

AMRL-TR-65-11

AD 615916

EXPERIMENTAL BONE AND TISSUE VIBRATOR ASSEMBLY

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APRIL 1965

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VIBRATOR ASSEMBLY**

ROBERT W. BENSON, PhD

FOREWORD

This report was prepared by Robert W. Benson & Associates, Inc., Nashville, Tennessee, for the Aerospace Medical Research Laboratories under Contract No. AF 33(657)-11335, Project No. 7231, "Biomechanics of Aerospace Operations," Task No. 723103, "Biological Acoustics in Aerospace Environments." The principal investigator for the program was Dr. Robert W. Benson. Mr. Samuel H. Pearsall was responsible for the design, construction, and calibration of the vibrator assemblies and was aided by Mr. J. Ronald Chapman and Mr. Richard T. Lee. Dr. Charles W. Nixon and Lt Colonel Elizabeth Guild, Biophysics Laboratory, Biodynamics and Bionics Division, provided project direction. Research was initiated June 1963 and completed August 1964.

This technical report has been reviewed and is approved.

J. W. HEIM, PhD
Technical Director
Biophysics Laboratory

ABSTRACT

A special purpose laboratory vibrator has been developed for use in experimental investigations of hearing by bone and tissue conduction and of mechanical driving point impedance of tissue and bone. The vibrator assembly is floated on an air bearing to provide resonance-free operation over the frequency range of 100 - 10,000 cps and at intensity levels of 60 decibels above threshold of hearing. Special sensors within the unit provide measurement of the tip velocity of the alternating pressure transmitted by the head and the force due to an external load. Design features and calibration procedures are discussed in this report.

TABLE OF CONTENTS

	<u>Page</u>
Introduction.....	1
The Vibrator Assembly.....	2
Calibration Procedures.....	8
Vibrator Assembly Performance.....	14
Recommendations For Future Work.....	16
Summary.....	17
Appendix - Electronic Circuitry.....	19

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Cross-Section of Unit, Illustrating Suspension System And Mounting of Driver Element.....	4
2	Cross-Section of Unit, Illustrating Force And Velocity Sensors.....	5
3	Photograph Showing Vibrator Assembly Suspended in Reference Frame and Associated Electronic Amplifiers.....	9
4	Voltage Generated by Velocity Pickup Versus Measured Velocity. Data Taken Over Wide Frequency Range..	10
5	Output of Force Pickup Versus External Mass Coupled to Adaptor Tip.....	12
6	Approximate Relationship Between Voltage on Driver and Tip Displacement.....	15
7	Schematic Diagram of Velocity and Force Preamplifiers.....	20
8	Schematic Diagram of Cathode Followers and Associated Power Supply.....	22

INTRODUCTION

The measurement of sensitivity of hearing caused by the introduction of vibratory motion into the skull and body has been limited by the nonavailability of an adequate range of suitably controlled excitation. The objective of this program was to develop an integrated vibrator assembly to provide such excitation for the experimental investigation of hearing by tissue and bone conduction, and in addition, for the simultaneous physical measurement of mechanical driving point impedance. The special purpose assembly was designed to provide additional knowledge to allow a better understanding of the bone conduction phenomenon and its role in noise exposure, communications in noise and during vibrations, and other related problems associated with vibration and noise environs.

Several systems for the measurement of mechanical impedance have been reported in the literature. The systems currently available for use on mechanical structures are primarily designed for use at the lower frequencies for which mechanical vibration is a major problem. The earliest reports of measurements of mechanical impedance of parts of the human body were made by Barany¹ and von Békésy². This early work was restricted to measurements made over a limited frequency range. Later measurements by Franke³ covered the frequency range from 200 cps to 1600 cps and included a study of the variation of driving tip size and static coupling force.

In 1955, additional work was reported by Corliss and Koidan⁴ with an extension in range of frequencies used. The system for these studies used a barium titanate cylinder as the force generator, providing for impedance measurements up to 7000 cps. The driving system was referenced to a massive concrete pillar so that it was possible to mount the driving tip with respect to only a few locations on the head. Specifically, impedance at the mastoid and at the forehead were measured.

¹ E. Barany, Acta Oto-Laryngologica, Supplement, XXVI, 56, (1938).

² G. von Békésy, JASA, Vol. 20, page 749, (1948).

³ E. K. Franke, JASA, Vol. 24, No. 4, July, (1952).

⁴ Corliss and Koidan, JASA, Vol. 27, No. 6, November, (1955).

Any system that is capable of measuring mechanical driving point impedance may also be a source of vibratory motion for use in psycho-physical studies. Consequently, this same system was used to determine the threshold of hearing for bone conduction from 250 cps to 10,000 cps, and the results were reported in terms of dynamic displacement or force required for threshold. Of the work thus far mentioned, the system used by Corliss and Koidan showed the most merit for meeting the design objectives of this project. Major limitations of this system were the restriction on mounting position of the unit relative to the subject and the mechanical resonances within the unit. In addition, although mechanical impedance is the complex ratio of force to velocity, the unit measured force and displacement and velocity was derived.

After careful consideration of the methods of generating vibratory motion, it was decided that an approach should be made using a system similar to that reported above. This report describes the basic system which has been developed and constructed. A detailed description of the limitations imposed in accomplishing the above objectives is discussed. Calibration procedures and performance of the over-all system are also presented.

THE VIBRATOR ASSEMBLY

The basic components of the vibrator assembly include the suspension system, the force generator, the velocity sensor, and the force sensor. Each of the components of the system is described independently, indicating the principles of operation and the limitations of their use.

(A) SUSPENSION SYSTEM: In order to obtain a flexible mounting system by means of which vibratory motion may be introduced into the body at many different locations, it was desirable to eliminate the necessity of a rigid reference system. It is necessary, however, to provide a reference which is independent of the suspension system for the measurement of either velocity or displacement. For this reason, it was decided to use a reference mass whose impedance was large compared to the impedance presented by the body surface at most frequencies. The reference mass should be suspended freely, independent of any external mounting system. In order to accomplish these objectives, a cylindrical mass of approximately 1,500 grams was mounted within a cylindrical housing and

floated on a thin film of air, in order that it be independent of the housing.

The suspension system showing the reference mass, air inlets and outlets, and the force driver attached to the mass, is illustrated in Figure 1. During operation of the unit as a source of motion, a flow of air enters around the center portion of the mass and is exhausted through the two vents in front of and behind the mass. The clearance between the mass and its housing is approximately 0.001" and provides a complete isolation from the external suspension system when the mass is floated on air. The air pressure required to float the reference mass ranges from 10 to 20 psi with a relatively small flow of air. By controlling the exit ports, it is possible to provide a differential pressure between the front and back of the mass to support its weight and provide a static coupling force between the tip and load.

The impedance provided by the reference mass is proportional to frequency. It is therefore anticipated that the mass will exhibit motion for the lower frequencies for which the impedance of the load may be similar to that of the reference mass. It would therefore be desirable to use as large a reference mass as is possible. A second requirement, however, is that the over-all source of motion should not exhibit resonances within the desired frequency range. It is therefore desirable to limit the effective length of the vibrator unit so that it is small compared to a wave length at the highest frequency. The design objective was placed at having the first longitudinal mode at 20,000 cps. The actual measured resonance complete with tip was measured to be 17,000 cps.

