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Low frequency projectors for sound under water.

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ABSTRACT (UNCLASSIFIED)

The detection of submarines by means of passive sonars becomes more difficult as the radiated noise of submarines is gradually decreasing.
Hence there is a need for active sonar transducers that produce sound at frequencies below e.g. 1000 Hz.. Several kinds of low frequency transducers are presented, working on different principles, being commercially available.

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SAMENVATTING (ONGERUBRICEERD)

Het opsporen van onderzeeboten met behulp van passieve sonars wordt steeds moeilijker omdat onderzeeboten steeds minder lawaai gaan maken. Er is daardoor vraag naar geluidbronnen voor actieve sonars voor het frequentiegebied lager dan bijvoorbeeld 1000 Hz. Er worden verschillende soorten van laagfrequente transducenten beschreven, die in de handel verkrijgbaar zijn.

1 INTRODUCTION

Submarines nowadays are gradually becoming less noisy. This hampers the use of passive sonars for long range detection, giving rise to the need of active sonars. These may consist of a traditional passive towed array with an active adjunct projector. There is no doubt that the frequency should be low, e.g. lower than 1000 Hz. In this frequency range practical restrictions in weight and size prohibit the use of directional transducers. Hence the active adjunct projectors should be designed as omnidirectional sound sources [15].
In a preceding report [13] a treatise is presented of the design, the sensitivity and the maximum source level of small underwater sound transducers in which the electro-acoustical motor consists of a hollow sphere or tube of piezoelectrical ceramic. The scope of that report covered single elements of spherical transducers and of tubular types either with end-caps or with pistons, the latter being called "Tonpilz"-elements. Practical limitations on the size, the weight and the price of such transducers however restrict their application as efficient sound sources to frequencies above 1 kHz.
The present report can be considered as a sequel to the preceding one. It presents transducers to be used as sound sources at lower frequencies. The scope however is different: Less theory, mathematics and equations, but mainly descriptions and data of commercially available low frequency sound sources 1).
Low frequency omnidirectional projectors with dimensions small compared to the wavelength of the sound they produce are victims of an adverse physical rule: Their radiation load impedance is low with a strong reactive component (see figure 1). In order to produce a desired amount of acoustical power their radiating surfaces need to make large excursions while a multiple of reactive power is needed to make this possible. This becomes more severe as the frequency gets lower [15]. The result is a poor radiation efficiency and a restricted output power, being limited by mechanical constraints of the radiating surfaces.
In this report of a number of low frequency transducers the maximum possible "Source Level" is presented. This is 20 times the logarithm of the acoustic pressure in micropascal at 1 m distance, expressed in decibel re 1 μPa. In the next chapters the following types of transducers are described:

1. Double piston elements: Ch. 3
2. Open hollow cylinders: Ch. 4
3. Flextensional transducers: Ch. 5
4. Bender bar transducers: Ch. 6
5. Electro-dynamical systems: Ch. 7
6. Hydraulical driven vibrators: Ch. 8

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1) In this frequency range there is no need for special hydrophones. All transducers described [13] are useful as hydrophones at any low frequency too. Hence in this report attention is paid to projectors only.

A link with traditional active sonars using directional transmission is laid by starting with a presentation on the source levels of cylindrical arrays of Tonpilz-elements in chapter 2.

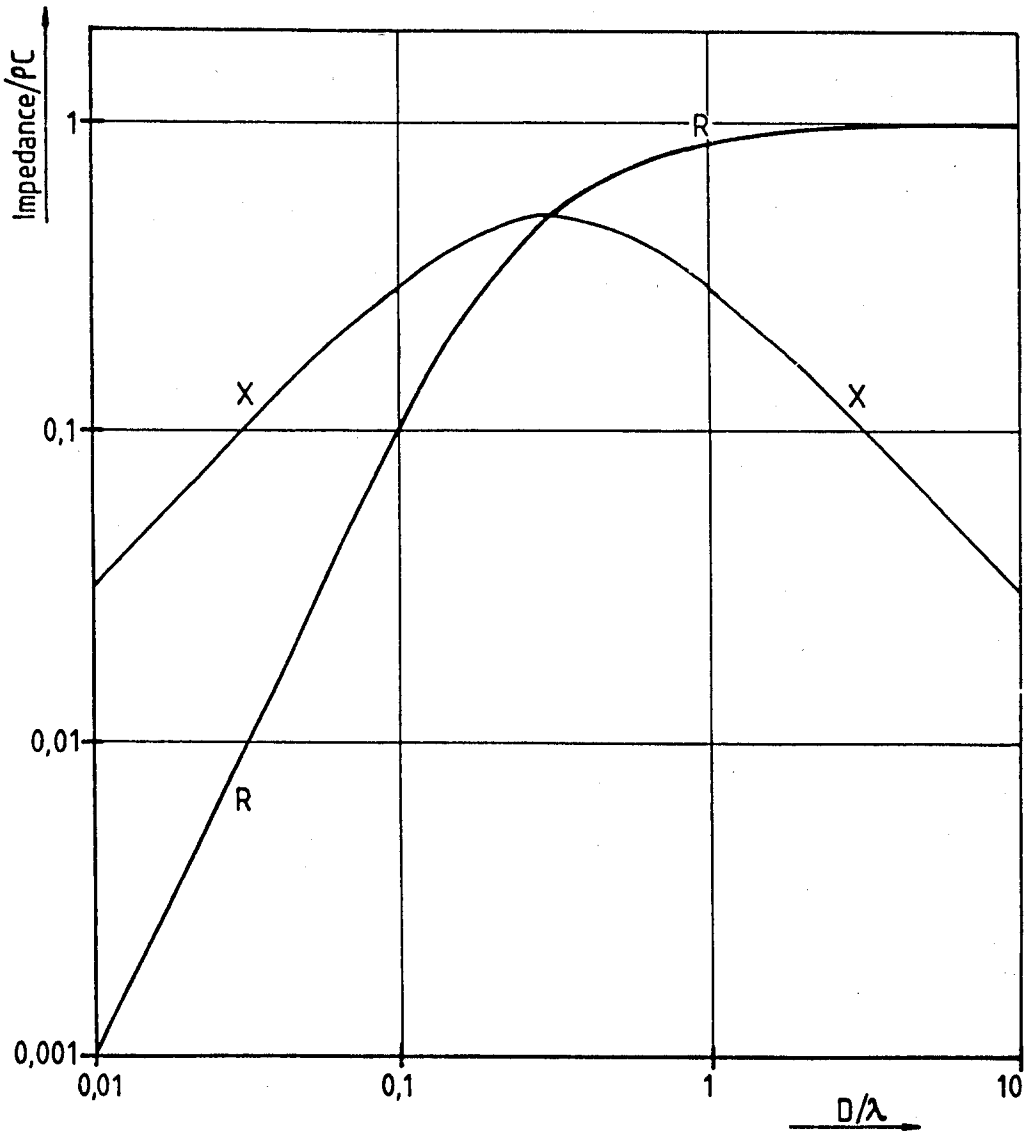


Fig. 1: Real (R) and imaginary (X) component of the radiation impedance $Z = R + jX$ of a pulsating sphere with diameter D, versus the ratio of the diameter to the wavelength λ.

2 CYLINDRICAL ARRAY OF TONPILZ ELEMENTS

Ref. 13, eq. 138 on page 77, gives the maximum source level of a single Tonpilz element with a diameter of half a wavelength at resonance:

$$\begin{aligned} SL &= 20 \log (3.2 \times 10^7 f_r^{-1}) + 120 \text{ dB re } 1\ \mu\text{Pa at 1 metre distance,} \\ &= -20 \log f_r + 270 \text{ dB re } 1\ \mu\text{Pa} \end{aligned} \tag{1}$$

Typically, an array of piston elements for a submarine detection Sonar may contain 360 elements, arranged with half wavelength spacings in a circular cylinder with vertical axis, consisting of 36 staves with 10 elements each (see figure 2).

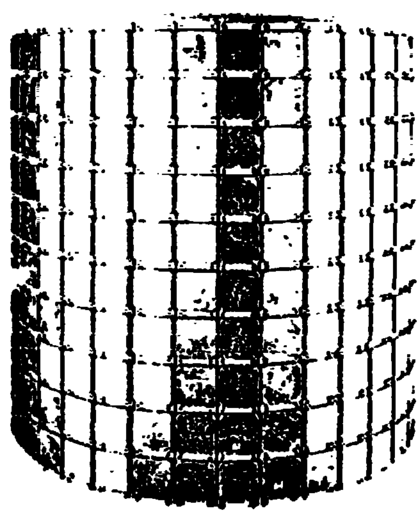


Fig. 2: Transducer for the Sonar SQS-505, consisting of an array of Tonpilz elements, arranged in 36 staves of 10 elements each.

Of such an array 12 adjacent staves are energised at full power with proper delays or phase shifts between the staves to form a beam in one direction. Such an array can be considered as a flat array of 5 wavelengths high and of the same width containing 120 elements. Then the total energy radiated by this array is 10 log 120 = 21 dB higher than of one element. Due to the beam formation the directivity index of the array is of the order of 25 dB (see [5], p. 201). Hence the source level on the acoustical axis of the beam is increased by the same amount. This changes eq. 1 into the source level of one beam:

$$SL = -20 \log f_r + 316 \text{ dB re } 1\ \mu\text{Pa at } 1\text{ m} \qquad (2)$$

In practice, due to interaction effects between the elements in the array, the source level may be a few dB lower (see [4], pp. 107-108).

Of four different sonar transducers the dimensions and the source levels are presented in table 1, in comparison with the theoretical design values according to the theory given above.

These source levels are shown in figure 3: A straight line for the theoretical values and 4 points for the practical examples.

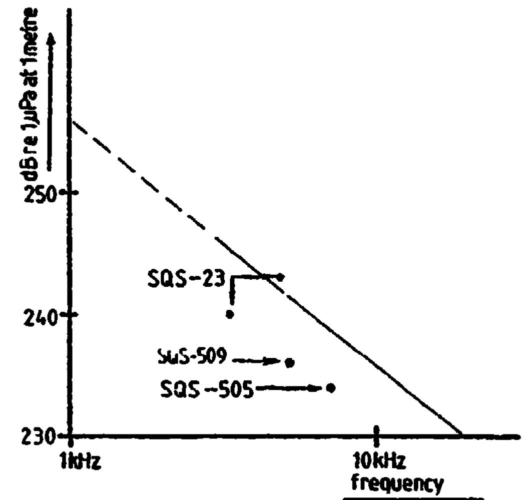


Fig. 3: Maximum source levels on beam axis of Naval Tonpilz arrays.
Theory ([13]) – – – ———
Practical values o

	Theory		Practice			
frequency (f_r)	SL	array D x H	Sonar	SL	array D x H	number of staves x elements
3.5 kHz	245 dB	2.5 x 2.2	SQS-23	240 dB	2.3 x 1.6	12 x 8
5 kHz	242 dB	1.7 x 1.5	"	243 dB	2.3 x 1.6	16 x 10
5.4 kHz	241 dB	1.6 x 1.4	SQS-509	236 dB	1.7 x 1.7	12 x 10
7.2 kHz	239 dB	1.2 x 1.1	SQS-505	234 dB	1.2 x 1.2	12 x 10

Table 1: Source levels and sizes of Tonpilz arrays.

