direction of the external acting force (and correspondingly the longitudinal deformation) coincides with the direction of the axis of polarization z; in cases (b) and (c) the direction of the external acting force F is perpendicular to the direction of the axis of polarization z. In case (a) we should use during the calculation of sensitivity of the transforming element the piezoelectric modulus d_{33}, and in cases (b) and (c), the piezoelectric moduli d_{31} and d_{32} respectively. In virtue of the inherent polarized piezoceramics of axial symmetry d_{31} and d_{32}, consequently the variants (b) and (c) are identical. If the dimension of the piezoelement in the direction of polarization is equal to l, the sensitivity in no-load conditions for case (a) is determined by the formula

$$\frac{E}{p_0} = g_{33}l,$$

and for cases (b) and (c) by the formula

$$\frac{E}{p_0} = g_{31}l = g_{32}l;$$

here p_0 — assigned pressure on planes perpendicular to the direction of the acting force F.

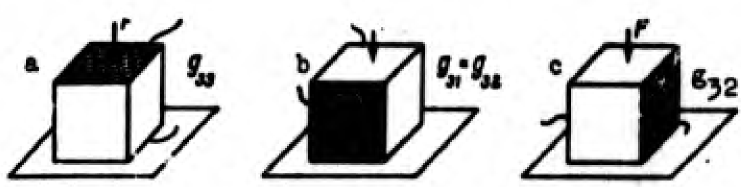

Fig. 21. Three variants of the simplest flat piezoelectric element of polarized ceramics.

As can be seen from Tables 4 and 5, values of parameters g_{33} and g_{31} for ceramic piezomaterials considerably yield to corresponding parameters of other piezomaterials. For instance, the ceramics of barium titanate yields 5 times in sensitivity to quartz to potassium phosphate, 10 times, and Seignette's salt, 39 times. Therefore, the designing on the basis of piezoceramics of sensing devices in the form of packs absorbing the external pressure by one of the lateral surfaces does not give satisfactory results. The basic leading idea in the designing of sensitive piezoceramic sound receivers should be the creation with the help of some form of mechanical transformation of increased stresses in the piezoelement with the corresponding development of the external surface of the sound receiver absorbing the sound pressure. In particular, this can be attained, using a thin-walled shell made of piezoceramic material. Of course, it is possible to go also by way of an increase of the effective dimension of the piezoelement l, i.e., the distance between the electrodes in the rod or pack sensing device; however, this is connected either with a decrease in the capacity of the piezoelement or with an increase in its geometric dimensions, which, for the most part, is undesirable.

The sensitivity of the sound receiver, supplied by a device for the mechanical transformation of forces, can be expressed in the general formula

$$\frac{E}{p_0} = Kgl,$$

where K — coefficient of the mechanical transformation. The larger the coefficient K, the more effective the piezoelectric material will be used.

With the designing of sound receivers with a spherical or circular directional characteristic it is natural to use as mechanical transformers spherical or cylindrical shells respectively. Fundamentally it is not absolutely necessary that the shell be completely made of piezoceramic material; the piezoelement can be built into the spherical or cylindrical shell, for instance, as it is shown in Fig. 22. With such construction the functions of the mechanical transformation and electromechanical transformation are divided between specialized elements of the sound receiver.

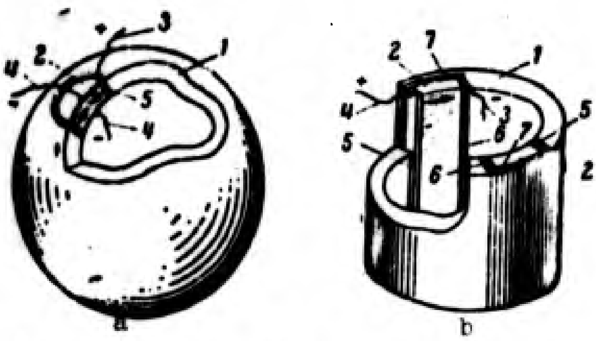

Fig. 22. Sound receivers with a spherical (a) and cylindrical (b) receiving surface. 1) thin-walled receiving shell; 2) ceramics; 3, 4) electrodes with outlets; 5, 6, 7) electric insulating spacers.

Let us determine the mechanical transformation factor for cases of spherical and cylindrical shells. For simplicity we will assume that the thickness of the wall of the shell is so small as compared to the external diameter, which it is possible to disregard the normal stresses in the material of the shell effective in radial direction and to consider that the external pressure having an effect on the shell surface creates in every diametrical section of the shell only the normal stress effective in a tangential direction. The ratio of the mechanical stress σ_τ effective in a tangential direction to the sound pressure having an effect on the surface of the shell, i.e., σ_τ/p_0, will determine in this case the coefficient of mechanical transformation. We will assume that the sound pressure is equal for all elements of the external surface of the shell, which in the final analysis means that the diameter of the shell is small as compared to the wave length. With the made assumptions it is possible not to consider during the calculation the tangential stresses which in other cases would be connected with shift deformations in the shell.

Let us consider at first the case of the thin-walled spherical shell. On the external surface of a sphere of R radius an external excess pressure p_0 is set. We dissect the sphere mentally into two mutually perpendicular great circles (Fig. 23). Then at the point of intersection of the diametrical cross sections of the sphere (i.e., at any point of sphere) one can determine the mechanical tangential stresses in the shell σ_τ and σ_ψ equal to each other in virtue of the spherical symmetry of the problem. The stresses σ_τ and σ_ψ can be determined by calculating the full external force F acting on the hemispheres in a direction perpendicular to the equatorial section.

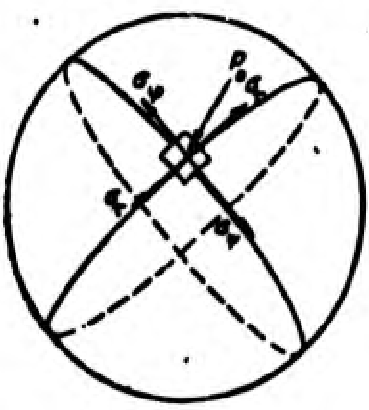

Fig. 23. Case of the thin-walled spherical shell.

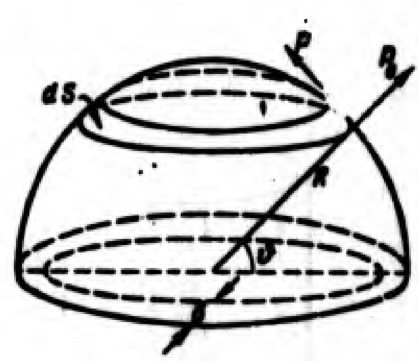

Fig. 24. The calculation of force F acting on the hemisphere.

Let us assume that the thickness of the shell is equal to δ ($\delta \ll R$), then the area of the equatorial section of the sphere will be $S = 2\pi R\delta$. The full force acting normally in this section is determined by the integral

$$F = \int_0^{\pi/2} p\,dS, \quad \text{or} \quad F = 2\pi p_0 R^2 \int_0^{\pi/2} \sin\theta\cos\theta\,d\theta.$$

The designations used here are clear from Fig. 24.[4] Integrating, we obtain

$$F = p_0 \pi R^2,$$

and consequently the mechanical stress σ_τ will be expressed in the following way: $\sigma_\tau = p_0 \frac{R}{2\delta}$. Analogously,

$$\sigma_\psi = p_0 \frac{R}{2\delta} = \sigma_\tau = \sigma.$$

Let us now assume that the small element of the shell shown in Fig. 23 is made of piezoceramic material with polarization in the direction of the radius of the sphere. Then the emf developed by the piezoelement owing to the presence of the mechanical stress σ_τ will be $E_\tau = \delta g_{31} \sigma_\tau$ and, correspondingly, the emf arising due to the presence of stress σ_ψ will be $E_\psi = \delta g_{31} \tau_\psi$. The full emf developed by the piezoelement will be

$$E = E_\tau + E_\psi,$$

or considering that $\sigma_\tau = \sigma_\psi = \sigma$ and $g_{31} = g_{32} = g$,

$$E = 2\delta\sigma g.$$

Substituting here the expression obtained earlier for σ, we finally obtain

$$E = R p_0 g = \frac{R}{\delta} \delta p_0 g,$$

and, consequently, the coefficient of mechanical transformation for the thin spherical shell will be

$$K = \frac{R}{\delta}.$$

Let us turn to the case of the thin-walled cylindrical shell (Fig. 25). On the external surface of the cylinder an excess pressure p_0 is put. Let us designate the external radius of the cylinder by R, the axial length by h, and the thickness of the wall by δ whereby $\delta \ll R$. Let us assume that the ends of the cylinder are protected from the action of the sound pressure. Then the cylinder can be freely deformed in an axial direction, and the mechanical stresses in any cross section of the cylindrical shell will be equal to zero ($\sigma_h = 0$). The tangential mechanical stresses σ_τ will appear only in the diametrical sections of the shell, i.e., in a direction mutually perpendicular to the forming cylinder.

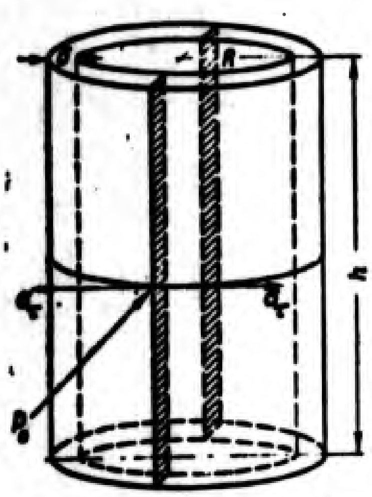

Fig. 25. Case of the thin-walled cylindrical shell.

Let us dissect mentally the cylinder by a plane including the axis, and let us determine the stress effective in the obtained section of the shell whose area is equal to $S = 2h\delta$. The force F effective in the given section is expressed by the integral

$$F = h\int_0^{\pi} p\,dS, \text{ or } F = hp_0R\int_0^{\pi}\sin\theta\,d\theta,$$

and the designations are clear from Fig. 26. Having accomplished integration we obtain

$$F = 2hRp_0.$$

Consequently, the mechanical stress σ_τ will be equal to

$$\sigma_\tau = p_0\frac{R}{\delta}.$$

By introducing into composition of the shell the piezoelectric element with radial polarization, as it is shown in Fig. 27, we obtain the expression for the emf developed by this piezoelectric element

$$E = E_\tau = \delta g_{31}\sigma_\tau = p_0\delta\frac{R}{\delta}g.$$

Hence we obtain the simple expression for the coefficient of mechanical transformation for the case of thin walled cylindrical shell

$$K = \frac{R}{\delta}.$$

We see that the coefficient of mechanical transformation for the thin-walled spherical shell and for the thin-walled cylindrical shell appears identical with identical values of the radius R and thickness of shell δ.

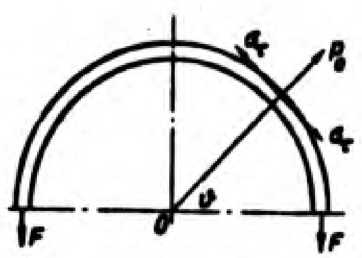

Fig. 26. The calculation of force F acting on the semicylinder

With sufficiently large ratios of R/δ a large magnitude of the coefficient of transformation can be obtained, and owing to this the sensitivity of the sound receiver with the shell can be increased tens and hundreds of times as compared to the sensitivity of the actual piezoelectric element built into the shell.

Above we took the defined orientations of the piezoelectric elements with respect to the general structure of the shell and made assumptions about the properties of the piezoelement itself only for clarity of account. It is obvious that the coefficient of mechanical transformation can be calculated for any orientation of the piezoelement with any piezoelectric parameters; here it is necessary to consider only the corresponding

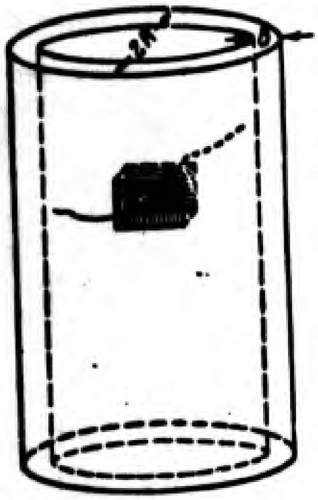

Fig. 27. Location of electrodes with radial polarization of a ceramic cylinder.

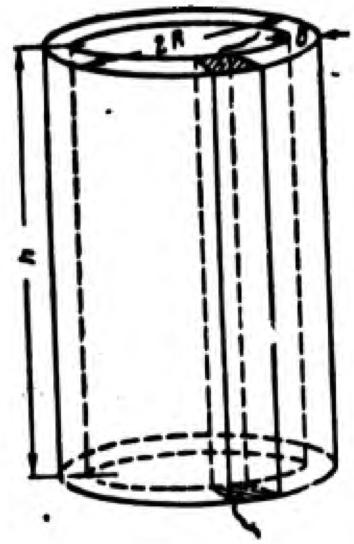

Fig. 28. Simple method of the location of electrodes for longitudinal polarization of a ceramic cylinder.

relationships between the piezoelectric moduli. It is natural that the conclusions drawn are accurate only in that case when the dimensions of the built-in piezoelement are small as compared to the dimensions of the shell and when the mechanical parameters of the material of the piezoelement differ little from the mechanical parameters of the material of the shell itself. If these conditions are not fulfilled the problem of the calculation is complicated. However, as one will see from further in the case of the piezoceramic sound receivers it appears expedient to make the shell from the same material as the piezoelement itself; it does not appear necessary to introduce corrections for the difference in parameters of the corresponding materials.

Let us consider the basic possible variants of the use of solid ceramic shells for making sound receivers. These variants appear first in connection with the possibility of use of separate parts of the shell or the shell as a whole as a converting piezoelement, and, secondly, in connection with the possibility of the use of different forms of polarization of piezoceramics on those sections of the shell which are selected as converting.

The simplest variant of the use of the cylindrical shell is shown in Fig. 27. Here the electrodes of equal area are applied opposite to each other on the internal and external surfaces of the shell. It is natural that in this case it is possible to use only the radial polarization of piezoceramics. The region of the shell concluded between the electrodes plays the role of the converting piezoelement and the remaining part of the shell, the role of the transformer of mechanical stresses. Using the conclusions made above we obtain directly the expression for the sensitiveness of the sound receiver of the given form:

$$\frac{E}{p_0} = K\delta g_{31} = R g_{31}.$$

We see that the sensitivity in this case does not depend on what part of the surface of the shell is occupied by the electrodes; only the capacity of the converter depends on this. It is possible to increase sensitiveness only by increasing the radius of the cylinder. Since for the most part it is desirable to increase the capacity of the converter, then it is most expedient to cover the external and internal surface of the shell completely by electrodes.

The second simple variant of the use of the cylindrical shell is shown in Fig. 28. Here the electrodes are applied to the face surfaces of the shell opposite each other in forming. For this case the sensitivity will be

$$\frac{E}{p_0} = K h g_{31} = \frac{R}{\delta} h g_{31}.$$

We see that in the given case the increase in sensitivity possible owing to the decrease in the thickness of the shell and increase in axial length of the cylinder h. However, this is inevitably connected with a decrease in the capacity of the converter. The given case has obtained at present, in literature, the name of the case of "longitudinal" polarization of a cylindrical piezoelectric converter.

It is natural that for an increase in the capacity one should cover completely by electrodes the face surfaces of the cylindrical shell. However, in most cases the capacity of such converting elements turns out to be, nevertheless, too small. Of course, it is possible by waiving the sensitiveness to increase the capacity, but to do this it is necessary to divide the cylindrical shell into sections (Fig. 29) of little height, for instance, by means of glass welding of a number of short cylindrical elements with applied face electrodes. In this case the directions of polarization of the neighboring rings should be opposite, which will make it possible to connect in parallel the sections of the converter. If the number of sections is equal to n the sensitivity will be

$$\frac{E}{p_0} = \frac{R}{\delta} l g_{31} = \frac{R}{\delta} \frac{h}{n} g_{31},$$

where l – axial length of the section. Thus the sensitivity of the sectionalized converter of given form decreases n times as compared to the sensitivity of the solid cylinder with face electrodes (with that same common axial length), and the capacity is also increased n times. Of course, the welding of the sections is easily accomplished only with relatively large thicknesses of the shell. It turns out, however, that with thin-walled shells it is not necessary to perform the sectioning as it is shown in Fig. 29. The large piezoelectric constant of piezoceramics permits carrying out longitudinal polarization with the surface application of electrodes shown in Fig. 30. Here the annular electrodes are applied only to the external surface of the cylindrical shell with the step l.

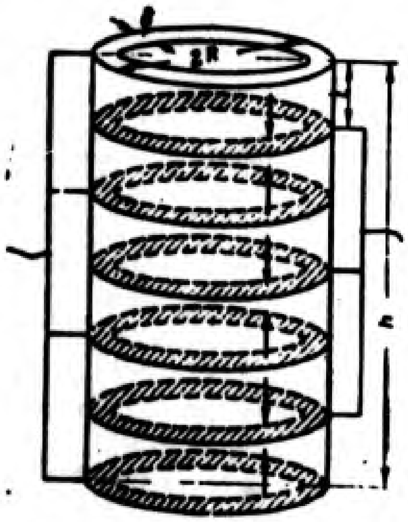

Fig. 29. Location of electrodes in a sectionalized cylinder for longitudinal polarization.

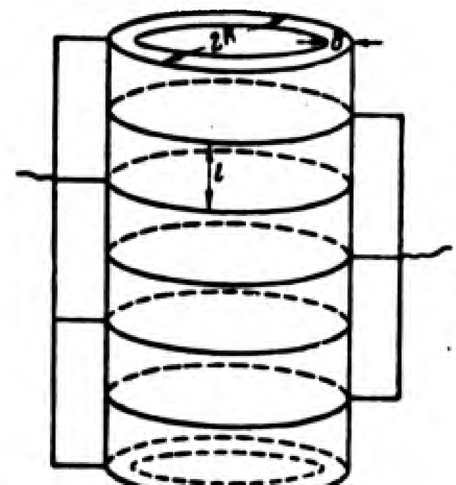

Fig. 30. Location of electrodes on an external lateral surface with longitudinal polarization of a thin solid cylinder.

With such a structure of the electrodes because of the fact that the thickness of the shell is considerably less than the distance between the electrodes and the dielectric constant of ceramics is three orders larger than the dielectric constant of the environment, polarizing field on the section between the electrodes is obtained to a sufficient degree uniform; however, with polarization it is nevertheless necessary to use a stress 30-40% greater than that usually used.

Perhaps the most convenient in this case will be that shown in Fig. 31 of the configuration of electrodes in the form of two-approach helix [194]. It permits the freeing of excessive soldering of the conductors to the electrodes.

The method of surface application of electrodes permits, however, a considerable improving of the sensitivity of the cylindrical sound receiver owing to the transition from radial or longitudinal polarization to tantential. The corresponding form of electrodes is shown in Fig. 32. If the distance between the electrodes l

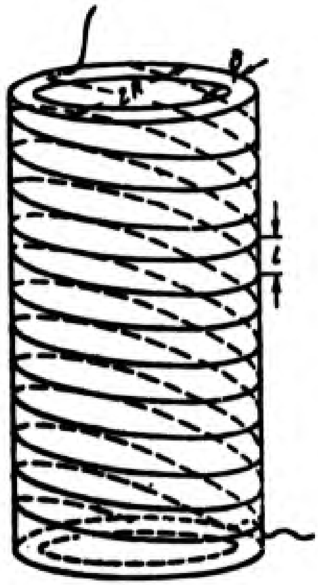

Fig. 31. Location of electrodes for longitudinal polarization of a thin solid cylinder in the form of a double spiral line.

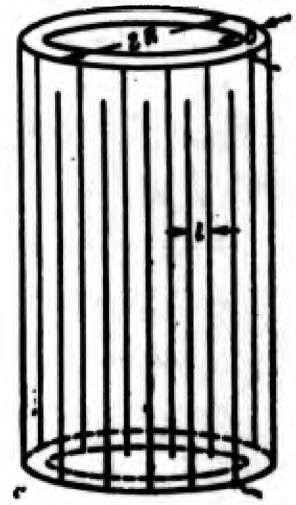

Fig. 32. Electrodes on the lateral surface of a solid thin ceramic cylinder for tangential polarization.

is equal to $2\pi R/n$, where n is the number of sections about the circumference of the cylinder, the sensitivity will be expressed in the following way:

$$\frac{E}{p_0} = Klg_{33} = \frac{2\pi R^2}{\delta n} g_{33}.$$

We see that the sensitivity in this case is formally expressed just as with the longitudinal polarization, but instead of the constant g_{31} there is the constant g_{33}. Therefore with other identical data we obtain the gain in sensitivity with respect to g_{33}/g_{31}.

Table 9

Method of polarization	Sensitivity µV/bar	Ratio of sensitivity	Capacity	Ratio of capacity
Radial	$Rg_{31} = 4{,}7R$	1	$\frac{\varepsilon Rh}{2\delta}$	1
Longitudinal	$Rg_{31}\frac{l}{\delta} = 4{,}7R\frac{l}{\delta}$	$\frac{l}{\delta}$	$\frac{\varepsilon R\delta}{2l}$	$\left(\frac{\delta}{l}\right)^2 \frac{l}{h}$
Tangential	$\frac{2\pi R^2}{\delta n} g_{33} = 71\frac{R^2}{\delta n}$	$\left(\frac{2\pi}{n}\frac{R}{\delta}\right)\frac{g_{33}}{g_{31}}$	$\frac{\varepsilon hn^2\delta}{8\pi^2 R}$	$\left(\frac{n\delta}{2\pi R}\right)^2$

Table 9 gives a comparison of data on the sensitivity and other parameters of cylindrical sound receivers with a thin shell with different methods of applying electrodes and different forms of polarization. Given in the table are formulas determing the sensitivity and capacity and expressions characterizing the ratios of these magnitudes to the corresponding magnitudes for the sound receiver with radial polarization and with electrodes applied to all the internal and external surfaces. Numerical coefficients are given for ceramics with average parameters shown in the conclusion of Chapter I. In the table the following designations are accepted: R — external radius of the cylinder, h — axial length of the cylinder, δ — thickness of the wall of the ceramic shell, l — distance between the electrodes, n — number of sections along the length or about the circumference of the cylinder. Expressions with numerical coefficients give the sensitiveness directly in μv/bar if the geometric dimensions are given in centimeters.

With the determination of the capacity in the case of surface application of electrodes it is accepted that the superficially applied electrode is equivalent to the electrode applied to the face surface of the section if partitioning is produced by means of welding of the sections (Fig. 33). Such an assumption is accurate in that case when $l' \ll l \approx \delta$.

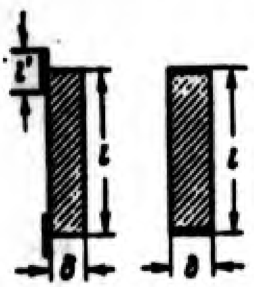

Fig. 33. Equivalent forms of electrodes.

Let us turn to the consideration of possible variants of the use of a thin-walled spherical shell. Here we have essentially only a choice between radial and tangential polarizations. On the basis of the same considerations as for the case of radial polarization, the solid application of electrodes to the internal and external surface of the spherical shell is expedient. With this the sensitivity of the sound receiver will be

$$\frac{E}{p_0} = K\delta g_{31} = Rg_{31}. \quad (4)$$

If by some considerations it will appear necessary to decrease the capacity of the converter, then it is possible to apply the electrodes opposite to each other to parts of the internal and external surfaces. The sensitivity will not be changed.

Of course, it is possible also to partition the electrodes with a series connection of them in pairs, for instance, as it is shown in Fig. 34. With this

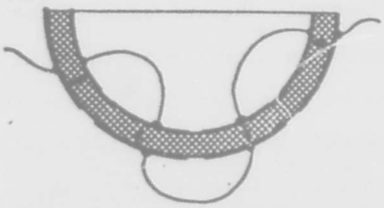

Fig. 34. Example of a series connection of separate sections of a spherical ceramic shell with radial polarization.

it is possible to attain increase in the sensitivity with a corresponding decrease in capacity. The configuration of the sections on the surface of the sphere should be such that the area of the sections are identical. Sections of the shell between the sections free of electrodes should be larger in dimension than the thickness of the shell.

Tangential polarization naturally cannot be obtained for all the shell as a whole; the corresponding electrodes should be in some way or other distributed by the external surface of the shell. Fig. 35 shows the possible configuration of the electrodes. Assuming that the regions with the tangential polarization almost wholly fill the surface of the sphere, it is possible to write the expression for the sensitivity of the spherical sound receiver with tangential polarization in the form

Fig. 35. Photograph of two halves of a tangentially polarized spherical piezoelectric element of ceramics of barium titanate.

$$\frac{E}{p_0} = Klg_{33} .$$

It is obvious that other things being equal the use of tangential polarization more suitable, since in the expression for sensitivity there is the piezoelectric modulus d_{33}.

Thus it can be said that the greatest sensitivity is ensured by the use of cylindrical and spherical shells with tangential polarization. In this case besides an increase in the sensitivity owing to the transformation of mechanical stresses (which takes place with any method of polarization of a thin-walled shell) it is possible to use the longitudinal piezoelectric modulus d_{33} which more than twice exceeds the transverse piezoelectric modulus $d_{31} = d_{32}$. Moreover, with the assigned coefficient of transformation, i.e., with the defined ratio R/δ, and with tangential polarization it is possible to increase the distance between the electrodes l. In other words, with tangential polarization of the shells it is possible to increase the sensitivity of the piezoelement owing to the increase in the ratio R/δ, the increase in l, and the use of the piezoelectric modulus d_{33}.

With longitudinal polarization it is possible to use only the increase in the ratio R/δ and increase in l. Therefore, the sensitiveness of the cylindrical sound receiver with longitudinal polarization will be less than that of the sound receiver with those values R, l, and δ but with tangential polarization. Radial polarization of spherical and cylindrical shells gives with set dimensions of the shell the least sensitivity but ensures simultaneously the obtaining of the largest possible capacity.

With radial polarization of the spherical shell the increase in sensitivity is possible only owing to the increase in the external radius, since an increase in the thickness of shell δ leads to a decrease in the coefficient of the mechanical transformation.

From what has been said above one can see that with the use of a thin ceramic shell as a sensing device of a sound receiver, it is possible to modify the parameters of the latter, for instance, to make receivers of low capacity and high sensitivity or to use elements with great capacity but not very high sensitivity. The selection of a certain solution depends on the concrete assignment of the sound receiver and on conditions in which it will be used (for instance, from the minimum permissible distance to the first amplifier stage, and so forth). The development of both forms of ceramic sound receivers is of practical interest.

It should be noted that the variation of parameters of the sound receiver with the help of different methods of applying the electrodes to the surface of the ceramic shell can be considered, to some degree equivalent to the electrical parallel or series connection of the separate elementary piezoelements. By using these technical methods we essentially solve the problem of expedient coordination of electrical impedance of the sound receiver with the input circuit of the amplifier. In certain particular cases, for instance, with the work of the sound receiver at low frequencies, the coordination can be obtained if at the input of the amplifier a transformer is used; with this we use the transformation of voltages. However, the application of closed thin-walled shells as piezoelements has fundamental advantages as compared to the use of simple flat or pack sensing devices, since in the case of the shell it is possible to still use the transformation of mechanical stresses in the material of the sound receiver. Increase in mechanical stresses in the material leads to an additional increase in the sensitivity of the sound receiver.

In order to estimate the role of the mechanical transformation it is possible to use as a parameter during the appraisal the ratio of reactive electrical power developed by the piezoelement with the assigned full volume of the piezomaterial when it is placed in a field of flat sound wave with an assigned specific acoustic power.

If one were not to consider the internal losses in ceramics the results of such an appraisal can be expressed by the formulas given in Table 10.

Table 10

Form of the receiving and method of polarization	Ratio of the reactive electrical power to the specific acoustic power.
Flat element with the use of the piezoelectric modulus d_{33}	$V\omega\rho c \frac{4\pi d_{33}^2}{\varepsilon}$
Flat element with the use of the piezoelectric modulus $d_{32} = d_{31}$	$V\omega\rho c \frac{4\pi d_{31}^2}{\varepsilon}$
Sphere with radial polarization	$V\omega\rho c \frac{4\pi d_{31}^2}{\varepsilon}\left(\frac{R}{\delta}\right)^2$
Cylinder with radial polarization	$V\omega\rho c \frac{4\pi d_{31}^2}{\varepsilon}\left(\frac{R}{\delta}\right)^2$
Cylinder with longitudinal polarization	$V\omega\rho c \frac{4\pi d_{31}^2}{\varepsilon}\left(\frac{R}{\delta}\right)^2$
Cylinder with tangential polarization	$V\omega\rho c \frac{4\pi d_{33}^2}{\varepsilon}\left(\frac{R}{\delta}\right)^2$

The following designations are accepted in the table: V — volume of the piezoelectric material, ω — angular frequency, ρc — wave resistance of the medium in which the sound receiver is placed, ε — dielectric constant of the material, R — radius of the shell, δ — thickness of the wall of the shell. From Table 10 one can see that the application of the transformation of mechanical stresses permits with the same quantity of material obtaining an increase in the reactive electrical power proportional to the square of the ratio of the radius of the cylindrical or spherical shell to the thickness of the wall.

Data for the cylinders given in Table 10 pertain to the case when the ends of the cylinder are protected from the influence of sound pressure. With tangential and longitudinal polarization such a method of the use of cylindrical sensing devices is the best.

Thus the calculation of static sensitivity of sound receivers made of ceramics of barium titanate shows that sound receivers in which sensitive piezoelements in the form of thin-walled spherical or cylindrical shells are used possess higher sensitivity than that of the sound receivers of simplest construction with a rod or pack piezoelectric element [195-197]. This is the result of a more rational use of piezoelectric material with spherical or cylindrical constructions.

It should be noted however, that measuring nondirectional sound receivers sometimes have special requirements in the sense of mechanical strength (for instance, with the investigation of explosive phenomena, during measurements of sound pressure in water at great depths, and others). In such cases it is necessary to put up with a certain decrease in the sensitivity of the sound receiver and to increase the thickness of the shell. Therefore, it is necessary to obtain calculation relationships connecting the sensitivity of the spherical or cylindrical sound receiver with its dimensions with a relatively great thickness of the shell.

3. Static Sensitivity of a Radial Polarized Spherical Piezoelement with a Finite Thickness of the Wall

Let us assume that the spherical sound receiver has an external radius b and internal radius a. On the external surface of the spherical shell there is an excess pressure $p_b = p_0$; inside the shell the excess pressure is $p_a = 0$. Let us consider the elementary volume of the piezomaterial limited by two spherical surfaces with radii R and R + dR, two mutually perpendicular planes passing through the center of the sphere, and two planes also passing through the center of the sphere and being with respect to the first two planes at angles $d\theta$ and $d\varphi$ respectively (Fig. 36).

In virtue of the spherical symmetry of the shell and symmetry of the external forces acting on the shell the electric field strength appearing with the deformation of the elementary volume is directed radially. The magnitude of this field strength E depends on the mechanical stresses σ_R, σ_τ and σ_τ corresponding to the radial and two mutually perpendicular tangential directions. We can record

$$E = E_R + E_\theta + E_\varphi,$$

where $E_R = g_{33}\sigma_R$, $E_\theta = g_{31}\sigma_\tau$ and $E_\varphi = g_{31}\sigma_\tau$.

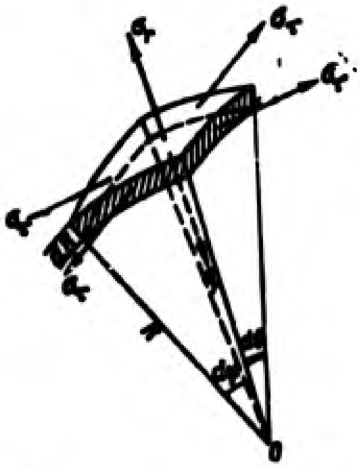

Fig. 36. Case of an elementary volume limited by two spherical surfaces.

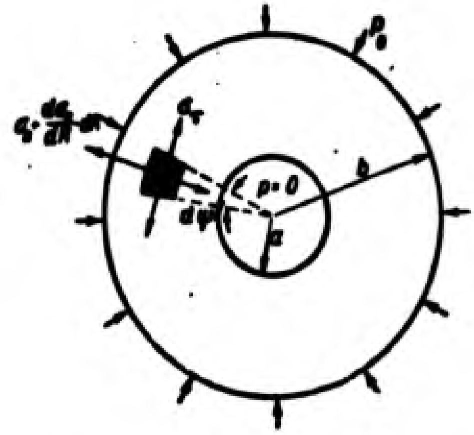

Fig. 37. Calculation of the stress σ_τ.