The basic system provides for the complete isolation of the vibrator assembly from the external mounting system with resonance-free operation over the desired frequency range. The sole limitation is that the reference mass has a finite impedance and will exhibit motion when the impedance presented to the driving tip becomes comparable to the impedance of the reference. Since the impedance of the mass is proportional to frequency, this limitation is apparent only for the lower frequencies. It is therefore necessary to provide a measurement of any motion of the reference mass.

(B) FORCE GENERATOR: The force generator used in the vibrator assembly consists of a PZT-4 ceramic cylinder as illustrated in Figure 2. The displacement along the longitudinal axis of the driving cylinder is proportional to the applied voltage

MARK II

NOTE: All dimensions are in inches

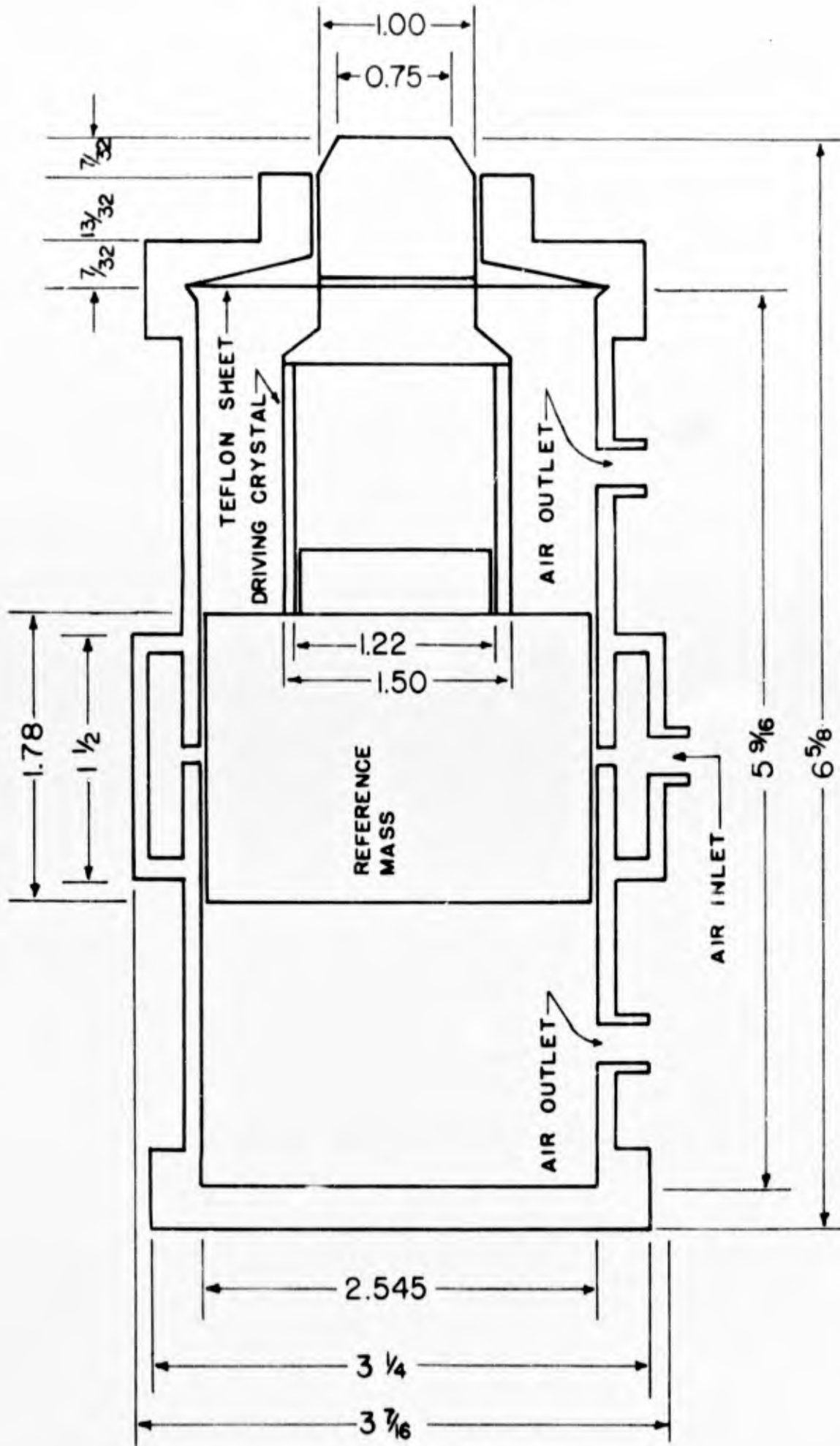


FIGURE 1. CROSS - SECTION OF UNIT, ILLUSTRATING SUSPENSION SYSTEM AND MOUNTING OF DRIVER ELEMENT.