Note: The array dimensions, D = diameter and H = height, are expressed in metres.

The theory considers arrays of 36 staves each with 10 elements, of which 12 staves are used for one beam. In practice the SQS-23 uses 12 staves of 8 elements for 3.5 kHz and 16 staves of 10 elements for the frequency of 5 kHz. In the latter case the array has 48 staves in total. Therefore the practical source level is 1 dB higher than theory predicts for 12 staves per beam.

In all other cases the practical source levels are 5 dB lower than theory predicts.

Due to the increasing size of these arrays when the frequency is lowered for practical reasons their application is restricted to frequencies above 3 kHz.

3 DOUBLE PISTON ELFMENTS

Ref. [13] describes in chapter 4 the design and performance of symmetrical piston transducers with two radiating faces. For low frequencies however, these transducers would become impractically large. E.g. for a resonance frequency of 1000 Hz the diameter would be of the order of 0.8 m (0.5 λ) and the length about 1 m (0.7 λ) while the radiation pattern would be strongly directive.

Transducers of this kind were designed and constructed by GERDSM in France with the name "JANUS" and subsequently produced by Pons, Aubagne (see [4] (pp. 105-106), [10] and [11]). Using slender stacks of ceramic discs between relatively heavy pistons the size of these transducers is appreciably smaller than of those described in [13], resulting in omnidirectional radiation patterns at frequencies up to resonance.

Table 2 summarizes the main characteristics of these transducers. Frequency response curves are shown in the figures 4 and 5. The directivity of some transducers (J-1100 and J-1600) at frequencies above resonance is illustrated by two curves: "Axial" means the level on the length axis perpendicular to the piston surfaces, "Equatorial" gives the level in the plane perpendicular to the length axis.

It is possible to construct an array of JANUS-transducers as a pile of elements with their axes mutually perpendicular, as shown in figure 6. This increases the source level (see table 2) and causes directivity in the vertical plane according to the length of the array expressed in wavelengths.

JANUS-transducers are supplied with an internal rubber air bag for hydrostatic pressure compensation. This increases the maximum depth of operation to 500 m.

Type	Piston diameter	Axial length	Resonance frequency	Maximum Source level
JANUS-500	0.3 m = 0.11 λ	0.7 m = 0.26 λ	560 Hz	191 dB
JANUS-800	0.3 m = 0.16 λ	0.6 m = 0.33 λ	820 Hz	195 dB
JANUS-1100	0.4 m = 0.3 λ	0.6 m = 0.44 λ	1100 Hz	207 dB
JANUS "Helmholtz"	0.3 m = 0.16 λ 0.22 λ	0.6 m = 0.32 λ 0.44 λ	800 Hz 1100 Hz	204 dB 207 dB
JANUS-1600	0.3 m = 0.33 λ	0.4 m = 0.4 λ	1500 Hz	195 dB
Array of 6 elements JANUS "Helmholtz"			800 Hz 1100 Hz	219 dB 221 dB
Array of 9 elements JANUS-1600			1600 Hz	210 dB

Ref. [4], [10] and [11].

Table 2: Some characteristics of double piston transducers.

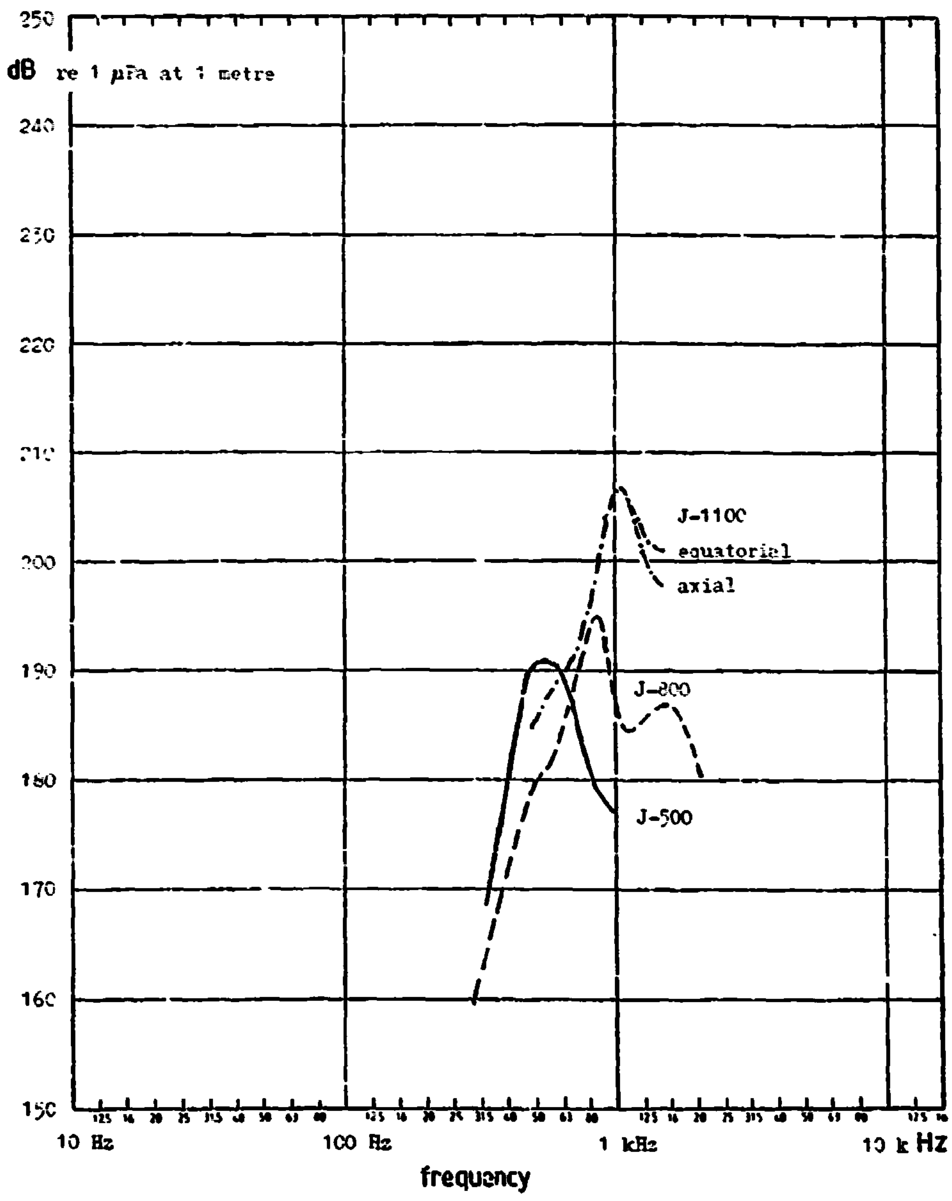


Fig. 4: Maximum source levels versus frequency of double piston transducers, type JANUS-500, JANUS-800 and JANUS-1100

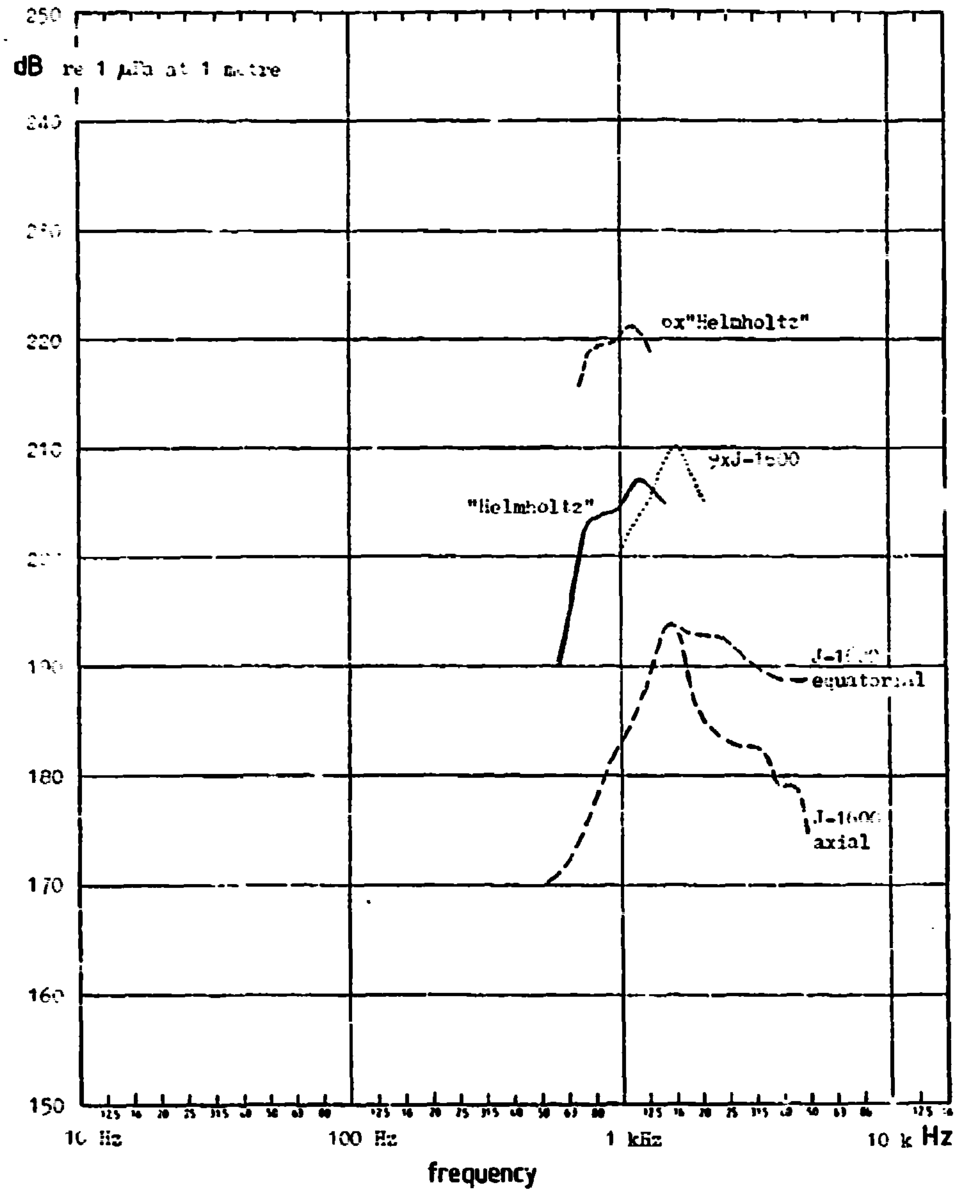


Fig. 5: Maximum source levels versus frequency of double piston transducers, type JANUS "Helmholtz" and JANUS-1600. Single elements and staves of 6 or 9 elements.