Thus,

$$E = g_{33}\sigma_R + 2g_{31}\sigma_\tau.$$

It is obvious that E depends on R, and this dependence appears through the dependency on the radius R of mechanical stresses σ_R and σ_τ. The potential difference appearing between the external and internal facings of the spherical piezoelement will be expressed by the integral

$$V = \int_a^b (g_{33}\sigma_R + 2g_{31}\sigma_\tau)\,dR. \tag{5}$$

The common expression for the radial stress σ_R in the spherical shell is recorded in the form [198]

$$\sigma_R = \frac{C}{R^3} + D,$$

where C and D – arbitrary constants determined by the boundary conditions $\sigma_{R=b} = -p_0$ and $\sigma_{R=a} = 0$. Hence

$$C = \frac{a^3 b^3}{b^3 - a^3} p_0; \qquad D = -\frac{b^3}{b^3 - a^3} p_0$$

and, consequently,

$$\sigma_R = \frac{b^3}{b^3 - a^3}\,\frac{a^3 - R^3}{R^3}\,p_0. \tag{6}$$

The expression for the stress σ_τ is easily found from the condition of equilibrium of the element cut from a spherical shell by two concentric surfaces with radii R and R + ΔR and a circular cone with a summit in the center of the shell and small angle dφ at the vertex (Fig. 37). With this we obtain

$$\sigma_\tau = \frac{d\sigma_R}{dR}\,\frac{R}{2} + \sigma_R,$$

where $d\sigma_R/dR$ and σ_R are determined from the expression (6). Finally the expression for the stress σ_τ takes the form [199]

$$\sigma_\tau = \frac{b^3(2R^3 + a^3)}{2R^3(a^3 - b^3)} \cdot p_0 .$$

Substitution of the value σ_τ and σ_R into the formula (4) leads to the expression for the sensitivity of the radial polarized ceramic sphere in the form of

$$\frac{V}{p_0} = \int_a^b \left(g_{33} \frac{b^3}{b^3 - a^3} \frac{a^3 - R^3}{R^3} + g_{31} \frac{b^3}{R^3} \frac{2R^3 + a^3}{a^3 - b^3} \right) dR ,$$

or

$$\frac{V}{p_0} = \frac{b^3}{b^3 - a^3} \left[g_{33} a^3 \int_a^b \frac{1}{R^3} dR - g_{33} \int_a^b dR - 2g_{31} \int_a^b dR - a g^3_{31} \int_a^b \frac{dR}{R^3} \right] .$$

After integration we obtain

$$\frac{V}{p_0} = \frac{b^3}{b^3 - a^3} \left[(g_{33} - g_{31}) - \frac{a(b^2 - a^2)}{2b^2} - (b - a)(g_{33} + 2g_{31}) \right] =$$
$$= \frac{b}{b^2 + ab + a^2} \left[(g_{33} - g_{31}) \frac{a(b + a)}{2} - b^2 (g_{33} + 2g_{31}) \right] . \qquad (7)$$

If one were to designate the ratio of the internal radius of the sphere to the external by $a/b = \eta$, then after simple algebraic transformations formula (7) assumes a simpler form:

$$\frac{V}{p_0} = \frac{b}{\eta^2 + \eta + 1} \left[\frac{\eta(1 + \eta)}{2} (g_{33} - g_{31}) - (g_{33} + 2g_{31}) \right] ,$$

or

$$\frac{V}{p_0} = \frac{b}{\eta^2 + \eta + 1} \left[\frac{\eta^2 + \eta - 2}{2} g_{33} - \frac{\eta^2 + \eta + 4}{2} g_{31} \right] .$$

It is convenient to make an analysis of the formula for the sensitivity of the receiver V/p_0 if one were to present the sensitivity as a function of the ratio of the thickness of the wall of the shell to the external diameter

$$\varkappa = \frac{b - a}{2b} ;$$

then

$$\frac{V}{p_0} = b \frac{1}{3 - 6\varkappa + 4\varkappa^2} \left[2\varkappa^2 - 3\varkappa + 1)(g_{33} - g_{31}) - (g_{33} + 2g_{31}) \right] =$$
$$= b \frac{1}{3 - 6\varkappa + 4\varkappa^2} \left[g_{33}(2\varkappa^2 - 3\varkappa) - g_{31}(2\varkappa^2 - 3\varkappa + 3) \right] . \qquad (8)$$

As can be seen from formula (7), the sensitivity of the ceramic sphere with radial polarization is proportional to the external radius of the sphere. Therefore for calculations it is convenient to use the curve plotted for the case b = 1 cm (Fig. 38). This curve is plotted for concrete values g_{33} and g_{31}, assumed by us as a basis of all the calculations of the sensitivity of ceramic converters (see Chapter I).

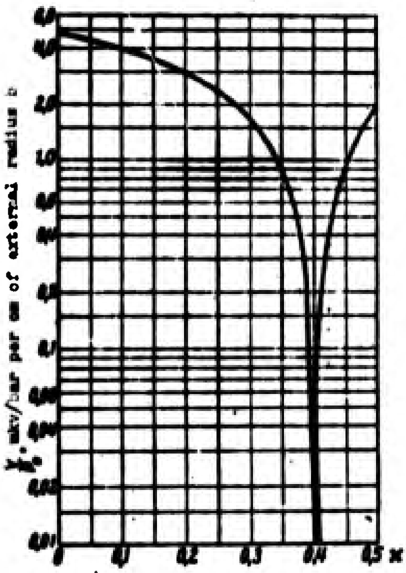

Fig. 38. Calculation of static sensitivity of spherical piezoelements of ceramics of barium titanate with a different thickness of the wall Radial polarization.

From formula (7) and from the curve it is obvious that with the defined value $\varkappa$ the sensitivity becomes equal to zero. This value $\varkappa$ can be easily obtained by equating to zero the expression in brackets in the formula (7):

$$g_{33}(2\varkappa^2 - 3\varkappa) = g_{31}(2\varkappa^2 - 3\varkappa + 3),$$

whence with the ratio of the constants $g_{33}/g_{31} = 2.4$ we obtain that the sensitivity of the radially polarized spherical sound receiver is equal to zero when $\varkappa = 0.402$. When $\varkappa = 0$, i.e., when the thickness of the wall is negligibly small as compared to the diameter of the shell we obtain

$$\frac{V}{p_0}\Big|_{\varkappa=0} = -bg_{31}.$$

This expression coincides with that obtained by us earlier for the case of the thin shell [formula (4)].[1] When $\varkappa = 1/2$, i.e., for a solid radial polarized ceramic sphere we have

$$\frac{V}{p_0}\Big|_{\varkappa=1/2} = -b(2g_{31} + g_{33}).$$

It is easy to see that the expression in parentheses is nothing other than the piezoelectric modulus for the case of hydrostatic stress. To judge as to what degree the theoretical assumptions with respect to the influence of the thickness of the shell converge with the practically obtained results, Table 11 gives parameters of experimental spherical sound receivers with an external diameter of about 2 cm with different thicknesses of the wall. From the table one can see that the static sensitivity calculated by the formula (8) converges well with the sensitivity obtained experimentally.

Table 11

External diameter of the spherical shell D, cm	Thickness of walls of the spherical shell δ, cm	Working frequency band, kc	Capacity, pf	Sensitivity, mkv/bar	
				calculated	measured
1,8	0,05	0÷120	20 000	4,05	3,0
2,2	0,40	0÷115	1700	2,20	2,0
2,1	0,35	0÷120	2300	2,20	2,0
2,0	0,25	0÷120	3800	3,00	2,9
1,9	0,15	0÷120	6300	3,42	3,0

[1]Formula (4) is obtained without taking into account the sign.

4. Static Sensitivity of a Cylindrical Piezoelement with a Finite Thickness of the Wall with Different Forms of Polarization

Langevin [200] obtained the expression for determining the sensitivity of cylindrical piezoelements with finite thickness of the wall for different forms of polarization and for different conditions on the ends of the cylindrical piezoelement. Inasmuch as with the designing of sound receivers intended for work in conditions of great hydrostatic pressure, it is expedient to use thick-walled cylindrical piezoelements and we consider it necessary to cite here the basic results of this work.

Langevin examined the different forms of polarization and variants of conditions on the ends (Table 12).

Table 12

Polarization	Conditions on ends
Radial	Ends are protected from the influence of sound pressure
	Sound pressure influences the annular face surfaces of the piezoelement
	Ends of the piezoelement are closed by plates perceiving the sound pressure. The diameter of the plates is equal to the external diameter of the piezoelectric element.
Longitudinal (along the z axis)	Ends are protected from the influence of sound pressure
	Sound pressure influences the annular face surfaces of the piezoelement
	Ends of the piezoelement are closed by plates perceiving the sound pressure. The diameter of the plates is equal to the external diameter of the piezoelectric element.
Tangential	Ends are protected from the influence of sound pressure
	Sound pressure influences the annular face surfaces of the piezoelement
	Ends of the piezoelement are closed by plates perceiving the sound pressure. The diameter of the plates is equal to the external diameter of the piezoelectric element.

For convenience of the comparison of results of Langevin with expressions obtained by us for the sensitivity of thin-walled cylindrical piezoelements, we will give the Langevin formula in the designations accepted by us. With cylindrical symmetry of the piezoelement it is natural in examining the elementary volume of the piezomaterial to select coordinates R, θ and z (Fig. 39). Correspondingly, we will designate the mechanical stresses of interest to us in the shell by σ_R, σ_θ and σ_z.

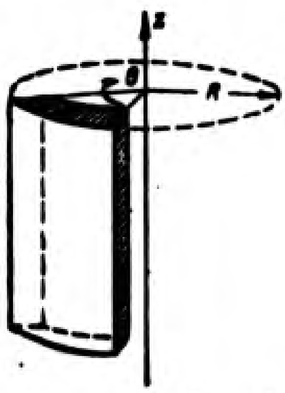

Fig. 39. Calculation of the static sensitivity of the cylindrical piezoelement.

In the case of radial polarization, i.e., with electrodes applied to the external and internal surfaces of the cylindrical shell the potential difference between the electrodes is determined by the integral

$$V = \int_a^b [g_{33}\sigma_R + g_{31}(\sigma_\theta + \sigma_R)]\, dR,$$

where b and a – external and internal radii of the cylindrical shell respectively.

With longitudinal polarization, i.e., with electrodes located on the annular face surfaces of the piezoelement we have

$$V = \frac{1}{\pi(b^2 - a^2)} \int_0^{2\pi}\int_a^b g_{33}\sigma_z + g_{31}(\sigma_R + \sigma_\theta)\, R\, dR\, d\theta,$$

and, finally, with tangential polarization, i.e., with electrodes dividing the cylindrical piezoelement into n sections developed potential difference is determined by the expression

$$V = \frac{2\pi}{nl \ln\frac{b}{a}} \int_0^l \int_a^b [g_{33}\sigma_\theta + g_{31}(\sigma_R + \sigma_z)]\, dR\, dz.$$

The mechanical stresses σ_R, σ_θ and σ_z appearing in these expressions depend on conditions at the ends of the piezoelement. For the case of faces protected from the influence of sound pressure we have

$$\sigma_R = \frac{a^2 b^2 p_0}{b^2 - a^2}\left(\frac{1}{R^2} - \frac{1}{a^2}\right), \quad \sigma_\theta = \frac{a^2 b^2 p_0}{b^2 - a^2}\left(-\frac{1}{R^2} - \frac{1}{a^2}\right), \quad \sigma_z = 0.$$

With the influence of the sound pressure on the annular face surfaces of the piezoelement

$$\sigma_R = \frac{a^2 b^2 p_0}{b^2 - a^2}\left(\frac{1}{R^2} - \frac{1}{a^2}\right),$$
$$\sigma_\theta = \frac{a^2 b^2 p_0}{b^2 - a^2}\left(-\frac{1}{R^2} - \frac{1}{a^2}\right), \quad \sigma_z = -p_0,$$

and, finally, in the presence on the ends of the plates perceiving the sound pressure the stresses will be equal to

$$\sigma_R = \frac{a^2 b^2 p_0}{b^2 - a^2}\left(\frac{1}{R^2} - \frac{1}{a^2}\right),$$
$$\sigma_\theta = \frac{a^2 b^2 p_0}{b^2 - a^2}\left(-\frac{1}{R^2} - \frac{1}{a^2}\right),$$
$$\sigma_z = -\frac{b^2}{b^2 - a^2} p_0.$$

Here everywhere p_0 – external excess pressure; the excess pressure in the internal cavity of the cylinder is taken equal to zero.

By substituting the expressions for the stress into the corresponding integrals determining the potential difference developed by the piezoelement, we obtain expressions for the static sensitivity of the cylindrical piezoelement (Table 13). Coefficient A in Table 13 will be expressed in the following way:

$$A = \frac{2\kappa b}{\kappa \ln \frac{1}{1-2\kappa}};$$

the axial length of the cylinder is designated by l.

Table 13

Polarization	Conditions on the fases: fases are protected from the influense of sound pressure	sound pressure influences the annular fase surfaces of the piezoelement	fases of the piezoelement are closed by plates perceiving the sound pressure
Radial	$b\left[\frac{\kappa}{1-\kappa} g_{33} + g_{31}\right]$	$b\left[\frac{\kappa}{1-\kappa} g_{33} + (1-2\kappa) g_{31}\right]$	$b\left[\frac{\kappa}{1-\kappa} g_{33} + \frac{3-2\kappa}{2-2\kappa} g_{31}\right]$
Longitudinal	$l\left[\frac{g_{33}}{2(\kappa-\kappa^2)}\right]$	$l\left[\frac{g_{33}}{2(\kappa-\kappa^2)} + g_{31}\right]$	$l\left[\frac{2g_{31} + g_{33}}{4(\kappa-\kappa^2)}\right]$
Tangential	$A\left[g_{31}\frac{\kappa}{1-\kappa} + g_{33}\right]$	$A\left[g_{31}\frac{\kappa(3-2\kappa)}{1-\kappa}\right] + g_{33}$	$A\left[g_{31}\frac{1-2\kappa}{2(1-\kappa)} + g_{33}\right]$

From the formulas given in Table 13 we plotted curves for the calculation of sensitivity of the piezoelement with values selected by us of the piezoelectric constants of ceramics. The corresponding curves given in the work of Langevin pertain to piezoceramics for which the piezoelectric constants g_{33} and g_{31} exceed only by 10% those accepted by us for the calculations.

Figure 4.4a gives a curve for the case of radial polarization of the cylindrical piezoelement. From the corresponding formulas one can see that the sensitivity is proportional to the external radius of the cylinder; therefore, the curve is plotted for b = 1.

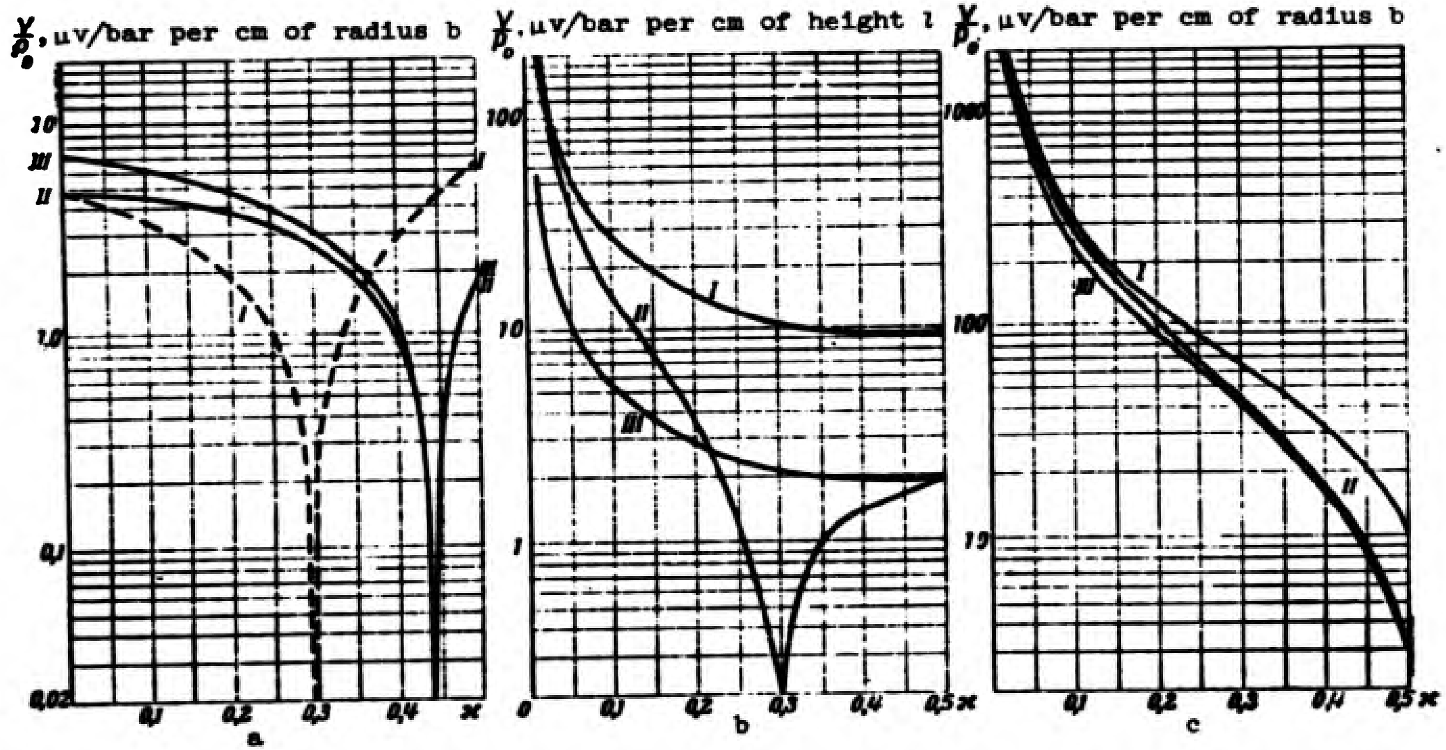

Fig. 40. Sensitivity of cylinders of ceramics of barium titanate with different ratios of thickness of the wall to the external diameter ϰ, b = 1 cm. a) with radial polarization; b) with longitudinal polarization; c) with tangential polarization.

Three curves are represented on the figure: for faces protected from the influence of sound pressure (curve I), for faces perceiving pressure by the annular surface (curve II), and in the presence of face plates (curve III). It is easy to see that the application of face plates increases the sensitivity of the piezoelement; with a thin shell ($\varkappa = 0$) this increase is about 50%. As in the case of the spherical shell, the sensitivity of the cylindrical piezoelement becomes zero with defined values of $\varkappa$ depending, of course, on conditions on the faces.

The curve pertaining to the case of longitudinal polarization is shown in Fig. 40b. Inasmuch as the sensitivity in this case is proportional to the axial length of the cylinder, the curve is plotted for $l = 1$. In this Figure, as in Fig. 40a, three cases are represented: for faces protected from the influence of sound pressure (curve I), for faces perceiving pressure along the annular surface (curve II), and in the presence of face plates 2b in diameter (curve III). The zero value of the sensitivity takes place only for curve II.

Finally, in Fig. 40c, a curve is given pertaining to the case of tangential polarization, for $n = 2$ and $b = 1$. The designations on the curves are the same as in Fig. 40a and b. It is natural that when $\varkappa = 0.5$ the sensitivity in this case becomes zero, since the coefficient A becomes equal to zero.

It is interesting to clarify the question with what ratios of the thickness of the wall to the diameter $\varkappa$ is it possible to use formulas given in section 2, and when one should apply a more accurate calculation. A comparison made in work [196] shows that with the designing of measuring sound receivers for work in a basin, in shallow water, and in air when the value $\varkappa$ does not exceed 0.05-0.06, it is possible to use approximation formulas.

Figure 41 gives the dependencies of static sensitivity of cylindrical and spherical sound receivers with radial polarization on $\varkappa$ with small values of this parameter. The dotted horizontal lines give the sensitivity calculated from approximation formulas; the solid curves correspond to the calculation from exact formulas. Curve 1 pertains to the case of a sphere, curve 2 — to the case of a cylinder with faces not protected from the sound pressure, curve 3 — to the calculation from approximation formulas identical for these two cases, curve 4 — to the case of a cylinder with hard face diaphragms with a diameter of 2b, curve 5 — to the same case during calculation from approximate ormulas.

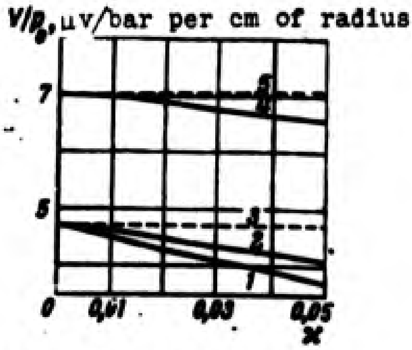

Fig. 41. Calculation of static sensitivity of a radially polarized spherical and cylindrical shell of ceramics of barium titanate.

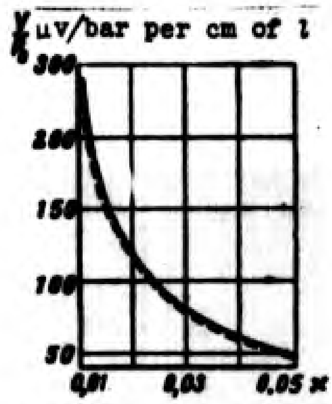

Fig. 42. Calculation of static sensitivity of a cylinder with longitudinal polarization. Faces of the cylinder are shielded from pressure.

As can be seen from the figure, when $\varkappa = 0.05$ the divergence between the results of the calculation by approximation and exact formulas is for a sphere 2.1 decibels, for a cylinder with unprotected faces, 1.2 decibels, and for a cylinder with face diaphragms, 0.73 decibels. The same comparison is shown in Fig. 42 for the case of a cylinder with longitudinal polarization and unprotected faces. The divergence between results of the calculation by the exact formula (solid curve) and by the approximation formula (dotted curve) is very small: when $\varkappa = 0.05$ it is a total of 0.46 decibels.

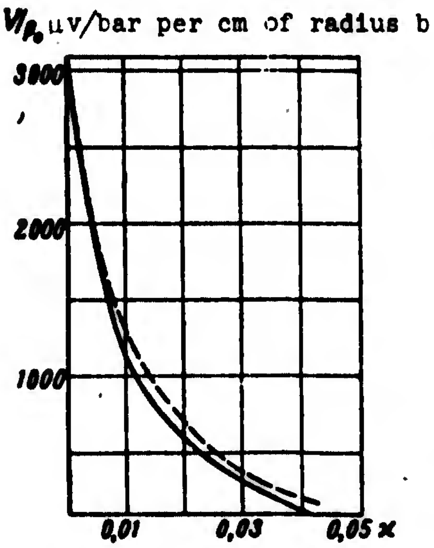

Fig. 43. Calculation by exact and approximation formulas of the static sensitivity of tangentially polarized cylinders of ceramics of barium titanate.

Figure 43 gives a comparison of the approximate and exact calculations for a cylinder with tangential polarization. Here the divergence when $\varkappa = 0.05$ is 1.16 decibels. Thus when $\varkappa \ll 0.05$ it always appears possible to calculate the sensitivity of ceramic sound receivers by approximation formulas.

It is interesting to cite a comparison of the sensitivity of thin-walled piezoelements of different forms with solid piezoelements of different forms with solid piezoelements made of ceramics equivalent to overall dimensions. In these limiting cases formulas for the calculation of sensitivity take a very simple form. Such a comparison is given graphically in Fig. 44 where in each series

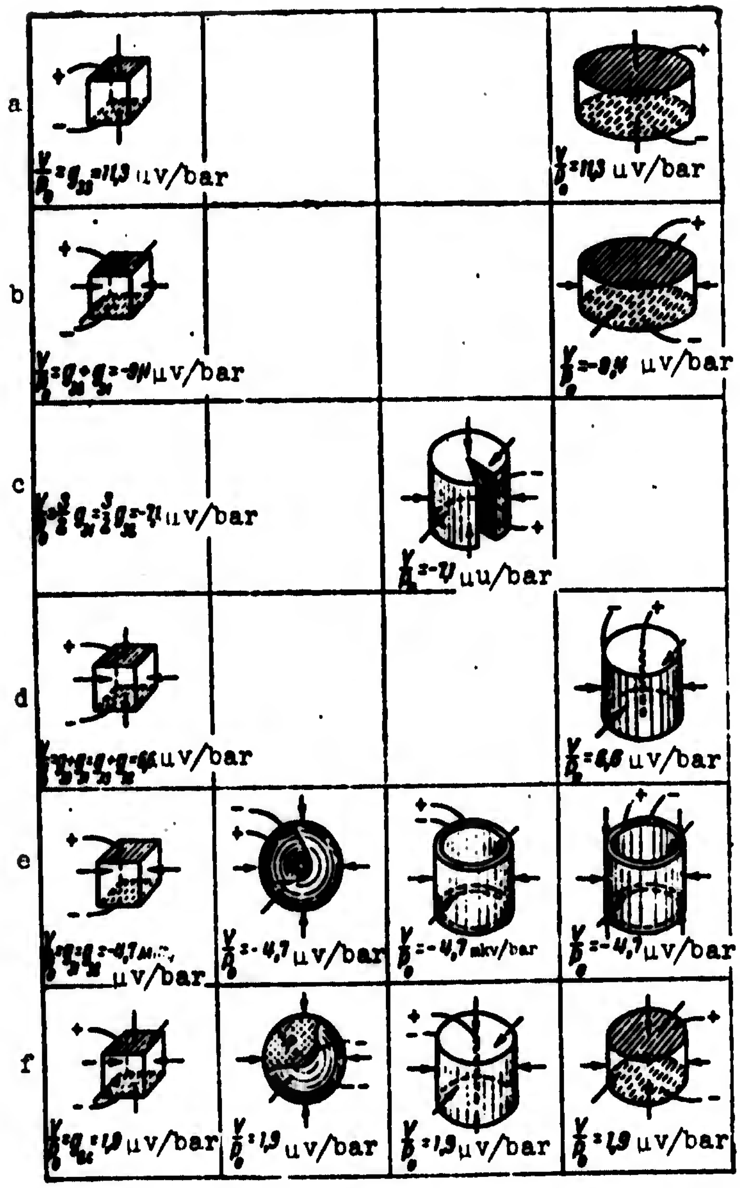

Fig. 44. Table of the comparison of the sensitivity of spherical and cylindrical piezoelements with the sensitivity of the simplest piezoelements in the form of a cube or flat plate (radius of the cylinder or sphere is equal to the cube edge or thickness of the plate).

piezoelements with an identical sensitivity are placed. Figure 44a shows a cubic piezoelement with longitudinal polarization (the side of the cube is equal to 1 cm) and, equivalent to it in sensitivity, a disk piezoelement 1 cm thick; in both cases the direction of the external force is in parallel to the direction of polarization. Fig. 44b, gives the same cubic and disk elements subjected to hydrostatic lateral stress; here the direction of deformations is perpendicular to the direction of polarization. Figure 44c shows a thin-walled cylindrical shell of unit radius with radial polarization and hard face plates; the external pressure acts on the whole external surface of the piezoelement. In Fig. 44d, there are a unit polarized cube with deformation in two directions (perpendicular and parallel to the direction of polarization) and a solid radial polarized cylindrical piezoelement of unit radius subjected to hydrostatic lateral stress, which are equivalent to each other. Figure 44e, gives a unit cube subjected to deformation in a direction perpendicular to the direction of polarization, a thin radially polarized spherical shell of unit radius with hydrostatic stress, radially polarized cylindrical shell of unit radius subjected to great hydrostatic stress, and such a shell of unit radius with unprotected faces. Finally, Fig. 44f, shows a unit cube, a solid radially polarized sphere of unit radius, a solid radially polarized cylinder of unit radius, and a disk element of unit thickness, and all are subjected to hydrostatic stress.

Here we do not have possibility to consider elements with tangential polarization, since for them the sensitivity is determined not only by geometric dimensions of the shell as a whole, but also by the number of electrodes placed. Figure 44c, and e graphically show that thin-walled shells provide incomparably better use of ceramic piezomaterial than any solid ceramic piezoelements.

5. Cylindrical and Spherical Sound Receivers with Piezoelements Built into the Receiving Shell

As was already stated, in principle it is possible to create sound receivers in which the shell (being an acoustic antenna) would be made of an arbitrary material, or metal, glass, plastic, and so forth, and would play the role of a mechanical transformer, whereas the piezoelement would be built into this shell. With large overall dimensions of the cylinder or sphere and the small thickness of the wall a large coefficient of mechanical transformation can be obtained; at the same time with small elements of a built-in element it was possible to expect that it will not have consider- . influence on the oscillatory properties of the shell.

On the basis of these considerations, we started an investigation of a number of variants of sound receivers with piezoelements of ceramics of barium titanate built into the shell. The basic data obtained are given in Table 14.

Methods of the constructive connection of the shell of the piezoelement correspond to that shown in Fig. 22.

Table 14

Form of the shell	Material	Dimension of the shell: diameter, mm	Dimension of the shell: thickness of wall, mm	Dimensions of the piezoelement	Capacity of the piezoelement	Coefficient of transformation	Calculation sensitivity of the sound receiver uV/bar
Cylindrical	Steel	38	2.0	2 X 6 X 40 mm	100	9.5	57
Spherical	Glass	50	1.5	Diameter 10 mm, thickness, 2 mm	37	7.5	37
	"	29	1.5		37	4.8	37

The metallic shell could naturally simultaneously serve as an electrostatic shield. The application of a glass shell (or any other shell of electric insulating material) requires an introduction of an additional shield, which in such cases we accomplished in the form of a silver covering applied to the internal surface of the shell by a chemical process.

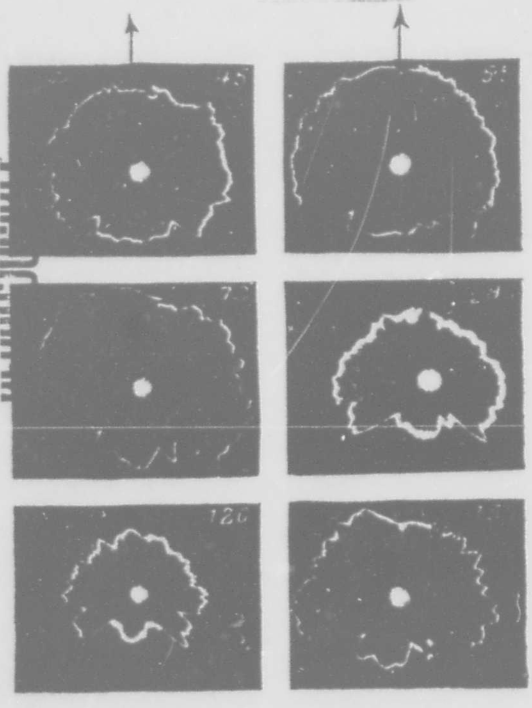

Fig. 45. Directional characteristics of the sound receiver with a spherical receiving shell and built-in sensitive ceramic piezoelements. Numbers on the figure denote frequency in kilocycles.

Figure 45 gives directional characteristics of a sound receiver with a glass spherical shell 5 cm in diameter. The diameter of the built-in ceramic piezoelement in this case was equal to 1 cm. Zero directions of the reading of angles on the directional diagrams are shown by arrows; they correspond to the position of the receiver tested. The piezoelement was built into the back side of the shell where the fastening of the shell was accomplished constructively to the turning device with the removal of the directional characteristic. It is easy to see that at frequencies of 45-150 kilocycles the directional characteristics are close to circular in the front hemisphere and noticeably distorted in the rear hemisphere, which was conditioned, apparently, by the deviation in asymmetry in the construction owing to inclusions in the symmetric receiving shell of a piezoelement of another material with other elastic constants. Moreover, an imperfection of the bonding of the piezoelement with the shell could be shown. With imperfect bonding, defects and heterogeneities can undoubtedly introduce into it distortions in the directional characteristics of the sound receiver.

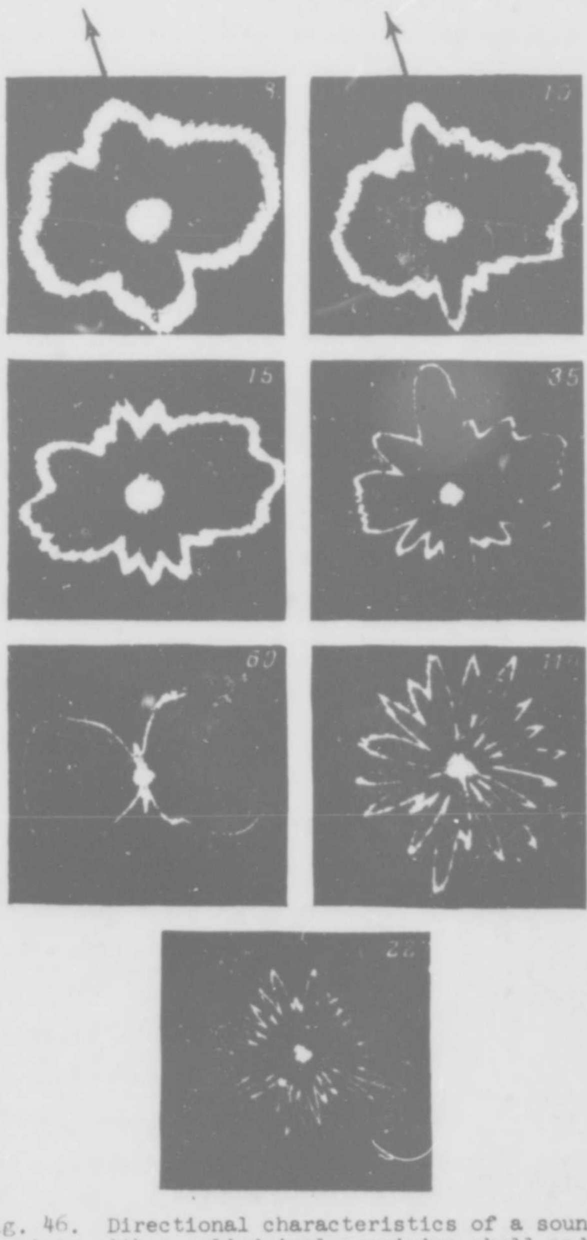

Fig. 46. Directional characteristics of a sound receiver with a cylindrical receiving shell and built-in ceramic piezoelement. Numbers on the figure denote frequency in kilocycles.

