FILE COPY

AD-A232 072

## REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

②

**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
1990

**3. REPORT TYPE AND DATES COVERED**
Proceedings of Meeting

**4. TITLE AND SUBTITLE**
Transducer needs for low-frequency sonar

**5. FUNDING NUMBERS**
Work Unit # Various
Assession # N/A

**6. AUTHOR(S)**
R. W. Timme, A. M. Young, and J. E. Blue

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Underwater Sound Reference Detachment
Naval Research Laboratory
P.O. Box 568337
Orlando, FL 32856-8337

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Various

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**
This article appeared in the Proceedings of the Second International Workshop on Power Transducers for Sonics and Ultrasonics held in France 12-13 June 1990

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Available for public release; distribution unlimited

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

The continued advances in the acoustic quieting of submarines may necessitate the use of active sonar as an adjunct to the traditional passive sonar as a means of detecting submarines. Therefore, there is a growing need for transducers that produce sound underwater at frequencies below 1000 Hz. However, reality is such that it is very difficult to design for low frequency, high power, and high efficiency and still maintain a device possessing reasonable size, weight, reliability, and cost. Different design approaches and transducer types are discussed and compared.

**14. SUBJECT TERMS**
Low-frequency sonar
Transducers

**15. NUMBER OF PAGES**
27

**16. PRICE CODE**

**17. SECURITY CLASSIFICATION OF REPORT**
Unclassified

**18. SECURITY CLASSIFICATION OF THIS PAGE**
Unclassified

**19. SECURITY CLASSIFICATION OF ABSTRACT**
Unclassified

**20. LIMITATION OF ABSTRACT**
SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

## GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements.***

**Block 1.** Agency Use Only *(Leave blank)*.

**Block 2.** Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

**Block 3.** Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

**Block 4.** Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

**Block 5.** Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C - Contract
G - Grant
PE - Program Element
PR - Project
TA - Task
WU - Work Unit Accession No.

**Block 6.** Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

**Block 7.** Performing Organization Name(s) and Address(es). Self-explanatory.

**Block 8.** Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

**Block 9.** Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

**Block 10.** Sponsoring/Monitoring Agency Report Number. *(If known)*

**Block 11.** Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

**Block 12a.** Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

**DOD** - See DoDD 5230.24, "Distribution Statements on Technical Documents."
**DOE** - See authorities.
**NASA** - See Handbook NHB 2200.2.
**NTIS** - Leave blank.

**Block 12b.** Distribution Code.

**DOD** - Leave blank.
**DOE** - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
**NASA** - Leave blank.
**NTIS** - Leave blank.

**Block 13.** Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

**Block 14.** Subject Terms. Keywords or phrases identifying major subjects in the report.

**Block 15.** Number of Pages. Enter the total number of pages.

**Block 16.** Price Code. Enter appropriate price code *(NTIS only)*.

**Blocks 17. - 19.** Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

**Block 20.** Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

# SECOND INTERNATIONAL WORKSHOP ON POWER TRANSDUCERS FOR SONICS AND ULTRASONICS.

# DEUXIEMES JOURNEES D'ETUDES SUR LES TRANSDUCTEURS SONORES ET ULTRASONORES DE PUISSANCE.

June 12th & 13th 1990.
12 et 13 Juin 1990.
Toulon FRANCE.

*Organised by* / Organisées par :
Laboratoire d'Acoustique de l'Institut Supérieur d'Electronique du Nord.

isen

*Workshop sponsors* / Partenaires des journées d'études

Direction des Recherches, Etudes et Techniques (DRET),

Thomson Sintra ASM

Schlumberger Etudes et Productions

CNRS

Toulon Var Technologies (TVT)

## PROCEEDINGS

## TEXTE DES CONFERENCES

*Edited by* / Edité par :
[illegible], B. Hamonic, O.B. Wilson, J.N. Decarpigny.

# CONFERENCE SCHEDULE
# PROGRAMME DES CONFERENCES

## Tuesday 12 June 1990 / Mardi 12 Juin 1990.

**09h15 - 10h00**

*Opening lecture* / Conférence d'ouverture.
**Bernard TOCQUET**
*Conference chairman* / Président du Comité Scientifique.

**10h00 - 12h30**

**SESSION 1:** *GENERAL TRENDS*
TENDANCES GENERALES

**Chairman: Bernard TOCQUET**
Thomson-Sintra, ASM, Valbonne, France

10h00 - 10h40

*TRANSDUCER NEEDS FOR LOW-FREQUENCY SONARS*

LES BESOINS RELATIFS AUX TRANSDUCTEURS UTILISES DANS LES SONARS BASSE FREQUENCE

**Robert TIMME, Mark YOUNG and Joe BLUE**
Naval Research Laboratory, USRD, Orlando, FL, USA

10h40 - 11h00 *BREAK* PAUSE

11h00 - 11h30

*TRANSDUCER NEEDS FOR OCEANOGRAPHY*

LES BESOINS RELATIFS AUX TRANSDUCTEURS UTILISES EN OCEANOGRAPHIE

**Roland PERSON,**
IFREMER, Plouzane, France

RWT/AMY/JEB

# Transducer needs for low-frequency sonar

R.W. Timme, A.M. Young, and J.E. Blue

Naval Research Laboratory, Underwater Sound Reference Detachment,
P.O. Box 568337, Orlando, Florida, USA 32856-8337

The continued advances in the acoustic quieting of submarines may necessitate the use of active sonar as an adjunct to the traditional passive sonar as a means of detecting submarines. Therefore, there is a growing need for transducers that produce sound underwater at frequencies below 1000 Hz. However, reality is such that it is very difficult to design for low frequency, high power, and high efficiency and still maintain a device possessing reasonable size, weight, reliability, and cost. Different design approaches and transducer types are discussed and compared.

## I. INTRODUCTION

The continued advances in the acoustic quieting of submarines may necessitate the use of active sonar as an adjunct to the traditional passive sonar as a means of detecting submarines. Therefore, there is a growing need for transducers that produce sound underwater at frequencies below 1000 Hz. However, reality is such that it is very difficult to design for low frequency, high power, and high efficiency and still maintain a device possessing reasonable size, weight, reliability, and cost. Different design approaches and transducer types are discussed and compared.