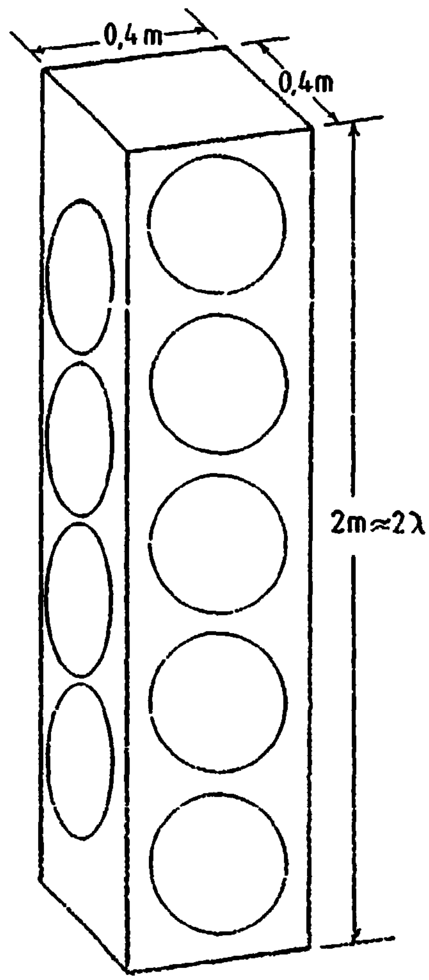


Fig. 6: Array of 9 elements of JANUS-1600

4 OPEN HOLLOW CYLINDERS

A classical publication by McMahon [6] presents the possibility to use free flooded piezoceramic rings as efficient sound sources. Since then transducers of this kind are commercially available. They have the shape of a rubber moulded open cylinder without pistons or endcaps or any pressure release material. Therefore they can be used at any depth

These transducers vibrate radially with two fundamental resonance modes:

The radial resonance of the ceramic ring and the cavity resonance of the enclosed water volume. At both frequencies the radiation has a relatively high efficiency of about 50 to 70% but with some directivity in the plane through the axis of the ring. In that plane the source level is maximum in the direction perpendicular to the ring axis with a beam width between the -3 dB directions of about 60 to 90° with secundary lobes in the axial directions (see figure 7, borrowed from [6]). See also [3].

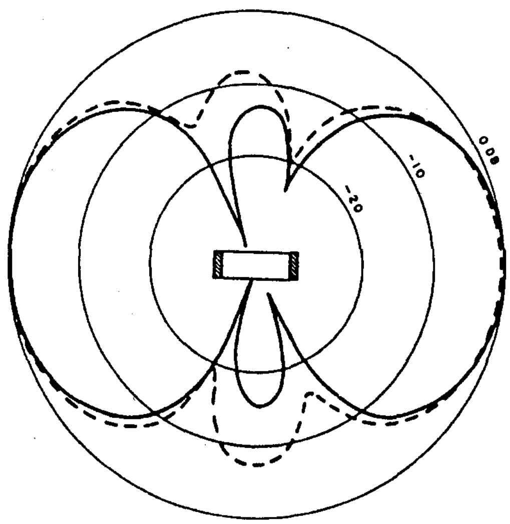


Fig. 7: Directivity patterns of free flooded open ring transducer at two frequencies:
at cavity resonance ———
at radial ring resonance - - -

Both resonance frequencies are inversily proportional to the mean diameter D of the ceramic ring while the cavity resonance frequency f_c also depends on the axial length of the ring.

The frequency of radial resonance f_r can be approximated by the relation:

$$f_r \approx \frac{1200}{D}$$

which makes the diameter close to 0.8 λ at this frequency, where λ is the wavelength in water.
The cavity resonance frequency f_c is lower than f_r, depending on the ratio of the length to the diameter of the ring. For relatively short rings f_c is only slightly lower than f_r with a strong and efficient coupling between them. When the length to diameter ratio increases, f_c decreases while f_r remains almost the same. This gives the transducer a larger bandwidth but a lower efficiency.
The largest rings commercially available cover the frequency range of 500 to 1000 Hz with maximum source levels of the order of 213 to 222 dB. Smaller units produce lower levels.
Attainable source levels are presented in figure 8 for three transducers made by the International Transducer Corporation (ITC), U.S.A., and one by Sparton, Canada. The main characteristics of these transducers are summarized in table 3.

Type:	ITC-2010	ITC-2012	ITC-2015	Sparton
Outside diameter	0.41 m	1.25 m	0.37 m	0.68 m
Inside diameter	0.33 m	1.00 m	0.26 m	-
Axial length	0.30 m	0.30 m	0.20 m	-
Length to mean diameter ratio	0.8	0.25	0.6	-
Cavity resonance frequency	1 kHz	0.7 kHz	1.8 kHz	1 kHz
Maximum SL at cav. resonance	194 dB	213 dB	213 dB	220 dB
Radial ring res. frequency	3 kHz	1.1 kHz	4 kHz	2 kHz
Maximum SL at ring resonance	199 dB	211 dB	206 dB	220 dB
Maximum electrical RMS-voltage	2 kV	5 kV	3 kV	3 kV
Maximum electrical power	1 kW	25 kW	15 kW	100 kW

Ref: ITC catalog of underwater sound transducers.
Sparton data sheet.

Table 3: Characteristics of some ring projectors.

Note: The diameters and the length are given including the rubber encapsulation, which may be several millimetre thick.

The peak source levels as shown in figure 8 are restricted mainly by the different power handling capabilities of the transducers. It further appears that the largest bandwidth occurs with the transducer which has the greatest ratio of length to diameter (ITC-2010), causing the largest difference between both resonance frequencies. With shorter relative lengths the resonances come closer together. The greater length of the ITC-2010 causes the radial resonances to radiate stronger than the cavity resonance. With the shorter transducers this is just the reverse.

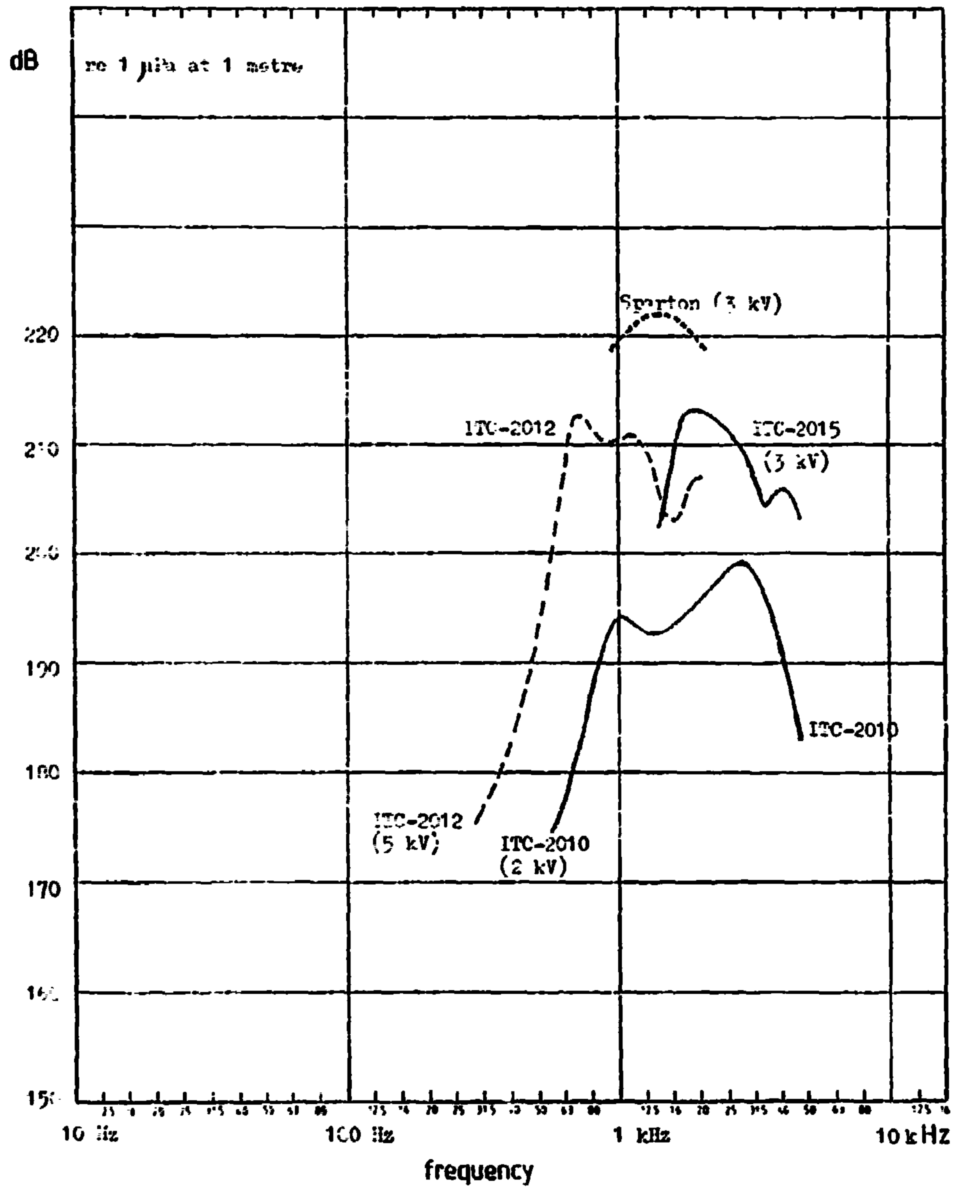


Fig. 8: Maximum source levels versus frequency at constant driving voltage (2 to 5 kV RMS) of three open hollow cylinder transducers from ITC (USA) and one of Sparton (Canada).

Source level, directivity and bandwidth can be enhanced by assembling several rings in a coaxial arrangement to form a line array. Optimum performance is obtained with relatively short rings, mounted with a spacing between the rings of slightly more than a half wavelength at the cavity resonance frequency [6].