Figure 46 gives the directional characteristics taken in a water medium of a sound receiver with a steel cylindrical shell 3.8 cm in diameter and 4 cm in length. Dimensions of the two piezoelements built-in along the whole length of the cylinder, as it is schematically shown in Fig. 22b, were 4 cm × 0.6 cm with a radial thickness of 0.17 cm. Zero directions of readings of angles are shown on the figure by arrows. We see that in the given case the complete dissecting of the shell by two built-in piezoelements with a probable imperfection of the bonding leads to considerably larger distortions of the directional characteristics than in the case of the spherical shell.

For improving the directional characteristics of such sound receivers it is obviously necessary to strive for a more rigid connection of the piezoelement with the shell, for a selection of materials of the piezoelement and shell with close elastic parameters, and for a decrease in dimensions of the built-in piezoelement.

In spite of the fact that the obtained results, especially for the spherical shell, showed that the idea of the sound receiver with piezoelements built into the shell in principle is realized, nevertheless the practical realization of such sound receivers encounters considerable technological difficulties. Therefore, we subsequently proceeded to study nondirectional sound receivers with thin-walled shells made wholly of ceramics of barium titanate.

It is possible, however, that technological convenient variants of the connection of the shell and built-in element can be found.

Thus with spherical symmetry the construction shown schematically in Fig. 47 is possible. Two steel hemispheres are rigidly united by means of electric insulating plates with the equatorial belt in the form of a ring made of polarized ceramics of barium titanate. Such construction will allow making a reliable and uniform bonding and can be useful for low-frequency nondirectional sound receivers of large diameter.

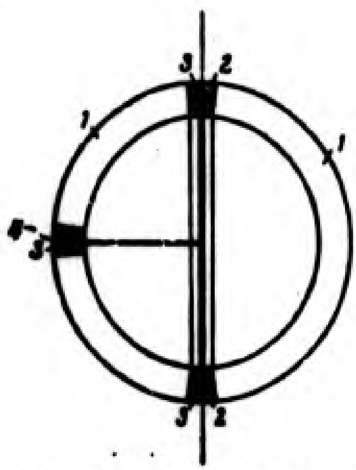

Fig. 47. Example of the connection of a receiving spherical shell with a sensitive ceramic element 1) steel hemispheres; 2) equatorial belt in the form of a ring of ceramics of barium titanate; 3) electric insulating material; 4) electric lead.

6. Spherical Broad-Band Nondirectional Sound Receiver with a Thin-Walled Shell of Ceramics of Barium Titanate

We investigated a number of variants of spherical piezoceramic sound receivers with radial polarization and with the application of electrodes along the whole internal and external surface of the spherical shell. The requirement of minimum disturbance of the spherical symmetry of the shell leads to the tendency, as far as possible, to decrease the hole necessary for the conductor lead from the internal electrode. It is very difficult to make a whole hollow sphere with a thickness of the wall equal in any section and small hole for the lead of the internal electrode technological, and therefore we produced two hemispheres (1 in Fig. 48) and selected from them the spherical element with a diametrical seam 4. The hemispheres were machined on an optical machine with a precision of 0.05-0.1 mm; electrodes 2 and 3 were applied to the internal and external surface of the hemispheres by means of double or triple brazing of silver. The connection of the two hemispheres during assembly of experimental dummies of sound receivers was produced by gluing with carbinol glue or carbinol glue with a hard filler (talc powder, barium titanate, and so forth). The hemispheric procurements were subjected to polarization before assembly simultaneously and in identical conditions. All the basic measurements necessary for the appraisal of properties of the sound receivers of given construction were made on dummies assembled in such a way.

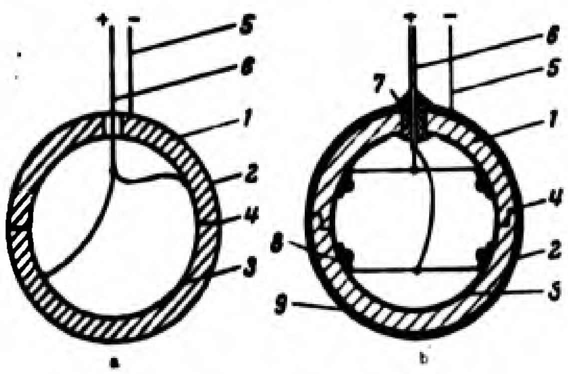

Fig. 48. Sensitive ceramic element of the spherical sound receiver. a) for work in air; b) for work in water. 1) ceramic hemisphere; 2) external electrode; 3) internal electrode; 4) bonding by the diametrical seam; 5) lead from the external electrode; 6) lead from the internal electrode; 7) glass passage insulator; 8) copy of glass; 9) external glass covering.

However, in the final variants of sound receivers a more improved method of connecting the two hemispheres was used, welding by glass. The lead of the conductor from the internal electrode is accomplished through the glass insulator founded in the hole in the ceramic shell. For more reliable moisture protection the whole spherical element, moreover, was completely covered by glass enamel. A schematic diagram of a spherical sound receiver of such construction is given in Fig. 48b.

As follows from our experience, the assembly of such spherical piezoelements is carried out best of all in the following sequence:

1) the two hemispheres prepared by means of grinding on an optical machine are metallized by the method of silver brazing on the external and internal surfaces; the internal surface is covered with silver in such a manner that the small belt along the diametrical seam remains free from metallizing;

2) to the internal metallized surface of the hemispheres the connecting conductors of a thin silver wire (diameter 0.1-0.2 mm) are welded; each conductor is fastened by a drop of glass (8 in Fig. 48) at one and two points to the internal electrode 3, and an electrical connection is carried out by means of a layer of silver applied to the conductor and internal electrode additionally by the method of brazing of silver paste;

3) the lead is accomplished from the internal electrode 6 through the hole in one of the two hemispheres; for this in the hole a silver wire (diameter 0.5-1 mm depending upon the dimensions of the spherical element) is founded by glass. This hard lead conductor is also used for the assembling of the sound receiver as a whole to the corresponding connecting element;

4) the two hemispheres are welded along the diametric seam 4 forming a single spherical piezoelement;

5) on the entire external surface of the sphere (including the seam) metallizing is applied by the method of silver brazing;

6) the external surface of the spherical element is covered by a moisture protective shell of glass enamel 9;

7) polarization of the assembled piezoelement is carried out.

With the indicated sequence of assembly the recovery temperature of the silver from silver paste should be 100-150° lower than the melting point of glass, which is used for welding hemispheres and covering the external surface.

The spherical sensing devices assembled from the two hemispheres have two links disturbing the symmetry, the lead from the internal electrode and the welded diametrical seam. The lead from the internal electrode and the welded diametrical seam. The lead from the internal electrode in the construction of a sound intended for work in water requires additional waterproofing in its connection with the cable, which to an even greater degree disturbs the symmetry of the construction. To estimate the influence of the seam and hermetically sealed lead we conducted two series of experiments. At first the directional characteristics of two spherical sound receivers of the simplest construction were taken, the sensing devices of which had a seam for one in the plane including the lead, which we will conditionally call meridional, and for other, in the equatorial plane. The directional characteristics were taken in the equatorial plane of the sound receiver. Figure 49a shows the directional characteristics for a sound receiver with a meridional seam; Fig. 49b shows the corresponding characteristics for a sound receiver with an equatorial seam. It is easy to see that characteristics for both sound receivers with identical frequencies are practically identical. This shows that the seam does not considerably affect the receiving properties of the ceramic shell. Let us note that the seam does not affect the directional characteristics neither with welding by glass nor with a less perfected method of bonding by means of carbinol glue.

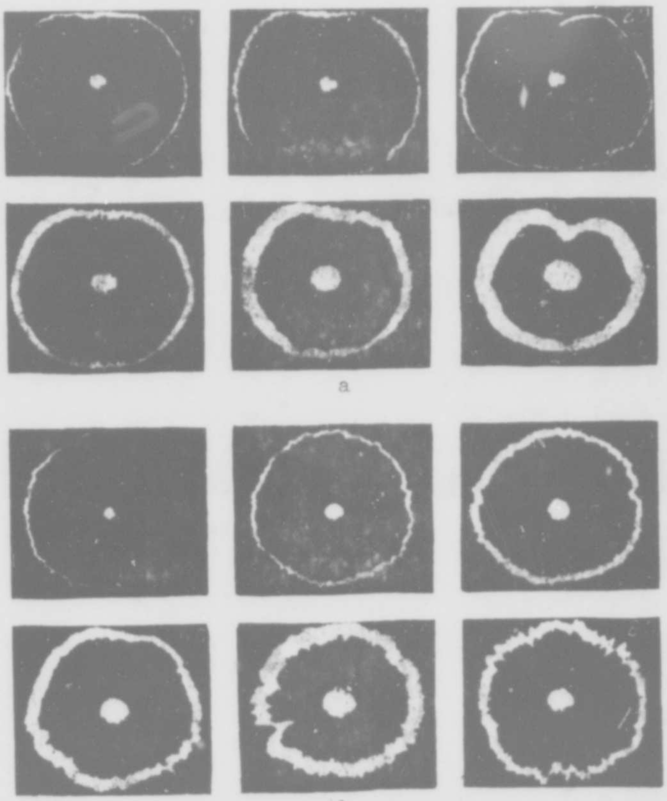

Fig. 49. Directional characteristics of two spherical sound receivers with a meridional (a) and equatorial (b) seam. Numbers of the figure denote the frequency in kilocycles.

The second series of experiments was for the purpose of clarifying how much the form of the directional characteristics is distorted because of the presence of elements necessary for the reliable hermetic sealing of the lead from the internal electrode.

Figure 50a gives the initial directional characteristic taken in the equatorial plane at a frequency of 40 kilocycles for a sound receiver 3.4 cm in diameter and Fig. 50 b-h, directional characteristics at the same frequency obtained with a patch on the equator of the sphere of disks of nonceramic materials. The thickness of these disks was 1.5 mm; the diameter in fractions of the wave length in water at 40 kilocycles is shown for every case in Fig. 50. Additional elements on the surface of the spherical sensing device, as can be seen from the figure, considerably influence the directional characteristic.

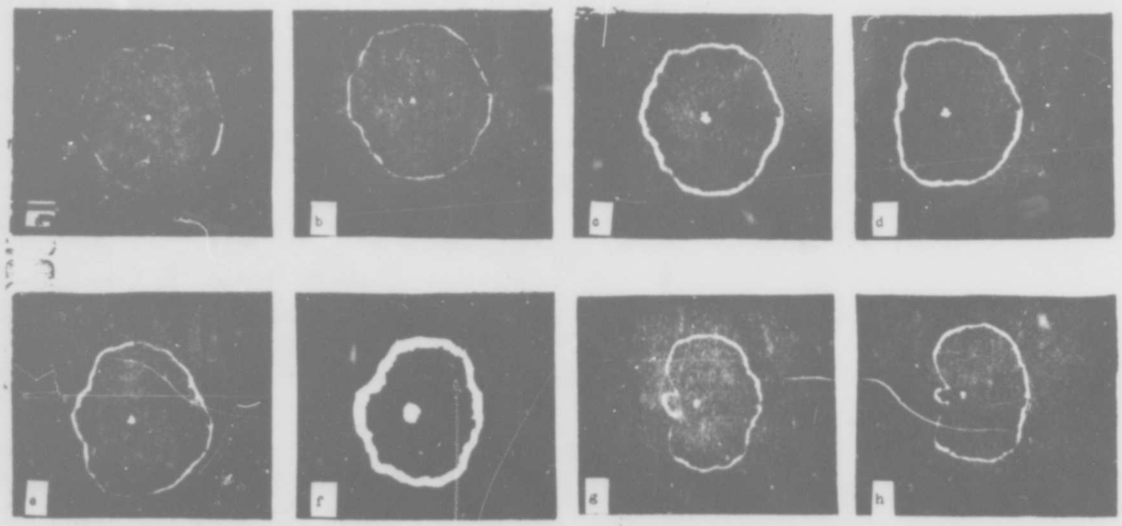

Fig. 50. Directional characteristics of a spherical sound receiver with a diameter D; part of the receiving surface is closed by a screen with a diameter D' a) spherical sound receiver ($D \approx \lambda$); b) brass ($D' \approx 0.25\lambda$); c) organic glass ($D' \approx 0.35\lambda$); d) organic glass ($D' \approx 0.8\lambda$); e) plug ($D' \approx 0.35\lambda$); f) lead ($D' \approx 0.8\lambda$); g) microporous rubber ($D' \approx 0.7\lambda$); h) plug ($D' \approx 0.8\lambda$).

On the basis of the described experiments it is possible to conclude that for nondirectional sound receivers it is possible to use spherical sensing devices with an equatorial seam; in order to decrease the distortion of the directional characteristic in the plane containing the lead of the internal electrode, it is necessary with the fulfillment of the hermetic lead to obtain as far as possible the minimum dimensions of its constructive elements.

Let us turn to the consideration of the resonance properties of spherical shells utilized in the construction of nondirectional ceramic sound receivers. A characteristic of the sound receiver is its working frequency band, i.e., the frequency domain in which the sensitivity of the sound receiver with definite tolerances is constant. This band is limited from above by the frequency of the first resonance of the shell. It appears that the selection of the method of connection of the hemispheres considerably affects the value of this frequency.

For clarification of the influence of the method of bonding on the character oscillations of the shell of the sound receiver, with the help of a special piezoelectric probe we studied the distribution of the amplitude of oscillations on the surface of the shell. Experiments were conducted in an air medium, and on the electrodes of the sound receiver was fed a voltage of different frequency from the ultrasonic generator. It turned out that for shells welded along the seam by glass the first resonance appearing on the frequency response corresponds to the zero mode of oscillations of the shell. With weaker bonding (for instance, with bonding by carbinol glue) the first resonance appearing on the frequency response corresponds to the form of oscillations of the shell shown schematically in Fig. 51. The two identical hemispheres are united along the diametrical seam AB. We have here an oscillation with an axial symmetry characterized by the presence of two nodal lines (CD and EF – diameters of nodal circumferences). The resonance corresponding to the zero mode does not at all appear and does not appear in the frequency responses of the sound receivers. Inasmuch as the modal frequency corresponding to Fig. 51 with identical geometric dimensions of the shell is higher than the frequency of the zero mode, it would be possible to assume that the weaker bonding is more suitable since it provides a displacement of the first limiting working band of resonance upwards in frequency. However, such a solution can be accepted only with the construction of sound receivers designed for work in air and at low static pressures; in the majority of the cases one should use a durable connection at least because of a certain lowering of the upper cutoff frequency of the working range of frequencies of the sound receiver.

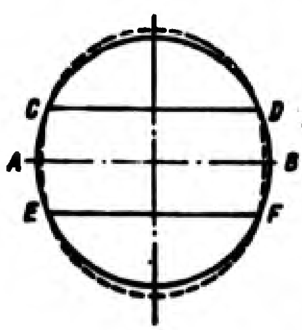

Fig. 51. Form of oscillations of a shell with an imperfect diametrical seam.

As was already said earlier, the cutoff frequency is conveniently determined on the basis of the measurement of electrical impedance of the sound receiver; indeed, before the first resonance the sensitivity of the sound receiver differs little from static, and knowledge of the static sensitivity and position of the first resonance essentially already determines the working range of frequencies of the sound receiver. Of course, for the calculation of the influence on the frequency response of diffractional phenomena in the end the removal of the frequency response of the sound receiver in real conditions of its work always turns out to be necessary, i.e., in air or in water.

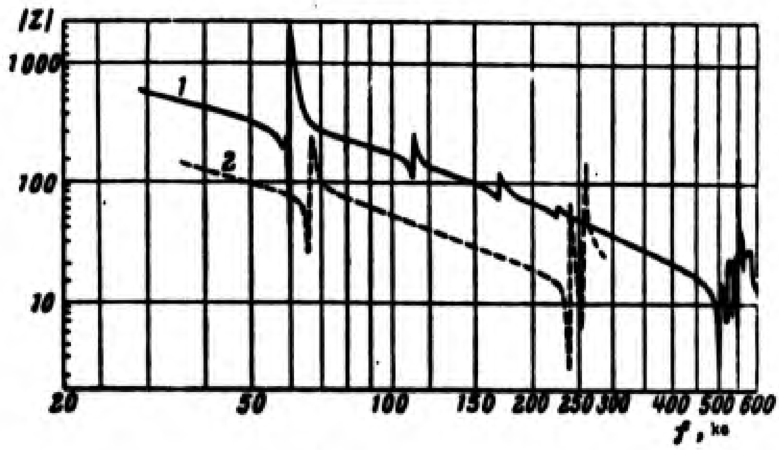

Fig. 52. Modulus of electrical impedance of two spherical sound receivers joined along the diametrical seam. External diameter, D = 50 mm; 1) thickness of the wall, 5 mm; 2) thickness of the wall, 10 mm.

Figure 52 gives examples of frequency responses of the electrical impedance of spherical sound receivers joined by means of bonding with carbinol glue. Curve 1 pertains to a sound receiver with an external diameter of 50 mm and a thickness of the wall of 5 mm; curve 2 refers to a sound receiver of the same diameter but with a thickness of the wall of 10 mm.

Figure 53 gives an analogous characteristic for a sound receiver joined with use of glass welding. Here the diameter of the sound receiver is 30 mm, and the thickness of the wall is 1.5 mm. Finally Fig. 54 gives a typical frequency response of a spherical sound receiver with a diameter of 30 mm and a thickness of the shell of 1.5 mm obtained in water. The lowering of the sensitivity before resonance (position of the resonance frequency on the figure is marked by a dotted line) is caused by diffractional phenomena; at lower frequencies the frequency response appears even, and the sensitivity is practically equal to the static.

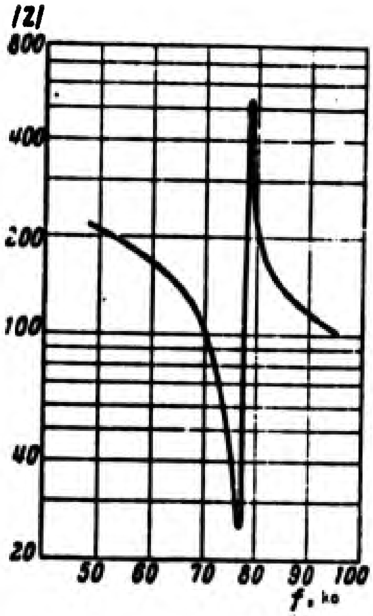

Fig. 53. Modulus of electric impedance of a spherical sound receiver with a welded diametrical seam. External diameter, D = 30 mm.

Let us turn to the consideration of certain constructive questions of having considerable importance in the development of nondirectional broad-band sound receivers. First of all we should discuss methods of fastening the sensing device to the holder or another transition bracing element ensuring the connection of the sound receiver with the cable or preamplifier. Such a connecting element in the case of a sound receiver designed for work in air has the requirements of strength, reliability of connection, and continuity of the electric shield. In the case of the sound receiver designed for work in water the requirement of airtightness of the connection is added. It should be noted that the fulfillment of these requirements leads, as a rule, to an increase in the dimensions of the connecting devices, and this in turn can lead to the distortion of directional characteristics of the sound receiver in the meridional plane. Unsuccessful construction of the connecting elements can also lead to the impairment of the frequency response.

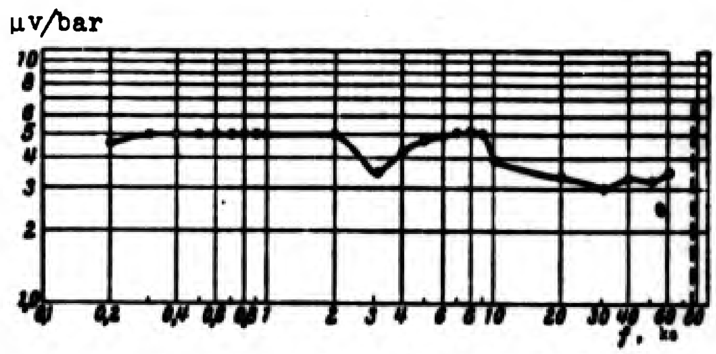

Fig. 54. Frequency response curve of a spherical sound receiver. External diameter, D = 30 mm.

For an example let us consider the case of a sound receiver with a rigid fastening of the spherical element to a metallic tube (Fig. 55). On the end of the tube there is metallic cup in which, with the help of carbinol glue, the spherical piezoelement is glued. Figure 56a gives directional characteristics in the equatorial plane of such a sound receiver with a diameter of the piezoelement of 1.5 cm with a thickness of the wall of 1.5 mm. The diameter of the metallic

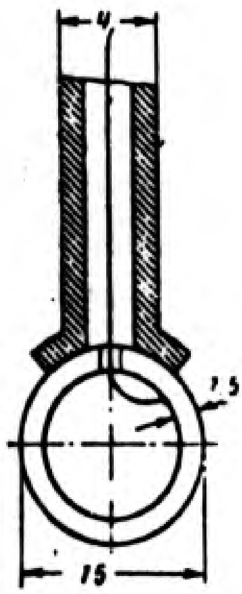

Fig. 55. Sound receiver with rigid bracing of the sensitive spherical piezo-element.

tube in this case was equal to 4 mm and the length, 35 cm. Figure 56b, gives the directional characteristics in the meridional plane for the same frequencies. It is easy to see that these characteristics are sharply distorted, and this distortion is reflected on the characteristics for an equatorial plane. On almost all the frequencies the directional characteristics in the meridional plane have sharply expressed maxima at angles of incidence of the sound wave ±65°30' to the axis of the holder. A detailed investigation showed that the presence of these maxima and, in general, the sharp distortion of directional characteristics in the meridional plane are conditioned by the fact that the tube of the holder becomes a unique additional sound antenna distorting the directional properties of the spherical sensing device. The rigid bond of the sound receiver with the holder influences the frequency properties of the sound receiver. For an example Fig. 57 shows the frequency-response curve of the electrical impedance of sound receivers. The dotted curves indicate the dependences for the piezoelement separately and solid curves, for the assembled sound receiver, i.e., in totality with the holder. As one should have expected, the presence of the holder somewhat lowers the resonance frequencies and decreases the quality factor on the resonance.

The examples given of distortions in directional characteristics and the possible additional irregularities in the frequency responses of the sound receivers indicate an unfavorable influence of the rigid connection of the sensitive piezoelement with the holder. Therefore, we gave up the rigid bracing of sensitive piezoelements on holders and used a construction in which the piezoelement is separated from the holder by pliable elements playing the role of a mechanical decoupling filter. As an example Fig. 58 gives a diagram of the fastening of a piezoelement of large diameter directly to the lead out cable. Here the spherical piezoceramic element 1 is fastened to the current-carrying cable with help of a sufficiently pliable rubber bushing of conical form 6, which is put on the dielectric of the cable 7 with rubber cement. This bushing is glued also by its base to the external surface of the piezoelement and jointly with an electric insulating figure bushing of textolite 2 (or other insulating material) also accomplishes waterproofing of the electrical lead from the internal electrode of the piezoelement.

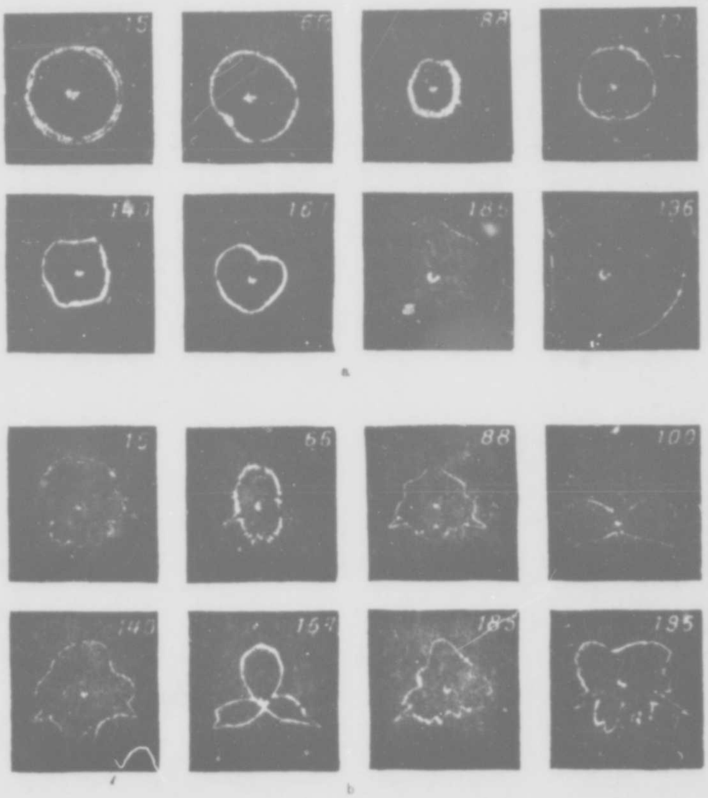

Fig. 56. Directional characteristics in the equatorial (a) and meridional (b) plane of the sound receiver with a rigid bracing of the sensitive spherical element. External diameter of the piezoelement, 15 mm. Numbers on the figure denote frequency in kilocycles.

Directional characteristics of a spherical sound receiver with such bracing in a meridional plane differ practically little from the characteristics given in Fig. 45. They can be considered satisfactory, although in the rear hemisphere distortions introduced by bracing are nevertheless considerable.

With small dimensions of the spherical elements characteristic for high-frequency sound receivers it is inexpedient to fasten the sensing device on the end of the coaxial cable. In this case the cable itself becomes an obstacle noticeably distorting the sound field. Therefore, it is necessary to use other constructions of holders and decoupling devices.

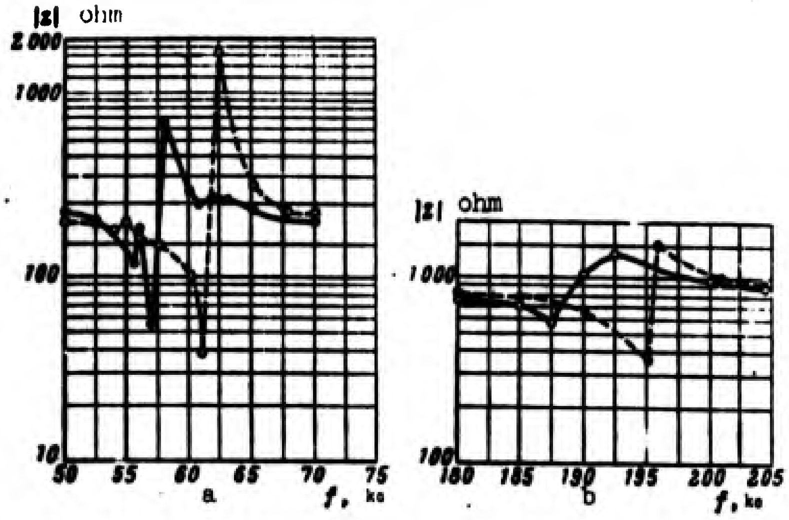

Fig. 57. Frequency-response curve of the modulus of electrical impedance of spherical piezoelements and sound receivers. a — external diameter of the piezo-element, 50 mm; b — external diameter, 15 mm.

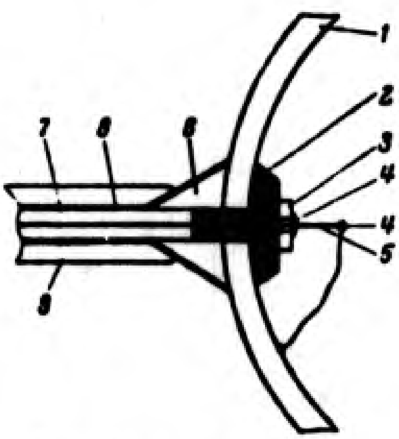

Fig. 58. Diagram of fastening spherical sensing device of the sound receiver to the cable. 1) spherical ceramic element; 2) textolite bushing; 3) metallic washer; 4) tin soldering; 5) central strand of the coaxial cable; 6) rubber conical bushing; 7) dielectric of the coaxial cable; 8) screen of the cable; 9) external rubber or plastic covering of the cable.

small spherical sound receiver.

Here piezoelements 1 welded on the diametrical seam by glass are used with an electrical lead from the internal electrode in the form of a silver rod fastened by a glass passage insulator 5. The sequence of the manufacture process of such piezoelements was described earlier. The assembly of sound receivers with such piezoelements of the design represented in Fig. 61 requires of assemblers, fitters and mechanics a special accuracy and definite skills. The skill of assembly should be especially great in the manufacture of sound receivers with spherical piezoelements 5-4 mm and less in diameter.

We developed a series of broad-band nondirectional sound receivers of the type with diameters from 50 to 4 mm (Fig. 60). The measured static sensitivity of such sound receivers with an external diameter D = 15 mm is 1.34 μv/bar; when D = 30 mm it is 2.9 μv/bar and when D = 50 mm, 7.9 μv/bar; the measured static sensitivity differs very little from the calculated.

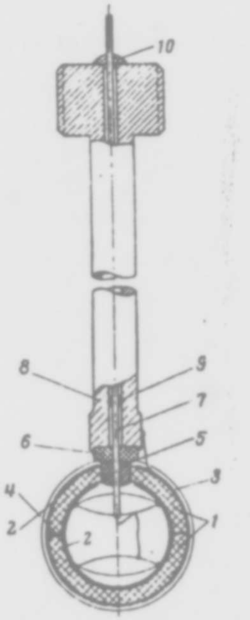

Fig. 59. Diagram of fastening the small spherical sensing device of the sound receiver to the holder. 1) ceramic piezoelement; 2) metallic covering by glass enamel; 4) glass welding of the seam; 5) glass passage insulator; 6) rubber decoupling element (waterproofing); 7) rod lead from the internal electrode; 8) tube of the holder; 9) insulating bushings; 10) bonding by carbinol glue.

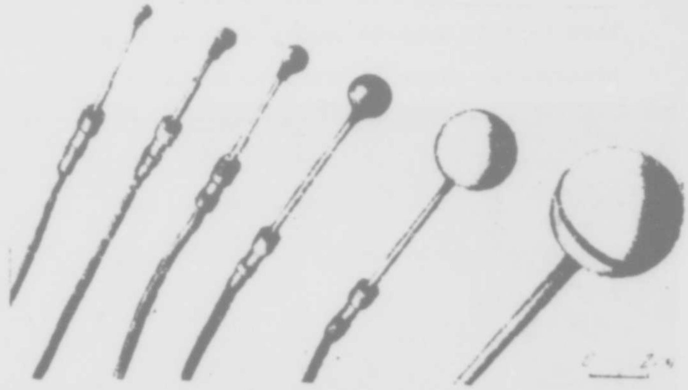

Fig. 60. Collection of measuring spherical sound receivers.

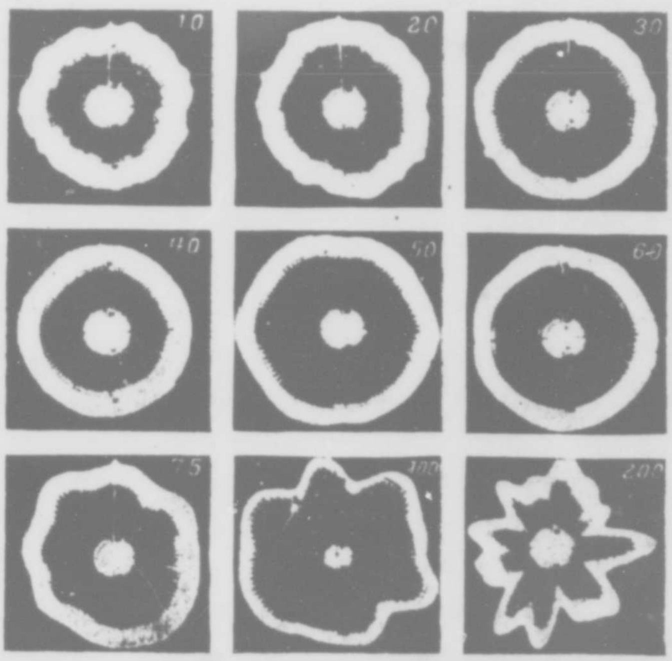

Fig. 61. Directional characteristics in the equatorial plane of the spherical ceramic sound receiver. External diameter D = 50 mm. Numbers on the figure denote frequency in kilocycles.

To judge the directional characteristics of such sound receivers we can turn to Fig. 61 where the equatorial directional characteristics for a sound receiver with an outer diameter of 50 mm are given.

Let us note that with adequate equatorial characteristics sound receivers of this type in a meridional plane can be considered nondirectional only in the front hemisphere, since in the rear hemisphere the distorting influence of the holder nevertheless turns out to be noticeable.

One of the operational merits of the series of spherical sound receivers whown in Fig. 60 is the possibility of preserving completely the sound receiver during various kinds of damages of the current-carrying cable (break, leak, and so forth).

However, the most reliable in operation during work in water are the spherical sound receivers whose sensitive piezoceramic element is completely vulcanized in rubber jointly with the end of the current-carrying cable on which the sensitive piezoelement is fastened. Our experiment showed that a rubber covering of 1-2 mm practically does not change the sensitivity of broad-band spherical radially polarized ceramic sound receivers from 50 to 10 mm in diameter within the working frequency band. For instance, the average sensitivity in the working band for the sound receiver with a spherical element completely covered by rubber is equal to 5 μv/bar with the diameter of the piezoelement at 30 mm and 8 μv/bar with the diameter of the piezoelement at 50 mm.

In conclusion we should note that besides the radial polarization of spherical piezoelements a tangential polarization of them is possible. For the realization of tangential polarization it is possible to propose, for instance, the location of the electrodes shown in Fig. 35. The layer of metallizing on a photograph is seen as a lighter background, and the dark circles are the nonmetallized part of the ceramics. This layer is one of the electrodes; the sections small in area of metallizing in the center of each disk united by soldered conductors form in totality the second electrode.