## II. FACTORS DRIVING LOW-FREQUENCY SONAR TRANSDUCER NEEDS

Given that there is a need for active acoustic projection, any competent acoustician can tell you that generally means operating at frequencies below 1 kHz for reasons of range, resolution, and scattering. Fig. 1 shows sound scattering intensity from a rigid cylinder at normal incidence to the side as a function of ka where k is $2\pi$ divided by the wavelength of the incident sound and $a$ is the radius of the cylinder.[1] Assuming a 5-m radius as somewhat typical for a submarine and seeing from Fig. 1 that frequencies where $ka \geq 1$ give good sound scattering, one might conclude that frequencies above 100 Hz might be of interest in submarine detection at normal incidence.

## III. LIMITING FACTORS ON HIGH-POWER, LOW-FREQUENCY SONAR PROJECTORS

Transducers designed to produce underwater sound at low frequencies generally have dimensions small compared to the wavelength of the sound produced $(\lambda \gg D)$. For illustration purposes, let us consider a pulsating sphere of radius $a$ where $\lambda \gg a$. Fig. 2 shows the relationships that are important for low-frequency radiation. These relationships for power and source level are plotted in Fig. 3. Note that at 100 Hz, a volume displacement of 1000 cm$^3$ (0.001 m$^3$) will radiate $10^4$ watts of acoustic power and give a source level of 211 dB re 1 μPa at 1 m. However, as can be seen from Fig. 4 for λ>>a, the total input power necessary to supply the acoustic power is controlled primarily by the reactive impedance, and the resistive component of the impedance is very low. Thus, the basic problem is one of poor acoustic loading due to very long acoustic wavelengths in water at low frequencies. Simply stated, this means the transfer of mechanical power at the surface of the radiator to the water in the form of radiated acoustic power is very inefficient. Since the overall efficiency is the product of the radiation and mechanical transduction efficiencies, it will also be low even if the mechanical transduction efficiency is high.

Because high-power, low-frequency sound production requires large volume velocities, the projector must meet the conflicting requirements of counteracting large hydrostatic forces while offering a pressure release mechanism to the interior of the vibrating surface. Virtually none of the pressure-release techniques used at high frequencies are practical at low frequencies. Table 1 compares various pressure-release mechanisms for use in low-frequency transducers.

The most commonly used pressure-release mechanism at low frequencies is compressed gas. If the interior of a transducer is filled with gas at the same pressure as the surrounding water, the transducer is obviously balanced against the forces due to hydrostatic pressure and the large impedance mismatch provides an excellent pressure release.

Compressed gas systems, however, are not without disadvantages:

- the impedance of the gas changes as a function of pressure, thus the acoustic performance of many designs varies as a function of depth,

- since most low-frequency transducers have a large internal volume, applications requiring many depth changes may require a large high-pressure gas storage volume, and
- for applications at very great depths, high-pressure gas systems can become complicated and pose a reliability problem.

Transducers can be made essentially independent of operating depth by filling the enclosed volume with liquid. To do so, however, provides essentially no pressure release. For a given frequency and acoustic output, liquid-filled transducers will be larger, heavier, and require larger driving forces than will transducers using some other compensation mechanism.

As a compromise usable to moderate depths, sealed, air-filled, oval metal tubes can be inserted into the liquid-filled cavity to increase its compliance. This technique provides decreasing pressure-release capability as a function of depth until the compliant tubes are collapsed by the hydrostatic pressure.

Some transducer designs can be made to be simply self-supporting by filling the internal cavity with air at some predetermined pressure. The primary disadvantage, of course, is the severely limited depth capability.

To summarize (see Table 2) from the transducer designers point of view, cost, size, weight, and level of difficulty in design of low-frequency sources increases with:

- decreasing frequency
- increasing sound pressure level
- increasing bandwidth
- increasing operational depth

Most design techniques used at higher frequencies do not scale well to low-frequency applications and each new requirement is essentially a new design problem.

## IV. TRANSDUCER TYPES

Before discussing any of the specific transducer types, it should be noted that there is no general way to quantitatively compare different transduction mechanisms. The ratio of output power to total weight is frequently used, but it neglects the effects of bandwidth, transduction efficiency, and reliability.

Since all of the available low-frequency transducers cannot be treated here, only those most likely to be encountered will be addressed. The most common transduction mechanism in use is, of course, piezoelectric ceramics. Design techniques used at higher frequencies, such as the longitudinal resonator, are not feasible at low frequencies because of the size that would be required to generate the required volume velocities. Low-frequency ceramic designs attempt to take advantage of vibrational modes not normally used at higher frequencies.

### A. Ceramic Flexural Disc

The trilaminar configuration of the ceramic flexural disc transducer shown in Fig. 5 lends itself reasonably well to the high-power, low-frequency application. In the trilaminar configuration, an inactive disc (normally steel or aluminum) is laminated between two ceramic disc composites; when the two ceramic discs are driven in opposition, a flexing motion is produced in the trilaminar structure. To keep the size of the ceramic within reasonable limits, the ceramic discs may be assembled in a mosaic instead of one piece.

In a common configuration, two trilaminar structures are mounted back to back with a spacer ring forming the housing between them which is the compliant annular cavity. The volume between the discs may either be gas filled or oil filled with compliant tubes inserted to provide the necessary pressure release. The enclosed volume can simply be oil filled at the expense of reduced acoustic output.

The ceramic flexural disc can offer a good power-to-weight ratio for some applications over a bandwidth of 1 to 1.5 octaves. Its primary disadvantage is the sensitivity of the resonance frequency to the impedance of the internal cavity.

The maximum input power is limited by the electrical field and maximum stress that the ceramic can withstand.

## B. Flextensional Transducers

In its common form, the flextensional transducer shown in Fig. 6 consists of an elliptically shaped housing, or shell, with a longitudinally vibrating ceramic stack mounted along its major axis. Unlike the flexural disc transducer, the housing (not the ceramic) forms the radiating surface. The ceramic stack is compressively prestressed by the shell to assure that it does not go into tension and fracture at high drive levels.