- 1. REFERENCE MASS
- 2. CERAMIC DRIVING ELEMENT
- 3. CERAMIC FORCE ELEMENT
- 4. TIP ADAPTER

- 5. INTERCHANGEABLE TIPS
- 6. TEFLON SHEET
- 7. VELOCITY PICKUP
- 8. COMPENSATION PICKUP
- 9. PLENUM CHAMBER

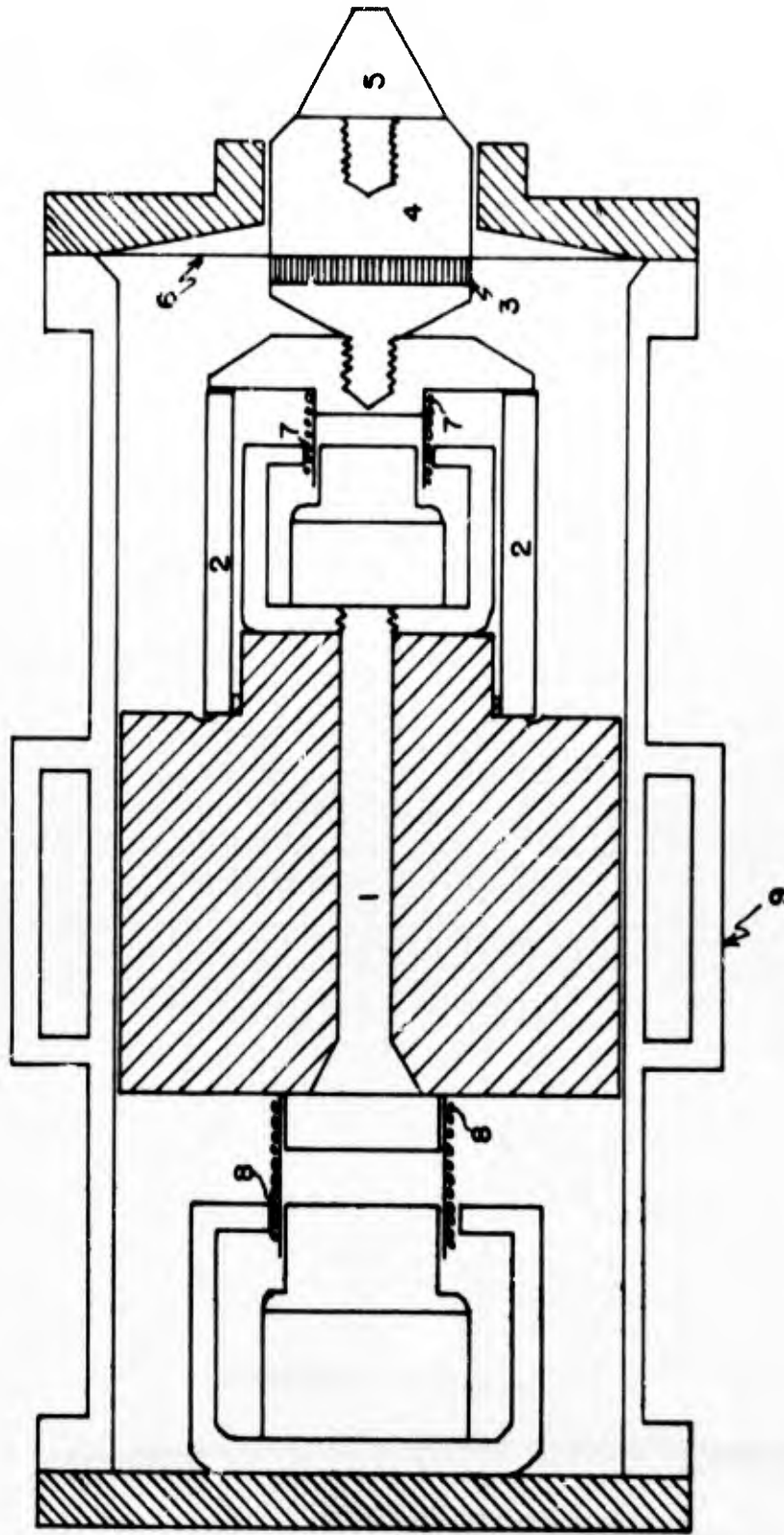


FIGURE 2. CROSS-SECTION OF UNIT, ILLUSTRATING FORCE AND VELOCITY SENSORS.

and independent of frequency over the desired range. The cylindrical nature of the driving element is used in order to accommodate the velocity sensor which is described below.

It has previously been shown that the threshold of hearing by bone conduction is essentially independent of frequency for constant acceleration. It is therefore understood that the choice of a constant displacement generator will limit the performance for the lower frequencies. However, the choice of alternate generators produces severe limitations on the high frequency performance. In order to obtain a unit which would have the greatest useable dynamic range over the audiofrequency range, it was decided that the ceramic element would come closest to meeting the requirements. If emphasis were to be placed on the lower frequency region, it would be preferable to use an electro-dynamic source whose output velocity is constant with respect to frequency. Such systems, however, which are used extensively in vibration excitors, are limited by resonance modes of their suspension systems to one or two kilocycles per second.

(C) VELOCITY SENSOR: The unit was basically designed for sinusoidal operation so that it would be possible to measure either displacement, velocity, or acceleration and derive the actual tip velocity and phase from a measurement of any of the variables. Since the unit is intended for the continuous monitoring of impedance, it was desired that velocity be measured directly. It was also possible to install a sensor whose output is proportional to velocity with no addition to the suspension system. As illustrated in Figure 2, a coil is rigidly cemented to the driving tip adaptor and mounted in the air gap of a magnet, which is rigidly attached to the reference mass. In this manner, the voltage produced by the coil is directly proportional to the relative velocity between the tip adaptor and the reference mass. Since the coil and magnet are rigidly attached, there are no extraneous resonances produced by the velocity measurement system.

The actual velocity of the driving tip is dependent upon the velocity of the reference mass and it is therefore necessary to provide a second sensor to detect any motion of the reference mass with respect to an external reference. A second coil is therefore mounted on the rear of the mass and its magnet assembly is attached to the external housing. Since the mass and entire vibrating system is suspended on an air-bearing, the external housing is essentially free of vibratory motion. The actual velocity of the driving tip is therefore the velocity of the tip with respect to

the reference mass minus the velocity of the mass with respect to the external housing.

(D) FORCE SENSOR: The measurement of force is accomplished by the insertion of a PZT ceramic crystal between the driving element and the tip adaptor. Two precautions must be exercised in the measurement of force. The first is concerned with the radial motion provided by the driving crystal which may be transmitted to the force sensor. The basic excitation of the driving crystal is a contraction and expansion of the thickness of the cylinder wall which, in turn, results in a longitudinal component along the axis of the cylinder. Although this longitudinal component is the desired motion, there is an accompanying radial motion, due to the expansion and contraction of the diameter of the cylinder. If the force sensor is cemented directly to the plate coupling the motion to the tip, the output of the force sensor due to the radial motion predominates. For this reason, it is necessary to de-couple the radial motion from the force sensors and yet provide a rigid coupling for the transfer of the longitudinal component. A transverse break is introduced between the supporting plate and the crystal mounting, which reduces the radial coupling without a corresponding reduction in the longitudinal motion.

In front of the force sensor is cemented an adaptor tip which is threaded and provides for the mounting of tips of various sizes. The use of such a mounting system introduces a mass, dependent upon tip mass. This causes a force output, superimposed upon that due to the load presented by the tissue and bone. Although the impedance presented by the various tips, in conjunction with the tip adaptor, can be explicitly determined, it is desirable to provide additional means for measuring force when the particular shape of the driving tip is not critical. For this purpose, special tips having a flat circular surface are also provided where the active force sensor is mounted directly on the face of the tip. The internal force sensor sees an effective mass of approximately 30 grams, plus the mass of the selected driving tip. The external sensors see an effective mass ranging from a fraction of a gram up to 14.6 grams, dependent upon the surface area of contact. If the provision for variable tips were not necessary, it would be possible to provide a voltage which would correspond to the effective mass of the sensor so that direct measurement of force due to external loads might be made. In the present case, it is necessary to correct for the self-mass of the force measuring system for all measurements.

(E) ELECTRONIC AMPLIFICATION: The measurement of mechanical impedance requires the determination of the ratio of magnitudes of force and velocity and the phase angle between them. In order to assure a measurement of the absolute phase of the force signal, it is necessary to provide an impedance transformation so that instruments used for measurements will not introduce a phase shift. For this purpose, a high-input impedance, vacuum-tube cathode follower was constructed, followed by an amplifier capable of 40 decibels gain. Attenuators were provided to give an 80 dB range in addition to the dynamic range of the amplifier itself. This wide dynamic range is necessary due to the extremes in impedance which may be measured over a wide frequency range.

An amplifier was constructed to provide a signal output which is a true indication of the tip velocity. A differential input was used to subtract the velocity of the reference mass from that of the primary velocity sensor. The adjustment was made by blocking the driving tip and adjusting the relative sensitivities so that no velocity signal is obtained for the condition of infinite impedance presented to the tip. Complete compensation was obtained for the entire frequency range. A gain of 60 dB was provided so that signal levels sufficient for external meters would be available.

The complete unit with its associated amplifiers is shown mounted in a reference frame in the photograph of Figure 3.

CALIBRATION PROCEDURES

The over-all unit was calibrated in a two step procedure. The first step was to provide an accurate determination of the voltage output of the velocity sensor with respect to a given tip velocity. For this purpose, a frequency modulated capacitance probe suitable for making absolute measurements of dynamic displacements was used. Since the velocity of the driving tip, with constant voltage applied to the driving crystal, should be proportional to frequency, it was possible to determine the behavior of the unit over a wide frequency range. Measurements were made for various driving voltages and at various frequencies from 100 to 10,000 cps to establish an accurate sensitivity for the velocity pickup. The measurements are illustrated graphically in Figure 4, for several displacements of the driving tip and various frequencies. The resulting sensitivity is 130 cm/sec/volt out of the velocity pickup.