Since the electrodes are located on the same (internal) side of the shell, then for achievement of a uniform polarization one whould select a polarizing field (600-700 v/cm during polarization with heating up to the Curie point in accordance with the maximum distance between the electrodes.

The electrodes can be applied not only to the internal or external but also to both surfaces of the spherical shell. With a very thin wall of the shell (0.2-0.3 mm) it is more convenient to apply altogether one system of electrodes (for instance, the central) to the internal and the other system to the external surface of the spherical shell. With this outside the sphere there will be only two lead wires in all. With a very thin wall of the shell the sensitivity of such piezoelements with tangential polarization can attain hundreds of µv/bar with a diameter of shell of 3-5 cm. Spherical piezoelements with tangential polarization can certainly find application in the construction of air sound receivers-microphones.

7. Cylindrical Broad-Band Sound Receivers with a Thin-Walled Shell of Ceramics of Barium Titanate

To solve a number of acoustic problems it is possible to use sound receivers with a circular directional characteristic in one plane. Therefore, we started the development of sound receivers with cylindrical sensing devices of ceramics of barium titanate.

As was shown earlier, as sensitive piezoelements the ceramic cylinders allow three methods of polarization and three variants of conditions on the ends. In accordance with this different constructive forms of cylindrical sound receivers are possible.

We developed two types of cylindrical sound receivers: 1) receivers with sensing devices in the form of ceramic radially polarized cylinders with face plates and 2) receivers with sensing devices in the form of tangentially polarized cylinders with ends protected from the influence of sound pressure.

In the first case the piezoelement possesses great capacity, which permits the designing of sound receivers of very small dimensions with an even frequency response in the broad-band.

In the second case the capacity of the piezoelement will be smaller, but then the sensitivity can be very high.

As in the case of spherical sound receivers the method fastening the cylindrical piezoelement to the holder has an influence on the characteristics of the sound receivers. Figure 62 shows the construction of the cylindrical sound receiver with radial polarization of the piezoelement and with its bracing.

The cylindrical piezoelement 1 with external and internal metallizing, allowing to carry out radial polarization of the ceramics with the help of a hot fitting, is mounted in the metallic cups 2. These cups play the role of face plates perceiving sound pressure. One of the cups is the end of the tube-holder 3 through which the conductor from the internal electrode is lead. Waterproofing

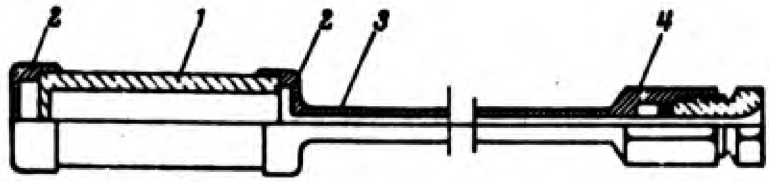

Fig. 62. Cylindrical sound receiver with a radially polarized sensing element and rigid bracing 1) cylindrical piezoelement; 2) metallic cups; 3) tube-holder; 4) connecting coupling.

of the input of the cable, as always, is accomplised with the help of the connecting coupling 4 with a sealing rubber stuffing box. Such sound receivers can be used only with an asymmetric entrance of the amplifier, since the external metallizing of the piezoelement serves simultaneously as a screen electrically united with the metallic parts 2, 3, and 4. As was stated, the cups weré planted on the piezoelement by the method of hot fitting; then they were soldered by Wood's alloy with the external metallized surface of the piezoelement, which ensured the hermetic sealing of the whole piezoelement.

Directional characteristics of such sound receivers in a plane perpendicular to the axis are obtained in a wide interval of frequencies almost ideally circular. This can be seen from characteristics given in Fig. 63 for a cylindrical sound receiver of the given type with an external diameter of 3.2 cm and an axial length of the piezoelement of 8.1 cm with a thickness of the wall at 5 mm taken in water. Regarding the directional characteristics in the plane including the axis (Fig. 64), at certain frequencies they are quite satisfactory and at others have clearly expressed secondary maxima. Partially the presence of such secondary maxima depends on simply the natural characteristic of the cylindrical piezoelement of finite length; however, the presence of the most significant secondary maxima undoubtedly is caused by the influence of bracing. However, for cylindrical sound receivers this shortcoming is not as important as for spherical.

For clarification of the influence of bracing on characteristics of the cylindrical sound receiver we used an experimental sound receiver (Fig. 65) in which the piezoelement was secured as "softly" as possible. For this purpose the piezoelement was mounted with the help of two rubber cups 2 and 3, one of which plainly closed the face of the cylinder and the second served as a pliable decoupling element with assembling of the sound receiver to the cable.

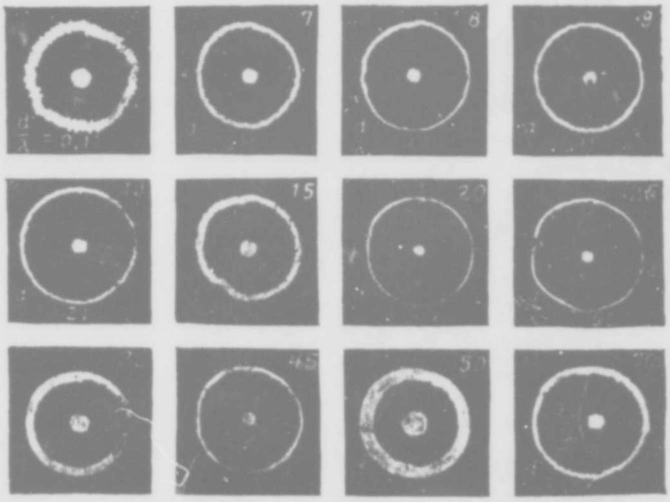

Fig. 63. Directional characteristics of the cylindrical sound receiver of ceramics of titanate with radial polarization. Characteristics are taken in a plane perpendicular to the axis of the cylinder. The frequency is shown in kilocycles.

Directional characteristics of cylindrical sound receivers, with a rigidly secured sensing device and with soft bracing in a plane perpendicular to the axis, differ little from the circular up to very high frequencies (350-450 kc) when dimensions of the sound receiver become considerably larger than the wave length. For instance, when the diameter $D \approx 6\lambda$ at the working frequency of 300 kc the directional characteristic differs from the circular by not more than ±15%, i.e., ~ 1.2 db. Equally the sound receivers with rigid and soft bracing differ little from each other in angular width of the main lobe. The width of the main lobe coincides well with the calculation which one can see from Fig. 66 where the theoretical dependence of the width of the main lobe on the frequency (dotted curve) is given for the cylinder of final length; dots denote the corresponding experimental values obtained with rigid bracing of the piezoelement.

The experimental sound receiver shown in Fig. 65 made it possible to clarify the influence of conditions of bracing on the frequency response of the sound receiver. Figure 67a, gives the frequency-response curves of the sensitivity (taken in a plane perpendicular to the axis in water) for three identical sound receivers with rigid bracing of the piezoelement. Figure 67b, gives the corresponding characteristic for the piezoelement identically applied in these sound receivers but with the soft bracing of it to the cable.

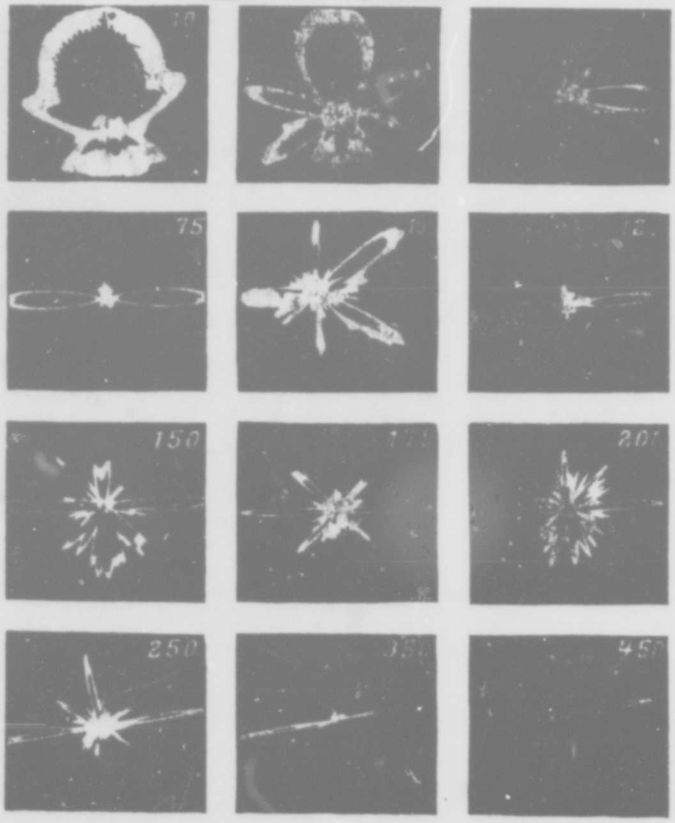

Fig. 64. Directional characteristics of the cylindrical sound receiver with rigid bracing of the sensitive radial polarized ceramic element. Characteristics are taken in the axial plane of the cylinder. Numbers on the figure denote frequency in kilocycles.

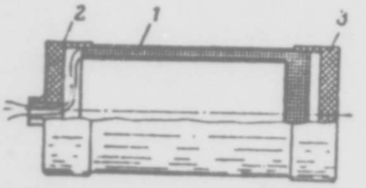

Fig. 65. Cylindrical sound receiver with soft bracing of the sensing device to the cable. 1) ceramics; 2 and 3) rubber.

It is easy to see that with soft bracing up to the approach of resonance the frequency response is obtained considerably more even than with rigid bracing. Figure 67b shows two clearly expressed resonances.

As is known, the cylindrical shell can have three systems of natural resonances; 1) determined by average the diameter of the shell D_1 (condition of the first basic resonance of this type has the form $\pi D_1 = \lambda$); 2) determined by oscillations of the cylinder with height h (condition of the first basic resonance has the form $h = \lambda/2$); 3) connected with oscillations

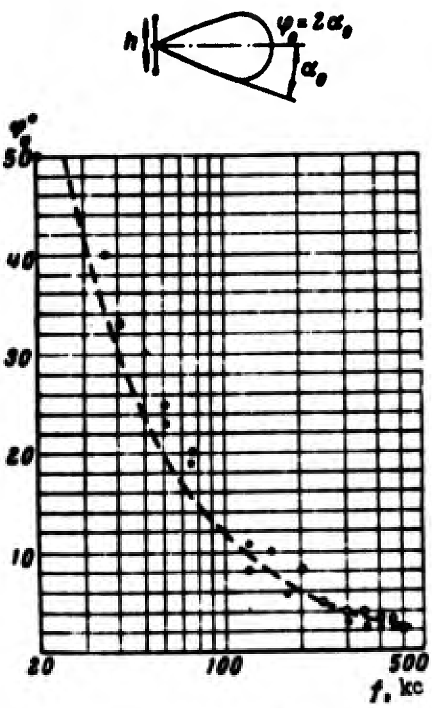

Fig. 66. Width of the basic lobe of the directional characteristic of a cylindrical sound receiver in an axial plane.

by the thickness of the wall δ (condition of the first basic resonance has the form $\delta = \lambda/2$). However, not all types of natural oscillations appear equally with different methods of polarization of the cylindrical shell. In particular, with radial polarization all three forms of resonances appear; however, either the longitudinal or radial resonance limits the working band. In the particular case shown in Fig. 67b, where calculated positions of frequencies of longitudinal f_h and radial f_r resonances are shown the first of them limits the working band.

The continual increase of sensitivity, evident from Fig. 67a, at frequencies up to 10 kilocycles, the dip at a frequency of 15 kilocycle, the displacement of the first low-frequency resonance downwards (from 25 to 20 kilocycle), and the appearance of additional resonance peaks are caused by the influence of rigid bracing of the piezoelement. However, sound receivers with rigid bracing are very reliable in work and are easy to handle, since they differ by a large safety factor and allow measurements at comparatively great hydrostatic pressure (of the order of 5-7 atm).

Table 15 gives parameters of two identical cylindrical sound receivers with rigid bracing of the piezoelement.

As can be seen, the reproducibility of the parameters is good. The sensitivity of these receivers is small due to the relatively great thickness of the wall.

With further development of broad-band cylindrical sound receivers with radial polarization, we considerably decreased the ratio of the thickness of the wall to the diameter and used only the variant with face washers.

Figure 68 gives a model construction of such a sound receiver. Here the cylindrical radial polarized sensitive piezoceramic element 1 is used, the ends of which are sealed by hard plates 2 (metallic or ceramic) perceiving sound pressure. In one of the face plates there is a hole for the lead-in of the cable, which is hermetically sealed by the stuffing box 6 located in the internal cylindrical cavity of the sound receiver.

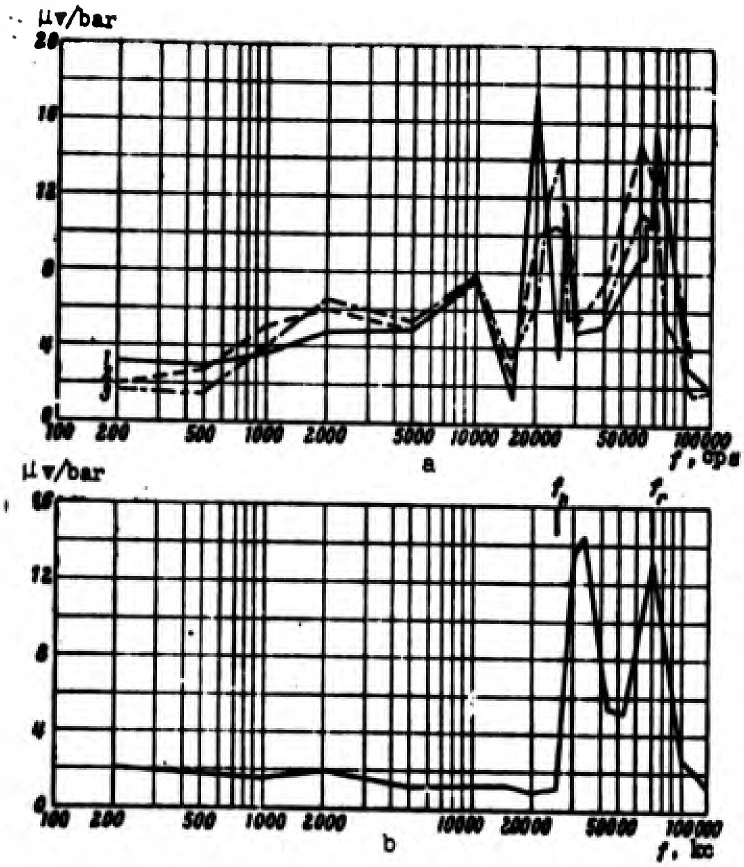

Fig. 67. Frequency-response curves of cylindrical sound receivers of ceramics of barium titanate with radial polarization. a) with rigid bracing of the sensing device to the holder; b) with soft bracing of the sensing device to the cable; f_n and f_r – frequencies of longitudinal and radial resonances.

Table 15

Dimensions of the piezoelement			Capacity, pf	Resonance frequencies, kc		
height, mm	external diameter, mm	thickness of the wall, mm		longitudinal resonance	radial resonance	depth resonance
81,3	32	5	8 800	14,45	55,5	435
81,3	32	5	8 200	15,3	55,5	435

Figure 69 shows a number of sound receivers of this type. Their parameters are given in Table 16.

Figure 70 gives frequency responses of cylindrical sound receivers of the described construction with external diameters of 50, 30, 15 and 10 mm.

For sound receivers with a diameter of the sensing device less than 6 mm the fastening of the sound receiver to the cable appears inconvenient. For such receivers we used a tube-holder of practically the same construction as for

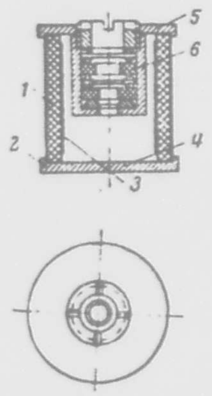

Fig. 68. Constructive diagram of a cylindrical ceramic sound receiver with face cover plates. 1) piezoelement; 2) external metallic covering; 3) internal metallic covering; 4) front end washer; 5) rear metallic end washer; 6) stuffing box.

spherical sound receivers with soft bracing. Such a construction is schematically shown in Fig. 71.

Sound receivers of such type were constructed by us with diameters of the piezoelement from 3 to 6 mm. Figure 72 shows one of these sound receivers.

In certain special cases we nevertheless fastened the miniature cylindrical piezoelements directly to the cable. Thus in 1959 we constructed a sound receiver for the Therapeutic Institute of the Academy of medical sciences designed for insertion into the heart cavity during the investigation of heart noises. The external diameter of this sound receiver was 3 mm. The appearance of the first dummy intracavity sound receiver for diagnostics of heart disease and components of it are shown in Fig. 73.

Broad-band cylindrical sound receivers with radial polarized sensitive ceramic elements at present already are widely used along with spherical nondirectional sound receivers. They possess, as it was shown, sufficiently great natural capacity and satisfactory sensitivity in a wide frequency band and also nondirectionalness in one plane. The process of manufacture of cylindrical piezoelements (especially miniature and subminiature) and the procedure of assembly of cylindrical sound receivers in a number of cases are noticeably simplified as compared to the manufacture of spherical sound receivers.

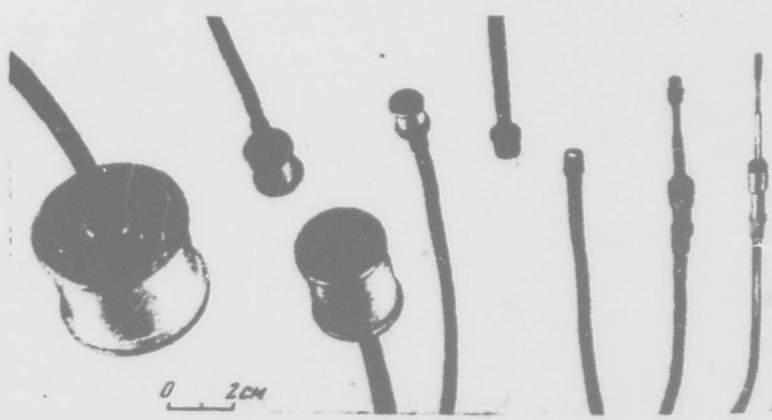

Fig. 69. A collection of broad-band cylindrical sound receivers of ceramics of barium titanate.

Table 16

External diameter of the cylinder, mm	Height of the cylinder, mm	Thickness of the wall, mm	Capacity pn	Static sensitivity, µv/bar	Frequency of the first resonance, kc
52	40	3,0	15000	8,4	20
30	30	1,5	23000	7,0	50
15	12	1,0	4500	3,0	100
10	10	1,0	3000	2,0	150
8	8	0,5	3500		
6	6	0,5	1000	0,8	200

Let us turn to the consideration of cylindrical sound receivers with tangential polarization of the piezoelement. An increase of the sensitivity of sound receivers with a radial polarized cylindrical piezoelement is possible only with an increase in the external diameter. The application of tangential polarization permits considerably increasing the sensitivity of the ceramic sound receivers.[1]

The construction of a cylindrical piezoelement with tangential polarization assuming a separation of the cylinder on a number of sections covered by metallizing along the longitudinal ends and then assembled with the help of bonding into a single cylindrical element is unfit for sound receivers with a thin-walled shell, since a large number of the bondings disturbs the completeness of the shell and undoubtedly should lead to the impairment of the directional characteristics. Such construction can be applied during the making of cylindrical piezoelements with great thickness of the wall and large volume of the piezoelectric material, for instance, for purposes of sound radiation.

Therefore, we exclusively used solid cylindrical shells with the application of electrodes to the external, internal, or simultaneously to the external and internal surfaces of the piezoelement. Figure 74a shows an example of a cylindrical piezoelement with applied electrodes. The electrodes should be connected every other one in parallel; this is possible to do with the help of connecting conductors as is shown in Fig. 74b; however, to decrease the number of solderings it is considerably more convenient to make the connection of electrodes as is shown in Fig. 74c, by means of applying the connecting conductors on the surface of the piezoelement by the method silver brazing.

[1]Cylindrical elements with longitudinal polarization occupy an intermediate position in sensitivity and capacity between the radially polarized and tangentially polarized elements; therefore, they do not give advantages with the use in cylindrical sound receivers perceiving sound pressure by its lateral surface.

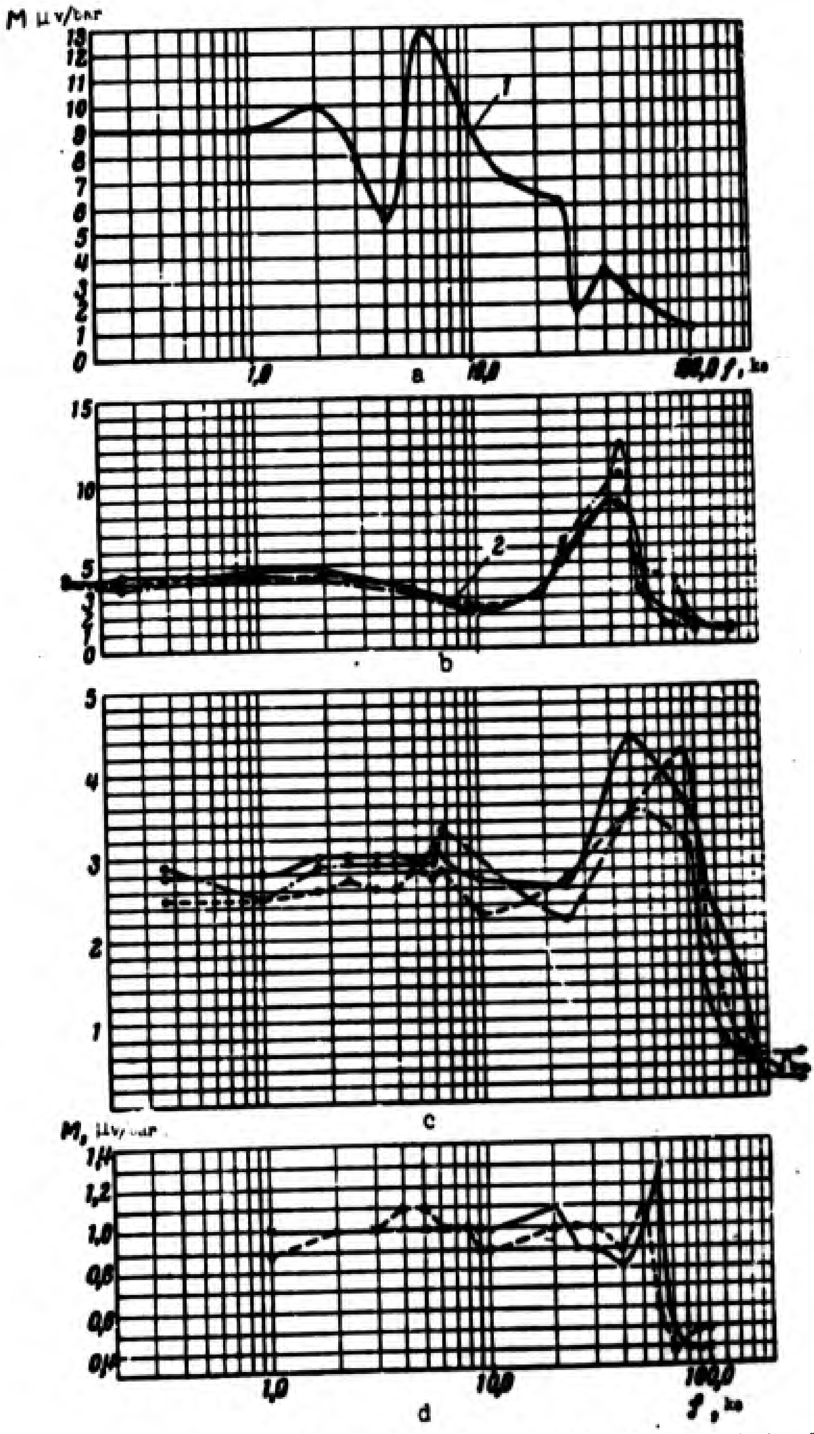

Fig. 70. Frequency-response curves of cylindrical sound receivers with a different external diameter of the piezoceramic cylinder a) 50 mm; b) 30 mm; c) 15 mm; d) 10 mm.

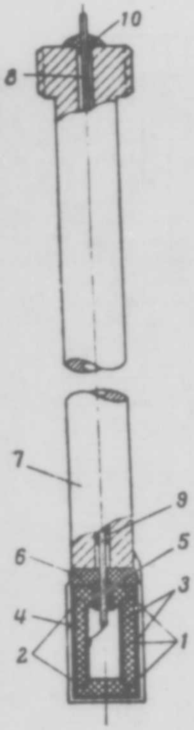

Fig. 71.

Fig. 72.

Fig. 71. Fastening a miniature sensitive cylindrical piezoelement to the holder. 1) piezoelement with face washers of ceramics of barium titanate; 2) glass welding; 3) external and internal metallizing; 4) external covering by glass enamel; 5) glass partition insulator; 6) rubber washer; 7) tube-holder; 8) rod conductor; 9) insulators in the tube-holder; 10) bonding by carbinol glue.

Fig. 72. Miniature measuring cylindrical sound receiver.

The increase in sensitivity of the sound receiver with the use of tangential polarization occurs according to the following causes: 1) with the use of a thin-walled cylinder the great coefficient of mechanical transformation K is realized; 2) the maximum piezoelectric modulus of ceramics d_{33} is used; 3) it is possible to increase the distance between electrodes not changing the thickness of the wall and diameter of the cylindrical shell.

It is necessary to make a few preliminary remarks with respect to the design features of sound receivers with cylindrical piezoelements with tangential polarization. The fact is that such sound receivers cannot have a solid external electrode which could serve as an electric shield. The shield of a sound receiver designed for work in air can be easily made in the form of a cylindrical

Fig. 73. Sound receiver for medical purposes made at the Acoustic Institute of the Academy of Sciencess of the USSR.

sound-transparent grid sufficiently remote from electrodes applied to the surface of the piezoelement. Therefore, any simple constructions of piezoelements with an external, internal, or combined application of the electrodes are permissible here.

There is another position for sound receivers designed for work in water. The water medium will inevitably form an additional electrode, which with the application of the electrodes to the internal surface of piezoelement can lead to the essential impairment of the parameters of the sound receiver. Therefore, for hydroacoustic sound receivers with tangential polarization it is necessary to apply an external insulating covering of a dielectric with a small dielectric constant and only on the external side of such a covering is it possible to place a sound-transparent (for instance, mesh) shield.

We developed a number of variants of cylindrical sound receivers with tangential polarization of piezoelements designed for use in air and water. Since the application of face washers with tangential polarization is inexpedient, because the sensitivity of the sound receiver decreases, then all the sound receivers of a given type developed by us provided protection of the faces from the influence of sound pressure.

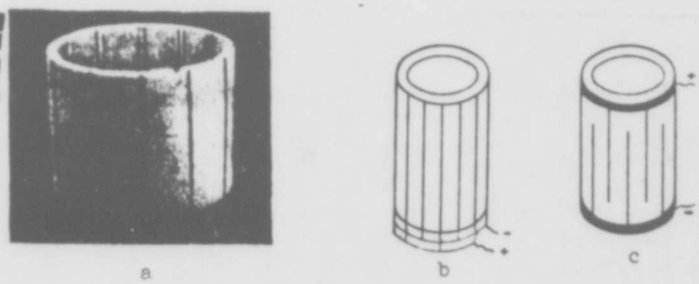

Fig. 74. Appearance of a cylindrical piezoelement of ceramics with tangential polarization (a) and examples of possible location of the electrodes (b, c).

Figure 75 gives a typical construction of such a sound receiver designed for operation in water.

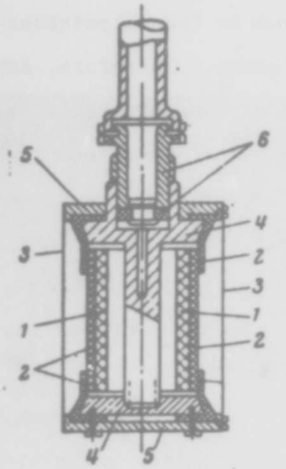

Fig. 75. Diagram of the fastening of the sensitive cylindrical piezoelement with tangential polarization to the holder. 1) cylindrical piezoelement; 2) rubber covering; 3) external mesh shield; 4) internal metallic part; 5) constructive parts; 6) stuffing box for lead-in of the cable.

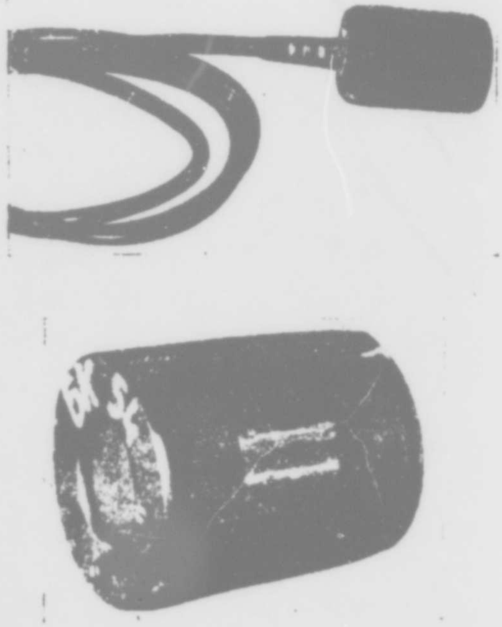

Fig. 76. Hydrophone with a cylindrical tangentially polarized ceramic element.

Table 17

Dimensions of the cylinders, mm		Thickness of the walls, mm	Capacity, pf	Static sensitivity, μ /bar		Sensitivity with radial polarization μ v/bar	Operating frequency band up to, kc
height	diameter			Calculated	average measured		
40	52	1,5	500	264—238	234	17	20
40	52	1,5	500	264—238	250	17	20
40	52	1,5	500	264—238	240	17	20
40	52	3,0	900	132—110	135	16,2	20
40	52	3,0	900	132—110	106,5	16,2	20
40	52	3,0	900	132—110	101,5	16,2	20
40	30,9	0,9	690	127,5—115	101	10,9	50
40	32,0	1,5		73	64,4	10,7	50
23,6	14,6	1,0	—	19	—	4,75	100

We usually covered piezoelements for air sound receivers only by a film of glass enamel for protection from outside humidity.

Figure 76 shows a hydroacoustic cylindrical sound receiver.

In certain models of sound receivers instead of a mesh we used a solid metallic screen over the rubber covering. This led, however, to a noticeable decrease in the sensitivity. The use of solid screens appears expedient only when their thickness is small, which requires development of methods of applying stable metallic coverings directly to the surface of the rubber or other insulating plastic.

Table 17 gives parameters of a number of cylindrical sound receivers tested by us with tangential polarization. For a comparison the same table gives the calculated sensitivity of receivers with radial polarization with the same dimensions of the shells and with face washers.[1] We see that with the use of tangential polarization the sensitivity is increased up to 15 times with capacities of the piezoelement still large enough.

Sound receivers having 12 sections (their parameters are given in Table 17) could be used directly with a coaxial cable (PK-19 or PK-49) 3-4 m in length. With the use of a preamplifier located near the sound receiver or (with a large diameter of the latter) in its internal cavity it is possible to go still further by way of an increase in the sensitivity.

It should be noted that for sound receivers with tangential polarization the sensitivity very sharply depends on the thickness of the wall of the shell (much more than for sound receivers with radial polarization). Therefore, the thickness of the wall of the shell of piezoelements with tangential polarization with an external diameter of 50-15 mm should not be larger than 1-1.5 mm. It is desirable to have an even thinner shell. Piezoelements of the given type for this reason have very thin walls and possess reduced strength. For air sound receivers and hydroacoustic sound receivers designed for operation at low hydrostatic pressures, this circumstance is not of significant importance. On the contrary, for hydroacoustic receivers designed for operation on great depths considerations of static strength prove to be most important. Nevertheless, if high sensitivity is required, for such cases the possibility is not excluded of the application of thin-walled piezoelements with tangential polarization on condition that there is compensation of the external static pressure.

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[1]For cylinders with the faces protected from the influence of sound pressure the sensitivity with radial polarization would be still less (1.5 times).

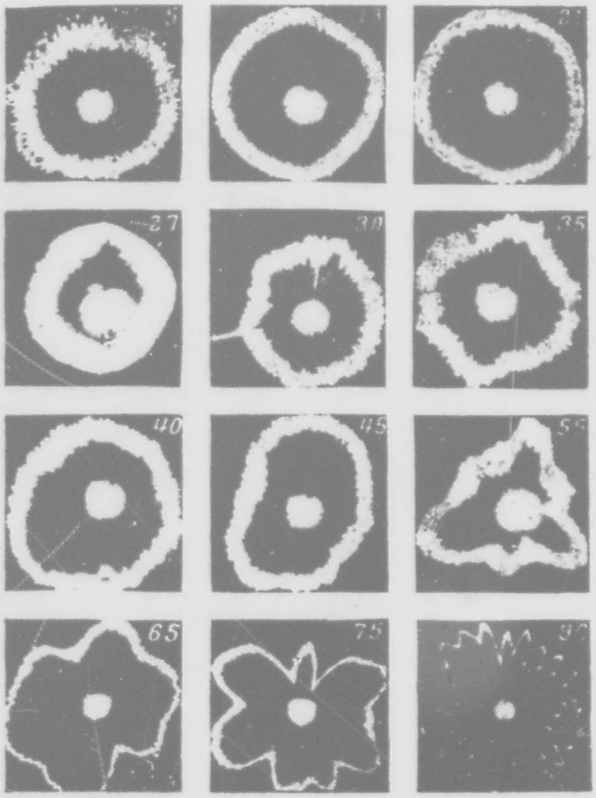

Fig. 77. Directional characteristics of a sound receiver with a sensitive cylindrical tangentially polarized piezoelement taken in a plane perpendicular to the axis. External diameter of the piezoelement, 50 mm, n = 12. Numbers on the figure denote frequency in kc.