A single large shell may be used or several small shells may be stacked together in a line configuration. In either case, the open ends of the shell are sealed and the resulting internal volume may be either gas filled or oil filled and compliant tubes inserted. For relatively shallow depths, the transducer can be made self-supporting by filling the cavity with air at atmospheric pressure. To do so, however, means that the prestress on the ceramic and, therefore, the safe driving voltage decreases as a function of depth.

The flextensional transducer does offer a good power-to-weight ratio, but they are resonant devices and have a Q higher than most non-ceramic designs. It can also be highly efficient. Its primary disadvantage compared to other low-frequency ceramic transducers is difficult design, particularly for low-resonance frequencies.

## C. Ceramic Bender Bar Transducers

The ceramic bender bar transducer shown in Fig. 7 typically consists of multiple "bars" arranged in a "barrel stave" configuration around a cylindrical housing. Each bar consists of two segmented stacks of ceramic and is "hinged" at each end. When the stacks are driven in opposition, a bending motion is produced in the bars.

The barrel stave configuration of the transducer results in a central cavity which is normally oil filled to compensate for hydrostatic pressure. Compliant tubes are inserted into the cavity to increase its compliance and to provide the necessary pressure release mechanism for radiation from the inner surfaces of the bars. Some very low frequency designs do, however, use compressed air as the pressure-release mechanism.

The transducer is capable, however, of producing moderately high output power levels over a frequency range of an octave or so and at depths to several hundred meters; it does have the advantage of proven reliability. However, its design is such that it uses a very large amount of ceramic, thus it is heavy and expensive.

As in the case of the flexural disc, the input power is limited by the electric field and maximum stress that the ceramic can withstand.

## D. Moving-Coil Transducer

The electrodynamic, or moving coil, transducer shown in Fig. 8 is one of the oldest designs still in use and derives its driving force from the interaction between an ac current moving in a conductor and a large magnetic field. In the most common configuration, the force is used to drive a rigid piston radiator. When applied to the requirements of low-frequency sources, the moving coil offers some distinct advantages:

- it can be, and usually is, designed to have a very low resonance frequency,
- being a typically large compliance system, it can accommodate large linear displacements,
- wide operating bandwidths are relatively easily achieved.
- very low levels of harmonic distortion may be achieved.

It does, of course, also have several disadvantages:

- the moving coil is typically an inefficient transduction mechanism,
- it is a relatively small force device,
- compressed gas is used as a pressure release mechanism.

Being a large compliance system with a gas pressure-release mechanism, low-frequency, moving-coil transducers typically exhibit large changes in performance as a function of depth.

As a relatively low-force device, the moving-coil transducer is capable of producing moderate output power levels when used as a single surface radiator. For higher acoustic output requirements, it is normally used in arrays.

The limitation upon the maximum input electrical power is determined by how well the heat generated in coil can be dissipated.

## E. Hydraulically Actuated Transducers

In a common form, the hydraulically actuated transducer as shown in Fig. 9 consists of two opposing flexural discs driven by a central hydraulic amplifier. A low-level electrical signal with the desired acoustic waveform is used to control the hydraulic amplifier while the hydraulic power is supplied by an electrically driven pump. The hydraulic system can essentially be housed within the transducer module, eliminating the need for handling high-pressure hydraulic lines from the surface. The transducer is normally designed to be self-supporting to depths of several hundred meters and may be gas compensated to go deeper.

Hydraulic transduction seems ideally suited for low-frequency broad bandwidth applications because of the ability to produce very large mechanical forces from a relatively small package and yet allow for the required large linear displacements. A hydraulically actuated source typically produces moderately high acoustic output levels over bandwidths of two octaves or more. The power-to-weight ratio is comparable to or slightly less than that for some of the ceramic sources.

The primary disadvantage of hydraulic transduction is reliability; it is a relatively complex system and, as such, must be maintained to a greater extent than other transduction mechanisms.

## F. Other Sources

There are source types other than C-W, and the restrictions on the use of impulse type sources (sparkers, air guns, "water hammer" devices, etc.) are primarily set by the requirements of the experiment. If the repeatable complex waveform from a C-W source is not essential, the use of impulse sources should be considered since they are generally easier to design and operate. There is no general basis for comparing impulse sources with other types.

In the discussion above on flexural discs, flextensionals, and bender bar transducers, no mention was made of utilizing rare earth iron alloys as the transduction mechanism in place of ceramic. These alloys can, of course, be used, and the potentially greater transduction energy density will provide certain advantages. However, the overall efficiency of the transducer will not be appreciably changed because of the dominance of the radiation efficiency which results from the fact that ka is small.

There are other transduction mechanisms, such as the tow-powered source and the thermoacoustic source, which have not been discussed here because they are still very much in the development phase. They are radically different from the conventional methods and will be described later in these proceedings.

### G. Summary

Table 3 compares some of the advantages and disadvantages of the types we have discussed. If, for example, broadband acoustic power is required at depths of several hundred meters, the hydraulically actuated source is probably the logical choice; the same bandwidth and acoustic requirements at a shallower depth may make the moving-coil transducer the most attractive; and yet, if the bandwidth requirement is reduced and the depth requirement retained or increased, one of the ceramic or rare earth iron alloy driven transducers could become the best choice.

## V. CONCLUSION

We are entering an era in which active sonar may become more important. Transducers will be needed which operate over a frequency range extending from perhaps 100 Hz or so up to about 1000 Hz, although it is unlikely to expect one transducer to operate over this entire band. The required source levels will likely be high - on the order of at least 200 dB re 1 $\mu$Pa at 1 m. Emphasis will also be on efficiency and reliability, and cost will always be a factor. Knowledgeable users will not insist upon small size because of the greater efficiency concern. It is also likely that for the sonar application, these transducers will be operated in close-packed arrays for the gain and directivity.

In conclusion, there is no general answer to the question of "which type of transduction mechanism is best suited for low-frequency applications?" The user and the transducer designer must decide which transducer type best suits the requirements of a particular experiment. The transducer designer cannot make the decision alone since the user defines the restrictions as well as the requirements.