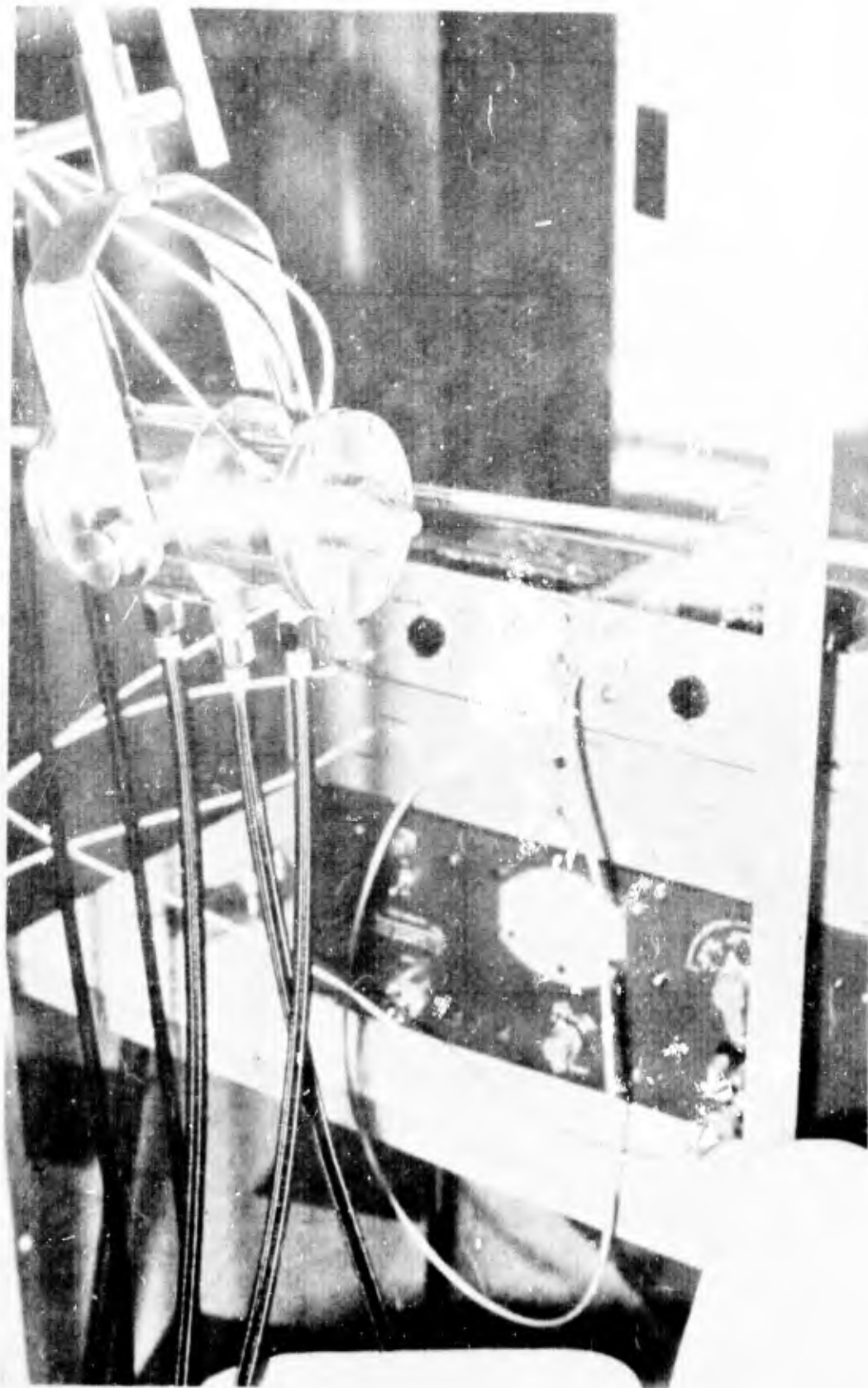


FIGURE 3. Photograph showing vibrator assembly suspended in Reference Frame and associated electronic amplifiers.

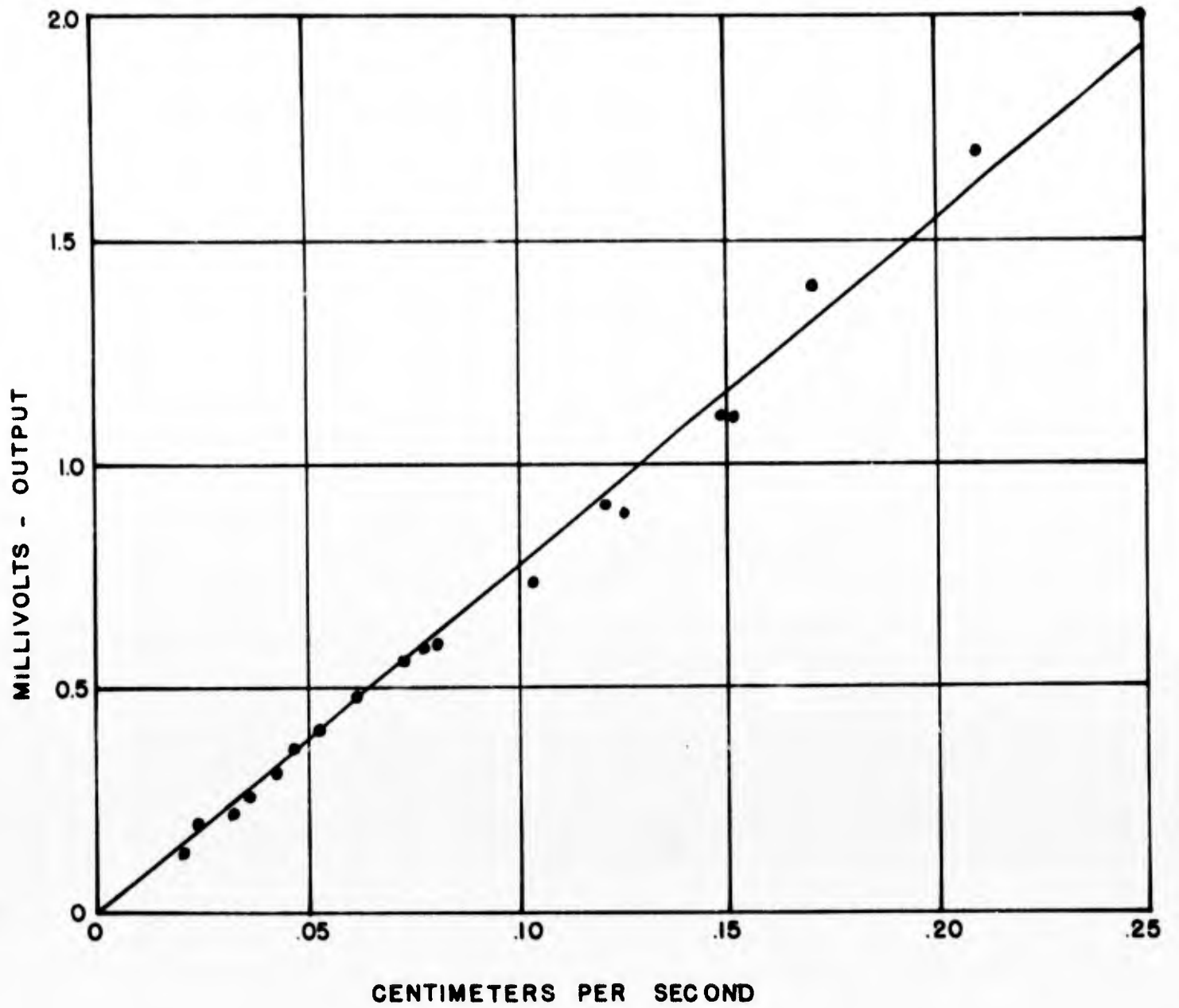


FIGURE 4. VOLTAGE GENERATED BY VELOCITY PICKUP
 VERSUS MEASURED VELOCITY.
 DATA TAKEN AT VARIOUS FREQUENCIES
 FROM 100 TO 10,000 CPS