Let us turn to the examination of directional characteristic of the described sound receivers. As an example Fig. 77 gives the directional characteristics taken in water (in a plane perpendicular to the axis) for a sound receiver 50 mm in diameter, and Fig. 78 shows such characteristics for a sound receiver 32 mm in diameter. Both sound receivers had a piezoelement divided into 12 sections.

In comparing these characteristics with those for cylindrical receivers with radial polarization we see that with tangential polarization the range of frequencies in which the directional characteristics preserve a satisfactory form is narrower than with radial polarization. Here, undoubtedly, the fact is that with radial polarization the piezoelement has an axis of symmetry of the order of ∞, while with the tangential polarization the axis of symmetry has a finite order. Therefore, the influence of diffractional phenomena should be considerably more with tangential polarization than with radial polarization.

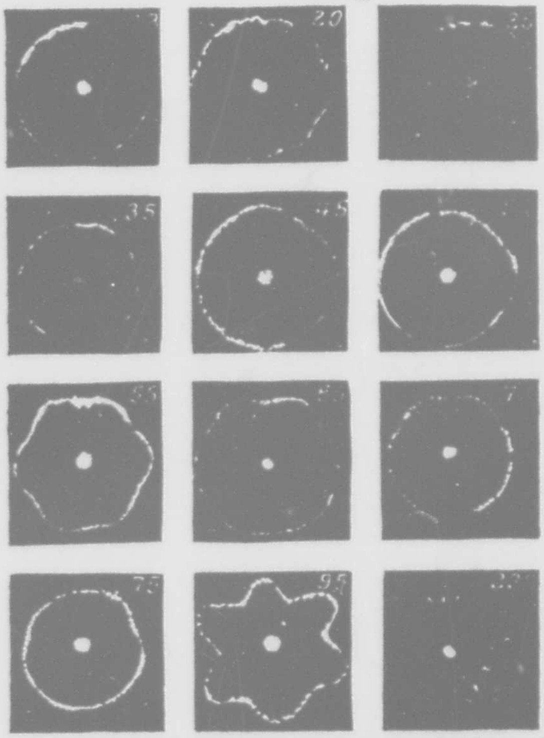

Fig. 78. Directional characteristics of a sound receiver with a sensitive tangentially polarized piezoelement taken in a plane perpendicular to the axis. External diameter of the piezoelement 32 mm, n = 12. Numbers on the figure denote the frequency in kc.

It is natural that approximately simultaneously with the disturbance of the form of the directional characteristic there appear irregularities in the course of the frequency response of the sound receiver. Therefore, the actual working range of frequencies for receivers with tangential polarization is somewhat narrower than for receivers with radial polarization; the upper cutoff frequency is determined now not by the approach of the first resonance of the shell but by the appearance of the indicated irregularities of the frequency response. As an example Fig. 79 gives the frequency-response curve of sound receivers with tangential polarization with the diameter of the piezoelement at 50, 30, and 15 mm. Here the irregularities of the characteristic appearing earlier than the first resonance are clearly evident.

Nevertheless sound receivers with tangential polarization permit obtaining a sufficiently wide working range of frequencies and satisfactory directional characteristics in this range of frequencies. Therefore, in virtue of their high sensitivity they can find an even wider application than receivers with radial polarization.

In conclusion we will discuss the question about the use of cylindrical piezoelements with longitudinal polarization in the construction of sound receivers. As follows from what has been said (see section 2) such piezoelements with identical geometric dimensions of the ceramic shell have parameters intermediate as compared to those for cases of radial and tangential polarization. However, they, just as piezoelements with tangential polarization, require the use of a dielectric protective layer on the external surface of the cylinder and from this point of

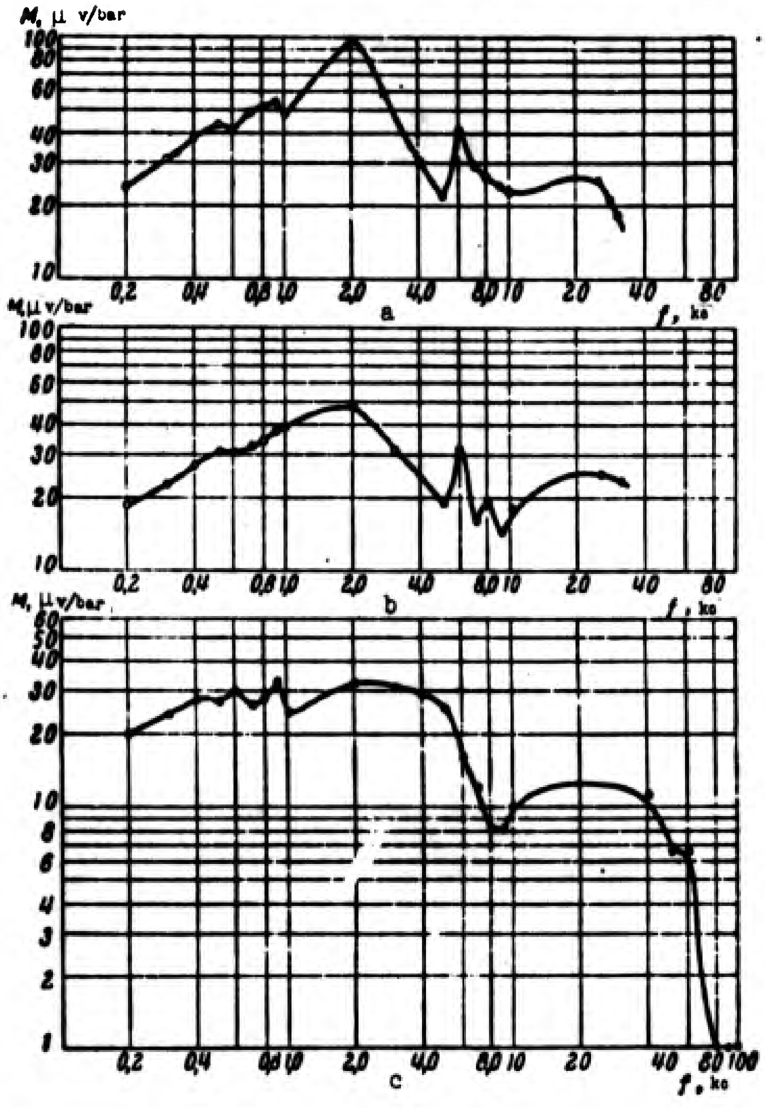

Fig. 79. Frequency-response curves of sound receivers with a sensitive cylindrical tantentially polarized piezoelement of ceramics of barium titanate. a) external diameter of the ceramic cylinder, 50 mm; b) external diameter, 30 mm; c) external diameter, 15 mm.

view do not have constructive advantages over piezoelements with tangential polarization. For these reasons we used piezoceramic elements with longitudinal polarization, as this will subsequently be presented in detail only with the creation of sound receivers with a flat receiving diaphragm where such type of piezoelement appears convenient.

CHAPTER IV

BROAD-BAND SOUND RECEIVER WITH FLAT RECEIVING DIAPHRAGMS

1. Sound Receivers of Symmetric Construction with Two Receiving Diaphragms

We investigated several variants of sound receivers of the symmetric type with two receiving diaphragms and piezoelements in the form of a cylindrical shell with different forms of polarization. A diagram of such a sound receiver is shown in Fig. 80. In certain cases even with metallic diaphragms the necessity of the application of an insulating layer 5 decreased (for instance, if it were possible to apply electrodes not to the whole surface of the piezoelement). Moreover, in certain types of sound receivers we used diaphragms made of a dielectric material.

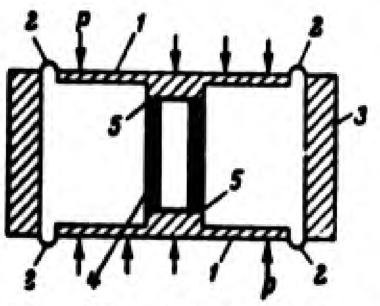

Fig. 80. Sound receiver with two receiving diaphragms 1) flat diaphragms; 2) ring-shaped suspension of the diaphragms; 3) cylindrical body of the sound receiver; 4) cylindrical piezoelement; 5) insulating shell of a solid dielectric.

The thickness of the diaphragms was selected large enough so that in the working range of frequencies their oscillatory motions could be considered piston. The distance between the two receiving diaphragms 1 determined by the height of the piezoelement 4 was selected small as compared to the length of the sound wave on the upper boundary of the working range of frequencies; therefore, it was possible to consider the pressures having an effect on the diaphragms as cophasal.

The sensitivity of the sound receiver made from such a constructive diagram is determined by the formula

$$\frac{V}{p_0} = Kgl,$$

where l — distance between the electrodes of the piezoelement; g — corresponding piezoelectric constant; K — coefficient of mechanical transformation. In this case the coefficient of mechanical transformation is equal to simply the ratio of the area of the diaphragm S_g to the face area S_n of the cylindrical piezoelement. If the radius of the diaphragm is equal to R and the external and internal radii of the cylindrical piezoelement are equal to b and a respectively the coefficient of transformation will be

$$K = \frac{R^2}{(b^2 - a^2)}.$$

Introducing, as earlier, the parameter $\varkappa = (b - a)/2b$, we obtain

$$K = \frac{1}{4}\left(\frac{R}{b}\right)\frac{1}{\varkappa(1-\varkappa)}.$$

Using this expression for the coefficient of transformation, it is easy to obtain formulas for the static sensitivity of a sound receiver of the considered type. With polarization we have

$$\frac{V}{p_0} = g_{31} b \frac{1}{2(1-\varkappa)}\left(\frac{R}{b}\right)^2,$$

or with the values of piezoconstants of ceramics selected by us:

$$\frac{V}{p_0} = 2{,}35 \frac{b}{1-\varkappa}\left(\frac{R}{b}\right)^2.$$

With longitudinal polarization accordingly

$$\frac{V}{p_0} = g_{33} l \frac{1}{4\varkappa(1-\varkappa)}\left(\frac{R}{b}\right)^2 = 2{,}83 l \frac{1}{\varkappa(1-\varkappa)}\left(\frac{R}{b}\right)^2.$$

And, finally, with tangential polarization:

$$\frac{V}{p_0} = g_{31} l \frac{1}{4\varkappa(1-\varkappa)}\left(\frac{R}{b}\right)^2 = 1{,}17 l \frac{1}{\varkappa(1-\varkappa)}\left(\frac{R}{b}\right)^2.$$

Thus the static sensitivity of a sound receiver with a flat diaphragm, as one should have been led to expect, is proportional to a certain characteristic dimension (b or l depending upon the form of polarization) and in other respects is a function of two dimensionless parameters, the ratio of the diameters of the diaphragm and piezoelement and ratio of the thickness of the wall of the piezoelement to its external diameter.

Figure 81 gives curves for the calculation of static sensitivity with different values of R/b and $\varkappa$. For radial polarization (Fig. 81a) a curve is given for b = 1 cm, for longitudinal and tangential polarizations (Fig. 81 b, c), for l = 1 cm.

From the formulas and curves one can see that in sound receivers of the type described it is most favorable to use the longitudinal polarization of the piezoelement; the least favorable is radial polarization.

With longitudinal and tangential polarization a decrease in the thickness of the shell leads to an increase in the sensitivity but owing to the decrease in the capacity. With an equal thickness of the shell, form the point of view of the capacity of the piezoelement the radial polarization is the most advantageous.

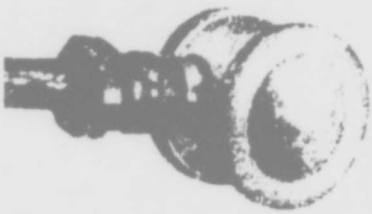

Fig. 82. Sound receiver with two receiving metallic diaphragms.

Figure 82 shows a sound receiver of the type described with diaphragms made of brass (D = 30 mm); the elastic element providing mobility to the diaphragm was girdling groove in the brass part forming the diaphragm. Figure 83 shows a sound receiver with the same external diameter but with diaphragms made of ceramics of barium titanate. The suspension of the diaphragms is carried out here on rubber collars.

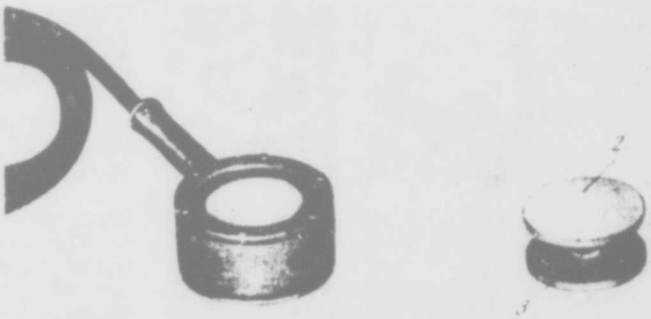

Fig. 83. Sound receiver and piezoelement with receiving ceramic diaphragms. 1) housing of the sound receiver; 2) diaphragm; 3) cylindrical piezoelement.

In the sound receivers described we used cylindrical thin-walled piezoelements both with radial and with longitudinal polarization. In the first case, naturally, the electrodes were applied to the internal and external surface of the cylinder; in second case we used, for the most part, the application of electrodes to the external surface of the piezoelement in the form of a double helix about which will be described in detail below [201].

Table 18 gives basic data of several models of monotypic sound receivers for the case of radial polarization of a piezoelement with a diameter of the receiving diaphragm at 30 mm. The dimensions of the sensitive ceramic element are the following: external diameter 2b = 4 mm; height h = 12.7 mm; thickness of the wall δ = 0.3 mm.

Table 18

Sound receiver	Capacity	Sensitivity (measured), μv/bar
1	2420	16,1
2	2500	21,7
3	2350	26,7

It is natural that the directional characteristics of such sound receivers at any high frequencies should be worse than for sound receivers with a spherical receiving element. This can be seen from Fig. 84 where directional characteristics are given of the sound receiver with a diameter of the diaphragms of 20 mm and a length of the cylindrical sensitive piezoelement of 16 mm. Therefore, it is impossible to consider such sound receivers at high frequencies as absolutely nondirectional and when using them in measuring work one should observe the definite orientation of the sound receiver.

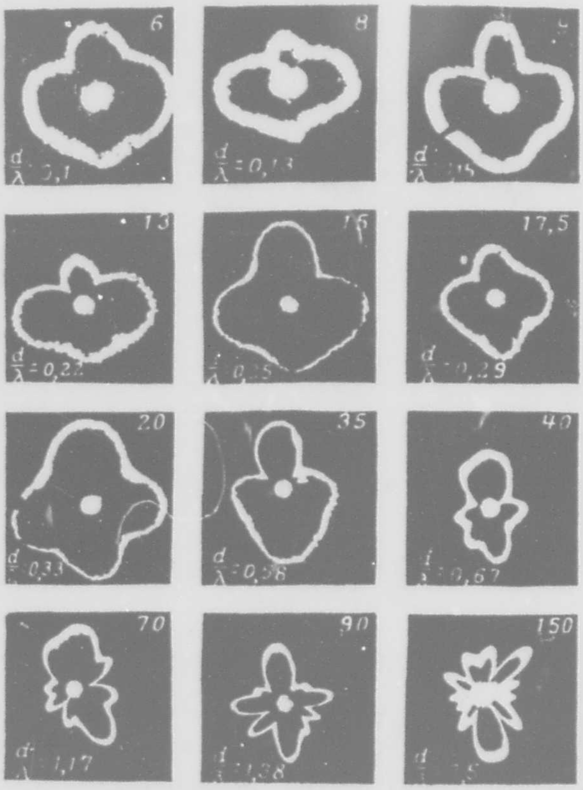

Fig. 84. Directional characteristics of a sound receiver with two flat receiving diaphragms. On the figures the frequency is shown in kilocycles.

2. Sound Receivers with a Flat Pliable Diaphragm Made of Ceramics of Barium Titanate

The principle of increasing the sensitivity of the sound receiver by means of using as a piezoelement a deformed shell ensuring a large magnitude of the coefficient of mechanical transformation can be used not only with the construction of spherical or cylindrical sound receivers but also in the case of sound receivers with a flat deformed diaphragm.

If we have a thin flat diaphragm which sags under the action of sound pressure, then in the material of such a diaphragm great tangential stresses appear, which can be used for increasing the sensitivity of the sound receiver having arranged correspondingly the electrodes on the surface of the diaphragm and accomplishing tangential polarization of the thin flat ceramic plate. For this on the surface of the thin plate it is necessary to apply electrodes in the form of concentric circumferences. With this the effective piezoelectric constant will be g_{33}.

The thin pliable diaphragm of ceramics of barium titanate also allows polarization during which the constant $g_{31} = g_{32}$ is used if the electrodes are applied by a solid shell on both surfaces of the diaphragm. Such a method of polarization is analogous to radial polarization of the spherical or cylindrical shell.

With the first method of the application of the electrodes it is possible to obtain a very high sensitivity of the sound receiver with a small capacity of the piezoelement; in the second case less sensitivity is obtained but the capacity can be very great. Different methods of the fastening of edges of the diaphragm are possible: they can be free, supported, or rigidly secured (pinched). With rigid fastening along the edge mechanical stresses in the central and peripheral regions of the diaphragm appearing under the action of pressure evenly distributed in area of the diaphragm have opposite signs. These regions are divided by a circular "neutral" belt in which the mechanical stresses are equal to zero [202]. Therefore when using, in sound receivers, a piezoelectric diaphragm, rigidly secured along the edge, it is necessary to use (even with polarization in depth) not solid electrodes but the system of electrodes schematically shown in Fig. 85. The connection of the electrodes with polarization should differ from the connection of electrodes of the selected and operating sound receiver.

With the supported (without the pinching moment) and with the free edge the sign of the mechanical stresses in the diaphragm does not change, and therefore during polarization in depth the electrodes can be solid as shown in Fig. 86.

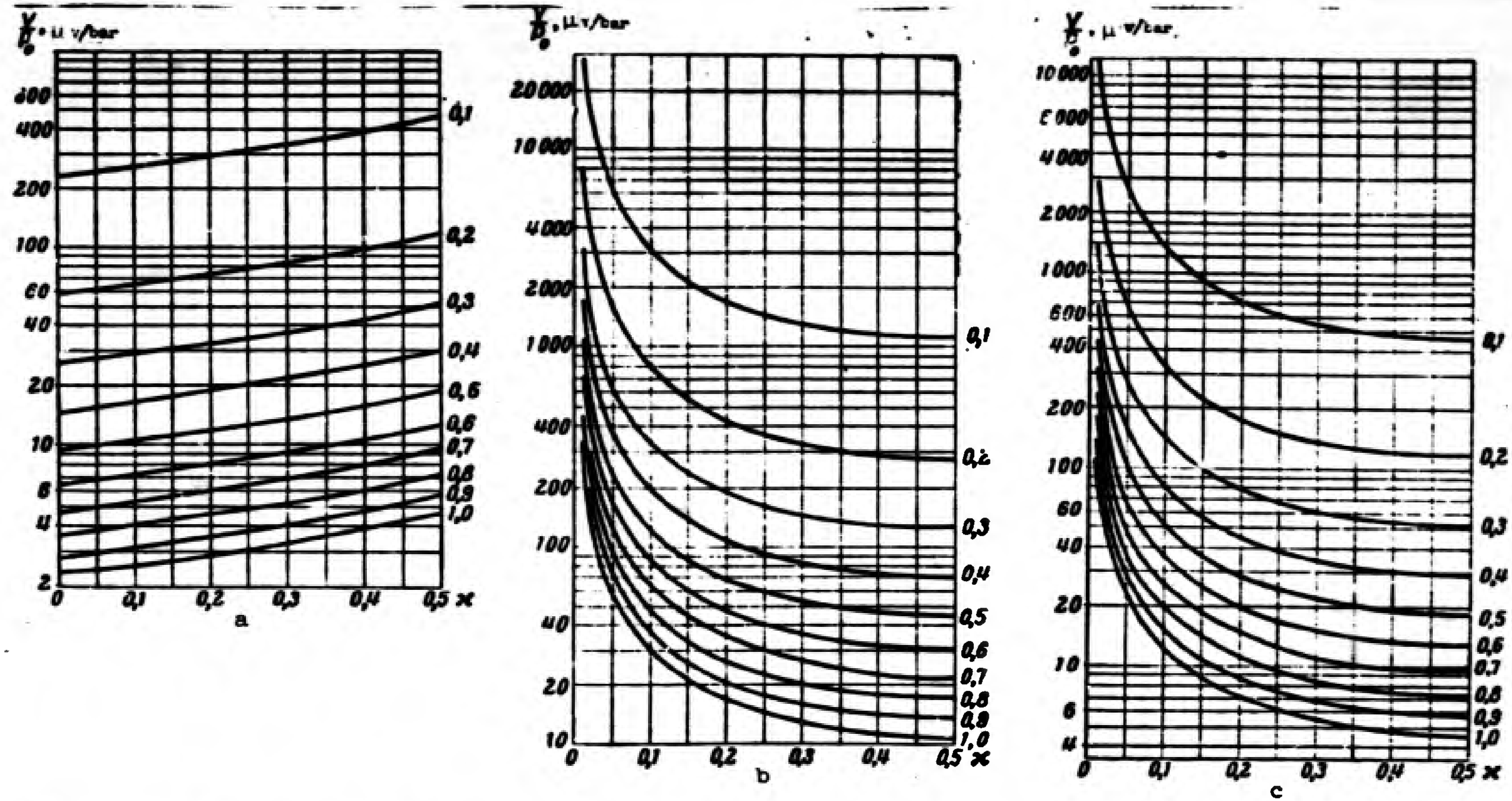

Fig. 81. Sensitivity of a sound receiver with two receiving diaphragms and a sensing device in the form of a tube of polarized ceramics of barium titanate with different ratios of diameters of the tube and diaphragm (scale on the right). a) radial polarization of the ceramic tube; b) longitudinal polarization of the tube; c) radial polarization of the ceramic tube.

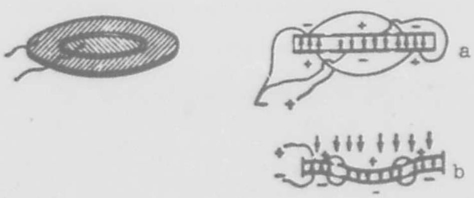

Fig. 85.

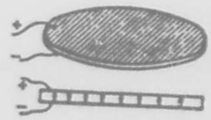

Fig. 86.

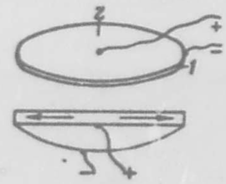

Fig. 87.

Fig. 85. System of the connection of electrodes. a) with polarization; b) with operation of the piezoelement.

Fig. 86. Solid electrodes for polarization of a ceramic diaphragm in depth.

Fig. 87. Form of electrodes with tangential polarization of the diaphragm. 1) annular electrode along the periphery of the diaphragm; 2) central electrode.

In this case and with tangential polarization the form of the electrodes (which, of course, can be applied to one side of the diaphragm) is obtained simply (Fig. 87).

With tangential polarization and the pinched edge of the diaphragm such a simple system of electrodes in the process of polarization is impossible to use, since we would obtain a decrease in the sensitivity. Therefore, in this case with polarization there is used a system of electrodes shown in Fig. 88a, b ensuring the various directions of polarization in the central and peripheral regions of the diaphragm. With the operation of the sound receiver only peripheral and central electrodes (Fig. 88c,) are used. We investigated sound receivers of the type described with a diameter of the diaphragm of 50 mm and a thickness of 0.3-0.35 mm. The static sensitivity of such sound receivers with polarization in depth on the average is 40-50 μv/bar, and the capacity is 60-70 thousand pf. With tangential polarization the sensitivity attains 6000 μv/bar with a capacity of 10-20 pf [203].[1]

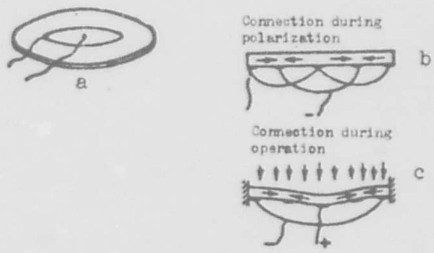

Fig. 88. System of electrodes for tangential polarization in opposite directions of the central peripheral diaphragm.

In conclusion let us note that sound receivers of the type described are more useful for use in an air medium (for instance, as microphones) in virtue of the

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[1]Very recently Tomita and Yanaguti published a work dedicated to the use of thin ceramic piezoplates with polarization in depth in sound receivers designed for telephony [204].

fragility of thin-walled diaphragms. However, the possibility is not excluded of the use of this principle in low-frequency hydroacoustic sound receivers under the condition of compensation of the action of external static pressure.

CHAPTER V

SPECTRA OF NATURAL FREQUENCIES OF PIEZOCERAMIC SPHERICAL AND CYLINDRICAL

1. Natural Frequencies of the Spherical Piezoceramic Shell

Earlier we examined broad-band sound receivers for which the operating range is a frequency domain in which the sensitivity of the sound receiver is approximately equal to the static; this region is limited from above by the approach of resonances of the shell. Thus that region of frequencies where resonance properties considerably appear lies higher than the working range of the broad-band sound receiver and therefore until now has not been considered in detail by us.

However, it is natural that the sensitivity of the sound receiver at resonance frequencies is considerably greater than the static; therefore, in a number of cases it can appear useful to use piezoceramic sound receivers with the spherical or cylindrical shell as resonance. From this point of view it is interesting to consider in detail the spectra of natural frequencies of spherical and cylindrical piezoelectric shells. In the case of the spherical shell devoid of defects[1] it is necessary to consider radial oscillations (zero mode) and transverse oscillations of the wall.

The resonance connected with oscillations of the wall in depth is high-frequency; the natural region of frequencies is approximately the same as that with transverse oscillations of the flat plates. However, in the case of the shell we do not have one definite frequency of first longitudinal resonance as takes place for rods; here we observe the whole spectrum of resonance frequencies spaced closely to each other.

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[1]For instance, in using a shell composed of two hemispheres with the help of glass welding.

On the contrary, more low-frequency radial oscillations of the shells appear in purer form, and with little thickness of the wall we observe a clearly expressed resonance at a frequency corresponding to the zero mode.

The equation determining the natural frequencies with free radial oscillations of the isotropic spherical shell with an arbitrary thickness of the wall, according to [205], has the form

$$\frac{\gamma ak + \operatorname{tg} ak\,(k^2a^2 - \gamma)}{(a^2k^2 - \gamma) - \gamma ak \operatorname{tg} ak} = \frac{\gamma bk + \operatorname{tg} bk\,(k^2b^2 - \gamma)}{(b^2k^2 - \gamma) - \gamma bk \operatorname{tg} bk}; \qquad (9)$$

here b is the external radius of the shell; a is the internal radius of the shell ; $k = \frac{2\pi f}{c}$ is the wave number; γ is the parameter determined by the ratio

$$\frac{2\lambda}{2\mu + \lambda} = 2 - \gamma,$$

where γ and μ are coefficients of Lamé.

The transcendental equation (9) can be solved graphically. In this equation the left side is a function of the argument ak and right, a function of the argument bk. Considering ak = z, we reduce equation (9) to the form

$$f(z) = f\left(z\frac{b}{a}\right),$$

where b/a is a parameter. Thus for graphical solution it is necessary to construct the basic dependence

$$f(z) = \frac{\gamma z + (z^2 - \gamma) \operatorname{tg} z}{(z^2 - \gamma) - \gamma z \operatorname{tg} z}$$

with the concrete value γ for the selected material. Taking further different values of the parameter b/a, it is easy to obtain curves $f(z\,\frac{b}{a})$ by means of a simple change of the scale along the axis of the abscissas. Intersections of curves f(z) and f(z b/a) give roots of equation (9) with the selected value γ. Inasmuch as $\gamma = \frac{E\sigma}{(1 + \sigma)(1 - 2\sigma)}$ and $\mu = \frac{E}{2(1 + \sigma)}$, it is possible to calculate values of γ for piezoceramics by knowing the magnitudes of Young's modulus and Poisson's ratio. Assuming $E = 1.05 \cdot 10^{12}$ and $\sigma = 0.27$, which corresponds to the speed of sound $c = \sqrt{\frac{\lambda + 2\mu}{\rho}} = 4.7 \cdot 10^5$ cm/sec with a density of $\rho = 5.5$ g/cm^3, we obtain $\gamma = 1.36$.

Let us note that the value of Young's modulus $E = 1.05 \cdot 10^{12}$ is accepted on the basis of measurements conducted by us on transversely polarized rods of ceramics of barium titanate. According to these measurements the speed of sound under these conditions is equal to 4376 m/sec exceeds the speed of sound for nonpolarized ceramics by 1.9%. This speed was accepted by us for the determination of Young's modulus. The value of Poisson's ratio is accepted from reference data.

In Fig. 89 the function f(z) for the above-indicated value γ is shown by a solid curve; the dotted line represents the curve f(z b/a) for b/a = 2. The intersection of these curves gives the concrete value z = ak corresponding to the given value of the parameter.

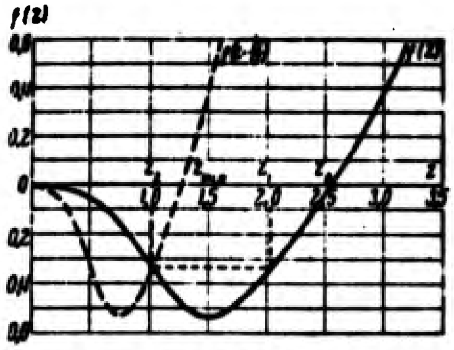


Fig. 89. Dependence f(z) for γ = 1.36.

Using such curves and assigning by concrete values of the resonance frequency f_r, it is easy to construct a nomogram for the calculation of values of f_r by assigned values b and a. Such a nomogram is shown in Fig. 90. Every point on the curve of the nomogram corresponding to the determined resonance frequency determines the combination of values b and a ensuring the obtaining of a given resonance frequency. The straight line a/b = 1 corresponds infinitely to the thin shell and axis of the abscissas to the solid sphere. It is easy to see that in the region of the nomogram lying between the straight lines a/b = 1 and a/b = 0.55 the curves of the nomogram can be well approximated by straight lines. In this region the shells can be considered "infinitely thin," and the error in the determination of the resonance frequency under this assumption will not exceed 1%. With a/b lying from zero to 0.085 the shell from the point of view of the calculation of the natural frequency can be considered a "solid sphere." For these special regions of the nomogram it is easy to obtain approximate formulas for the determination of the natural frequency. When $0 \leq a/b < 0.085$ and with the accepted value γ we obtain

$$f_r \approx \frac{177}{b}\ \text{kc},$$

if b is expressed in centimeters. For the region of "thin shells," i.e., when $0.55 < a/b < 1$ we have with the approximation of curves of the nomogram by straight lines

$$f_r \approx \frac{203.8}{b+a}\ \text{kc}.$$

Finally, for a maximally thin shell (b/a = 1)

$$f_r = \frac{104.4}{b}\ \text{kc}.$$

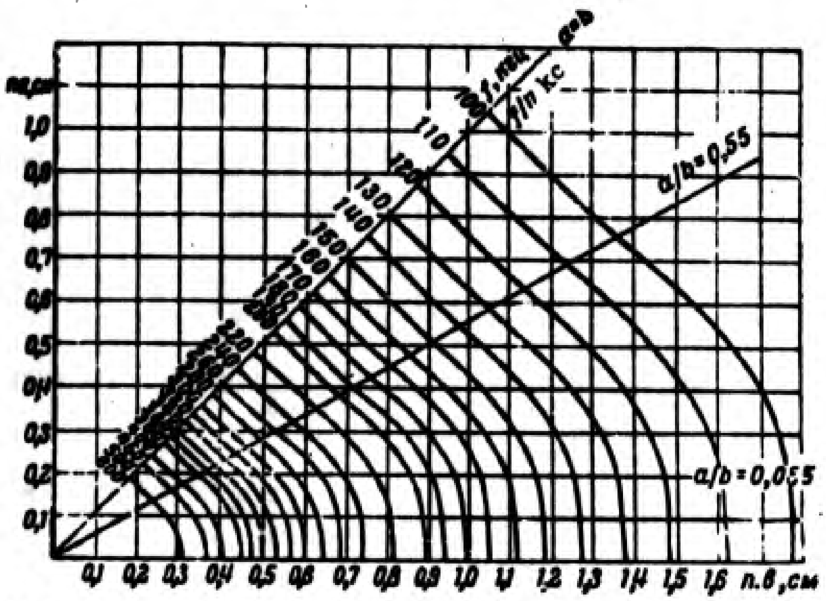


Fig. 90. Calculated resonance frequencies of spherical radial oscillating shells with an arbitrary thickness of the wall.

Approximate formulas are accurate for calculating the resonance frequency correct to 1%.

We measured the natural frequency of the spherical radial by polarized ceramic shells with different external diameters and thicknesses of the wall. A determination of the position of the natural frequencies was carried out on the basis of frequency characteristics of the electrical impedance.