Note:The piezoceramic rings can be replaced by magnetostrictive rings with toroidal windings, giving the same performance but with the advantage of low electric impedance operation, eliminating the need of high voltage insulation of the rings against the sea water.

A good magnetostrictive material for this purpose is Vanadium Permendur [14].

5 FLEXTENSIONAL TRANSDUCERS

5.1 General

The first publications on flextensional transducers appeared between 1965 and 1970 by Royster (see [12]). The principle of this concept is based on the volume variations of a vibrating ellipsoidal shell (see figure 9).

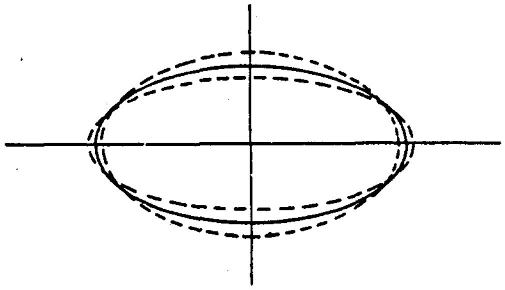


Fig. 9: Principle of a flextensional transducer.

When the long axis of an ellipsoid is set into vibration, the length of the short axis will vibrate with a much larger amplitude. This makes the ellipsoid to an efficient radiator of acoustic energy at low frequencies. In general the frequency of fundamental resonance of ellipsoidal shells is so low that its length is small compared to the wavelength in water. Hence these transducers radiate sound omnidirectionally.
Royster [12] grouped different flextensional designs into five classes (see figure 10):

- *Class I* has the shape of an ellipsoid of revolution around the long axis, like an egg. This axis is excited by means of a pile of piezoceramic discs.
- *Class II* results from attempts to increase the frequency of resonance while maintaining the power handling capability and hence the length of the ceramic stack. The length axis is still the axis of revolution.
- *Class III* is a variation of class II, with two spheres, giving coupled resonances and hence a wider bandwidth.
- *Class IV* has the shape of an elliptical cylinder, again with stacks of piezoceramic discs along the long axis of the elliptical cross section.
- *Class V* finally is again an ellipsoid of revolution but now around the short axis, like a discus. The excitation of the long axis circumference can be performed by means of a piezoceramic ring, or, in the smaller high frequency types, by means of a ceramic disc.

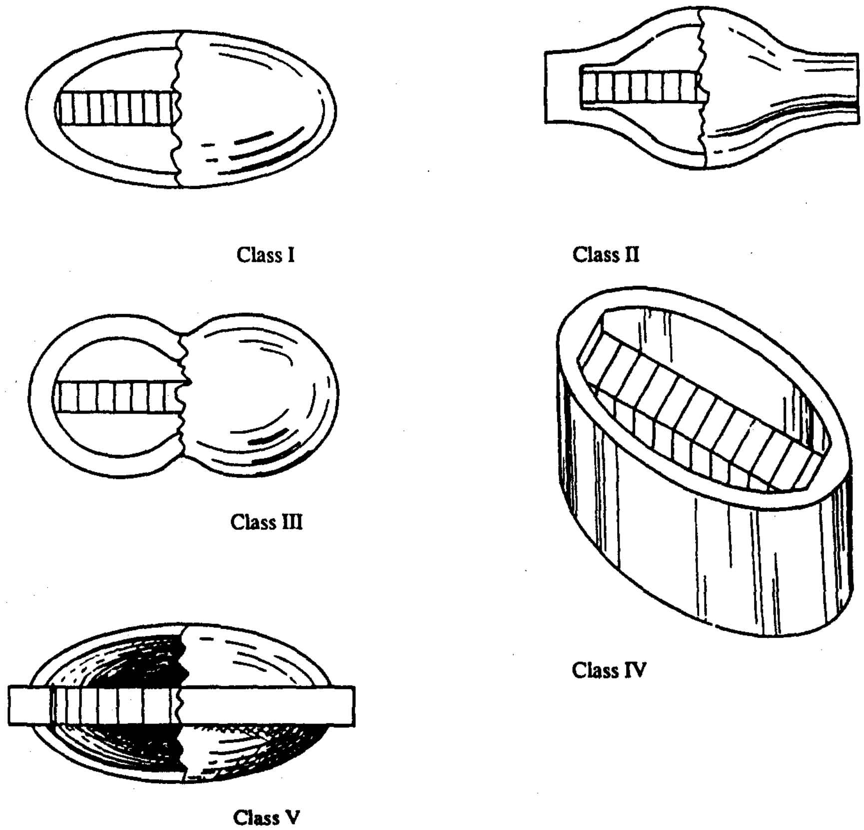


Fig. 10: The 5 original classes of flextensional transducers.

For low frequency underwater sound projectors the classes IV and V are applied in general. They are the easiest to manufacture and they have a high electro-acoustic efficiency of more than 50% at resonance over a large bandwidth of the order of one octave.

Note:The subdivision in the classes I to V as suggested by Royster is not adopted by other authors. E.g. [4] (p. 123) uses the following classification:

- class I is the same as Royster's class I,
- class II is the same as Royster's class V,
- class III is a new concept: In stead of an ellipsoid of revolution it has the shape of a hyperboloid of revolution (see figure 11)

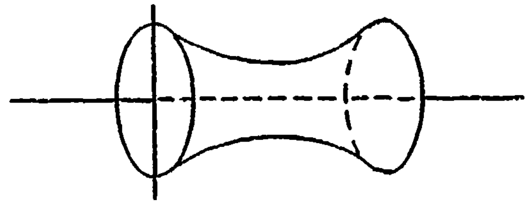


Fig. 11: Shape of "new" class III flextensional transducer.

This has the advantage over class I that the end plates vibrate in phase with the hyperbolical surface and that the hydrostatic pressure increases the prestress of the ceramic stack, rather than decreasing it as in classes I and IV (see par. 5.2), thus making the device capable to be operated at greater depth. However, the problems with manufacturing such hyperbolical shells at present impede the practical realisation of such transducers.

- Class IV again is the same as Royster's class IV.

5.2 Class IV flextensionals

Elliptic-cylindrical flextensionals are commercially available, either with aluminium shells (British Aerospace. UK) or with filament wound composite materials like glass or carbon fibre epoxy (EDO, USA) (see figure 12).

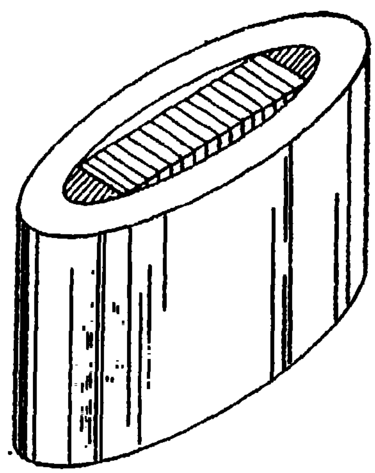


Fig. 12: Class IV flextensional transducer unit without end plates.

In these designs the ratio of major to minor axis of the ellipse is of the order of 2 to 3. In order to avoid spurious resonances the height of the elliptical cylinder is less than the length of the major axis, but arrays can be built by piling up several units on top of each other. Each unit is provided with watertight end plates (see [2], [4] (pp. 121-133), [8] and [9]).

Typical dimensions range from 15 to 60 cm major axis length with a wall thickness from 10 to 40 mm and with resonance frequencies from 3 kHz down to 300 Hz with a Q-factor of around 3. The ceramic stacks along the major axis are prestressed by elastic deformation of the shell: slightly oversized stacks are inserted in the shell after squeezing it along the minor axis, thus elongating the major axis. After removing of the squeezing force the stacks are compressed by the elastic stress of the shell. Under water however the hydrostatic pressure acts mainly on the minor axis, thus releasing the prestressing force on the stacks. Without pressure compensation the operating depth of the transducer is limited to about 300 m (see [4], pp. 121-123).

Due to their relative small size, small compared to the wavelength in water, at low frequencies the acoustic load is low and strongly reactive, requiring a large velocity amplitude of the radiating surface. Hence the allowable maximum stress in the shell is a limitation in the power output of transducers with low resonance frequencies. In this respect the filament wound epoxy (of EDO) may be superior to aluminium (from UK) as shell material.

For smaller transducers with higher resonance frequencies the power output is limited by the amount of ceramic discs which can be housed inside the shell. A single transducer of about 20 cm long and high, resonating at about 2 kHz, may radiate an acoustical power of 1 kW, causing an omnidirectional source level of 201 dB. Larger units of 50 x 50 cm can produce source levels of 208 dB at a frequency of 350 Hz, radiating 5 kW omnidirectionally (see [4], pp. 129-130). Higher source levels are possible with staves built up with several units, giving some directivity in the planes containing the stave axis.

Some frequency characteristics of the maximum source levels of three aluminium shell flextensionals are shown in figure 13, derived from data extracted from [2], [4], [8] and [9].