Once the sensitivity of the velocity sensor was determined, it was possible to determine the sensitivity of the force pickup by the measurement of the impedance of various masses. A range of masses was used up to the mass of the reaction mass. The larger masses can only be used for the lower frequency range, for which wave motion in the mass is negligible. The measurements are illustrated graphically for a particular frequency in Figure 5. It will be noted that the output of the force sensor corresponds to the effective mass of the tip adaptor and force sensor when no external load is applied. The extrapolated value for the effective internal mass is approximately 30 grams. The actual measured mass of the tip adaptor before assembly was 25 grams, and the mass of the crystal was 10 grams. It is therefore concluded that the empirically determined mass is accurate. The sensitivity for the internal force sensor was determined to be 700,000 dynes per volt. In a similar fashion, the external force sensors with reduced effective mass were also calibrated.

It should be noted that the measurement of impedance of a mass is accurate for those frequencies for which the mass is truly lumped and for which wave motion does not occur. It should also be noted that, during the measurement of the various masses, the phase relationship between the force and velocity signals was 90° as is required by a mass reactance. For the larger masses, the calibration procedures were only used at the lower frequencies.

The range of impedances which may be measured by the unit is influenced by several factors. The minimum impedance which may be measured is obtained when the force is a minimum and the velocity is a maximum. The minimum force which can be measured is limited by the equivalent input noise of the force amplifier. The maximum velocity is limited by the maximum voltage that may be applied to the driving crystal. The magnitude of impedance which may be measured, due to the noise limitation of the force amplifier, is a function of frequency ranging from 100 dyne-sec./cm. at 100 cps to 1 dyne-sec./cm. at 10,000 cps. The maximum impedance is obtained when the force is a maximum and the velocity is a minimum. The range of signals accepted by the force amplifier is 120 decibels, so that extremely large impedances (10^8 dyne-sec./cm.) may be easily measured.

For each of the force sensors, there is an equivalent mass ranging from 0.85 grams to more than 35 grams. At the higher frequencies, there will be a limit on the minimum impedance which

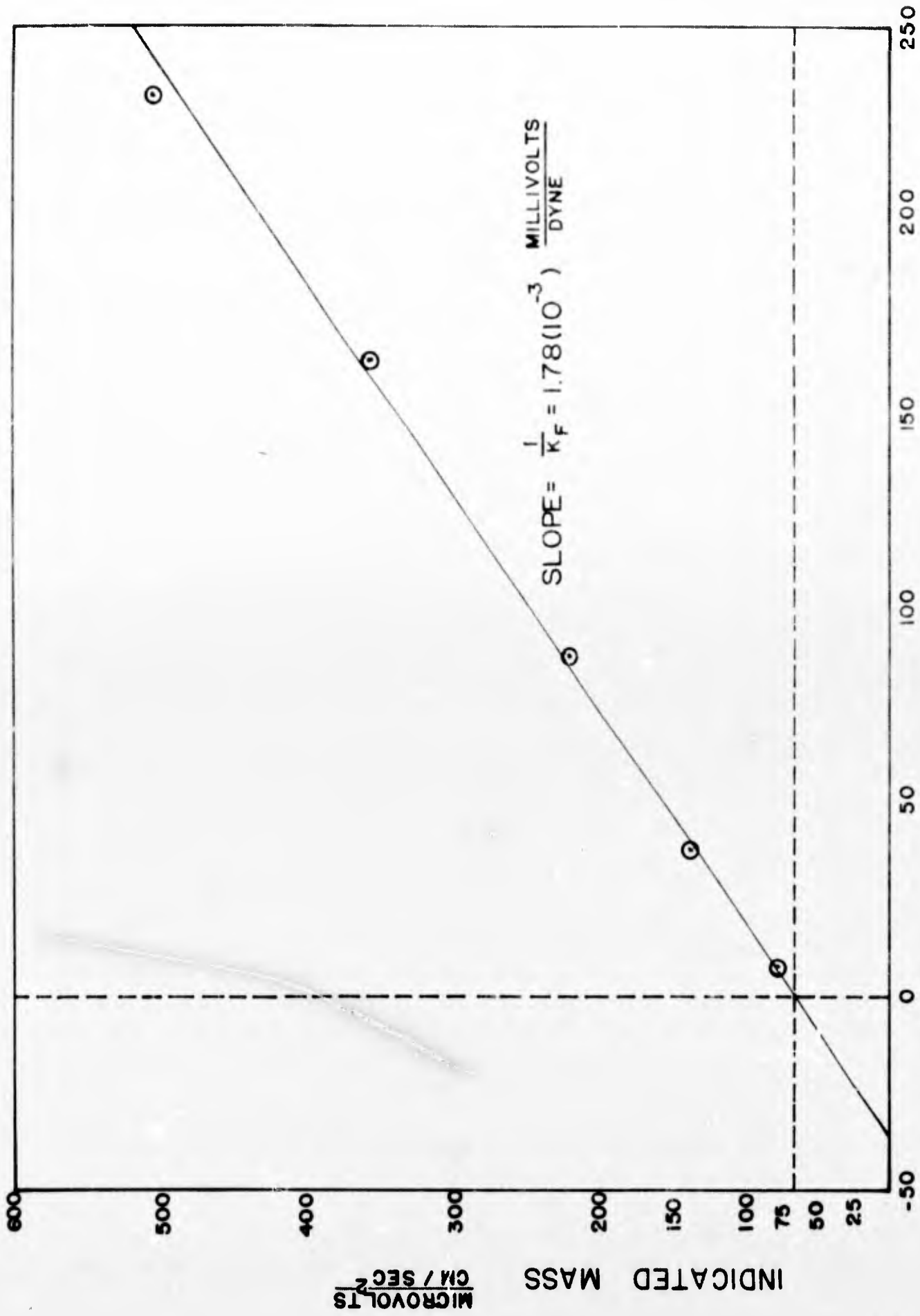


FIGURE 5. OUTPUT OF FORCE PICKUP VERSUS EXTERNAL MASS COUPLED TO ADAPTER TIP.

can be measured, due to the self-mass of the force crystal. For the external tips provided, this self-mass has an impedance whose magnitude is comparable to the magnitude of impedance presented by the body at the higher frequencies. It is possible, however, to observe changes in both magnitude and phase of the force signal due to body impedances, which are large compared to the signal which is obtained from the self-mass of the sensors. For the internal force sensor, the sensitivity for measurement of body impedance is marginal. It is therefore recommended that the external force sensors, with their reduced self-mass, be used for impedance determinations. The design requirement that various shaped tips be accommodated limits the possibility of a compensation for the self-mass and, therefore, imposes a minimum on the external impedance that can be measured at the higher frequencies.