Table 19

Sample	External diameter, mm	Thickness of the wall, mm	Measured frequency of the first resonance f_{p0} kc	Calculated frequency of the radial resonance f_{p0} kc
1	10	0,8	240	230
2	10	1,0	255	235
3	8	1,0	330	300
4	16	1,0	150	135
5	5	0,5	445	445
6	30	1,5	78,5	74,0
7	30	2,0	80	75,0
8	30	3,0	81	78

Table 19 gives a comparison of the measured and calculated frequencies of the first resonance (with a zero mode) for spherical shells composed of two hemispheres welded along the diametrical seam by glass. From the table one can see that the experimental values of natural frequencies coincide well with the calculated values.

This shows that the presence of small defects in the real spherical shell (diametrical welding, presence of a hole for a lead-out of electrode sealed by glass) does have an essential influence on its resonance frequencies.

2. Natural Frequencies of Cylindrical Piezoceramic Shells

There is extensive literature on oscillations of free cylindrical shells (see, for instance, [205]). However, up to now there has been no complete theoretical solution to the problem on the spectrum of natural frequencies of a cylindrical shell of finite length with an arbitrary thickness of the wall. Therefore, we conducted a detailed experimental investigation of the spectra of natural frequencies of freely oscillating cylindrical piezoelectric shells:

1) we measured the natural frequencies of a number of ceramic cylinders having equal diameters and equal height but differing from each other in thickness of the wall; measurements were taken on cylinders with radial longitudinal and tangential polarization;

2) with the three methods of polarization we measured the natural oscillation of the cylinders (of different height) with identical diameters and identical thickness of the wall.

A similar series of measurements allowed the separation of resonances connected with oscillations according to the height of the cylinder from resonances corresponding to radial oscillations and also the separation of natural frequencies connected with oscillations according to the thickness of the wall.

An investigation was conducted by means of the determination of the frequency dependence of the modulus of electrical impedance of each piezoelement. Table 20 gives information on the geometric dimensions of the investigated piezoelements, and the radial polarization corresponds to the letter P, the tangential to the letter T, and longitudinal polarization to the letter П.

Figure 91a gives the totality of frequency-response curves of the modulus of electrical impedance for radially polarized cylindrical elements with an identical external diameter (3.2 cm) and with the thickness of the wall measuring from 1.3 to 0.1 cm. The curves are located so that a decrease in the thickness goes downward. Along the axis of abscissas the frequency is plotted in kilocycles; the logarithmic scale along the ordinates for all curves is the same. Such a method of presentation permits graphically judging the displacement on natural frequencies with a change in the geometric dimensions of the shell.

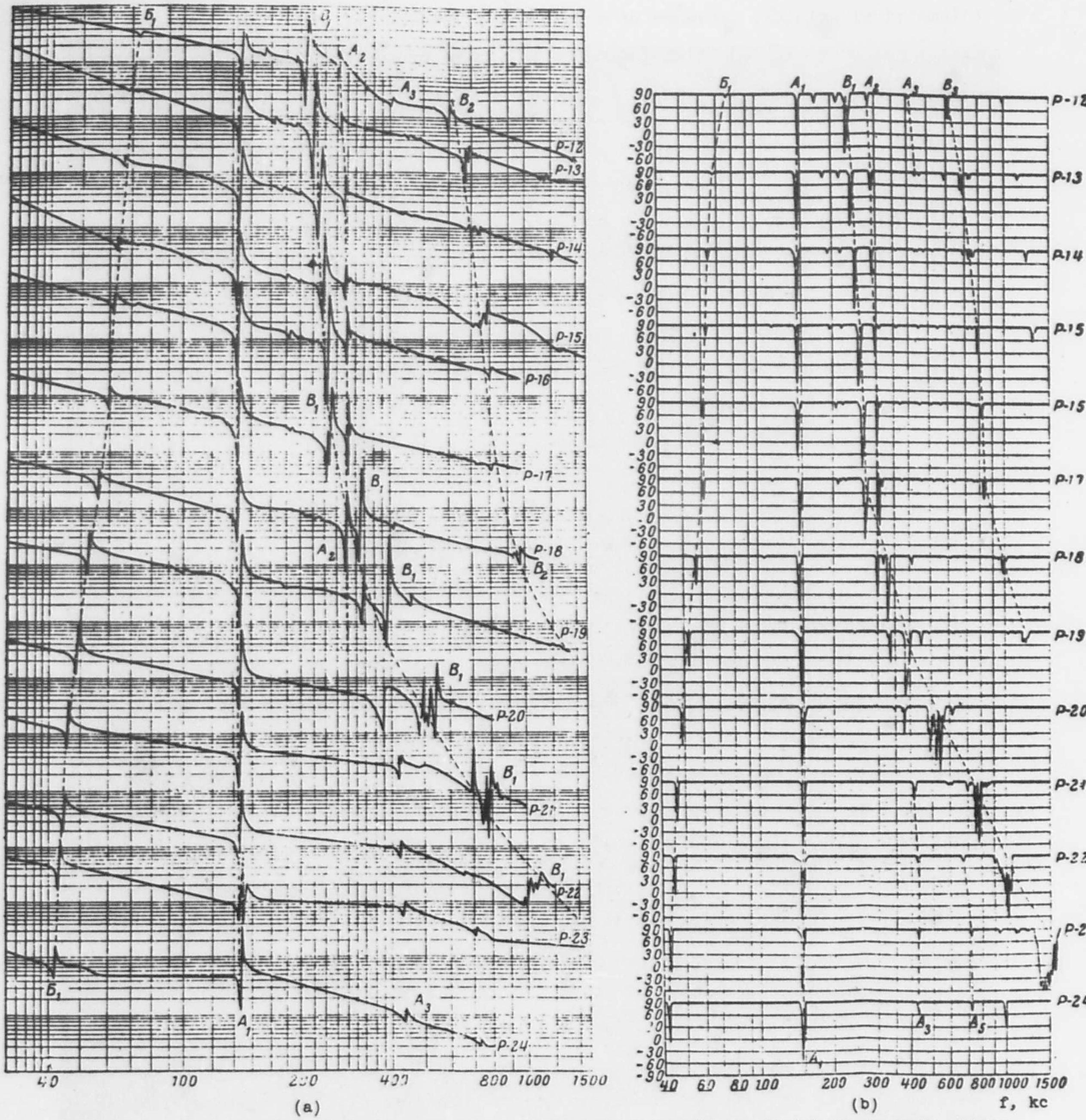


Fig. 91. Frequency dependence (a) of the modulus of electrical impedance and (b) phase angle shifts between the current and voltage of radially polarized cylinders of ceramics of barium titanate with a different thickness of the wall.

h = const = 1,5 cm

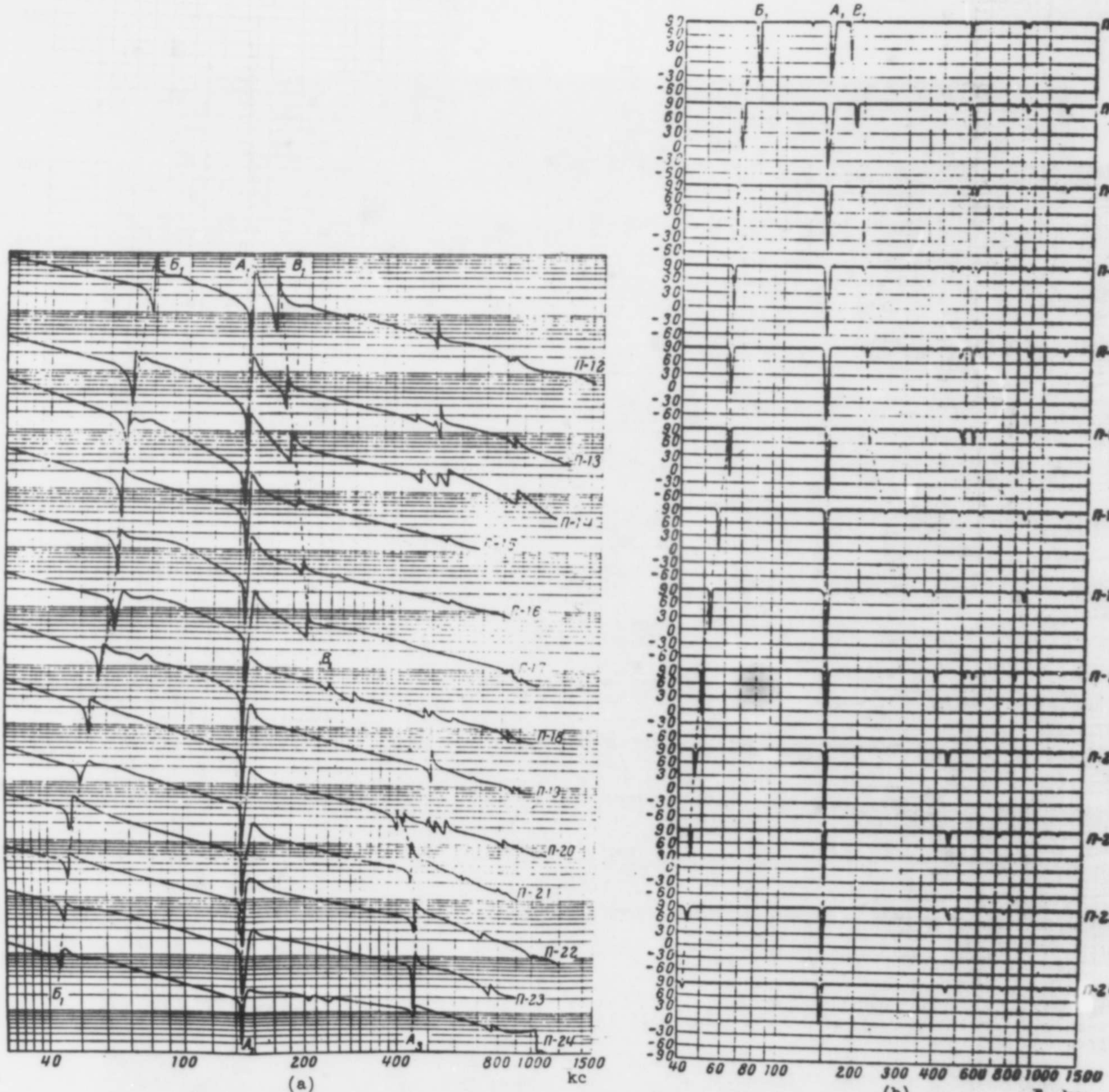


Fig. 92. Frequency dependence (a) of the modulus of electrical impedance and (b) phase angle shift between the current and voltage of longitudinally polarized cylinders of ceramics of barium titanate with a different thickness of the wall

h — const — 1,5 cm

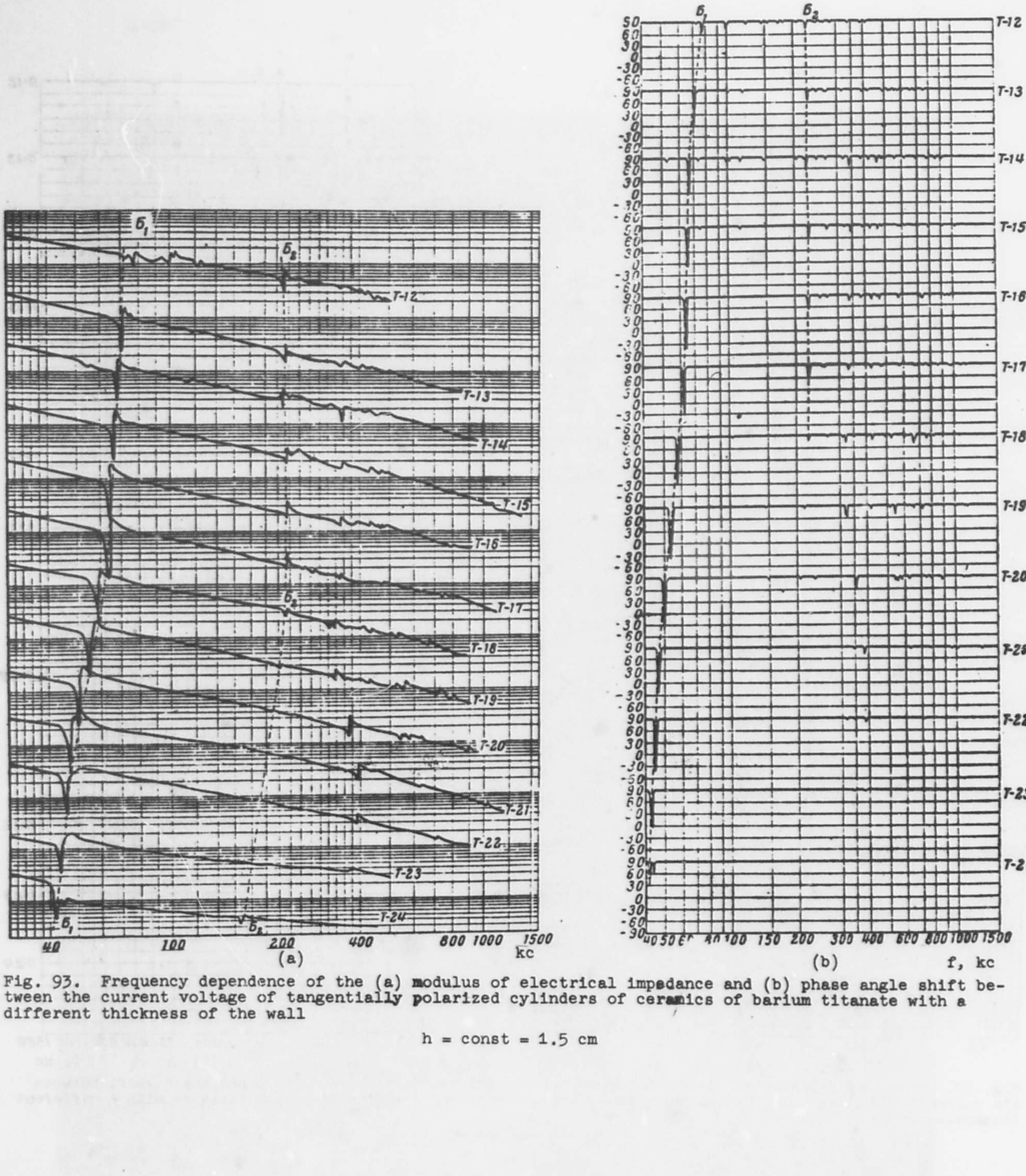


Fig. 93. Frequency dependence of the (a) modulus of electrical impedance and (b) phase angle shift between the current voltage of tangentially polarized cylinders of ceramics of barium titanate with a different thickness of the wall

h = const = 1.5 cm

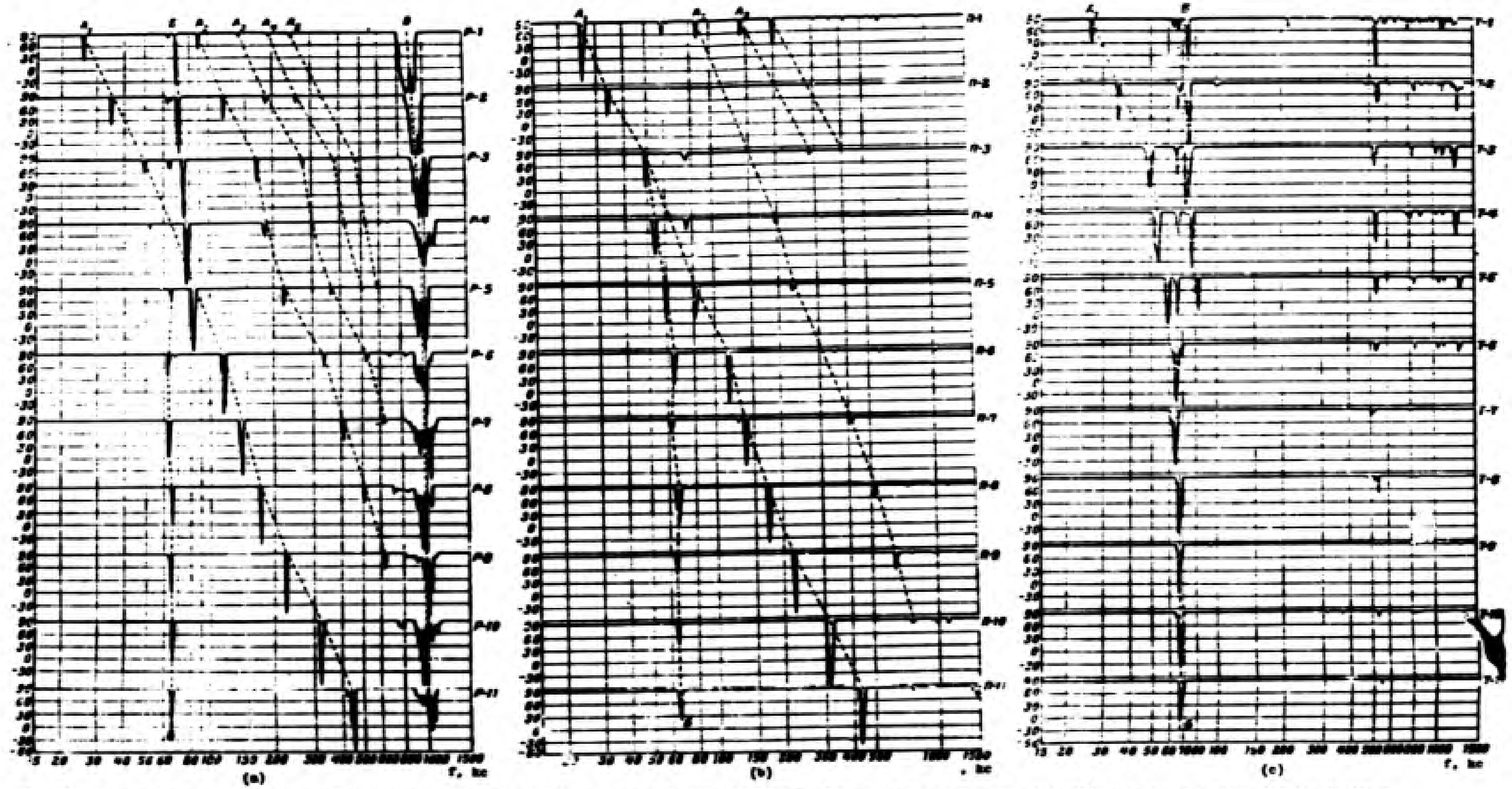


Fig. 94. Spectra of natural frequencies of cylindrical tubes of different axial length of ceramics of barium titanate. a – with radial polarization; b – with longitudinal polarization; c – with tangential polarization.

Table 20

Radial polarization				Longitudinal polarization				Tangential polarization			
conditional index of sample	height of cylinder, mm	external diameter, mm	thickness of the wall, mm	conditional index of sample	height of cylinder, mm	external diameter, mm	thickness of the wall, mm	conditional index of sample	height of cylinder, mm	external diameter, mm	thickness of the wall, mm
1P	8	2,3	0,25	1П	8	2,3	0,25	1T	8	2,3	0,25
2P	0	2,3	0,25	2П	6	2,3	0,25	2T	6	2,3	0,25
3P	4	2,3	0,25	3П	4	2,3	0,25	3T	4	2,3	0,25
4P	3,5	2,3	0,25	4П	3,5	2,3	0,25	4T	3,5	2,3	0,25
5P	3	2,3	0,25	5П	3	2,3	0,25	5T	3	2,3	0,25
6P	2	2,3	0,25	6П	2	2,3	0,25	6T	2	2,3	0,25
7P	1,5	2,3	0,25	7П	1,5	2,3	0,25	7T	1,5	2,3	0,25
8P	1,3	2,3	0,25	8П	1,3	2,3	0,25	8T	1,3	2,3	0,25
9P	1	2,3	0,25	9П	1	2,3	0,25	9T	1	2,3	0,25
10P	0.7	2,3	0,25	10П	0,7	2,3	0,25	10T	0,7	2,3	0,25
11P	0,5	2,3	0,25	11П	0,5	2,3	0,25	11T	0,5	2,3	0,25
12P	1,5	3,2	1,3	12П	1,5	3,2	1,3	12T	1,5	3,2	1,3
13P	1,5	3,2	1,1	13П	1,5	3,2	1,1	13T	1,5	3,2	1,1
14P	1,5	3,2	1,05	14П	1,5	3,2	1,05	14T	1,5	3,2	0,05
15P	1,5	3,2	1	15П	1,5	3,2	1	15T	1,5	3,2	1
16P	1,5	3,2	0,95	16П	1,5	3,2	0,95	16T	1,5	3,2	0,95
17P	1,5	3,2	0,9	17П	1,5	3,2	0,9	17T	1,5	3,2	0,9
18P	1,5	3,2	0,8	18П	1,5	3,2	0,8	18T	1,5	3,2	0,8
19P	1,5	3,2	0,65	19П	1,5	3,2	0,65	19T	1,5	3,2	0,65
20P	1,5	3,2	0,5	20П	1,5	3,2	0,5	20T	1,5	3,2	0,5
21P	1,5	3,2	0,33	21П	1,5	3,2	0,33	21T	1,5	3,2	0,33
22P	1,5	3,2	0,25	22П	1,5	3,2	0,25	22T	1,5	3,2	0,25
23P	1,5	3,2	0,15	23П	1,5	3,2	0,15	23T	1,5	3,2	0,15
24P	1.5	3.2	0,1	24П	1,5	3,2	0,1	24T	1,5	3,2	0,1

From Fig. 91a one can see that the position of resonances by height (A_1, A_2, A_3) practically does not depend on the thickness of the wall. Only the degree of expressivity of resonances of highest orders (for instance, A_2 and A_3) depends on the latter. The resonance frequency corresponding to radial oscillations (B) according to a decrease in the thickness of the wall is displaced downward. From the figure one can clearly see that with a great thickness of the wall the radial resonance weakly appears on the frequency-response of the frequency impedance.

Position of the first resonance according to the thickness of the wall (B_1) is also clearly seen on the figure; the corresponding resonance frequency is displaced in proportion to the decrease in the thickness of the wall upwards. With the thickness of the wall smaller than 0.65 cm the structure of the frequency curve of impedance in the region of resonance B_1 becomes complicated; instead of one resonance frequency there appears a combination of a considerable number resonance frequencies to one another. This phenomenon is analogous to the splitting of natural frequencies observed during oscillations of piezoelectric plates [206-208].

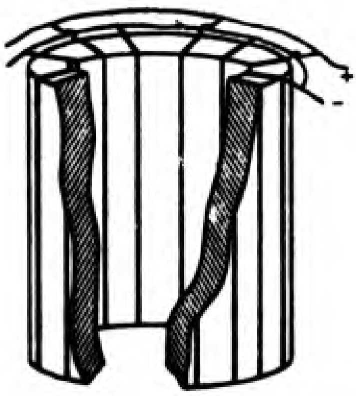


Fig. 95. Method of applying electrodes to the surface of the solid ceramic cylinder.

The group of natural frequencies designaled in Fig. 91a by B_2 apparently corresponds to the second resonance according to the thickness of the wall.

Figure 92a gives an analogous for the case of longitudinal polarization for piezoelements with the same overall dimensions as shown on Fig. 91a. The electrodes were in this case applied to the face annular surfaces of the piezoelement. Here the designations of A_1 and B_1 are the same as in Fig. 91a. The second longitudinal resonance (A_2) almost does not appear here; the third longitudinal resonance can be ascribed to peculiarities of curves of impedance designated on this figure by A_3, which appear, however, only with a small thickness of the wall. The remaining resonance frequencies in this case are difficult to identify.

Figure 93a gives the totality of frequency-response curves of electrical impedance for the case of tangential polarization of piezoelements with those constructive dimensions of the piezoelements. The number of sections of the piezoelement is equal to 12. Let us note that electrodes are applied to the surfaces of the solid ceramic cylinder as is shown in Fig. 95, i.e., each electrode passes by opposite internal and external forming, being connected radially to the face surfaces.

In this case the radial resonance B_1 is clearly expressed; it is possible to assume that peculiarities designated in Fig. 93a by B_2 are due by its origin to the second radial resonance. Longitudinal and thickness resonances partically do not appear here.

Let us make certain general remarks concerning Fig. 91a, 92a, and 93a. First of all we should note that those forms of oscillations appear clearest for which the direction of deformations coincides with the direction of polarization; these oscillations appear most clearly on the electrical side (with the exception of cases of some special connection of electrodes). A good example of this is Fig. 93a where the tangential polarization corresponds to the clearly expressed oscillations of the radial type to which the greatest tangential mechanical stresses correspond. The remaining oscillation modes (longitudinal and thickness) appear weakly, since they are excited only because of the presence of Poisson's ratio.

The case of the longitudinal polarization shown in Fig. 92a is intermediate. Here resonances on longitudinal oscillations corresponding to the direction of polarization are expressed most clearly. The radial (B) and thickness oscillations (B_1) are more slightly expressed, since corresponding oscillations are excited only because of the presence of Poisson's ratio, and the direction of deformation for them does not agree with the direction of polarization.

Finally, with radial polarization naturally the most expressed are thickness resonances, for which in this case the direction of deformation coincides with the direction of polarization. A gradual approach of longitudinal (A_1) and thickness (B_1) resonances, evident in Fig. 91a is natural within the given experiment, since for samples with number 18 the dimensions approach in height and thickness of the wall.

Let us discuss finally the "disappearance" of definite types of resonances which are observed on the figures. This degeneration observed on the electrical side is explained by the fact that with a definite location of the electrodes, direction of polarization, and direction of deformations in the region of the body of the piezoelement include between the electrodes with an increase in frequency complicated distributions can appear of mechanical stresses characterized by the presence of zones with opposite signs of voltage. This results in a well-known kind of compensation of charges and decrease in the coupling coefficient.

The conclusions made by us are confirmed with the analysis of results of measurements of the frequency dependence of the phase angle φ (shift of phases between the current and voltage), which we took for the same samples. Corresponding frequency dependences of the phase angle are given for a comparison with frequency dependencies of the modulus in Fig. 91b, 92b, and 93b.

A second series of measurements was carried out by us on samples of different height; the remaining dimensions were identical. The measurements were taken with piezoceramic cylinders with numbers from 1 to 11 (see Table 20), the thickness of the wall in all cases was equal to 0.25 cm, and the diameter was 2.3 mm, i.e., in this case we were dealing with thin-walled piezoelements. The measurements were taken by means of determination of frequency characteristics of the phase angle of electrical impedance. At frequencies more or less remote from resonance the phase angle φ differs little from 90°, since the electrical impedance of the converter is practically a purely capacitive reactance. Duration of the angle φ from 90° is determined only by internal dielectric losses in the ceramics. At resonance frequencies angle φ abruptly changes sign, and the higher the quality the closer the angle φ is to -90°.

Thus on the frequency characteristics of the phase angle resonances appear in the form of sharp overshoots downwards, and the magnitude of the overshoot increases with an increase in the quality at the given resonance frequency.

Figure 94 gives pictures of the change in frequency characteristics of the phase angle with a change in height of the cylindrical piezoelement for cases of radial, longitudinal, and tangential polarization. On all figures the decrease in height of the cylinder goes downward.

In Fig. 94a, on which spectra with radial polarization are given, inclined routes A_1, A_2, A_3, A_4..., are well traced and correspond to the first, second, third, fourth, etc., longitudinal resonances. The radial resonance Б is also well-defined. With a small thickness of the wall, thickness resonances lie high, and although they are well-defined they are already greatly split.

With longitudinal polarization (Fig. 94b) longitudinal resonances A_1, A_2, A_3... are also well-defined. The radial resonance Б is well-defined with small heights of the piezoelement and disappears at great heights from causes which were already noted above; in this case it disappears due to the appearance in height of a long cylinder of zones with opposite signs of deformation. Thickness resonance here is practically not at all expressed.

In Fig. 94c (tangential polarization) the clearest expressed are naturally radial resonances Б. The first longitudinal resonance with great heights of the cylinder A_1 is rather well-defined. With small heights of the cylinder for a given form of polarization even the first longitudinal resonance does not appear from the causes mentioned above for the case of the longitudinal polarization of a long cylinder. The remaining resonances here are weakly expressed, and it is difficult to identify them.

We see that experiments conducted for thin-walled cylinders of variable height confirm the data obtained during the carrying out of the series of measurements with thick-walled cylinders.

Namely, with the measurement of frequency dependencies of input electrical parameters (modulus of electrical impedance $|z|$ and phase angle φ) not all forms of natural resonances of the system are revealed by measurements on the electrical side with different polarization of the cylinderical models with the above described electrodes. So in the long (with respect to the diameter) tubes with longitudinal polarization radial resonance is not revealed; in the short (as compared to the diameter) tubes resonance of longitudinal oscillations during tangenial polarization is not revealed. For clarity Table 21 gives data on resonances appearing well on the electrical side with three possible methods of polarization. The "+" sign denotes reliably experimentally observed types of resonances and the "-" sign, completely absent resonances or very weakly expressed. The position proves to be different depending upon the relationship of the diameter D and axial length (height) of the cylinder l.

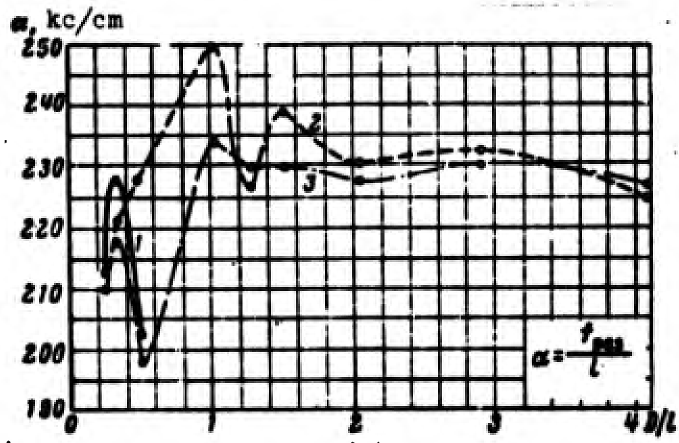
Table 21

Relationship of D and l	Polarization	Longitudinal resonance (by height of the cylinder)	Radial resonance	Resonance according to thickness of the wall
$l > D$	Radial	+	+	+
	Longitudinal	+	-	-
	Tangential	+	+	-
$D > l$	Radial	+	+	+
	Longitudinal	+	+	-
	Tangential	-	+	-

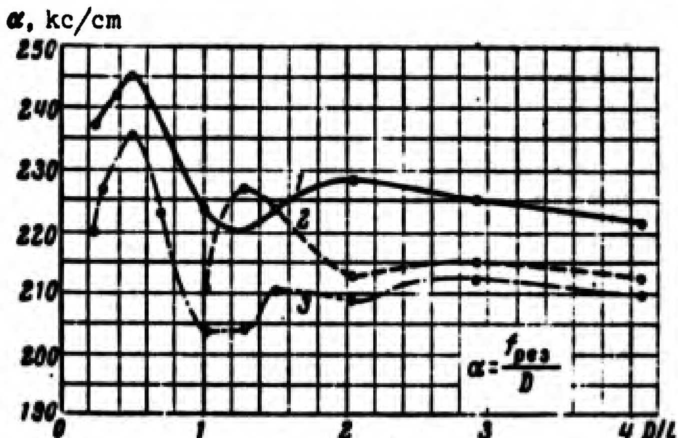
On the basis of everything presented the conclusion can be made that with the selected type of polarization and desire to obtain a satisfactory coupling coefficient, on a definite oscillatory mode one should arrange the electrodes and to select their number in accordance with the distribution in the body of the piezoelement of dynamic stresses corresponding to the given oscillatory mode.

With the selection of overall dimensions of cylindrical ceramic piezoelements for resonance sound receivers, it is useful to know the frequency constant of ceramics with longitudinal and radial oscillations of cylinders and with different forms of their polarization. By analogy with the case of the flat ceramic plate, we will call the frequency constant the ratio of resonance frequency to height or to the external diameter of the cylinder.

On the basis of the obtained frequency-response curves of the modulus and phase of electrical impedance for cylindrical tubes of different geometric dimensions, we constructed the dependence of the frequency constant for radial and longitudinal oscillations of the thin-walled ceramic cylinder on the ratio of the external diameter of the cylinder D to its axial length l. Figure 96a gives such a dependence for longitudinal oscillations with tangential 1, longitudinal 2, and radial 3 polarization, and Fig. 96b gives an analogic curve for the case of radial oscillations with the same designations.



(a)



(b)

Fig. 96. Frequency constant for oscillations of a cylinder of ceramics of barium titanate with different relationships of the diameter of the cylinder to its axial length. a) for longitudinal oscialla:ions; b) for radial oscillations.

Frequency constants are different for different forms polarization of cylindrical piezoelements and practically do not depend on the ratio D/l for low rings, when $D/l > 2$, and for cylinders for which the diameter and height are commensurable we obtained values of frequency constants different from frequency constants for low rings.

It is known [209] that by frequencies of resonances and antiresonances with radial and longitudinal oscillations of cylindrical piezoelements, one can determine the value of the coefficient of electromechanical coupling. With this the coefficient of the electromechanical coupling for radial oscillations is determined by the formula

$$k_r = \sqrt{\frac{2\pi\Delta f_r}{f_r}}.$$

The coefficient of the electromechanical coupling for longitudinal oscillations (resonance according to the height of the cylinder) will be

$$k_l = \sqrt{\frac{\pi^2}{8}\frac{2\Delta f_l}{f_l}} = \frac{d_{ik}}{\sqrt{\frac{s}{4\pi}}},$$

where Δf_r and Δf_l are the difference in frequencies of the antiresonance and resonance with radial and longitudinal oscillations; f_r and f_l are corresponding frequencies of the antiresonance; s is the constant of flexibility; d_{ik} is piezoelectric modulus.