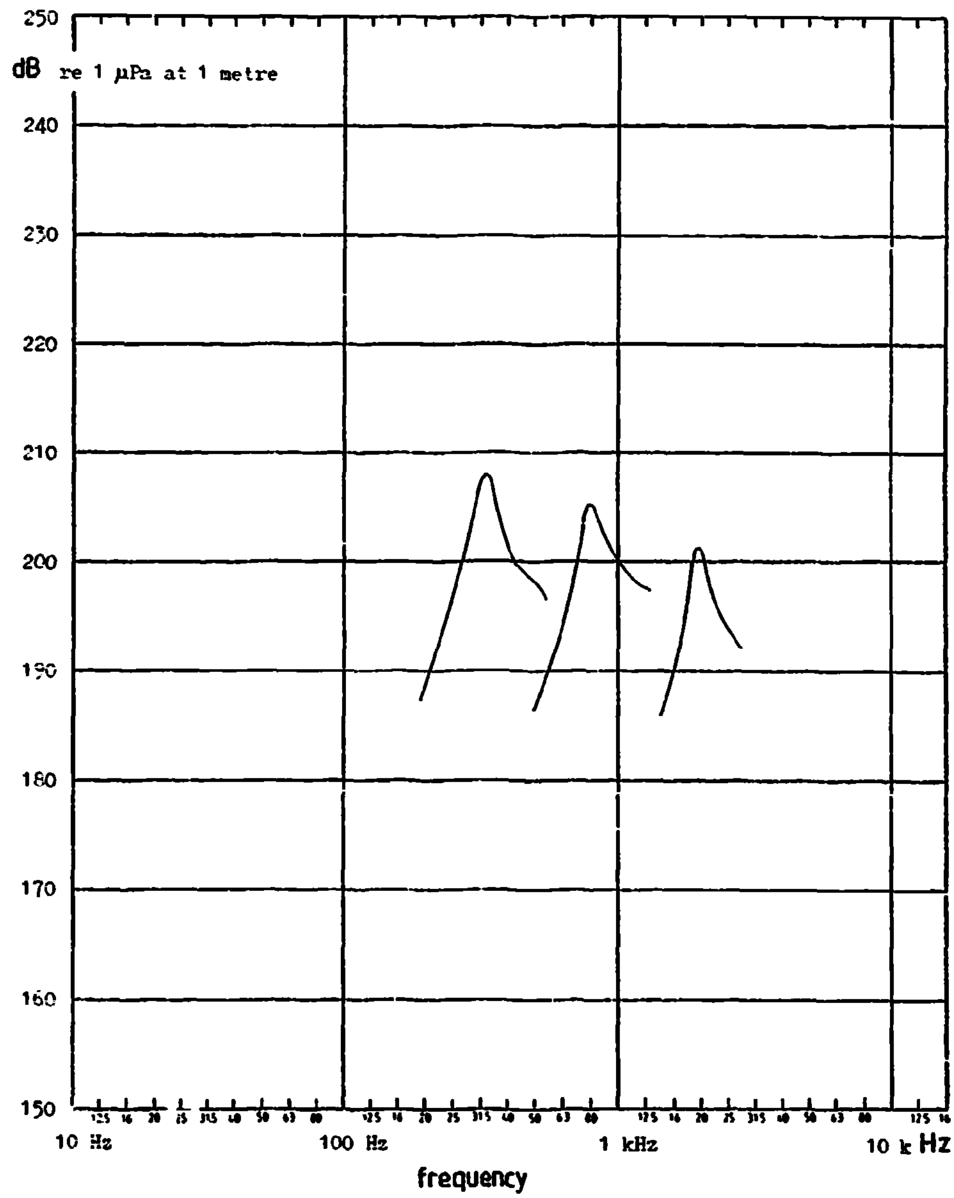


Fig. 13: Maximum source levels at a constant driving voltage of 2.5 kV RMS of three aluminium shell flextensional transducer elements.

5.3 Class V flextensionals

See [7]; low frequency high power class V flextensionals mainly consist of a segmented ring of piezeceramic blocks sandwiched between two circular convex metal shells (see figure 14).

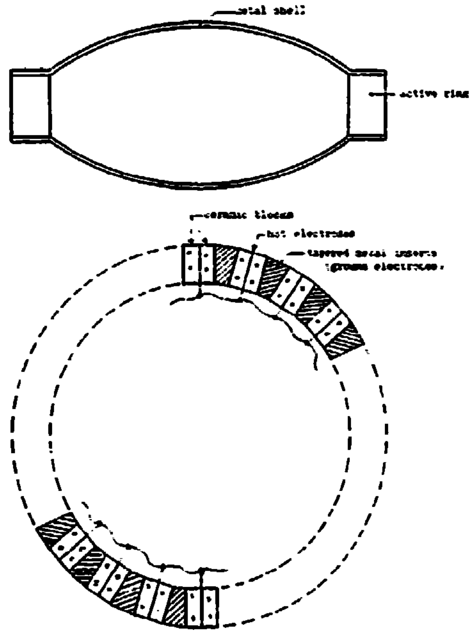


Fig. 14: Construction of "Ring-shell projector".

The radial vibration of the ring drives the attached metal shells in flexure with a considerable enhancement of the mechanical motion of the shell surfaces. The only known manufacturer of these transducers is "Sparton of Canada Ltd." which produces them under the name of "Ring-shell projectors". The active ring consists of pairs of piezoceramic blocks interleaved with tapered metal inserts, all glued together and prestressed by circumferential wrapping of fibreglass roving applied under tension and consolidated with epoxy resin. The metal shells conventiently are bolted onto the metal inserts of the ring.

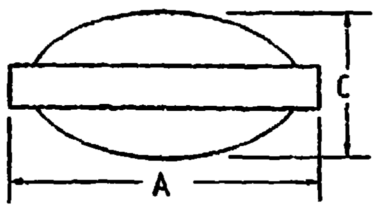
Typically the total thickness of the transducer (i.e. the minor axis of the ellipsoid) is of the order of 0.2 to 0.5 times the outside ring diameter.

As a result of its design this type of transducer exhibits two fundamental resonance frequencies: the lowest resonance occurs by the vibration of the two metal shells. The piezoceramic ring itself resonates at a higher frequency. At both resonances the electroacoustic efficiency of the transducer is high. At the shell

resonance frequency the wavelength is large compared to the transducer diameter which makes the radiation omnidirectionally. At the frequency of ring resonance however the wavelength is close to the transducer size, causing some directivity.
The range of resonance frequencies is the same as for the class IV flextensionals: from 300 Hz to 3 kHz, but the source levels in general are higher: up to 220 dB at 2.5 kHz. See table 4, giving some characteristics of four different Sparton-transducers. Of two of them the frequency response curves are shown in figure 15.

				shell resonance						ring resonance		
Sparton type	ring diam. A(cm)	shell thick-ness C(cm)	A/C	freq Hz	A/λ	max. SL dB	acoust. power kW	electr. power kW	band-width Hz	freq. kHz	A/λ	max SL dB
18A0325	47	10	4.5	325	0.1	205	2.5	4	75	3.6	1.1	219
34A0400	88	24	3.7	400	0.23	211	10	14	85	2.5	1.5	220
34A0610	88	30	2.8	610	0.36	213	15	20	140	2.5	1.5	220
34A1000	88	50	1.8	1000	0.6	217	40	50	200	2.5	1.5	220

Table 4: Characteristics of ring-shell transducers.



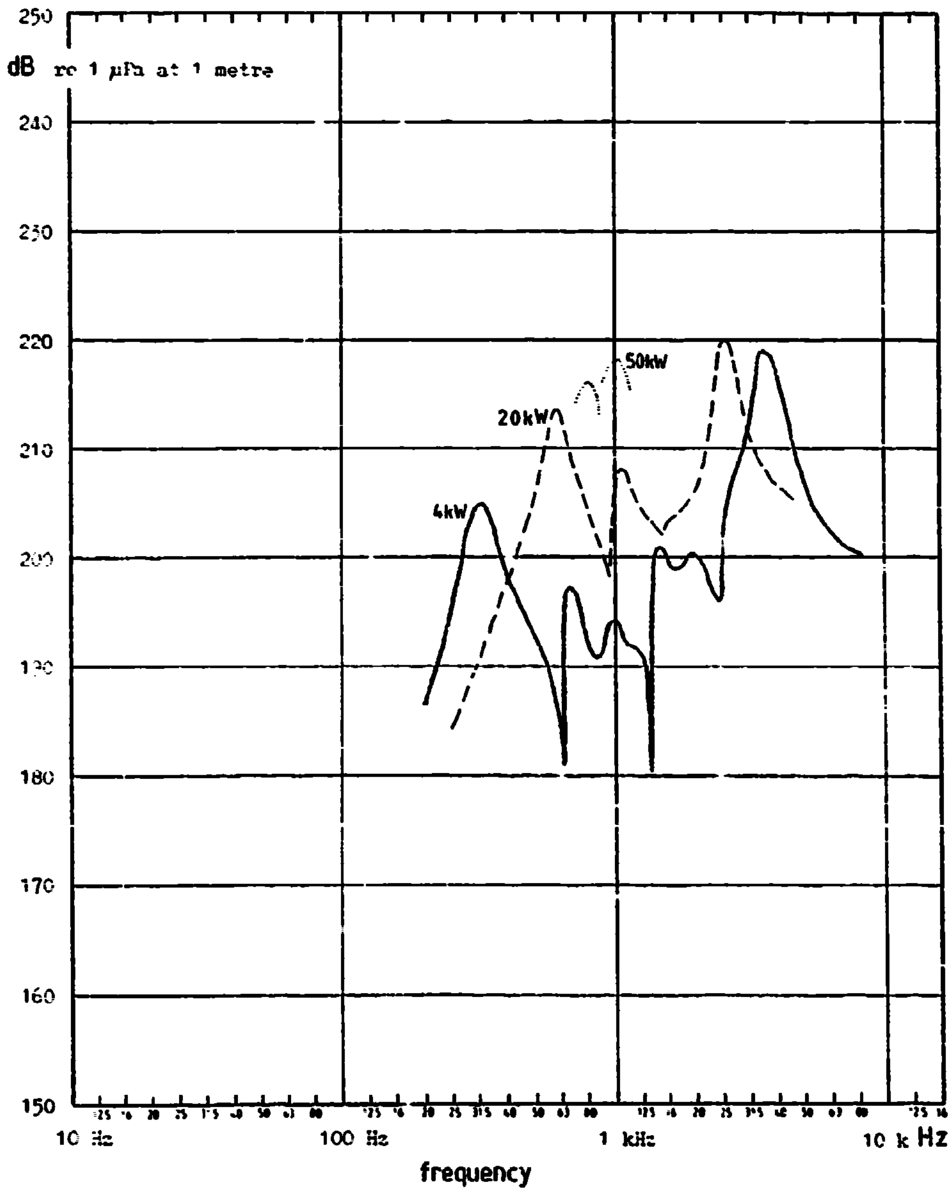


Fig. 15: Maximum source levels of some ring-shell transducers from Sparton
type 18A0325 (4 kW), ———
type 34A0610 (20 kW), - - - -
other types. ……

The thin flexible shells require some means of pressure compensation when the transducers are to be used at some depth under water. But also, like with the class IV flextensionals, the hydrostatic pressure tends to reduce the prestressing force in the ceramic ring. Therefore the empty space between the shells contains a flexible rubber bladder which has an open connection to the surrounding water while the cavity around this bladder is filled with compressed air. In this way the interior pressure is higher than (or at least equal to) the outside hydrostatic pressure, enhancing the operating depth of the transducer. Good performance is obtained to a depth of about 300 m while the survival depth is at least 500 m.
Because all parts of this type of transducer are vibrating, the mechanical mounting of these units to any fixed structure may pose some problems. A resilent suspension is needed which may not impede the free vibration of the device.
Likewise it seems difficult to assemble several units into a stave in order to increase the source level in one plane. Sparton themselves suggest a "bicycle arrangement" with two ring-shells mounted side by side in a frame with half a wavelength spacing, but this can be done only if the outside diameter is smaller than that (see table 4).
Compared to a single unit of a class IV flextensional projector a single ring shell is able to produce a higher source level at the same frequency, but the source level of a stave composed of several flextensionals mounted on top of each other can be superior to that of the ring shell.