The idea of designing single sources to cover a wide range of applications may not be as attractive as one might initially think. The transducer designer has no choice but to design for the worst case requirement, which usually means the maximum required volume velocity. If the required bandwidth is appreciable, the result will probably be a transducer which is grossly overdesigned for the higher frequency end of the band. One last thought concerns array interactions; if the projector is to be used in an array configuration, then consideration had best be given to interactions between a projector and its neighbors. Its performance will very likely be different than free-field.

## References

1. P.M. Morse and K.U. Ingard, Theoretical Acoustics (McGraw-Hill, New York, 1968).

# TABLE CAPTIONS

| | |
|---|---|
| Table 1. | Pressure release mechanisms for use in low-frequency transducers |
| Table 2. | Characteristics of low-frequency C-W acoustic sources |
| Table 3. | A comparison of the advantages and disadvantages of the several types of low-frequency sources |

Table 1. Pressure release mechanisms for use in low-frequency transducers

| Mechanism | Advantages | Disadvantages |
|---|---|---|
| Compressed Gas | Large impedance mismatch, good pressure release | Acoustic characteristics are depth dependent, depth limited |
| Liquid | Independent of depth | High mechanical impedance, poor pressure |
| Compliant Tubes | Better pressure release than liquid alone | Depth limited |
| Self-supporting | Simple | Severely depth limited |

Table 2. Characteristics of low-frequency C-W acoustic sources

| Characteristic | Attributable To: |
|---|---|
| Large size, low overall efficiency | Low radiation efficiency |
| Heavy, poor reliability | Large forces required |
| Expensive | Poor acoustic loading requires large amount of reactive power |

Table 3. A comparison of the advantages and disadvantages of the several types of low-frequency sources

| Type | Advantages | Disadvantages |
|---|---|---|
| Ceramic Flexural Disc | Relatively simple device, good power to weight ratio | Resonance frequency is sensitive to impedance of internal cavity |
| Flextensional | Good power to weight ratio | Difficult design |
| Bender Bar | Reliability | Power to weight ratio |
| Electrodynamic | Large linear displacements<br>Low resonance frequency<br>Wide bandwidth<br>Low harmonic distortion | Typically inefficient<br>Small force device<br>Compressed gas compensation |
| Hydraulically Actuated | Wide bandwidth high force device | Complicated design<br>Maintenance schedule required<br>Typically inefficient |

# FIGURE CAPTIONS

Fig. 1 - Scattering of sound from a rigid cylinder of radius a. ($k = 2\pi/\lambda$)

Fig. 2 - Relationships for radiation from a uniformly pulsating sphere of radius a where $ka \ll 1$.

Fig. 3 - Source level and acoustic power radiated from an harmonically pulsating sphere with $ka \ll 1$.

Fig. 4 - Components of acoustical impedance for a spherical harmonic wave from a pulsating sphere of radius a.

Fig. 5 - Flexural disk transducer.

Fig. 6 - Flextensional transducer.

Fig. 7 - Bender bar transducer.

Fig. 8 - Moving coil transducer.

Fig. 9 - Hydraulically actuated transducer.

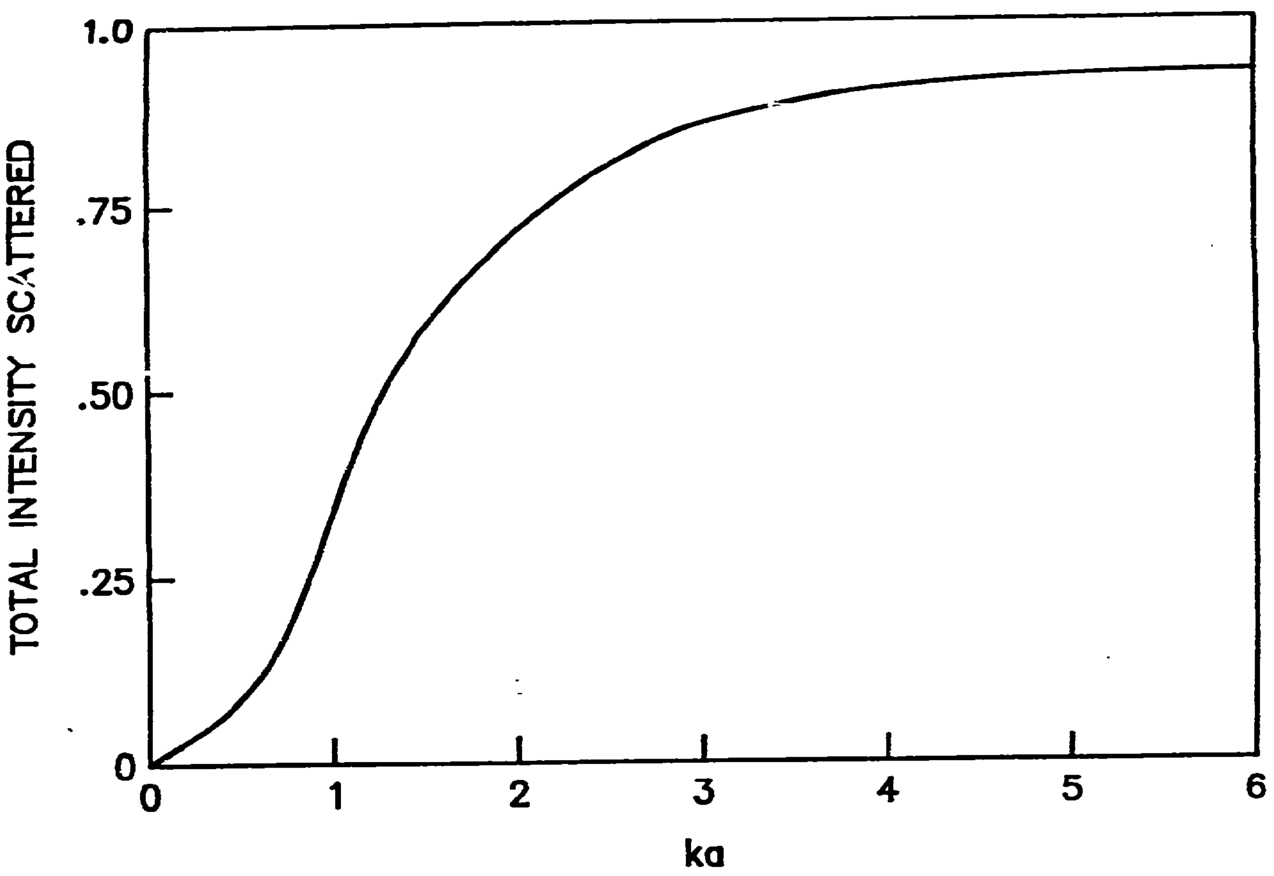

Fig. 1. Scattering of sound from a rigid cylinder of radius <u>a</u>. ($k = 2\pi/\lambda$)