The velocity sensor consists of two coils; one of which senses the main motion of the driving tip, and the second which detects the motion of the reference mass. Any movement of the reference mass will cause a voltage output, due to the compensation sensor, which will be seen as a noise in the velocity signal. Movement of the body or irregular airflow will cause a low frequency noise to appear in the velocity signal. The use of this system was dictated by the requirement of having a unit which was free to be placed on various parts of the body. The use of a massive reference, similar to that used by other investigators, would eliminate this source of noise. The low frequency noise which may be expected, due to the movement of the reference mass, appears in the velocity signal which is a maximum for measurements of minimum impedances. Although this noise is undesirable, it is only influential at the lower frequencies and when the impedance is small. Under these conditions, the reference mass will have a motion that is negligible and the compensation winding may be switched out of the circuit to eliminate this source of noise. For example, the reaction mass has an impedance equal to 8.8×10^5 at 100 cps, compared to the minimum which can be measured, due to electrical noise, of 100 dyne-sec./cm. Under these conditions, the reference mass may be assumed to be stationary and the compensation coil is no longer necessary.

The range of impedances which may be measured by the unit adequately covers those magnitudes which have been reported in the literature.

VIBRATOR ASSEMBLY PERFORMANCE

Many of the original objectives have been accomplished in the vibrator assembly which has been described above. The unit operates over the frequency range from 100 to 10,000 cps, with the main restriction being the dynamic range attained. The calibration procedure indicates that the control of motion is satisfactory and that the measurement of both force and velocity are accomplished with accuracy. The signals are of sufficient magnitude to measure a wide range of impedance.

In addition to the measurement of impedance, the unit provides sufficient signal for establishing the threshold of hearing by bone conduction. The dynamic range attained in the unit is illustrated by Figure 6., where threshold values are those reported by Corliss, Smith and Magruder⁵. The dynamic range, that is, the maximum sensation level which has been attained, is somewhat similar to that attained by the vibrators furnished with audiometers but with an extension in frequency range. Although this may appear to be a small gain, it should be emphasized that the motion of the tip is controlled and measured in an absolute manner.

The ceramic cylinder chosen as a force generator has a maximum limit of displacement imposed by the possibility of electrical breakdown at the lower frequencies and mechanical breakdown at the higher frequencies. The unit is operated far below the mechanical resonant frequency, so that the electromechanical conversion efficiency is very low. The only method of significantly increasing the displacement for an element of this type would be to increase the length of the element, however, any increase in the length would result in a lowering of the highest frequency for which the generator is useable.

It would have been possible to have produced larger displacements for the lower frequencies by the selection of an electrodynamic driver. Such a choice, however, would severely limit the high frequency performance due to the resonant frequency of the suspension system. Even the smallest electrodynamic units have upper frequency limits of approximately 2,000 cps. Furthermore,

⁵ Corliss, Smith and Magruder, Proceedings 3rd International Congress on Acoustics.

DISPLACEMENT - DECIBELS RE. 1 MICRON (RMS)

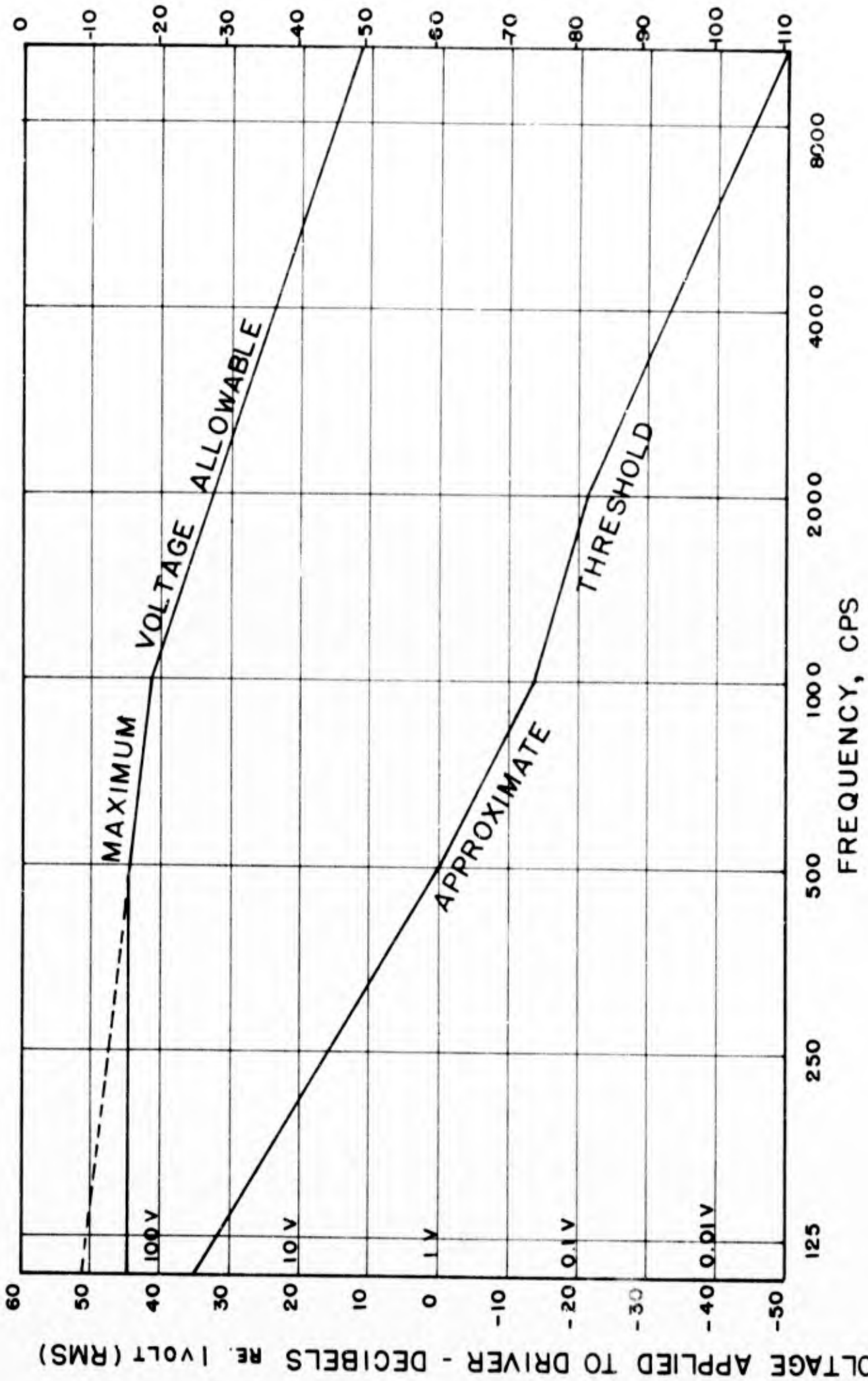


FIGURE 6. APPROXIMATE RELATIONSHIP BETWEEN VOLTAGE ON DRIVER AND TIP DISPLACEMENT.

the driver tips exhibit motion in many degrees of freedom even within their useable range. It was therefore decided that the ceramic element would come closest to meeting the over-all objectives of the program.