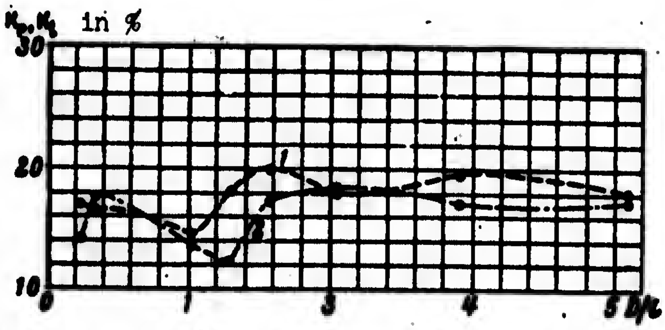


Fig. 97. Coefficient of the electromechanical coupling for longitudinal and radial oscillations of radially polarized cylinders of ceramics of barium titanate with different values of the ratio of the diameter of the cylinder to its axial length.

Figures 97, 98, and 99 give the values obtained by use of coefficients of electromechanical coupling for longitudinal and radial oscillations with different forms of polarization of thin ceramic cylinders depending upon the ratio of the diameter of the cylinder D to its axial length l. From Fig. 97 one can see that the radially polarized cylinders have an approximately constant value of the coefficient of the electromechanical coupling for longitudinal 1 and radial 2 oscillations (approximately 17-18%) irrespective to the ratio D/l.

Figure 98 gives results for longitudinally polarized cylinders for radial 1 and for longitudinal 2 resonances. Values of the coefficient of electromechanical coupling for radial and longitudinal oscillations in this case are different. This should be excepted, since with longitudinal resonance and longitudinal polarization the coupling coefficient is determined by the piezoelectric modulus d_{33}, whereas with radial resonance it is connected with the piezoelectric modulus d_{31}.

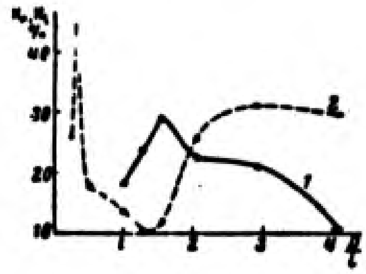


Fig. 98. Coefficient of electromechanical coupling for radial (1) and longitudinal (2) oscillations of a longitudinally polarized cylinder of ceramics of barium titanate with different values of the ratio of the diameter of the cylinder to its axial length.

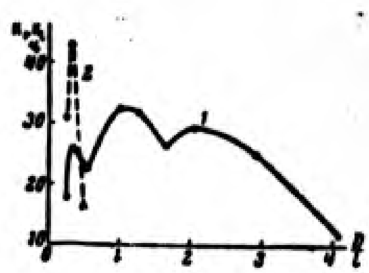


Fig. 99. Coefficient of electromechanical coupling for radial (1) and longitudinal (2) oscillations of tangentially polarized cylinders with different values of the ratio of the diameter of the cylinder to its axial length.

Figure 99 shows analogous results for the case of tangential polarization.

The results given by us have a tentative character. They show the scale of the change in coefficient of the electromechanical coupling with a change in the ratio of the diameter of the cylindrical piezoelement to its length with different forms of polarization. Using these data it is possible to estimate the limits of change of D/l at which the coefficient the electromechanical coupling will have sufficiently large values.

Let us recall that the obtained data (frequency constants and coefficients of electromechanical coupling) pertain first only to the case of the simplest systems of electrodes evenly distributed along the lateral surfaces of the cylinder and secondly, to the case of solid cylinders.

3. The Use of Sound Receivers with the Cylindrical Piezoceramic Element as Resonance

As can be seen from what has been stated, sound receivers with a cylindrical piezoelement of ceramics of barium titanate possess a spectrum of natural frequencies in which certain resonances are well-defined. At such defined resonances the sensitivity of the sound receiver considerably exceeds the static. This makes it possible in certain cases to use such receivers as resonance during the reception of sound of definite frequencies. So by using the sound receiver at high ultrasonic frequencies it is possible to use with radial polarization the region of resonances according to the thickness of the wall. Of course, it is possible to use more low-frequency resonances, especially with the application of such sound receivers for measuring purposes. For example, Table 22 gives data on the sensitivity of cylindrical sound receiver with radial polarization at the first radial resonance.

Table 22

Diameter of the piezoelement, mm	Capacity of the sound receiver, pf	Sensitivity in resonance, µv/bar	Static sensitivity, µv/bar
6	2200	2.1	1.4
15	4000	4.5	3.76
30	8000	10	7.0
50	2000	15	11.6

It is obvious that it is possible to use as resonance also sound receivers with a spherical piezoelement; the sensitivity of spherical piezoelements at a frequency of the first radial resonance with the ratio of the thickness of the shell to the diameter $\varkappa \approx 0.1$ exceeds the static 1.5-3 times.

Directional characteristics of sound receivers with radial polarized piezoelements in the region of low-frequency resonances are very close to circular. With tangential polarization of the cylinders there can be resonance frequencies, during which duration from the circular directional characteristic is noticeable; however, this duration, as a rule, does not exceed 6 decibel.

Therefore, in the region of low-frequency resonances spherical and cylindrical sound receivers can be used with success as nondirectional receivers with a sensitivity somewhat increased as compared to the static.

CHAPTER VI

RESONANCE SOUND RECEIVERS WITH CERAMIC PIEZOELECTRIC ELEMENTS

1. Resonance Sound Receivers with a Flat Receiver Diaphragm and Cylindrical Piezoceramic Elements

We investigated several types of resonance sound receivers with a converting element of ceramics of barium titanate and first turned to the use of piezoelements in the form of longitudinally or radially polarized cylinders connected by a certain method with the receiving diaphragm.

Such converters with different resonance frequencies were used, for example, as radiators for creating a sound field in measuring hydroacoustic tubes or with a different kind of measurements in a hydroacoustic basin (with calibration by the method of reciprocity as a reversing converter or auxiliary radiator, and so forth).

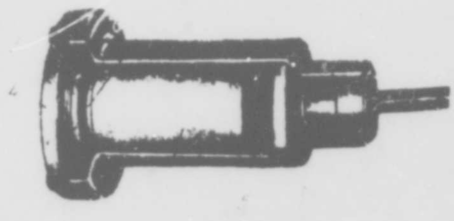


Fig. 100. Resonance sound receiver with a flat receiving diaphragm and cylindrical element of ceramics of barium titanate. 1 — cylindrical piezoelement; 2 — end diaphragm; 3 — packing rubber washer; 4 — ring clamping the packing; 5 — rear rubber catch; 6 — housing of the sound receiver; 7 — stuffing box for lead-in of the cable.

Fig. 101. Longitudinally polarized ceramic piezoelement for a resonance sound receiver. 1 — diaphragm; 2 — ceramic cylinder; 3, 4 — electrodes.

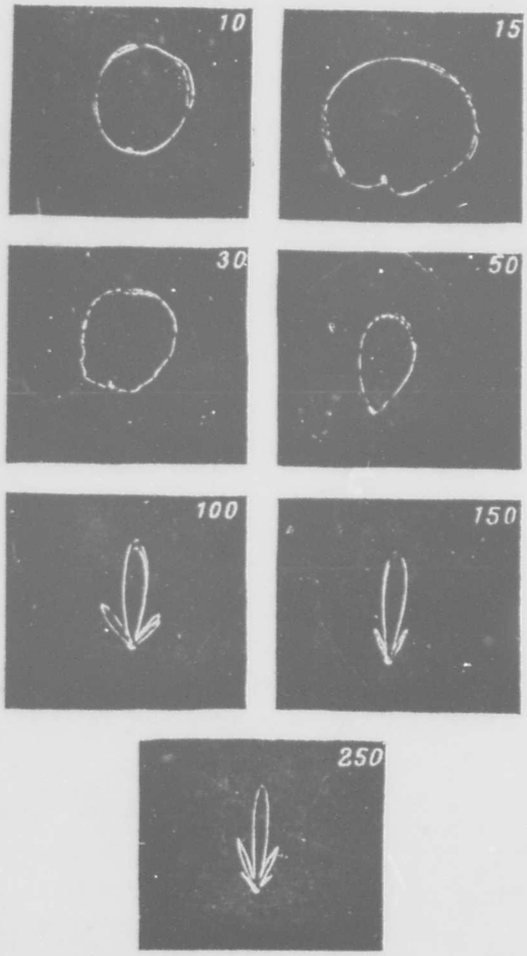


Fig. 102. Directional characteristic of a sound receiver with a flat receiving diaphragm. Numbers on the figure denote frequency in kilocycles.

Figure 100 shows a resonance converter with a cylindrical piezoelement 1 of the type investigated by us; part of the housing is cut away in order to show the internal mechanism of the instrument.

The rubber packing ring 3 covers the diaphragms 2 on the external edge; in front of the diaphragm is open and is an element perceiving the sound pressure. The figure shows a sound receiver with radial polarization of the piezoelement. Figure 101 shows separately the piezoelement for such a sound receiver but for the case of longitudinal polarization. The diaphragm 1 is also made of ceramics and covers one of the face surfaces of cylinder; silver electrodes 3 and 4 are applied to the external lateral surface of the ceramic cylinder 2 in the form of a double helical line.

Table 23

№	Type of polarization	$f_{рез}$, kc	h, mm	C, тыс. пф	l, mm	δ, mm	Resonance sensitivity μv/bar
1	Longitudinal	26,8	60	5,7	6	3	47,6
2		38	38	3,1	6	1,5	40
3		24	60	2,82	12	3	84
4	Radial	20	60	53	1	1	7,4
5		20	60	56,5	1	1	6,7
6	Longitudinal	32	52	3,48	6	1,5	30
7		60	28	2	6	1,5	30
8		23,5	65	5,7	6	1,5	31
9		9,4	165	11,7	6	1,5	40
10	Radial	20	60	56,2	1	1	7,8
11		23	60	17	3	3	15,7
12	Longitudinal	12,5	125	10,3	6	1,5	19,4
13		14,5	85	6,8	6	1,5	46
14	Radial	20	60	57	1	1	7,1
15		24	60	—	5	5	40

Designations: $f_{рез}$ — resonance frequency, kc; h — height of the cylindrical piezoelement, mm; l — distance between the electrodes, mm; δ — thickness of the wall of the piezoceramic cylinder, mm; C — capacity, thousand pf.

Table 23 gives data of parameters of converters of the described type tested by us.

The external diameter of the piezoelement in all cases was equal to 3.2 cm. The values of sensitivity given in the table have been determined on a hydroacoustic tube (see Chapter II, Section 4).

Figure 102 gives the usual directional characteristics of one of such sound receivers with a resonance frequency of 25 kilocycles. They are essentially determined by the frequency and external diameter of the diaphragm and, of course, by conditions of diffraction.

Frequency characteristics of the sensitivity of such sound receivers in virtue of the presence of the flat diaphragm were conveniently obtained with the help of the hydroacoustic tube or a metallic rod, waveguide (see Chapter II, Section 4). We used both methods.

Figure 103a gives, for example, the frequency-response curve of the sensitivity of a sound receiver with a resonance frequency of 24 kilocycles with a longitudinal polarization of the piezoelement (Table 23, No. 3) obtained in a hydroacoustic tube. Figure 103b given the same characteristic for sound receivers with the same frequency but with radial polarization (Table 23, No. 15).

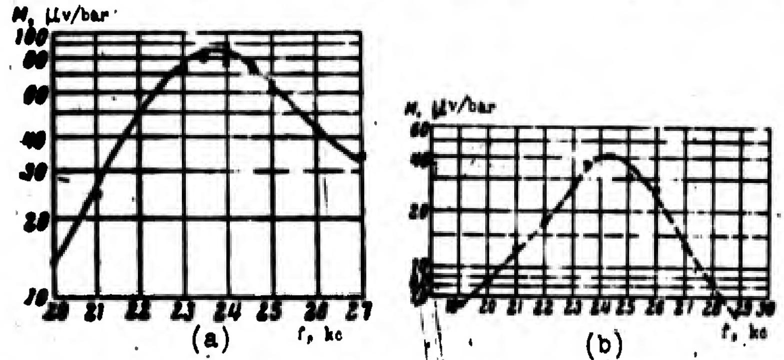


Fig. 103. Frequency characteristic of a resonance sound receiver with a flat receiving diaphragm either of (a) longitudinal or (b) radial polarized cylindrical piezo-element.

The difference in magnitude of the resonance sensitivity with measurements in the hydroacoustic tube and on a solid line was about near 2 decibels.

From the point of view of using the converters described with different kinds of calibrations it was interesting to clarify the frequency rate of the active and reactive components of the input acoustic impedance of the converter. Appropriate measurements were taken by us on the apparatus called the pulse tube [188]. Figure 104 gives the frequency-response curves of the active (R) and reactive (X) components of complete input acoustic resistance for the converter No. 15 (Table 23). It is easy to see that with resonance the sound receiver becomes acoustically pliable. This circumstance should be taken into consideration, for example, with the use of similar resonance sound receivers as reversible converters during calibrations according to the method of reciprocity, and so forth.

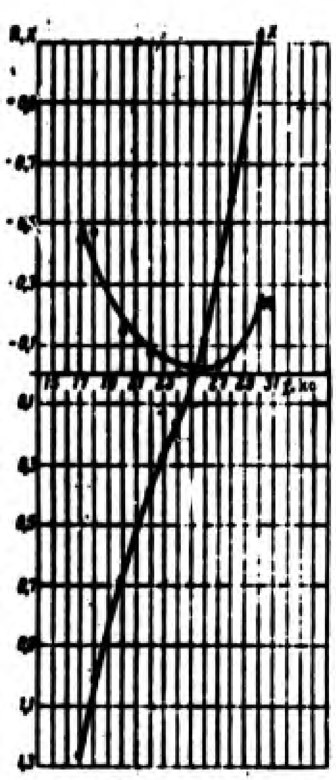


Fig. 104. Frequency characteristic of complete input acoustic resistance of a resonance sound receiver with a flat receiving diaphragm.

Sound receivers of the type described possess a comparatively small directivity due to the small diameter sound pickup diaphragm. A simple increase in the diameter of the diaphragm with one piezoelement, of course, leads to the narrowing of the main lobe of the characteristic but can cause also the growth of secondary lobes. It was more expedient for us to use with a large diameter of the diaphragm a "mosaic" of several cylindrical piezoelements. An example of such construction is shown in Fig. 105. Here we see a steel flat diaphragm and 13 ceramic cylinders with radial polarization; the cylindrical piezoelements were thoroughly matched in resonance frequency and were glued by the ends to the diaphragm by means of carbinol glue. The diaphragm was installed in the housing of the sound receiver with the help of a rubber packing ring.

Fig. 105. "Mosaic" of ceramic cylinders with a resoace frequency of 27 kilocycles.

Figure 106 shows the frequency-response curve in conditions of radiation of such a converter with the diameter of the diaphragm, 32 cm and resonance frequency, 27 kilocycles.

Let us note that the rear ends of cylindrical piezoelements in the given construction remained free.

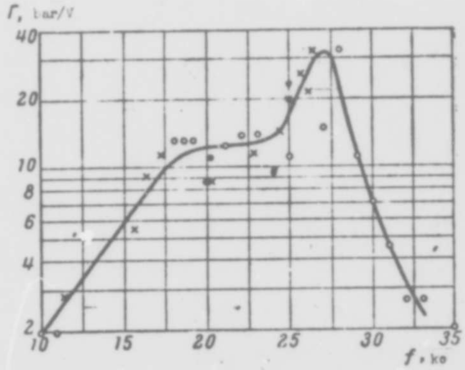


Fig. 106. Frequency-response curve of a "mosaic" converter with cylindrical elements.

"Mosaic" converters of such type are easily manufactured and can be made practically for any resonance frequency in a range of frequencies approximately from 10 to 200 kilocycles.

2. Resonance Sound Receivers with a Flat Piezoelectric Diaphragm

In many cases it appears convenient to use the very simple construction of the sound receiver shown in Fig. 107. A flat diaphragm of ceramics of barium titanate 1 polarized by the thickness is fastened to the edge with the help of a rubber ring 2 and bracing metallic ring 3 to the hermetic metallic frame 4. The external metallic covering of the diaphragm serves as one of electrodes and simultaneously is a screen electrically connected with the frame. Mostly we applied over the layer of metallizing a protective shell of glass enamel.

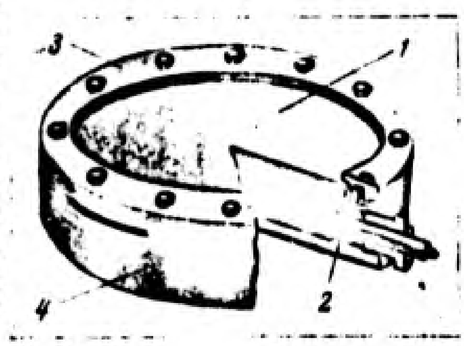


Fig. 107. Resonance sound receiver with a flat piezoelectric half-wave receiving diaphragm.

The lead from the internal electrode was achieved by the cable through the stuffing box. Sound receivers of such kind were used by us for hydroacoustic purposes. Basic parameters of certain sound receivers of this type are given in Table 24.

Table 24

No.	Dimensions of diaphragm		Resonance frequency, kc	Resonance sensitivity µv/bar	Capacity, pf
	thickness, cm	diameter cm			
1	3.2	10.7	65 to 75	170 to 200	3,500
2	1.35	12.2	160 to 165	120	7,800
3	0.75	12.7	349	95	16,000

The sensitivity of the sound receivers was measured in a basin by means of calibration on pulses by the method of reciprocity with the use of a signal reflected from the free surface of the water.

It should be noted that frequency responses of such sound receivers with a piezoplate oscillating according to thickness frequently reveal a different kind of irregularity of the type of splitting of resonances, and so forth. This appeared in the given case. Figure 108a gives the frequency-response curve of a sound receiver No. 1 (Table 24) with the greatest thickness of the diaphragm (3.2 cm). Here we have a clear example of the complicated spectrum in the region of the basic resonance. With an average thickness of plate of 1.35 cm (Fig. 108b, sound receiver No. 2) we have a very regular frequency response curve, and with the thicknes of the diaphragm at 0.75 cm (Fig. 108c sound receiver No. 3) again there are revealed irregularities in the structure of the frequency response curve.

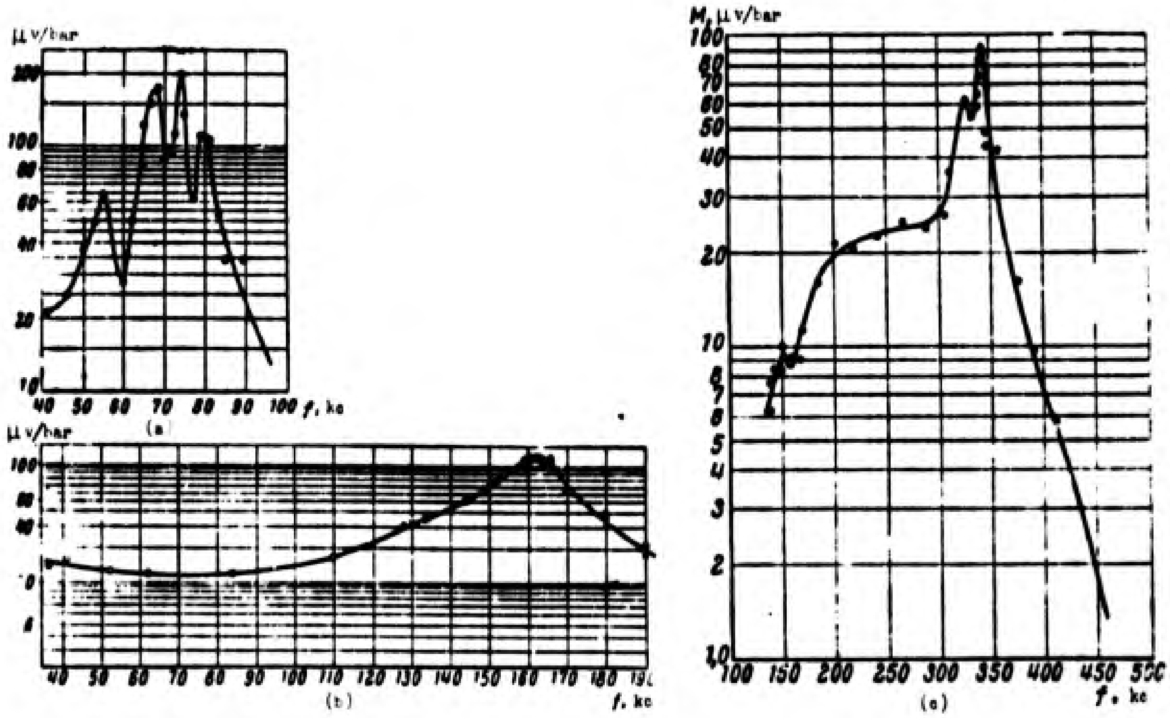


Fig. 108. Frequency-response curve of a sound receiver with a flat half-wave sensitive plate of ceramics of ι rium titanate. a) thickness of the plate, 3.2 cm; b) thickness, 1.35 cm; c) thickness, 1.75 cm.

Similar phenomena are apparently connected with the complicated picture of oscillations of a flat piezoplate with its small thickness as compared to the diameter and correspondingly the complicated distribution of the amplitude along the external surface of the plate [207, 208]. With the complicated structure of the frequency response in the region of the main resonance, it is difficult to discuss the frequency constant, high quality, or the width of the resonance curve. It is possible that in such cases one should introduce some average magnitude. Nevertheless a distinctive feature of ceramic sound receivers with a diaphragm in the form of a simple flat piezoceramic plate is the comparatively great high quality. Therefore, barium titanate can be considered a prospective material for the construction of narrow-band resonance converters of such type. The large high quality here is conditioned by the large value of the coefficient of electromechanical coupling with high wave impedance of ceramics of barium titanate.

The solution of the basic lobe of the directional characteristic of converters of the type described for different frequencies, as a rule, coincides with the result obtained on the assumption of a cophasal motion of the external surface of the diaphragm. However, at certain frequencies secondary maxima of the directional characteristic appear much stronger than that resulting from such a calcualtion. The latter circumstance is explained apparently by the presence of standing transverse waves in a limited ceramic plate.

Figure 109 gives an example of such a sharply distorted directional characteristic for a sound receiver with a flat piezoelectric diaphragm 10 cm in diameter and 3.2 cm thick at a frequency of 150 kilocycles. Converters with a flat piezoelectric diaphragm can be designed for relatively high frequencies.

For converters designed for operation at lower frequencies package construction appears more convenient in which a flat piezoelectric element is loaded from one or from two sides by metallic cover plates.

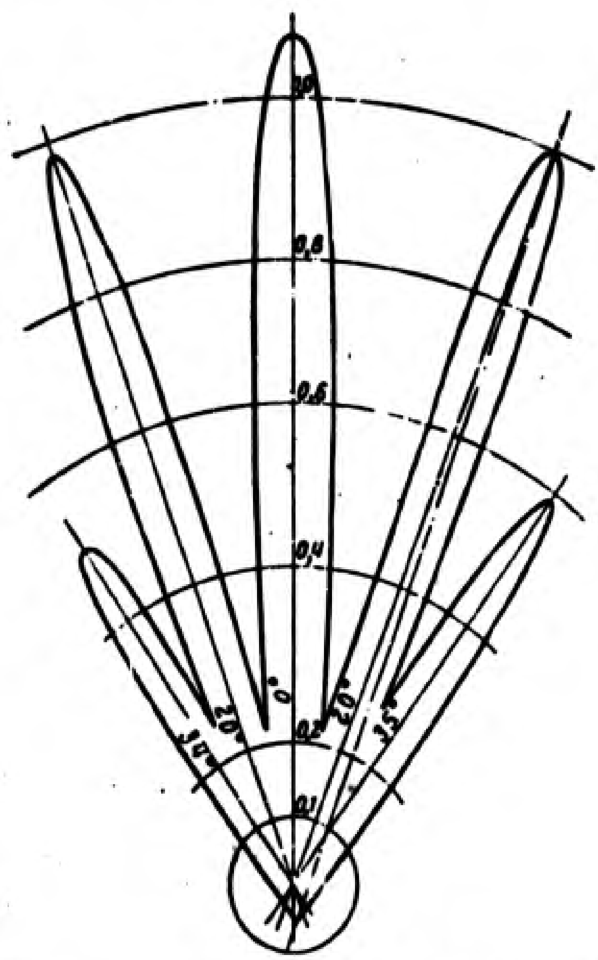


Fig. 109. Directional characteristic of a converter with a sensitive element in the form of a flat ceramic plate with noncophasal oscillation of its surface.

If it is necessary to make a converter of large diameter, then the construction of the type shown in Fig. 110 appears useful. Here on a circular steel plate 6 mm in thickness, being part of the cylindrical body 1, piezoelectric plates 7 of the dimension 20 mm × 20 mm × 5 mm are glued by carbinol glue in the form of a mosaic; all of them are connected electrically in parallel. On the front side the body is closed by a soundtransparent plexiglas cover 3 with a rubber packing 4. The internal cavity 8 is filled by transformer oil. The rear cover 2 is welded to the body 1 so that between the steel plate on which the ceramics is glued and the cover the cavity 6 filled by air is formed. The lead out of the cable is accomplished through the stuffing box 5.

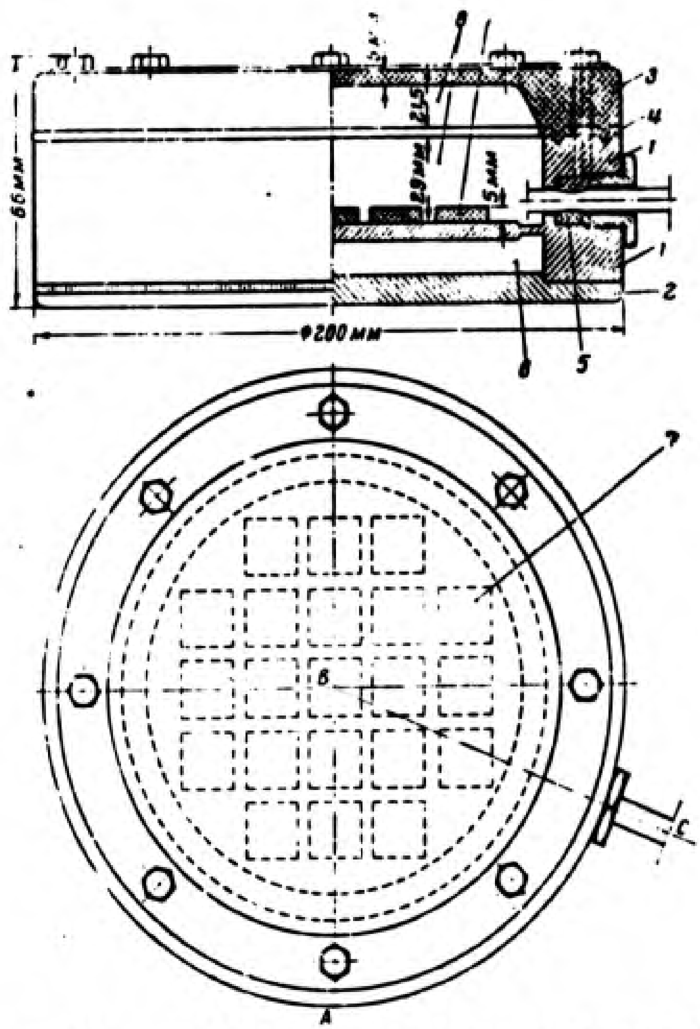


Fig. 110. Multilayer converter of the "mosaic" type with elements of ceramics of barium titanate.

Converters of this class are multilayered; characteristic of them is the complicated polyresonance spectrum of natural frequencies.

The position of resonance frequencies for laminar constructions of such kind is conveniently determined by calculating the frequency response of the acoustic transparency of the totality of the layers. We produced such calculations according to the method proposed by Tartakovskiy [210].

Let us give a comparison of the calculated and experimental data for a hydroacoustic sound receiver [211] consisting of a face piezoceramic plate 1.3 cm in thickness with thickness polarization and rear cover plate of aluminum 3.2 cm in thickness. The diameter of the pack was equal to 9.5 cm. The calculated frequency response of the acoustic transmittance of such a system of layers (water – barium titanate – aluminum – air) is shown in Fig. 111 where along the ordinate the transparency is plotted in arbitrary units.

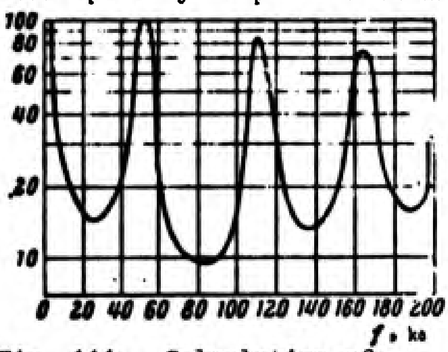


Fig. 111. Calculation of transmittance of a two-layered system equivalent to a one-sided converter with a sensitive ceramic element and rear cover plate.

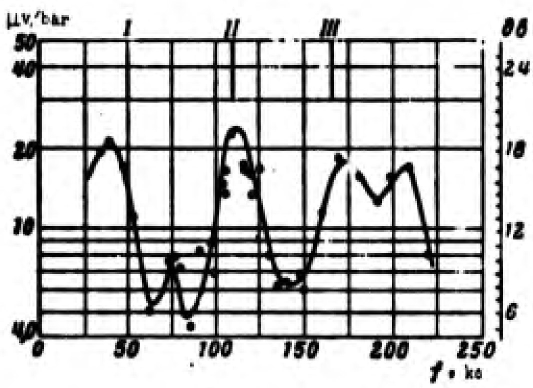


Fig. 112. Frequency response curve of a converter with a sensing device and rear cover plate.

Figure 112 gives the frequency response of the sensitivity of the considered sound receiver where vertical lines show the position of the first, second, and third calculation of transmittance maximums. The experimental spectrum of natural frequencies coincides well with the calculated.

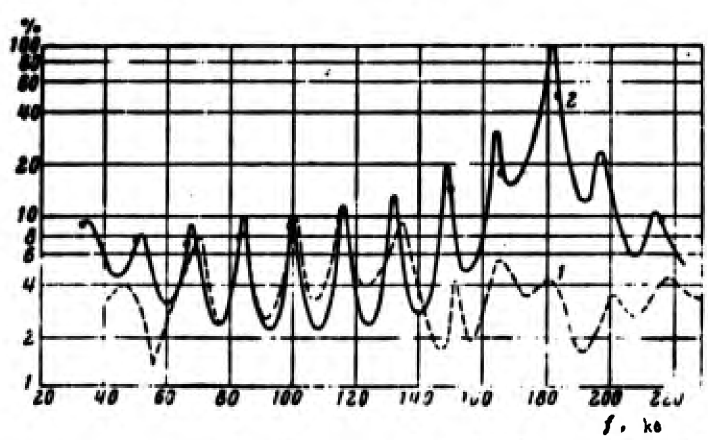


Fig. 113. Comparison of the frequency response of a multilayer converter with a calculation of the transmittance of the system of layers equivalent to it. 1 – experimental curve; 2 – calculated curve.

Figure 113 gives a comparison of the experimental frequency response of the sensitivity of the "mosaic" converter (see Fig. 110) (curve 1) with the calculated frequency response of transmittance of a system of layers including water, Plexiglas, oil, barium titanate, steel, and air (curve 2). Both curves are given along the ordinate in relative units. It is easy to see that in the case of even a very complicated laminar system the calculated spectrum of natural frequencies coincides well with the one obtained experimentally [212, 213].

Thus, the application of cover plates permits constructing converters with a wide spectrum of natural frequencies including considerably lower ones than those which would be peculiar to the actual piezoceramic layer used in the converter. However, the resonance sensitivity of a converter with cover plates is always obtained somewhat lower than the sensitivity of purely ceramic converters (1.5-2 times), which should apparently be attributed to the influence of losses in bonding or in other intermediate layers.

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LITERATURE

1. Langevin, M. P. Probing with sound. French patent No. 505703, 1918, No. 576281, 1924; No. 622035, 1926. Hydrographic Review, 1924, Issue, 2, 2, 51-121. Spec. Publ. Int. Hydropg. Bureau, 1926, No. 14. Ultrasonic probing instrument.

2. Nicolson, A. Mch. Piezoelectric effect in a complex crystal of Seignette's salt, Proc. Amer. Inst. Electr. Eng., 1919, Issue 38, 11, 1315-1333; Trans. Amer. Inst. Electr. Eng., 1919, 38, 1467.

3. Klein, E. Early stages of the development of Ultrasonics, Journal Acoust. Soc. Am., 1948, Issue 20, 5, 601.

4. Sawyer, C. B. Application of crystals of Seignette's salt in loudspeakers and microphones, Proc. Inst. Radio Eng., 1931, Issue 19, 2020-2029.

5. Andreyev, N. N. Author's certificate No. 27406, 1930.

6. Williams, A. L. Piezoelectric loudspeakers and microphones, Electronics, 1932, 4, 166-167; 1934, 25, 196; J. Soc. Motion Picture Eng., 1935, Issue 23, 1420-1421.

7. Ballantine, S. Piezoelectric loudspeaker for upper sound frequencies, Proc. Inst. Radio Eng., 1933, Issue 21, 1399-1408.

8. Ballantine, S. High-quality broadcasting transmission and reception ("sound stage" of Seignette's salt), Proc. Inst. Radio Eng., 1934, Issue 22, 564-629; 1935, 23, 1420-1421.