PRESSURE AT THE SURFACE OF THE SPHERE:

$$p(a) \cong \rho c v_n (ka)^2 - i\rho c v_n ka$$

$v_n$ = velocity of surface of sphere

TOTAL RADIATION IMPEDANCE:

$$Z = \frac{F}{v_n} = R_r + iX_r$$

with

$$R_r \cong \rho c(4\pi a^2)(ka)^2,$$

$$X_r \cong -\omega(4\pi\rho a^3).$$

SOURCE LEVEL IN THE WATER REFERENCED TO 1 METER FROM THE SPHERE:

$$|p|_{1m} = \frac{\omega\rho U}{4\pi} = \frac{\omega^2\rho X}{4\pi}$$

U = volume velocity, and

X = volume displacement

ACOUSTIC POWER RADIATED:

$$P = v_n^2 R_r = \frac{4\pi}{\rho c} p^2$$

Fig. 2. Relationships for radiation from a uniformly pulsating sphere of radius $\underline{a}$ where $ka \ll 1$.

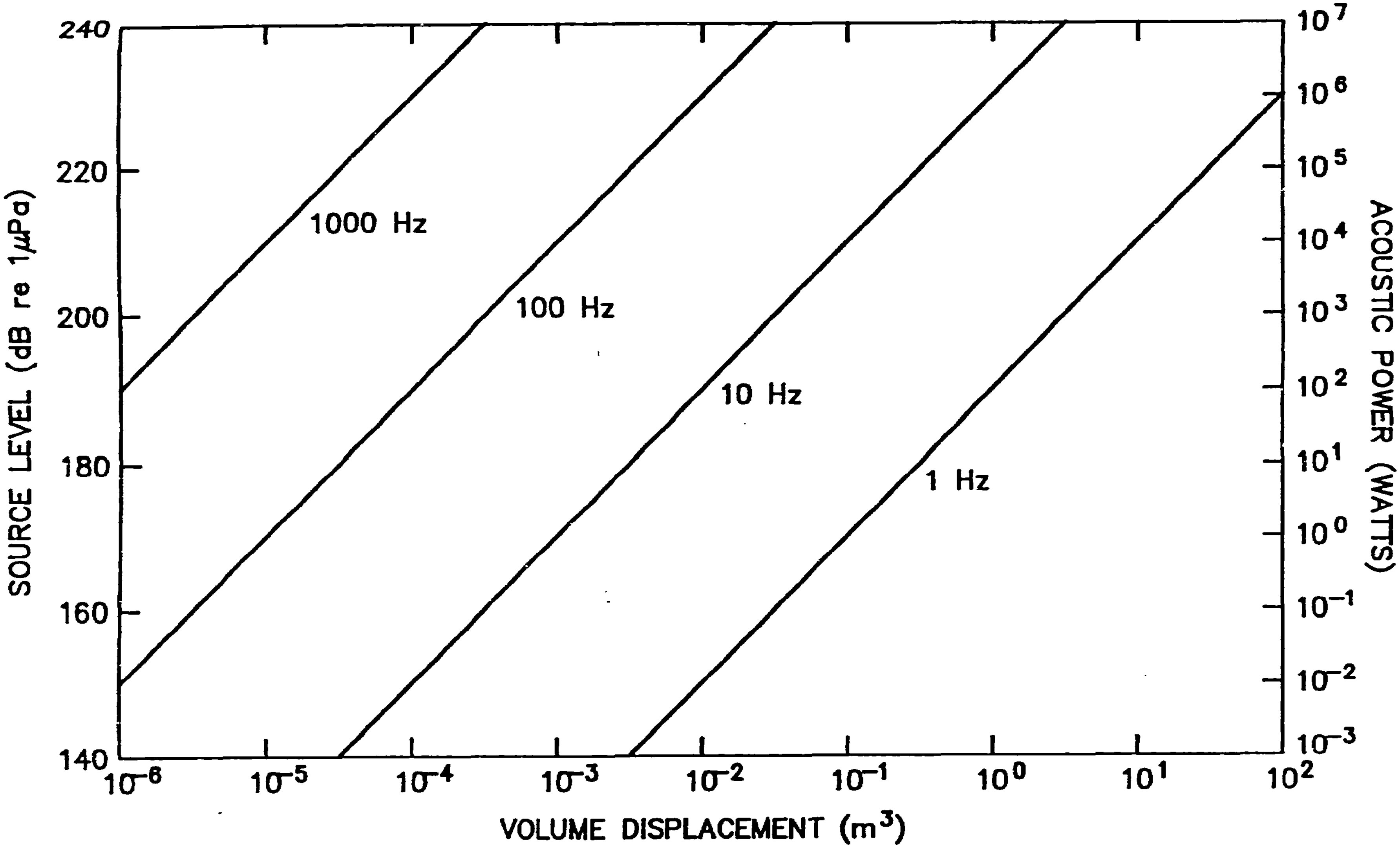

Fig. 3. Source level and acoustic power radiated from an harmonically pulsating sphere with $ka \ll 1$.