RECOMMENDATIONS FOR FUTURE WORK

The philosophy of the design of the integrated vibrator assembly was to provide a unit with maximum versatility of mounting while being capable of operating over a wide range of amplitude and frequency with provision for the continuous measurement of both force and velocity. These general objectives were attained during this program, however, certain limitations were necessarily imposed as a compromise between the extremes of low frequency and high frequency operation. It would therefore appear desirable to approach the problem with less severe requirements being placed upon a single unit. Basically the same requirements were placed on this electromechanical system as are placed on a purely electronic system. Although an electronic amplifier may be designed to operate over several decades, most electronic oscillators capable of good performance are restricted to a range of 1 decade without substantial change of components. It is therefore reasonable to expect that an electromechanical generator might require an even greater restriction of frequency range in order to attain maximum performance.

It is well known that mechanical systems can be operated efficiently only at resonance so that the analog to a discrete frequency, pure-tone audiometer might be considered where the particular driving element for each specific frequency is operated at mechanical resonance. The impedance determining sensors can be made to operate over a wide range of frequencies, but the source of mechanical energy, like an electronic oscillator, needs "tuning" to obtain optimum performance. With such a philosophy, it would appear reasonable that a dynamic range could be attained which would allow for the measurement of tolerance levels as well as threshold levels.

An alternate approach would consider the use of a low frequency and high frequency driver unit to cover the 2 decades from 100 to 10,000 cps. The low frequency driver could then take the advantage of electrodynamic systems whose output velocity is constant with frequency for constant input voltage. Furthermore,

the higher frequency element could be optimized for performance without the restrictions for low frequency operation.

One of the objectives of the program was to provide a variety of driving tips having diameters ranging from a few millimeters to several centimeters, and having shapes including flat circular discs, conical points, and spheres. The necessity of accomodating a variety of tips, while providing for the measurement of dynamic force, introduces a mass reactance which can override the external impedance presented by the body. It would simplify the design considerably if the internal force sensor were eliminated and impedance measurements were made only with flat circular tips, similar to the external force sensors which were provided. Other shapes of tips could also be accomodated, for which the velocity of the tip is measured but the resultant force is ignored. Since the total force is dependent upon the area of contact, the impedance seen by various shaped tips is of questionable value, due to the difficulty of interpretation.

The electronic instrumentation provided with the vibrator assemblies was designed to accomodate a variety of measurement-type instruments. Its purpose was to provide amplification of the signal and impedance transformation so that external instruments would not affect the phase of the signal being generated. Since the output voltages are directly proportional to force and velocity, it would be possible to design electronic circuitry which would continuously compute either the magnitude and phase of impedance or the real and imaginary components of impedance. It would be desirable to consider providing higher signal levels by the methods outlined above and to eliminate the use of internal force sensors so that the effective mass of the force sensor can be minimized or possibly eliminated entirely. Taking into account all of these factors, it would be possible to develop an over-all measurement system whose output would be the actual impedance by the body to a specific tip. It is therefore recommended that future work take into consideration the suggestions made herein, that would lead to an improved system for the automatic measurement of mechanical impedance.

SUMMARY

A vibrator assembly has been developed which allows for the measurement of mechanical driving point impedance at various

locations on the upper portion of the body. Flexibility in mounting position is attained by the use of a reference mass which is floated on an air bearing. Although the reference exhibits motion when the driving tip is subjected to large impedances, it has been possible continuously to compensate for the velocity of the reference mass. Sensors have been provided for the measurement of the tip velocity and the force which results due to an external load. A variety of tip sizes and shapes may be used for the purpose of obtaining threshold measurements by bone conduction. Additional tips have been provided with their own force sensors in order to obtain the most accurate measurement of impedance. Calibrations have been performed which indicate satisfactory performance from 100 to 10,000 cps.

APPENDIX

ELECTRONIC CIRCUITRY

Electronic amplifiers have been provided for use with the force and velocity transducers, in order to provide the proper impedance level for these transducers and to raise the signal level to a value which may be used to drive external indicating or recording instruments. Since the signal output of the transducers may be of quite low amplitude and frequency, the amplifiers were transistorized so far as possible in order to minimize the pickup of hum and other extraneous noise.

The velocity and force preamplifiers are mounted in one unit with their self-contained battery power supply (See Figure 7.). The velocity preamplifier consists of a differential input voltage amplifier having a gain in use of 60 dB and having an output impedance of 3,000 ohms. This differential amplifier is self-balancing and has an internal mode rejection of more than 60 dB. The attenuation switch associated with this amplifier has three positions, which are:

- (1) 60 dB gain with no compensation (the compensation input grounded).
- (2) +40 dB gain with compensation.
- (3) +60 dB gain with compensation.

The compensation potentiometer has been adjusted so that no velocity output is observed when the tip of the vibrator assembly is blocked. This adjustment having been carefully made necessitates the use of a given velocity preamplifier with its particular vibrator unit, i.e., Mark I preamplifier with Mark I vibrator unit, etc. This potentiometer should not be readjusted.

The input impedance of the velocity preamplifier with its associated attenuator and compensation network has been designed to provide the proper impedance match to both the velocity and compensation pickups in the vibrator assembly. The gains referred to are measured with the velocity preamplifier connected to these