6 BENDER BAR TRANSDUCERS

Bender bars or bimorphs belong to the most simple types of low frequency electroacoustic transducers. Its operation is based upon the flexure of a metal-ceramic sandwich, due to the variation in length with applied voltage of the ceramic with respect to the metal base plate (see figure 16).

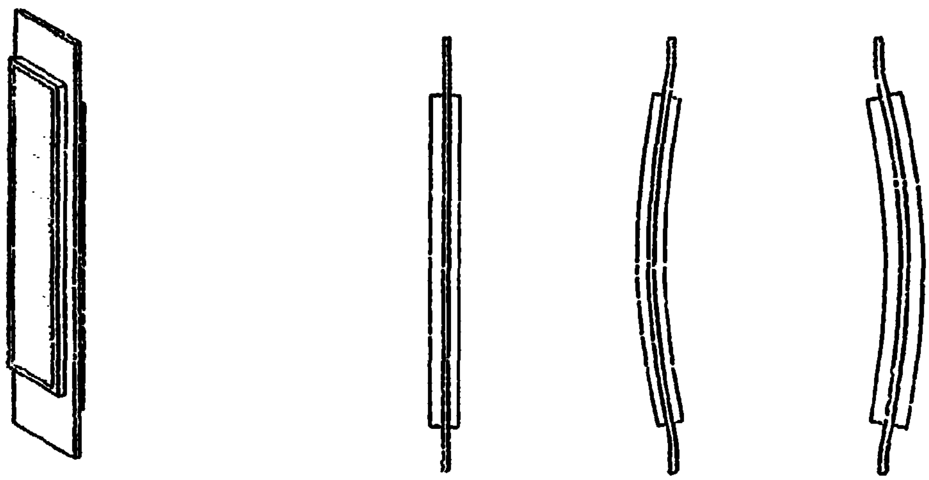


Fig. 16: Bender bars.

When fully submerged such a bender transducer is a poor radiator because of its small size expressed in wavelengths at resonance while both sides radiate with opposite phase. However, if a number of such bender bars is assembled to a cylindrical structure like a barrel, an efficient omni-directional radiator is obtained (see figure 17). For electric insulation of the high voltage electrodes on the ceramic slabs the whole assembly is coated inside and outside with rubber. When the interior space is open to the sea water the device behaves like an open hollow cylinder transducer as described in chapter 4.

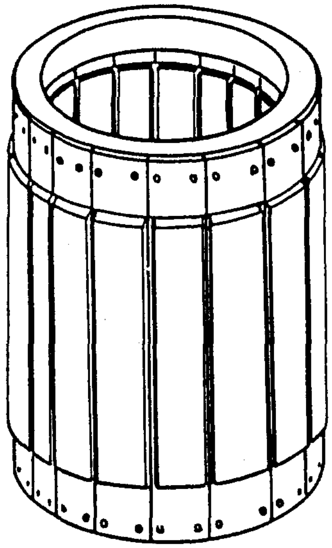


Fig. 17: Barrel stave transducer with bender bars

Bender bar transducers are manufactured by Honeywell, USA, under the name HX-90 for operation in the frequency range from 200 to 1000 Hz. The internal cavity is closed and filled with oil, containing compliant metal tubes to lower the internal impedance and to control the resonance frequency. The bandwidth and the maximum output power can be controlled by the viscosity of the oil: high viscosity oil gives a larger bandwidth but with a low viscosity a higher acoustic output is achieved. Two typical examples of maximum source levels are shown in figure 18.

The diameter and length of these transducers are of the order of 0.5 m and their weight is of the order of 600 kg.

Due to the liquid filled construction the depth capacibility goes down to 500 m, limited by the strength of the compliant tubes in the inner cavity.

Bender bar transducers easily can be assembled to staves of single elements, mounted on top of each other, in order to improve the source level and the directivity in a vertical plane.

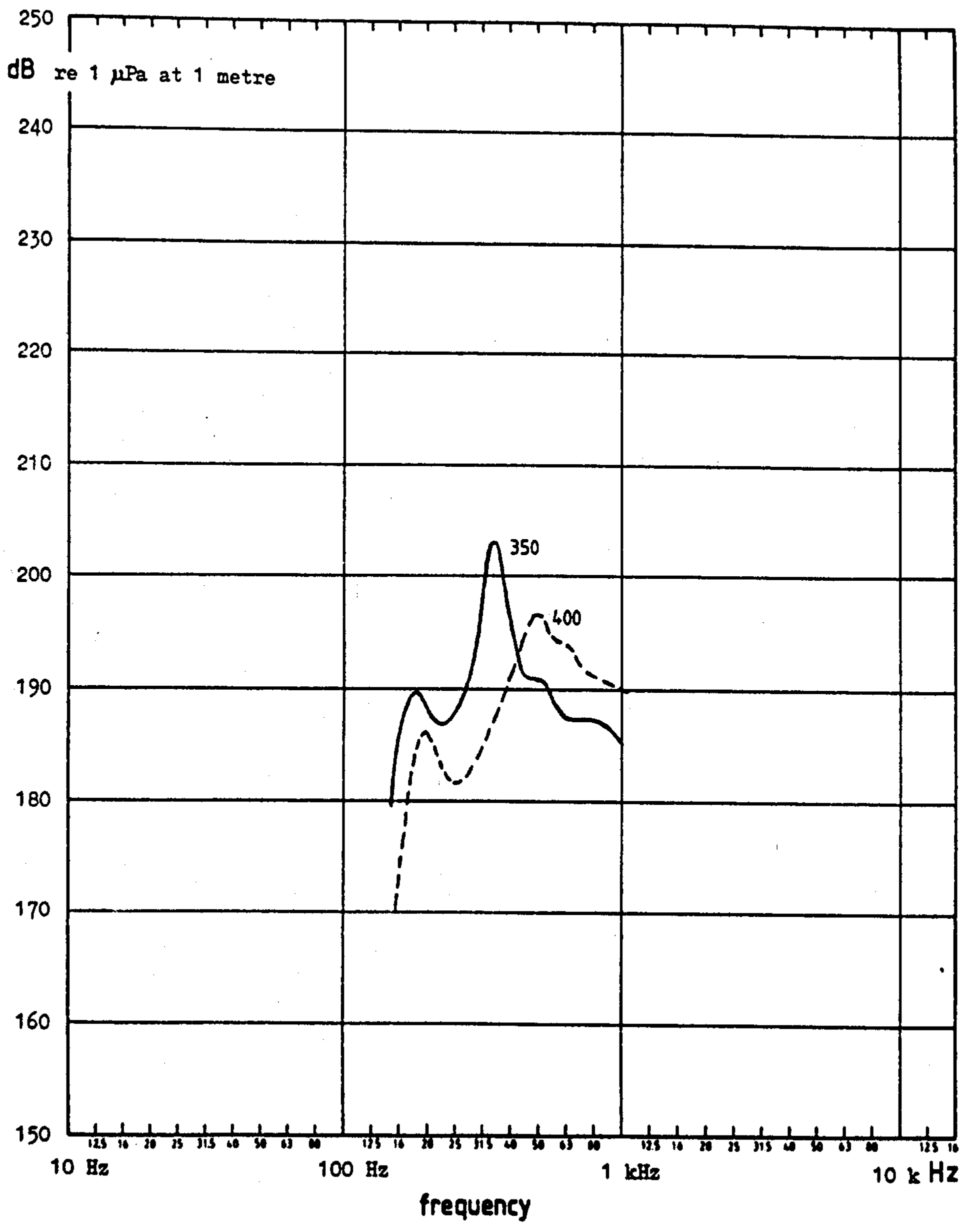


Fig. 18: Maximum source levels of two types of Honeywell Bender Bar transducers HX-90
350 Hz resonance, 3400 V, 3 kW ———
400 Hz resonance, 570 V, 1 kW - - - - -

7 MOVING COIL PROJECTORS

These transducers operate in the same way as electrodynamic loudspeakers of which the large paper cone has been replaced by a small rigid light-weight piston which has about the same diameter as the voice coil. They are produced in any size with weights between 10 and 1000 kg (see figure 19).

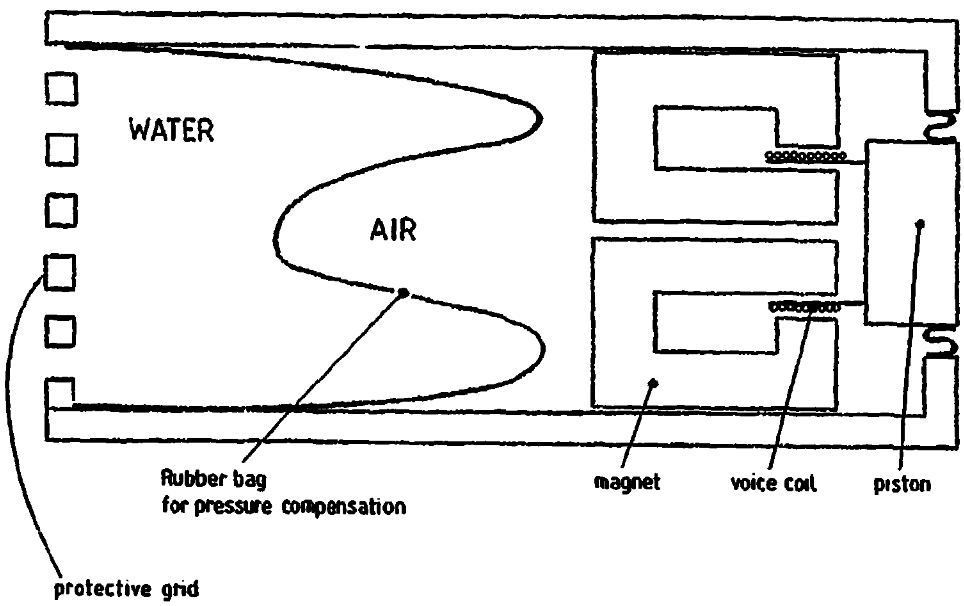


Fig. 19: Moving coil projector (schematic).

The smallest types have a diameter of about 10 cm and cover the frequency range of 50 Hz to 20 kHz with a rather flat frequency response curve but with a low efficiency (0.04 %). With an electric input power of 20 W they produce a source level of the order of 150 dB. Larger units give higher source levels with a better efficiency but within smaller bandwidths.

Well known types are the US Navy series J-9, J-11, J-13 and J-15, produced by Marine Resources in Florida, USA. The largest types reach a source level of about 170 dB in the frequency band of 50 to 500 Hz with an input power of 250 W. Of the same manufacturer are the types MR-214, MR-219 and MR-216 of which the specifications are summarized in table 5. MR-214 resembles the J-9, MR-219 is more like the J-13 while MR-216 is much larger. The latter type comes in two versions: one with a single piston, like all other types, and one with two pistons at opposite sides of the central magnet.