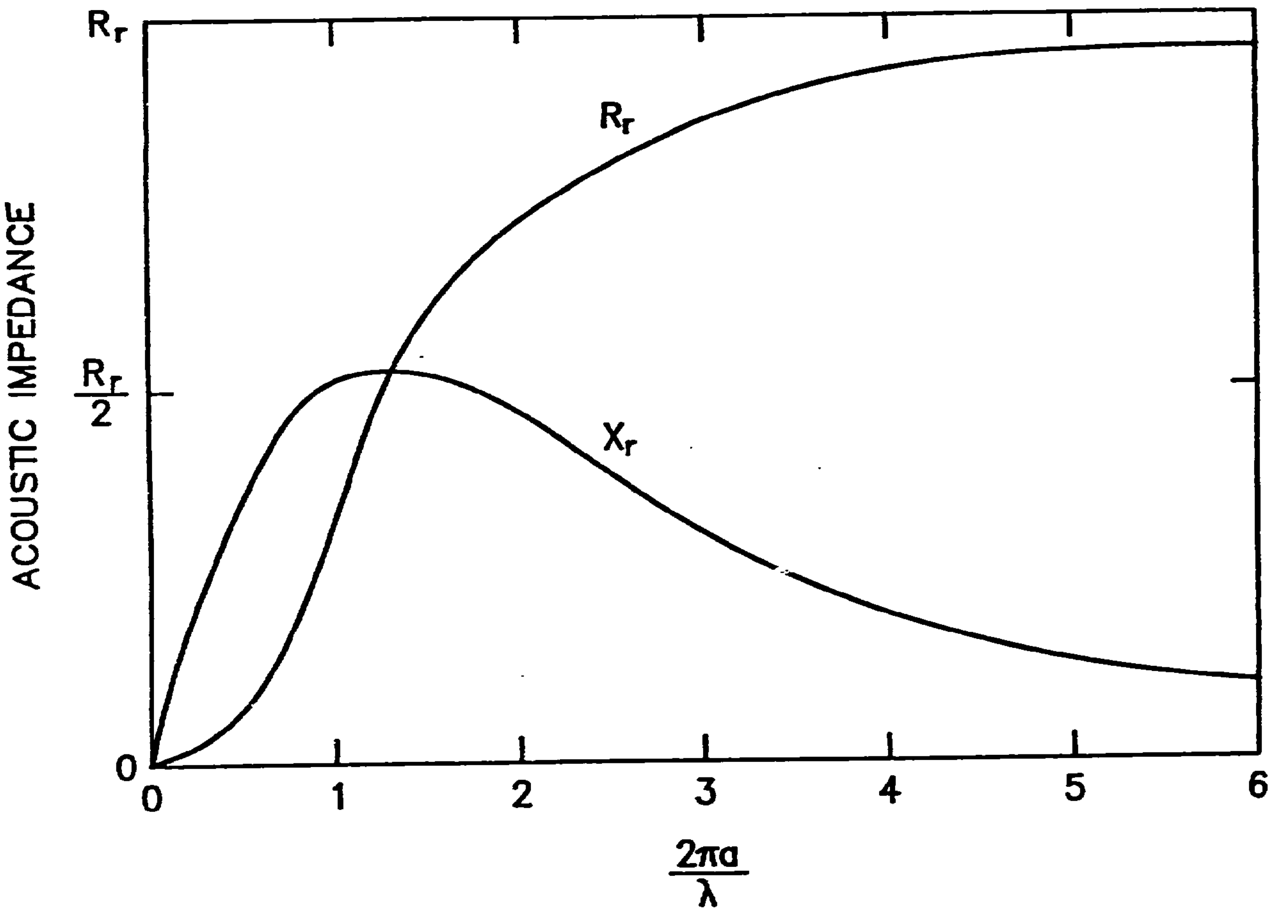

Fig. 4. Components of acoustical impedance for a spherical harmonic wave from a pulsating sphere of radius a.