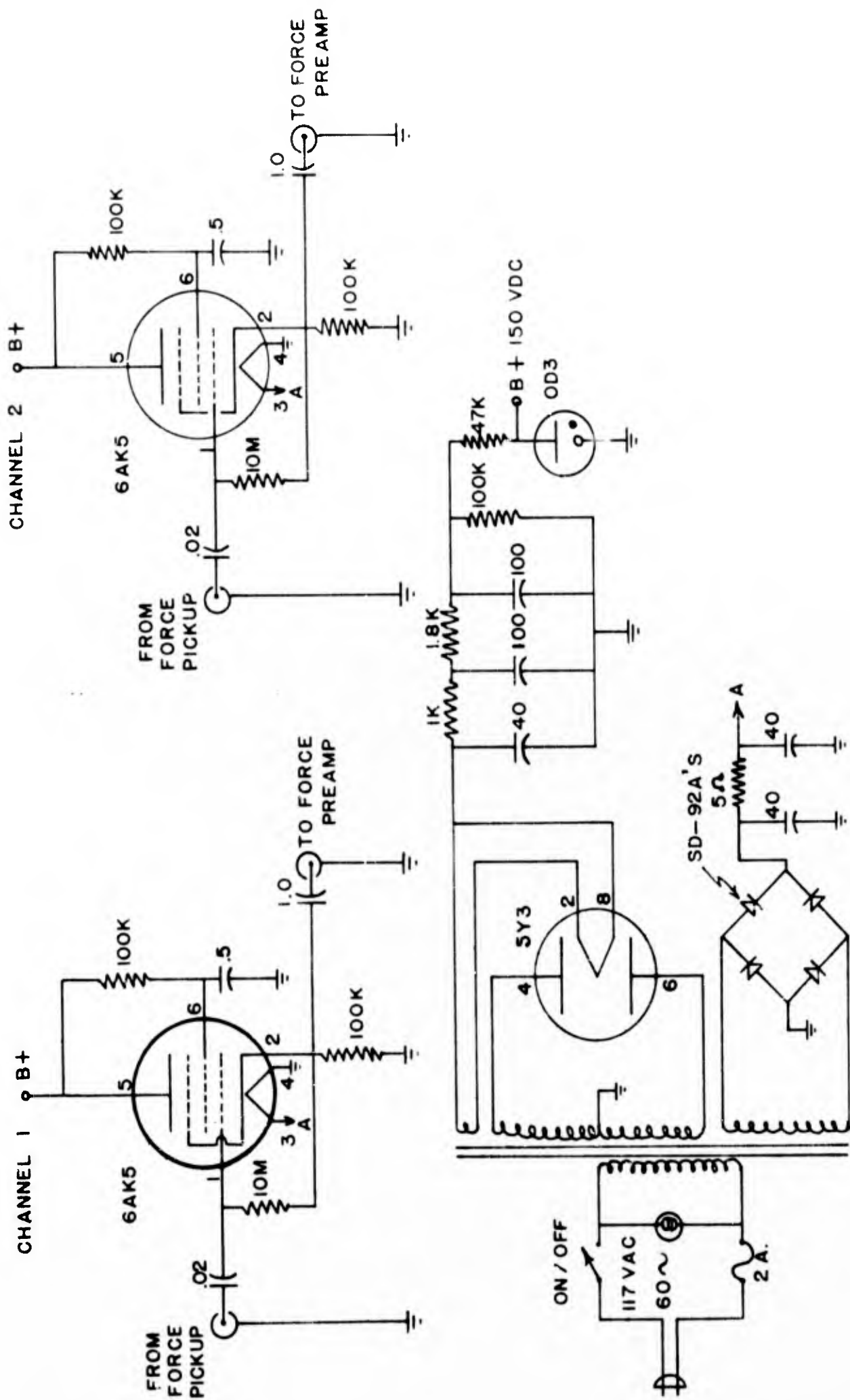
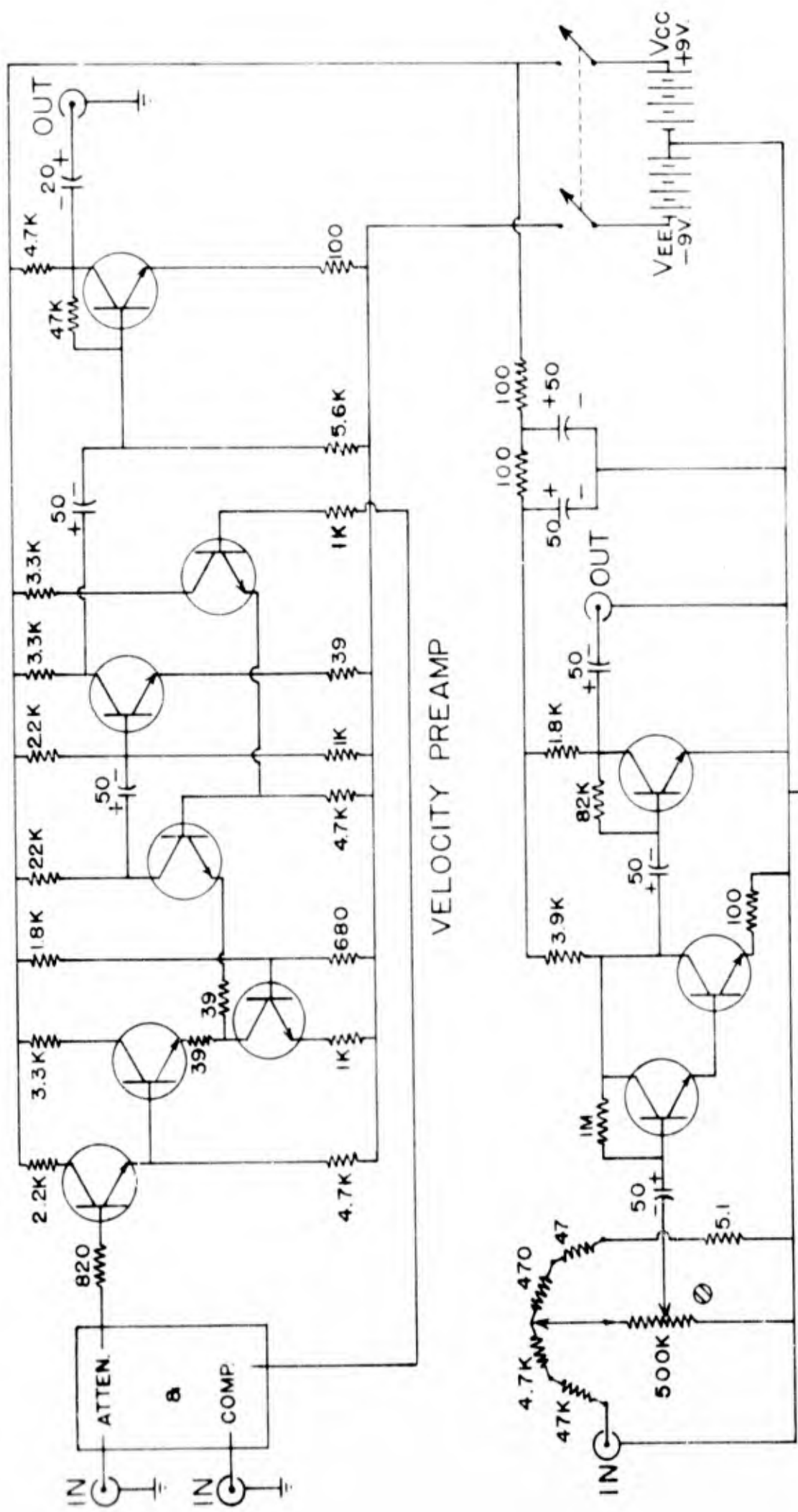


FIGURE 7. SCHEMATIC DIAGRAM OF CATHODE FOLLOWERS AND ASSOCIATED POWER SUPPLY

pickups. The three db points of the velocity preamplifier are 3 cps and 240 kcps, and the battery drain is nominally 18 mA.

The force preamplifier consists of two parts: the transistorized preamplifier mounted in the same unit as its associated velocity preamplifier, and a vacuum-tube cathode follower mounted in a separate unit. The first stage of this preamplifier consists of a compound or Darlington circuit designed to provide high input impedance. The output stage is of conventional design having an output impedance of 1500 ohms. The input potentiometer of this amplifier has been adjusted such that the over-all gains of from -40 dB to +40 dB are available in steps of 20 dB. The three dB points of this amplifier are 3 cps and 140 kcps. Its collector voltage supply is taken from the positive 9 volt battery through appropriate de-coupling filters and returned to ground. The nominal battery drain of this amplifier is 4 mA taken from the positive battery only.

Since the force transducers exhibit a capacitance reactance, it is necessary that they operate into an extremely high impedance in order to preserve the correct phase relationship. For this purpose, a cathode follower has been provided (See Figure 8.). This amplifier has an input impedance in excess of 100 meg.ohms, an output impedance appropriate to the transistorized force amplifier, and a gain of unity. The cathode follower amplifiers associated with both Mark I and Mark II systems are carefully shielded and mounted in the same unit with their power supply.



ALL CAPACITORS IN MICROFARADS
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FIGURE 8. SCHEMATIC DIAGRAM OF FORCE AND VELOCITY PREAMPLIFIERS.