		TYPE				
					Hydrosounders	
		MR - 214	MR - 219	MR - 216	type K	Bemice
Frequency range	[Hz]	30-6000	15-2000	10-250	50-5000	80-140
Maximum input power	[W]	35	225	1500	1000	3000
Efficiency	[%]	0.2	0.2	0.4	1	6
Maximum source level	[dB]	158	166	178	180	194
Electrical impedance	[Ω]	3	4	13	40	20
Piston diameter	[cm]	5.7	10	30	31	66
Transducer diameter	[cm]	14	22	61	55	73
length	[cm]	52	78	74	58	139
weight	[cm]	18	62	320	300	920
Maximum depth:						
- passive compensation	[m]	90	200	30	65	12
- active compensation	[m]	700	400	150	-	500

Tabel 5: Main characteristics of some moving coil projectors.

Other large moving coil projectors are manufactured in the UK by Gearing and Watson in Hailsham and by Derritron in Hastings. The Derritron Hydrosounder type K resembles the MR-216 (single piston type) in size and performance. A larger unit called "Bemice" operates with two opposite pistons in a narrow frequency band around resonance, which is about 100 Hz (see table 5 and the frequency response curves in figure 20). With a power input of 3 kW the Bemice produces a source level of 194 dB but its relatively high efficiency (7%) is paid with a narrow bandwidth. While all other moving coil projectors are equipped with permanent magnets the Bemice uses a coil with a DC current for its magnetic field. The additional DC power of 500 W, consumed by the field coil, however slightly reduces the overall efficiency of this transducer to 6%.

All these moving coil projectors need a pressure compensation device in order to equalize the inside pressure with the outside hydrostatic pressure. This is realised by means of an air filled rubber bag which can be compressed to a limited extent. Hence with this "passive compensation" the depth of operation of the transducer is restricted (see table 5). For greater depths the air bag can be pressurised by means of "Scuba diving gear" consisting of a bottle with pressurised air and a pressure regulating system. This is called "active compensation" in table 5 (see also [4], p. 117).

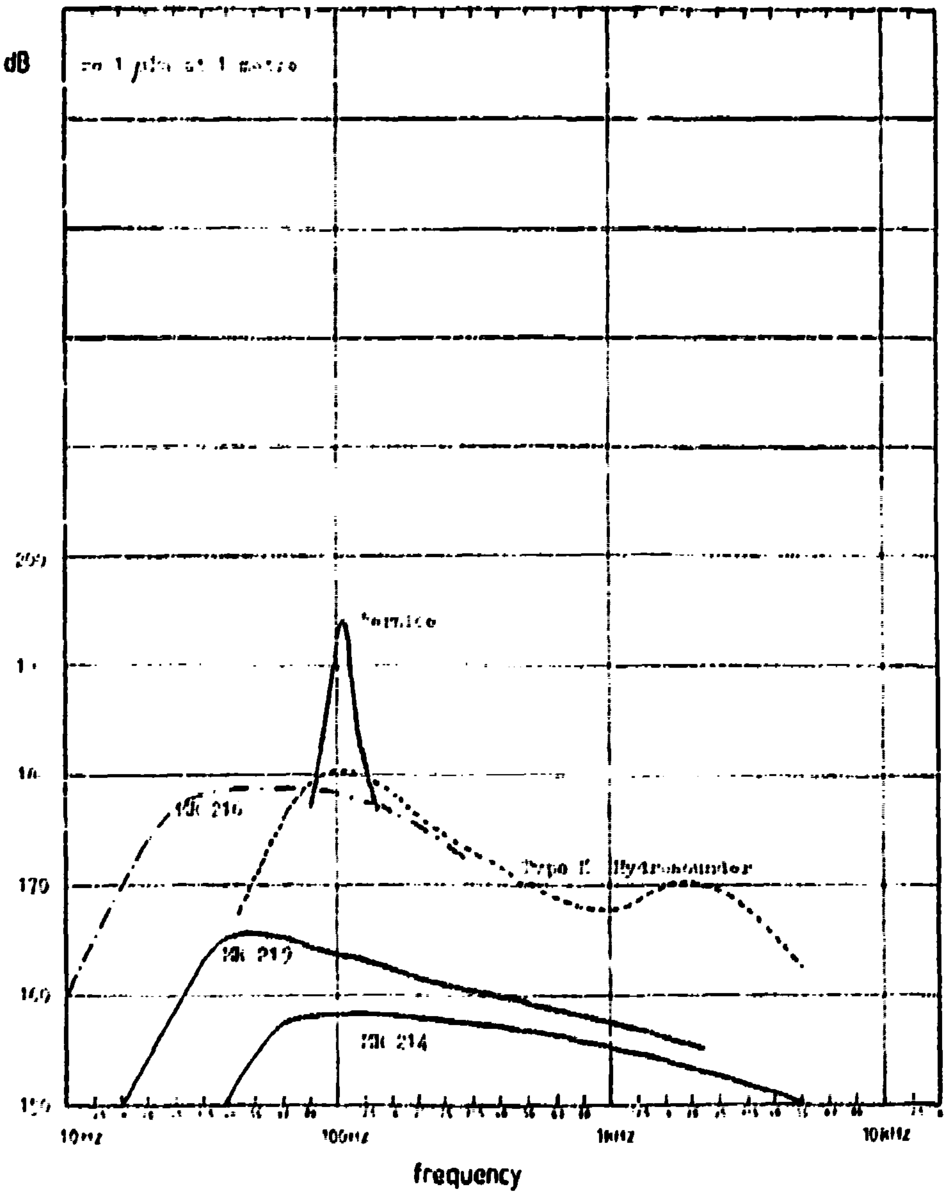


Fig. 20. Maximum source levels of some moving-coil projectors (MR = Marine Resources)

8 HYDRAULIC SYSTEMS

All transducers described before are driven by a piezoelectric motor, which is inherently a stiff system. But for creating a large displacement, needed for high power radiation at low frequencies, mechanical transformers are included like benders or curved shells. These are effective only in a limited frequency band around resonance.

Large displacements at low frequencies over a large bandwidth can be realised only by purely mechanical means like mechanically driven pistons. Of the several possible solutions for this the hydraulic actuation gives the best performance.

The principle is shown in figure 21 ([4], p. 116). Two opposing pistons are driven by a central hydraulic motor which is controlled by an electric signal of the desired frequency. The hydraulic pressure can be generated locally inside the transducer housing by an electrically driven pump. Hence the cable carries standard electric power for the pump and a low level electric signal for the control valve. The frequency range of operation is limited at the low frequency end by the available power and by the possible excursions of the pistons. The high frequency limit is dictated by flexural resonances of the pistons.

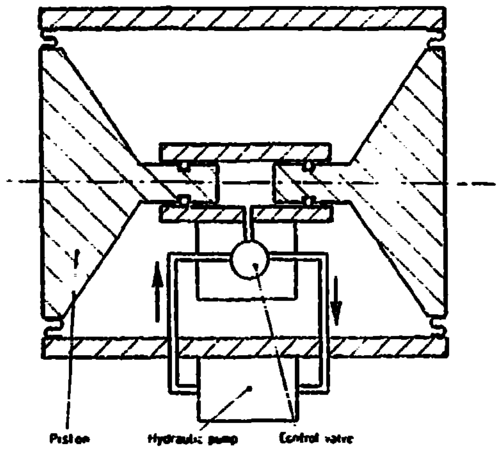
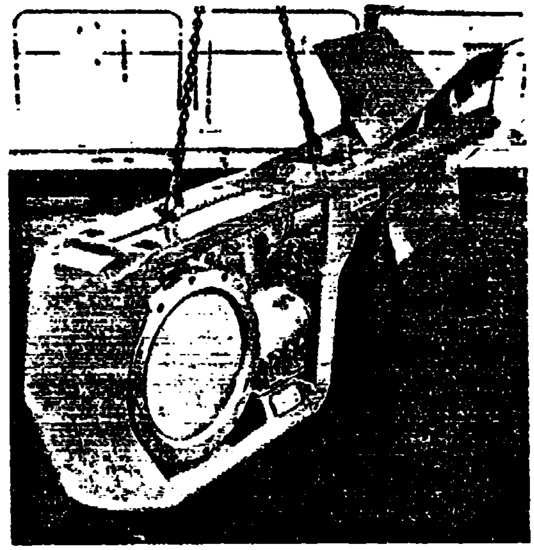


Fig. 21: Principle of hydraulic actuated projector.

The outside hydrostatic pressure can be compensated to a certain extent by the hydraulic pressure, which allows a depth of operation of the order of 100 m. With the aid of controlled internal gas pressure the transducer can go deeper.

A good example of this type of transducer is the SSH 60-300, made by Pons in Aubagne, France. It produces a source level of 193 dB in the frequency range of 60 to 300 Hz (see figure 22). This is close to the level of the Bemice, but its bandwidth is larger.

PURPOSE



This towed transducer is designed for low frequencies when very high source level and broad bandwidth are required.

It is well suited for :

- long range underwater transmission,
- propagation study.

Strongly built, the SSH 60-300 permanently controls its sound level. It can be towed at moderate speed, with a cable feeding electrical power and the modulating signal.

The same cable feeds back the different status variables of the transducer.

TECHNICAL CHARACTERISTICS

- Power supply :	3 x 380 V 60 Hz A.C.
+ control signal	
- Maximum transmitting level :	193 dB
- Usable frequency range :	60 Hz to 300 Hz
- Ocean depth without pressure compensation :	100 m
- Weight in air :	700 kg
- Weight in water :	385 kg
- Width :	0,850 m
- Length :	2.870 m
- Height :	1,430 m

STAGE of DEVELOPMENT

- In production

S.C.M. A. PONS - avenue de la Fleunde - Z.I Les Paluds - 13685 AUBAGNE - Tél. 42.82.90.90 - Télex : 440 041 F Ed 1988
Télécopie : 42.82.90.90

Fig. 22: Very low frequency hydraulic sound source.

9 SUMMARY AND CONCLUSIONS

Several kinds of commercially available low frequency transducers have been presented in this report. The maximum source levels of single omni-directional units are presented for mutual comparison in figure 23. Of each kind of transducer only those types were selected that give the highest levels at the lowest frequency. Of all these types the required electric input power is given which is equal to the power handling capability of that transducer.

With arrays composed of several units higher source levels can be obtained. As long as the size of the array remains smaller than half a wavelength the source level will increase by 10 log N, where N is the number of elements. If the size grows above half a wavelength, the directivity index of that array causes an additional increase of the source level in the direction of the acoustical axis.