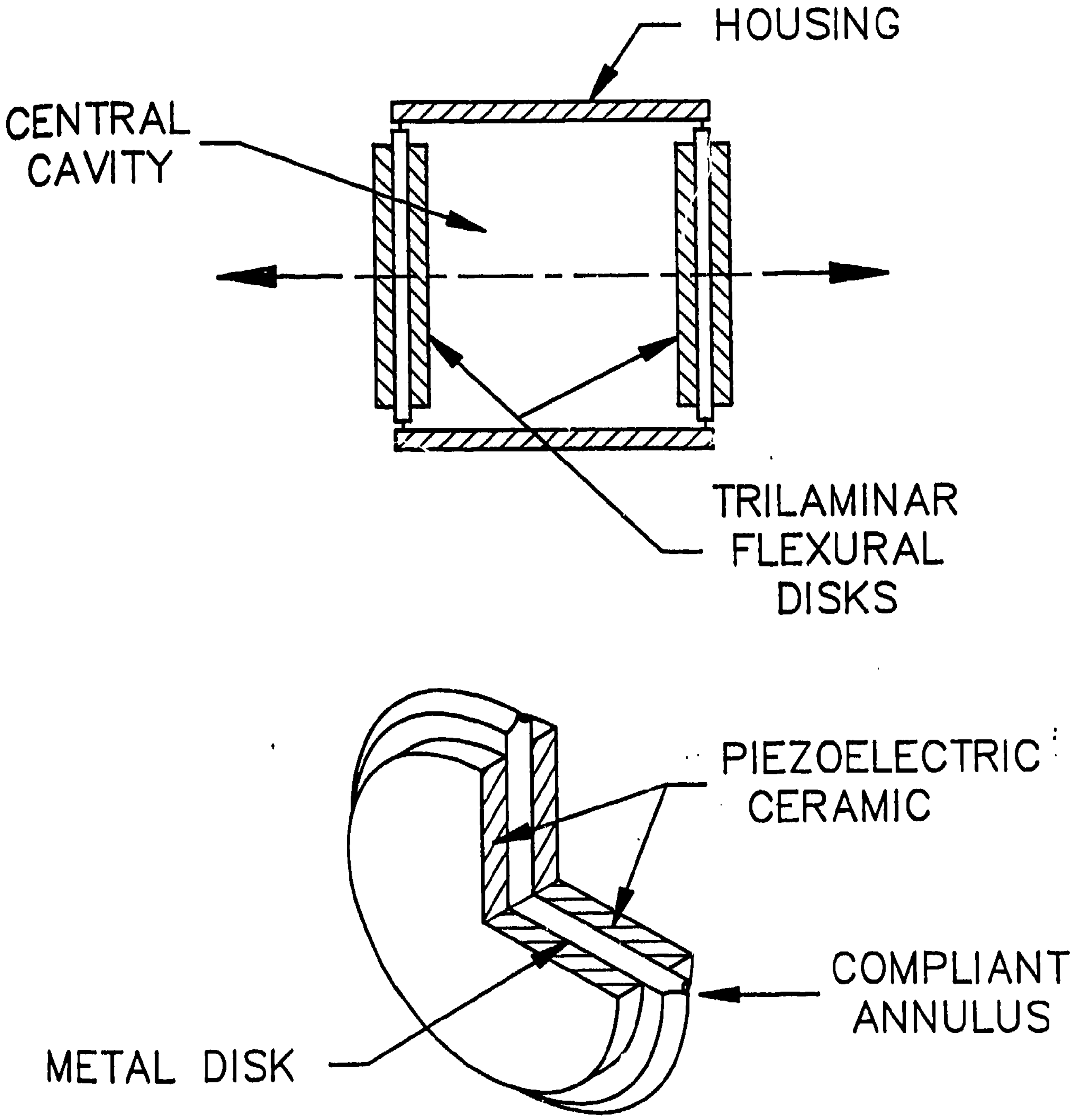

Fig. 5. Flexural disk transducer.

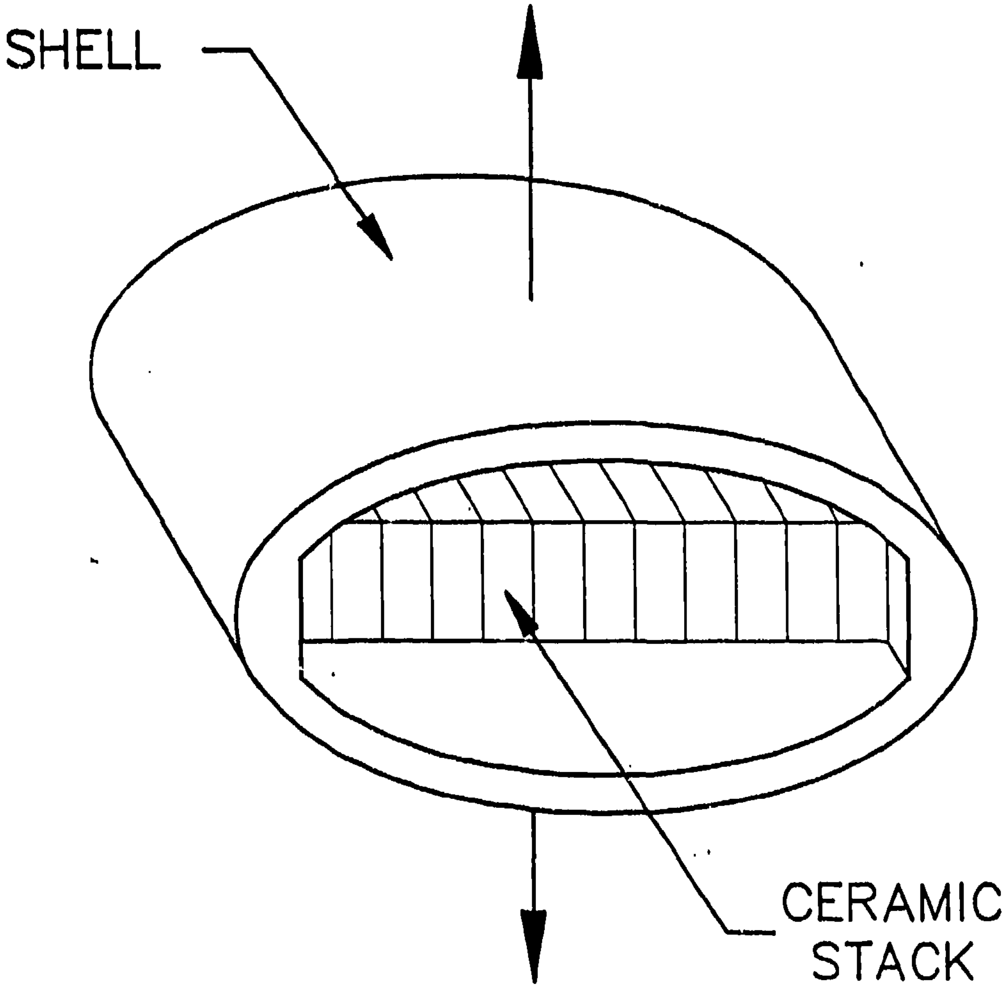

Fig. 6. Flextensional transducer.