9. Williams, A. L., Arndt, I. P. Construction of crystal microphone of directional effect, Electronics, 1935 [illegible] sue 8, 242-243.

10. Sugimoto, T. Microphone of [illegible] stal of Seignette's Salt and an underwater acoustic receiver, Rep. Radio Resear[illegible], Japan, 1936, Issue 6, 9-10.

11. Beerwald, P., Keller, H. Piezoelectric crystal devices for electroacoustic purposes (including bimorph cells of Seignette's salt), Funktechn. Monatshefte, 1938. No. 71, 345-348.

12. Beerwald, P., Keller, H. Theory and practice of microphones with a piezoelectric sound cell, Funktechn. Monatshefte, 1941, Issue 12, 187-190; Wireless Eng., 1942, 19, 1393A.

13. Keller, H. Piezoelectric "bending band" as an electromechanical converter, Hochfrequenztechn. u. Electroac., 1942, Issue 60, 5-10.

14. Sawdeg, R. S. Bimorph piezoelectric elements of Seignette's salt and their application, Radio, Issue 23 and following (September, 1943).

15. Kharkervich, A. A. "On the application of Seignette's salt in piezoelectric instruments." ZhTF, 1943, Issue 13, 585.

16. Lepeshinskaya, V. N. Piezoelectric instruments with Seignette's salt. Leningrad, 1943.

17. Mason, W. P. Elastic, piezoelectric, and dielectric constants of potassium dihyrophosphate and ammonium diohydrophosphate, Phys. Rev., 1946, Issue 69, 173. Properties of Monoclinal crystals, Phys. Rev., 1946, Issue 70, 9 and 10.

18. Bechman, R. Determination of elastic and piezoelectric coefficients of monoclinal crystals, including ethylene-diamine of tartrate, Proc. Phys. Soc., 1950, Ser. B-63, 577.

19. Spitzer, F. Piezoelectric crystals, Fernmeldetechn., Vol. I, Issue 3, 1950, 190-196; Vol. II, Issue 3, 1950, 234-243.

20. Spitzer, F. New synthetic piezoelectric crystals in electrocoustics and high-frequency technology, Arch. elektr. Ubertrag., 1951, Issue 5, 544-554.

21. Kedi, U. Piezoelectricity and its practical application, Foreign Literature Publishing House, 1949.

22. Mason, W. Piezoelectric crystals and their application in ultracoustics, Foreign Literature Publishing House, 1952.

23. Bechman, R. Elastic and piezoelectric coefficients of lithium monohydrate of sulfate, Proc. Phys. Soc., 1952, Issue 65, 5, 389.

24. Andreyev, N. N. "P'yezoelektricheskiye kristally i ikh primeneniye" (Piezoelectric crystals and their application), Elektrichestvo, 1947, 2, 5-13.

25. Fein, L. Ultrasonic underwater "point" probe, Acoust. Soc. Am., 1948, Issue 20, 590; 1950, Issue 22, 876

26. Rudnick, I., Rothenberg, H. C. Miniature high-frequency microphone, J. Acoust. Soc. Am., 1948, Issue 20, 594.

27. Günter, W. Crystalline microphone for measurements in water, Z. angew. Phys., 1950, Issue 2, 206.

28. Cooper, H. W. Miniature crystal converter, a probe for ultrasonic investigations, J. Acoust. Soc. Am., 1950, Issue 22, 86.

29. Anan'yev, P. V. Synthetic crystals and their application in coupling equipment. Transactions of the Commission for Acoustics, 1951, Issue 6, 3.

30. Vul, B. M., Gol'dman, I. M. Dielectric constant of titanates of metals of the 2nd group. DAN USSR, 1945, Issue 46, 4, 154.

31. Vul, B. M., Gol'dman, I. M. Dielectric constant of barium titanate depending upon the directivity in a variable field. DAN USSR, 1945, Issue 49, 3, 179-182.

32. Vul, B. M. Gol'dman, I. M. Dielectric hysteresis in barium titanate. DAN USSR, 1946, 51, 1, 21.

33. Vul, B. M. Vereshchagin, L. F. Dependence of the dielectric constant of barium titanate on pressure. DAN USSR, 1945, 48, 9, 662.

34. Vul, B. M. Dielectric constant of barium titanate at low temperatures. ZhETF, 1945, 15, 12, 735-736.

35. Vul, B. M. Substances with a high and ultra high dielectric constant. Electricity, 1946, No. 3.

36. Bretteville, J. Oscillographic investigations of dielectric properties of barium titanate, J. Am. Ceramic Soc., 1946, Issue 29, 303.

37. Adler, R., Cherry, W. L. Piezoelectric effect in polycrystalline barium titanate, Phys. Rev., 1947, Issue 72, 10, 981.

38. Roberts, S. Dielectric and piezoelectric properties of barium titanate, Phys. Rev., 1947, Issue 71, 890.

39. Vul, B. M., Gol'dman, I. M. On the new variety of barium titanate. DAN USSR, 1948, 60, 1, 41.

40. Rzhanov, A. V. Spontaneous polarization into the piezoeffect of barium titanate. Diss. FIAN, 1948.

41. Rzhanov, A. V. Spontaneous polarization of $BaTiO_3$ samples ZhETF, 1949, 19, 4, 335.

42. Rzhanov, A. V. Piezoeffect of barium titanate. ZhETF, 1949, 19, 6, 502-506.

43. Rzhanov, A. V. Barium titanate, a new ferroelectric. Achievements in Physical Sciences, 1949, 38, 4, 486-487.

44. Anal'yeva, A. A., Tsarev, V. M. Development of a nondirectional sound receiver for ultrasonic frequencies. Report of the Acoustic Laboratory of the Physics Institute of the Academy of Sciences 1951.

45. Hector, L. G., Koren, H. W. Ceramic sound pickup, Electronics, 1948, 94-96.

46. Howatt, G. N., Crowner, J. W., Drametz, A. New piezoelectric materials, Electronics, 1948, 97-99.

47. Bugosh, J., Yeager, E., Hovorka, F. High frequency hydrophone of barium titanate, Phys. Rev., 1950, (2), Issue 76, 1890.

48. Ackermann, E., Holak, W. Ceramic measuring microphone, Rev. Sci. Instr. 1954, Issue 25, 857-861.

49. Koren, H. W. Application of polarized ceramics for converters, J. Acoust. Soc. Am., 1949, Issue 21, 3. 198-201.

50. Mason, W. P. Ceramics of barium titanate as an electromechanical converter, Bell Lab. Rec., 1949, Issue 27, 285-289.

51. Mason, W. P., Wick, R. F. Converter of barium titanate for large drifts in ultrasonic frequencies, J. Acoust. Soc. Am., 1951, Issue 23, 209-214.

52. Johnston, T. F., Wertz, F. D. Cylindrical converters of barium titanate, J. Acoust. Soc. Am., 1950, Issue 22, 676.

53. Bredfield, G. Ultrasound in solid bodies, Res. Sci. Appl. J., 1953, Issue 6, 2, 68-79.

54. Camp, L. Wide-band radiator of barium titanate, J. Acoust. Soc. Am., 1953, 25, 297-301.

55. Matiat, O. Converter for creating ultrasonic waves, J. Acoust. Soc. Am., 1953, Issue 25, 991-996.

56. Hueter, T. F. Invariant temperature point of an impedance hodograph of a barium titanate converter. J. Acoust. Soc. Am., 1953, Issue 25, 152.

57. Jaffe, H. Titanate ceramics for electromechanical applications, Ind. Eng. Chem., 1950, 42, No. 2, 264-268.

58. Roth, R. S. Data of an elementary cell of lead niobate, Acta Cryst., 1951, Issue 10, 437.

59. Shirane, G., Suzuki, K. Crystalline structure, Phys. Soc. Japan, 1952, No.3, 7, 333.

60. Sewaguchi, E. Ferroelectricity and anti-ferroelectrictricity in a solid solution of $PbZrO_3$ and $PbTiO_3$, Phys. Soc. Japan, 1953, 5, 8, 615-629.

61. Goodman, G. Ferroelectric properties of lead metaniobate, J. Am. Ceramic Soc., 1953, Issue 36, 368.

62. Jaffe, B., Rofh, R. S., Mazzullo, S. Piezoelectric properties of solid solutions of ceramics of lead zirkonate and lead titanate, J. Appl. Phys., 1954, 6, 25.

63. Mason, W. P. Application of ceramics on the basis of barium titanate resistant to temperature and time changes in converters, in systems of pertubation of elastic waves, and for stress measurements, Acustica, 1954, 1, 200.

64. Jaffe, B., Roth, R. S., Mazzullo, S. Properties of piezoelectric ceramics in the form of solid solutions, J. Res. Bur. Stand., 1955, 55, No. 5, 239.

65. Egertone, L., Koonce, S. E. The influence of calcination on the structure and dielectric and piezoelectric properties of ceramics of barium titanate, J. Am. Ceramic Soc., 1955, Issue 38, 11, 413.

66. Berlincourt, D. Recent achievements in the field of ferroelectric materials for converters, IRE Trans. Ultrasonic Eng., 1956, Issue 4, 53-65.

67. Bechman, R. Elastic, piezoelectric, and dielectric constants of polarized ceramics of barium titanate and certain applications of piezoelectric equations, J. Acoust. Soc. Am., 1956, Issue 28, 3, 347-350.

68. Francombe, M. H. and B. Lawis. The structure and phase transition in ferroelectric sodium-lead niobates and other ceramics of the sodium niobate type, Electronics, 1957, 2, 4, 387-403.

69. Berlincourt, D., Krueger, H. U. Dependence of the relationship of piezoelectric coefficients on the density and composition of ceramics of barium titanate, Phys. Rev., 1957, Issue 105, 1, 56-57.

70. Herbert, J. M. Ferroelectric crystals and ceramics, J. of Electronics and Crystals and ceramics, J. of Electronics and Control, Ser. I, 1958, 1, 5, 2.

71. Crawford, A. E. Piezoelectric ceramics of lead zirkonate, Brit. Com. and Electr., 1959, 6, 7, 516-519.

72. Kulesar, F. Electromechanical features of ceramics of lead titanate of zirconate in which the lead is partially replaced by calcium and strontium, J. Amer. Ceramic Soc., 1959, 42, 1, 49,

73. Kulesar, F. Electromechanical properties of lead titanate of zirconate modified by certain three and four valence admixtures, J. Amer. Ceramic Soc., 1959, 42, 7, 343.

74. Egerton, L., Dillon, D. M. Piezoelectric and dielectric properties of ceramics of the sodium niobate-potassium niobate system, J. Amer. Ceramic Soc., 1959, Issue 42, 9, 438.

75. Smolenskiy, G. A. Ferroelectric properties of certain titanates and zirconates of bivalent metals having a structure of the perovskite type, ZhTF, 1950, 20, 2, 137.

76. Smolenskiy, G. A. New ferroelectrics. DAN SSSR, 1950, 70, 3, 405-407.

77. Smolenskiy, G. A. Electrostrictive phenomena in ceramic ferroelectrics, ZhTF, 1951, 21, 9, 1045-49.

78. Smolenskiy, G. A. Kozhevnikova, I. V., The question of the emergence of ferroelectricity. DAN SSSR, 1951, 76, 519-522.

79. Smolenskiy, G. A., Karamyshev, M. A., Rozgachev, K. I. Ferroelectric properties of certain solid solutions. DAN SSSR, 1951, 79, 53.

80. Smolenskiy, G. A. Ferroelectric properties of certain crystals. DAN SSSR, 1952, 85, 5, 985-87.

81. Smolenskiy, G. A. Ferroel ctrics with a structure of the perovskite type. Thesis, Leningrad, 1954.

82. Smolenskiy, G. A., Isupov, V. A. Ferroelectric properties of solid solutions of barium stannate in barium titanate. ZhTF, 1954, 24, 8, 1373-1376.

83. Smolenskiy, G. A., Tarutin, N. T., Grudtsin, N. P. Ferroelectric properties of solid solutions of barium zirconate in barium titanate. ZhTF, 1954, 24, 1584.

84. Smolenskiy, G. A., Roznachev, K. I. Ferroelectric properties of solid solutions in a system of barium titanate – strontium titanate. ZhTF, 1954, 24, 10, 1753.

85. Smolenskiy, G. A., Arganouskaya, A. N., Kalinin, A. M., Fedtova, T. M. Ferroelectric properties of solid solutions, ZhTF, 1955, 25, 12, 2134-2142.

86. Smolenskiy, G. A. New ferroelectrics and antiferroelectrics of the oxygen-octahedral type. News of AN SSSR, Physics series, 1956, 20, 2, 163.

87. Smolenskiy, G. A., Isupov, V. A., Agranovskaya, A. N. Phase transitions in the ferroelectric state of strontium pyrotantalate, DAN SSSR, 1957, 113, 4, 803-804 and 1053-1056.

88. Smolenskiy, G. A. New ferroelectrics and antiferroelectrics, Progress in Physical Sciences, 1957, 62, 1, 41-69.

89. Roy, N. A. Electromechanical properties of barium titanate and certain solid solutions on the basis of barium titanate, Thesis Candidate. M., AKIN, 1953.

90. Roy, N. A. Dielectric and piezoelectric properties of solid solutions of $(BaSr)TiO_3$, $Ba(TiSn)O_3$ and $(TiZr)O_3$, Acoustic Journal, 1956, 2, 1, 62-70.

91. Bokov, V. A. Piezoelectric properties of polycrystalline solid solutions of $(BaSn)TiO_3$, $Ba(TiCa)O_3$, and $Ba(TiZr)O_3$, 1957, 3, 2, 104-108.

92. Bokov, V. A. Behavior of ferroelectrics in strong electrical fields. Izv. AN SSSR, Physics series, 1957, 21, 3, 382.

93. Myl'nikova, I. Ye. Investigation of solid solutions possessing ferroelectric properties. Izv. AN SSSR, Physics, 1957, 3, 423-432.

94. Isupov, V. A., Kosyakov, V. I. Dielectric polarization and piezoelectric properties of ferroelectric solid solutions of metaniobates of calcium, strontium, and barium in lead metaniobate, ZhTF, 1958, 28, 10, 2175.

95. Isupov, V. A., Kosyakov, V. I. Dielectric polarization and piezoelectric properties of certain ferroelectric solid solutions on the basis of sodium niobate. FTT, 1959, 1, 6, 929.

96. Pasynkov, R. Ye. and Vinogradov, V. V. Stabilized piezoelectric materials. Izv. AN SSSR, Physics series, 1957, 21, 3, 450-454.

97. Megaw, H. D. Crystalline structure of binary oxides of the perovskite type, Proc. Phys. Soc., 1946, 258, No. 326, p. 133.

98. Megaw, H. D. Temperature changes in the crystalline structure of barium titanate, Proc. Roy. Soc., 1947, A189, 261.

99. Megaw, H. D. Crystalline structure of barium titanate, Nature, 1945, 155, 3938, 484-485.

100. Megaw, H. D. Changes in polycrystalline strontium-barium titanate during temperature phase transitions, Nature, 1946, 157, 20-21.

101. Matthias, B., Hippel, A. The structure of domains and the dielectric properties of monocrystals of barium titanate, Phys. Rev., 1948, 73, 1378.

102. Danielson, G., Matthias, B., Richardson, J., Bernd, I. Properties of single domain crystals of $BaTiO_3$, Phys. Rev., 1948, 74, 8, 986-987.

103. Merz, W. Dielectric properties of $BaTiO_3$ crystals, Phys. Rev., 1949, 75, No. 4, 687.

104. Merz, W. Influence of hydrostatic pressure on the Curie point of crystals of barium titanate, Phys. Rev., 1950, 78, 1, 52-54.

105. Schirane, G., Takeda, A. Change in volume during three phase transitions in $BaTiO_3$, J. Phys. Soc. Japan, 1950, 6, 128-129.

106. Köenzig, W., Maikoff, N. Is the ferroelectric phase transition at 120°C a transition of the 1st or 2nd type? Hel. Phys. Acta, 1951, 24, 4, 342-356.

107. Drougard, M. E., Joung, D. R. The effect of orientation of domains in monocrystals of barium titanate, Phys. Rev., 1954, 94, 15, 1561-1564.

108. Drougard, M. E., Joung, D. R. Dielectric properties of single domain crystals of barium titanate near the Curie point, Phys. Rev., 1954, 95, 5, 1152-1153.

109. Novosel'tsev, N. S., Khodakov, A. A. Dielectric hysteresis in single crystals of $BaTiO_3$, ZhETF, 1954, 27, 1(7), 94-96.

110. Forsberg, P. W. Influence of two-sided pressure on the Curie point of barium titanate, Phys. Rev., 1954, 93, 4, 686-692.

111. Drougard, M. E., Funk, H. L., Joung, D. R. Dielectric constant and losses measured about hysteresis loops on crystalline samples of barium titanate, J. Appl. Phys., 1954, 25, 9, 1166-1169.

112. Plesseur, K. W., Cook, K. A. Anomaly of the temperature coefficient of permeability in barium titanate, J. Appl. Phys., 1954, 4406, 682-683.

113. Wieder, H. H. Ferroelectric hysteresis in crystals of barium titanate, J. Appl. Phys., 1955, 26, 12, 1479-1482.

114. Mirazova, A. Temperature hysteresis of the dielectric constant of a single crystal, ZhTF, 1956, 6, 5, 527-9.

115. Bond, W. L., Mason, W., McShimin, H. J. Constant elasticities and electromechanical coefficients of the bond of single crystals of barium titanate, Phys. Rev., 1951, 82, 3, 442.

116. Vul, B. M., Gol'dman, I. M., Rozbash, R. Ya. Electrical strength of titanates of metals of the 2nd group of Mendeleev's table. ZhETF, 1950, 20, 5, 465-473.

117. Vul, B. M., Bogdanov, S. V., Rozbash, R. Ya. Influence of conditions of polarization on piezoproperties of barium titanate. Report cf the Physics Institute of the Academy of Sciences, 1952.

118. Vul, B. M., Bogdanov, S. V., Rozbash, R. Ya. Influence of conditions of polarization on piezoproperties of barium titanate. ZhTF, 1956, 26, 5.

119. Karpacheva (Anan'yeva), A. A. On the application of induced piezoelectric effect of barium titanate for acoustic purposes. Report of FIAN, 1949.

120. Zheludev, I. S., Rusakov, L. Z., Shuvalov, L. A., Kachkacheva, M. M. Low-temperature polarization of ceramics of barium titanate. News AN SSSR, Physics series, 1956, 22, 12, 1516.

121. Vul, B. M., Bogdanov, S. V. On the influence of a great mechanical load on the piezoelectric properties of polarized samples of barium titanate. Report of the Physics Institute of the Academy of Sciences, 1952.

122. Vul, B. M., Bogdanov, S. V., Rozbash, R. Ya. Dependence of the transverse piezoelectric modulus (d_{31}) of polarized samples of barium titanate on pressure. Report of FIAN, 1952.

123. Dobrer, Ye. K., Karmen, K. N. Certain peculiarities of the piezoeffect barium titanate in static conditions. ZhTF, 1957, 27, 3, 513.

124. Kozlabayev, I. P. Piezoelectric properties of barium titanate. Report of FIAN, 1950.

125. Rzhanov, A. V. Piezoelectric and elastic properties of polarized samples of barium titanate in dynamic conditions. Report of FIAN, 1950.

126. Roy, N. A. The phase transition of barium titanate near 120°C. DAN SSSR, Physics series, 1951, 81, 4, 545-547.

127. Piekara, A., Pajak, Z. Thermal pseudohysteresis of the dielectric constant of ferroelectric titanates, Acta Phys. Pol., 1951-1952, 11, 3-4, 256-262.

128. Kazarnovksiy, D. Ya. Change in the dielectric properties of ferroelectric ceramics in time ZhTF, 1952, 22, 553-558.

129. Khodakov, A. L. Dielectric losses in ceramic dielectrics and barium titanate at high frequencies. ZhTF, 1950, 20, 5, 529-533.

130. Piekara, A., Pajak, Z. Dependence of the dielectric constant of ferroelectric ceramic titanates on the intensity of the electric field, Acta Phys. Pol., 1953, 12, 3-4, 170-180.

131. Zavel'skiy, F. S. Investigation of the dependence of the dielectric constant of barium titanate on the duration of the effect of potential, ZhTF, 1953, 25, 479.

132. Plessuer, Cook. Anomalies of the temperature coefficient of permeability in barium titanate, Nature, 1954, 173, 682-683.

133. Drougard, M. E., Landuer, R., Joung, D. K. Dielectric properties of barium titanate in a paraelectric state, Phys. Rev., 1955, 98, 4, 1010.

134. Jezewski, Piech. Dielectric properties of ceramics $BaTiO_3$, Acta Physica Pol., 1955, 14, 395.

135. Mesuard, G., Eyrand, L. J. Dielectric properties of ceramics of barium titanate, Phys. Radium, 1956, 17, Suppl. 6, 62A, 78-80.

136. Sinyakov, Ye. V., Gal'perin, V. V. Investigation of the dependence of the dielectric constant and tangent of dielectric losses of barium titanate on the electric field strength of high frequency. ZhETF, 1956, 30, 675.

137. Itskohoki, I. A. Influence of pressure on the dielectric characteristics of ferroelectric ceramics. News of AN SSSR, Physics series, 20, 2, 199-200.

138. Feldman, C. Temporral changes in $BaTiO_3$, Appl. Phys., 1956, 27, 8, 870-873.

139. Lur'ye, M. S., Medovoy, A. I. Influence of pressure on the dielectric constant of $BaTiO_3$, ZhEFT, 1956, 26, 1437.

140. Skanavi, G. I. Lipayeva, G. A. Dielectric constant and loss angle of certain solid dielectrics with a wave length of 3 cm and their dependence on the temperatures and frequency. ZhETF, 1956, 30, 824.

141. Drougard, M. E., Huibregtse, E. J. Influence of the electrical field on transitions in barium titanate, J.B.M.J. Res. Develop., 4, 318-329.

142. Robendorst, H., Melichercik, J. Dielectric properties of barium titanate at high frequencies and low temperatures, Ann. Phys., 1958, Vol. 7, 1, 4-5, 261, 263.

143. Ksendzov, Ya. M., Rotenberg, B. A. Influence of pressure on the electrical properties of barium titanate in weak fields. ZhTF, 1959, 1, 4.

144. Takagi, J., Sawaguchi, F., Akioka, T. Ingluence of mechanical stresses on the permeability of barium titanate, J. Phys. Soc. Japan, 1948, 3, 270.

145. Valasek, J. Piezoelectric activity of Seignette's salt 478-491. Properties of Seignette's salt connected with the piezoelectric effect, Phys. Rev., 1922, 20, 639-664.

146. Kozlabayev, I. P. Stability of the piezoelectric effect in polycrystalline barium titanate. News of AN SSSR, Physics series, 1956, 22, 2, 185.

147. Mason, W. P. The aging of properties of barium titanate and ferroelectric ceramics similar to it, JASA, 1955, 27, 1.

148. Vul, B. M., Bogdanov, S. V., Rozbash, P. Ya. Piezoelectric modulus of the shear (d_{15}) of polarized barium titanate. Report of the Physics Institute of the Academy of Sciences, 1952.

149. Bronnikova, Ye. G., Stavitskiy, N. M. Industrial piezoelectric crystals and their application. Piezotechnology (Transactions of the Central Scientific Research Laboratory of Piezotechnology), 1956, Issue 1.

150. Bogdanov, S. V., Vul, B. M., Timonin, A. M. The connection between dielectric, piezoelectric, and elastic properties of polycrystalline ceramics and the single crystal. News of AN SSSR, Physics series, 1957, 21, 3, 374.

151. Bogdanov, S. V., Vul, B. M., Rozbash, P. Ya. Piezoelectric modulus of the shear of polarized barium titanate. "Crystallography," 1957, 2, 1, 115-118.

152. Smolenskiy, G. A., Zhukov, V. A. Ferroelectrics, Leningrad, Publication of the Society for the Propagation of Political and Scientific Knowledge of the RSFSR, 1957.

153. Berlincourt, Jaffe, H. Elastic and piezoelectric coefficients of barium titanate, Phys. Rev., 1958, 3, 1.

154. Rez, I. S., Smazhevskaya, Ye. G., Kachkacheva, M. M. The question of the obtaining of piezoceramics for work at increased temperatures, News of the Academy of Sciences of the USSR, physics series, 1958, 22, 12, 1520-1523.

155. Serov, I. L., Sluchevskiy, V. S., Strelets, I. L. The production of ceramic piezoelements. Sudpromgiz, 1959.

156. Prospect on the Ceramics of the Production of the French Republic Moscow, Exhibition of 1960.

157. Anan'yeva, A. A. Sound receivers of ceramics of barium titanate. Dissertation, Kiev, 1961.

158. Anan'yeva, A. A., Ugryumova, M. A., Strizhkov, B. V. The obtaining and study of properties of chemically pure ceramics of barium titanate. Report of the Acoustic Institute of Academy of Sciences of the USSR, 1959.

159. Ana'yeva, A. A., Ugryumova, M. A., Strizhkov, B. V. Dielectric and piezoelectric properties of chemically pure ceramics of barium titanate. News of AN SSSR, Physics series, 1960, 24, No. 11.

160. Konstantinova, V. P., Sil'vestrova, I. M., Aleksandrov, K. S. The obtaining of crystals of triglicinesulfate and their physical properties. Crystallography, 1959, 4, 1, 69.

161. Konstantinova, V. P., Sil'vestrova, I. M., Yurin, V. A. Twinning and dielectric properties of the crystal of triglicinesulphate. Crystallography, 1959, 4, 1, 125.

162. Sil'vestrova, I. M., Aleksandrov, K. S., Chumakov, A. A. Crystal growth of terpin monohydrate and their elastic and piezoelectric properties Crystallography, 1958, 3, 386.

163. Chumakov, A. A., Sil'vestrova, I. M., Aleksandrov, K. S. Dielectric, elastic and piezoelectric properties of single crystals of benzophenone. Crystallography, 1957, 2, 5, 707.

164. Chumakov, A. A., Sil'vestrova, I. M., and Aleksandrov, K. S. Crystal growth of l-rhamnose of monohydrate and the investigation of their dielectric properties. Crystallography, 1958, 3, 4.

165. Ana'yeva, A. A. Piezoelectric ceramic materials. Report of the Physics Institute of the Academy of Sciences, 1951.

166. Zheludev, I. S. Candidate Thesis, Institute of Crystallography of the Academy of Sciences of the USSR, 1953.

167. Zheludev, I. S., Sil'vestrova, I. M., Konstantinova, V. P. Investigation of piezoelectric textures. Moscow, Publishing House of the Academy of Sciences of USSSR, 1955.

168. Berlincourt, D., Jaffe, B., Jaffe, H., Krueger, H. Properties of ceramics of lead titanate-zirconate as converters, I.R.E. Nat. Convent. Rec., 1959, 6, 227-240.

169. Jaffe, H. Piezoelectric ceramics, J. Am. Ceramic Soc., 1958, 41, 11, 494-498.

170. Prokopalo, O. I., Fesenko, Ye. G. Investigation of properties of solid solutions of barium and lead titanate and ferrite, News of AN SSSR, Physics series, 1958, 22, 12.

171. Malinofsky, W. W., Kedesdy, H. Barium and ferric oxides isomorphous to hexagonal and tetragonal $BaTiO_3$, J. Am. Ceramic Soc., 1954, 76, 3090.

172. Yakel, H. L. Structure of certain compounds of the perovskite type, Acta Crystallogr., 1955, 8, 394.

173. Fesenko, Ye. G. Isomorphism of titanates and ferrates of strontium, barium, and lead, Crystallography, 1956, 1, Issue 5, 520.

174. Schofield, D., Brown, R. F. Investigation of certain barium titanate compounds for the application in converters, Can. J. of Physics, 1957, 35, 5, 594-607.

175. Cook, W. R., Jaffe, H. Ferroelectricity in oxides of a fluorite structure, Phys. Rev., 1952, 88, 1426.

176. Trifonov, I. A. High-temperature polymorphous transformations of barium titanate. News of AN SSSR, Physics series, 1958, 21, 12.

177. Anan'yeva, A. A., Ugryumova, M. A., Strizhokov, B. V. The equation of obtaining anomalous properties of chemically pure ceramics of barium titanate. Report on the 4th All-Union Conference on Ferroelectrics. January, 1960.

178. Vul, B. M. The obtaining and investigation of piezoelectric crystals of polycrystalline barium titanate. Report of the Physics Institute of the Academy of Sciences, 1950.

179. Pelevantsev, V. S. Technology of the production of barium titanate and its solid solutions of lead titanate. Report of AKIN of the Academy of Sciences of the SSSR, 1955.

180. Ugryumova, M. A, Sosnov, A. V. Technology of the production of ceramic barium titanate by the method of hot casting under pressure. Report of AKIN of the Academy of Sciences of the USSR, 1958.

181. Anan'yeva, A. A., Ugryumova, M. A., Sosnov, A. V. Manufacture of piezoelements by the method of hot casting under pressure. Advanced Scientifical and Technical Experiment, 1960, Issue I, Subject 3.

182. Goncharov, K. I., Krasil'nikov, V. A. Thermal mechanical oscillations (fluctuations) of piezoelectric crystals. News of AN SSSR, Physics series, 1956, 20, 2.

183. Gotsak, V. M. Universal broad-band phasometer UF-1. Advanced Scientifical and technical and Industrial Experiment 1958, Subject 38, Moscow.

184. Furduyev, V. V. Reciprocity theorems, State Technical Press, 1948.

185. Kazantseva, M. V. Self-calibration of an electroacoustic converter by the pulse method in a tube. ZhTF, 1953, 23, 9.

186. Kazantseva, M. V. One method of absolute calibration of sound receivers by the method of reciprocity. DAN SSSR, 1947, 58, 8.

187. Kazantseva, M. V. Absolute calibration of electroacoustic converters by the method of reciprocity. Transactions of the Commission on Acoustics, 1950, 5.

188. Ageyeva, N. S. The change in acoustic parameters of materials at ultrasonic frequencies with the help of a pulse tube. Akust. Zh., 1955, 1, 2.

189. Krasil'shchik, I. L. Standard measuring hydrophones. All-Union Acoustic Conference. Abstracts of reports. 1958, p. 87-88.

190. Abrikosov, A. I., Kalmykov, V. A. Instruments for measuring sound pressure. Control measuring ultrasonic instruments. Conference on Ultrasonics. Collection of Reports. 1960, p. 129-134.

191. Shapirovksiy, N., Gagel'gants, A. A. On the possibility of the use of ceramic sound receivers for the reception of seismic oscillations in the sea. News of Petroleum Technology, Geology series, 1959, Issue 5.

192. Romanenko, Ye. V. Miniature piezoelectric sound receivers. All-Union Conference on the Use of Ultrasonic Technology in Industry, 1957.

193. Romanenko, Ye. V. Miniature piezoelectric receivers of ultrasonics. Akust. Zh., 1957, 3, 4.

194. Anan'yeva, A. A. Author's declaration of 16 April 1960, No. 134294.

195. Anan'yeva, A. A. Sound receivers of ceramics of barium titanate. Report of AKIN of the Academy of Sciences of the USSR, 1955.

196. Anan'yeva, A. A. Nondirectional ceramic sound receivers. Akust. Zh., 1961, 2, 1.

197. Anan'yeva, A. A. Ceramic sound receivers. All-Union Conference on the Use of Ultrasonic Technology in Industry. Ultrasonic Measurements, 1957.

198. Timoshenko, S. P. The theory of elasticity. State Technical Press, 1934.

199. Bezukhov, N. N. The theory of elasticity and plasticity. State Press for Technical and Theoretical Literature, 1953.

200. Langevin, P. Electroacoustical sensitivity of cylindrical ceramic tubes, J. Acoust. Soc. Am., 1954, 26, 3, 421.

201. Berezin, V. A. Bilateral sound receivers with the use of transformation of mechanical stresses. Report of AKIN of the Academy of Sciences of the USSR, 1955.

202. Timoshenko, S. P. Plates and shells. ONTI, 1934.

203. Berezin, V. A. Sound receivers of thin plates of ceramic barium titanate. Report of AKIN AN SSSR, 1955.

204. Tomita, Yanaguti. Piezoelectric receiver, Elect. Commun. Lab. Techn. J., 1959, 7, 5, 138-145.

205. Lav, A. Mathematical theory of elasticity, ONTI NKT USSR, 1935.

206. Golyamina, I. P. The question of oscillations according to the thickness of polarized plates of barium titanate. Akust Zh., 1955, 1, 1.

207. Schow, E. A. G. Resonance oscillations of thick disks of barium titanate, J. Acoust. Soc. Am., 1956, 28, 1, 38.

208. Pavlov, L. Investigation of multiundulations of thin plates of ceramics of barium titanate. Moscow, AKIN of Academy of Sciences of the USSR, 1957 (thesis).

209. Frederici, M. Electrostrictional oscillations of barium titanate tubes, Alta Frequenza, 1959, 24, 1.

210. Tartakovskiy, B. D. The theory of the propagation of plane waves through uniform layers. DAN USSR, 1950, 71, 3, p. 465-468.

211. Anan'yeva, A. A. Test by radiators of ceramics of barium titanate. Report of AKIN of the Academy of Sciences of the USSR, 1955.

212. Anan'yeva, A. A. Tests of ultrasonic converters of barium titanate. Report of the Acoustic Laboratory of the Physics Institute of the Academy of Sciences, 1951.

213. Anan'yeva, A. A. Mosaic converter of ceramics of barium titanate. Akust. Zh., 1959, 5.