Looking at figure 23, there seems to exist a limit above which no source level is possible. This limit rises with the frequency with a slope of about 8 dB per octave. A possible explanation might be that practical and economical reasons restrict the size and weight of transducer elements to a certain limit. When the frequency gets lower, the transducers become smaller in terms of wavelengths which makes the radiation impedance less real and more reactive, requiring more reactive power and reducing the efficiency [15].

This effect is illustrated in figure 24 which gives the acoustic power (and the source level) of a spherical radiator with constant volume displacement versus the frequency (from [15]). Mechanical constraints and practical size limitations restrict the possible volume displacement of a single element transducer to about 10^{-3} m^3 at a frequency of 10 Hz and to about 10^{-4} m^3 at 300 Hz. However, with arrays of single elements this limit can be surpassed to a certain extent.

Example: One Bernice produces 194 dB at 100 Hz. Wavelength is 15 m.

With 10 Bernices the source level will be 204 dB if they are placed close together. Arranged along a straight line with half a wavelength spacing the directivity index of this 70 m long array is 10 dB, rising the source level to 214 dB in the broadside direction. It will be difficult however to tow such an array behind a ship, but it could be fixed to the bottom.

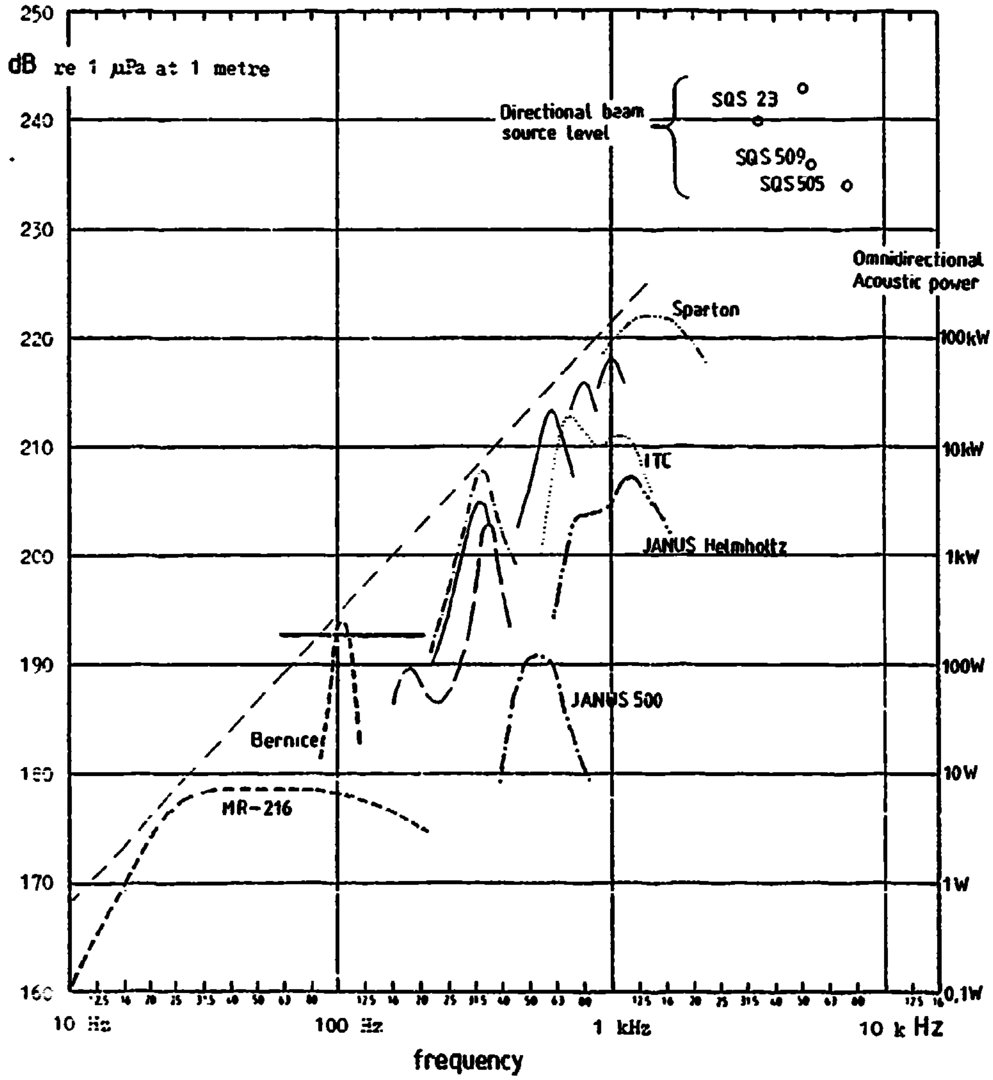


Fig. 23: Comparison of maximum source levels of different kinds of single element transducers.

Double Pistons:	JANUS 500:	200 W
" "	JANUS Helmholtz:	10 kW
Open hollow cylinders:	ITC:	25 kW
" "	Sparton:	100 kW
Flextensionals:	350 Hz:	10 kW
Ring shells:	325 Hz:	4 kW
	1000 Hz:	50 kW
Bender bars:		4 kW
Electro-dynamicals:	Bernice:	3 kW
	MR-216:	1.5 kW
Hydraulic		

o Beam level of array of elements

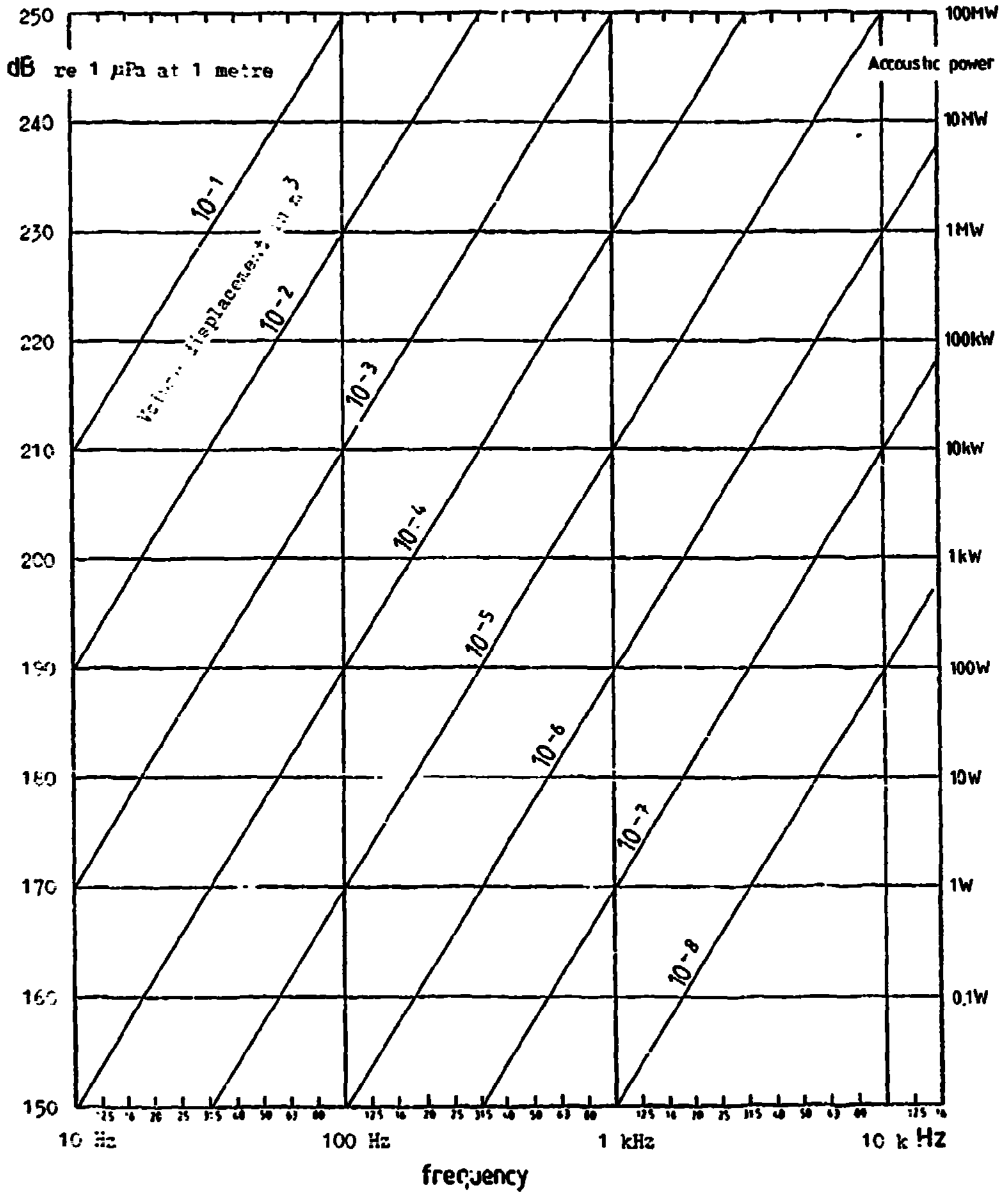


Fig. 24: Source level and acoustic power radiated from an harmonically pulsating sphere with diameter small compared to the wavelength at constant volume displacement in m3.

Final conclusions

1. If low frequency sound is required with a source level of the order of 210 dB or more, for practical reasons the frequency must be chosen above 300 Hz.
2. In the frequency range of 300 - 400 Hz a stave of flextensionals will produce sufficient sound. If the stave is shorter than 2 m the radiation will be omni-directionally. With longer staves directionality will occur.
3. In the frequency range of 400 - 1000 Hz open hollow cylinders may be a good choice, but the highest source levels are obtained with single Sparton Ring-shells. Staves of flextensionals can be applied too but with increasing frequency the directivity has to increase in order to maintain the required source level (see figure 13).

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THE DETECTION OF SUBMARINES BY MEANS OF PASSIVE SONARS BECOMES MORE DIFFICULT AS THE RADIATED NOISE OF SUBMARINES IS GRADUALLY DECREASING.
HENCE THERE IS A NEED FOR ACTIVE SONAR TRANSDUCERS THAT PRODUCE SOUND AT FREQUENCIES BELOW E.G. 1000 HZ. SEVERAL KINDS OF LOW FREQUENCY TRANSDUCERS ARE PRESENTED, WORKING ON DIFFERENT PRINCIPLES, BEING COMMERCIALLY AVAILABLE.

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UNDERWATER SOUND SOURCES	LOW FREQUENCY SOUND SOURCES
ACTIVE SONAR	
ACOUSTIC RADIATION	

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