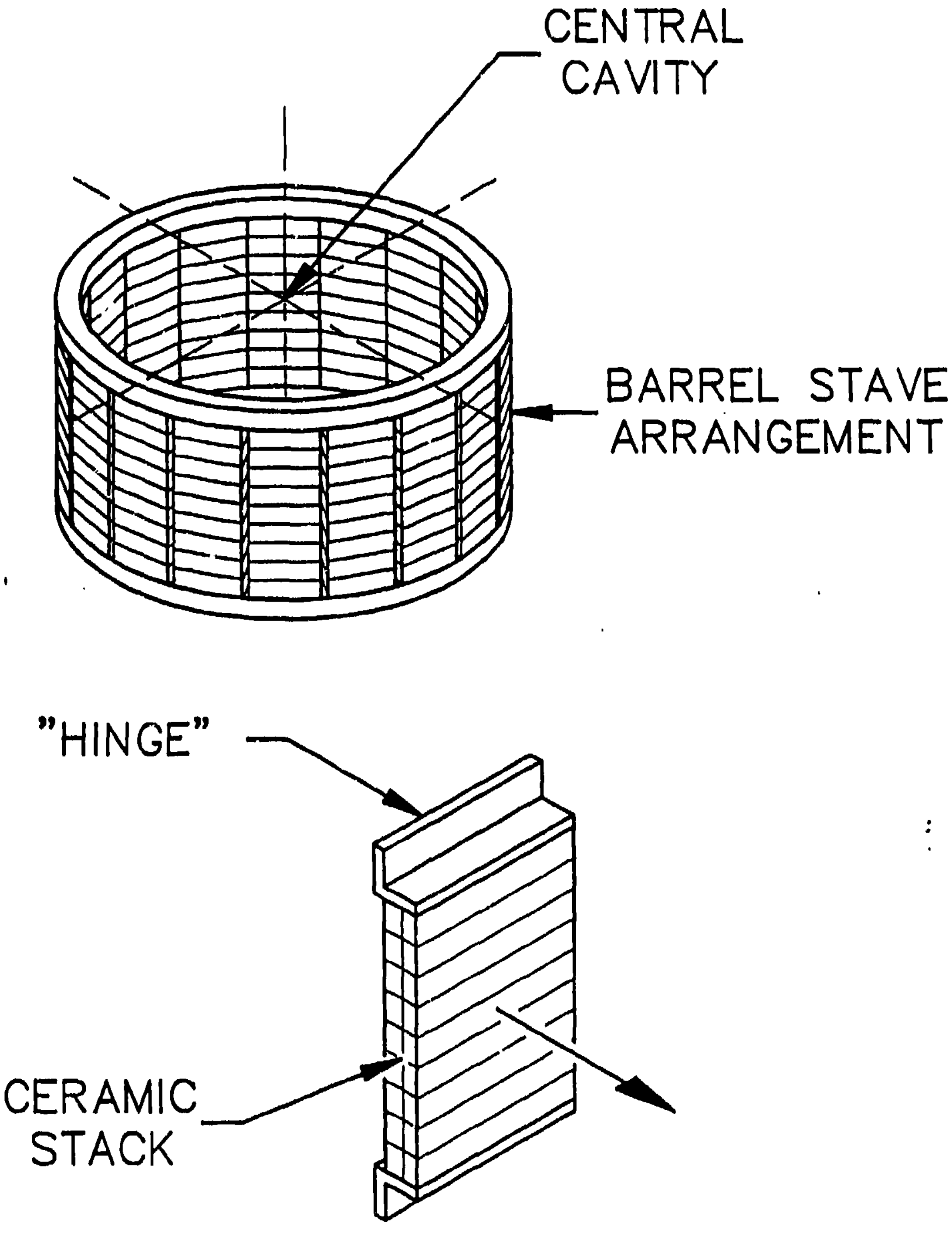

Fig. 7. Bender bar transducer.

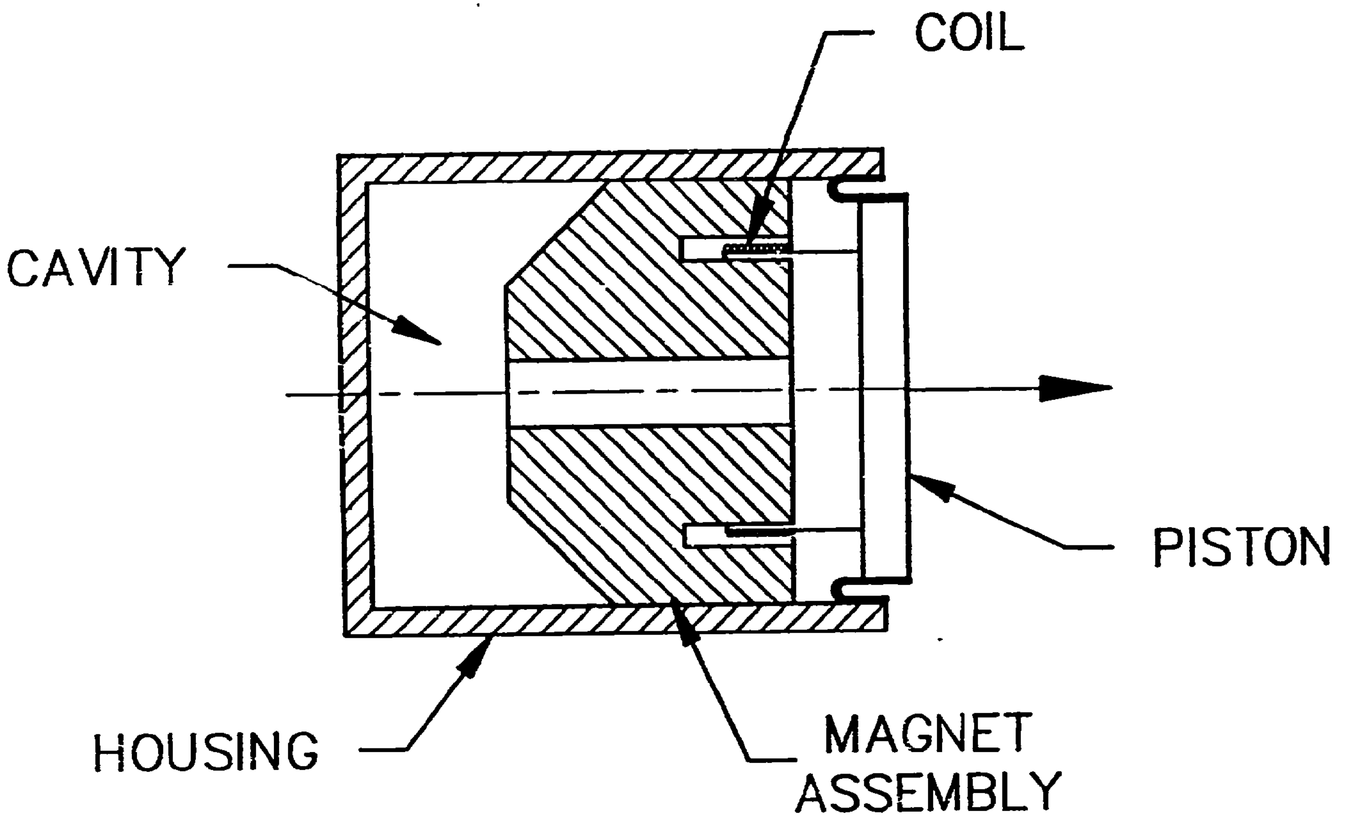

Fig. 8. Moving coil transducer.

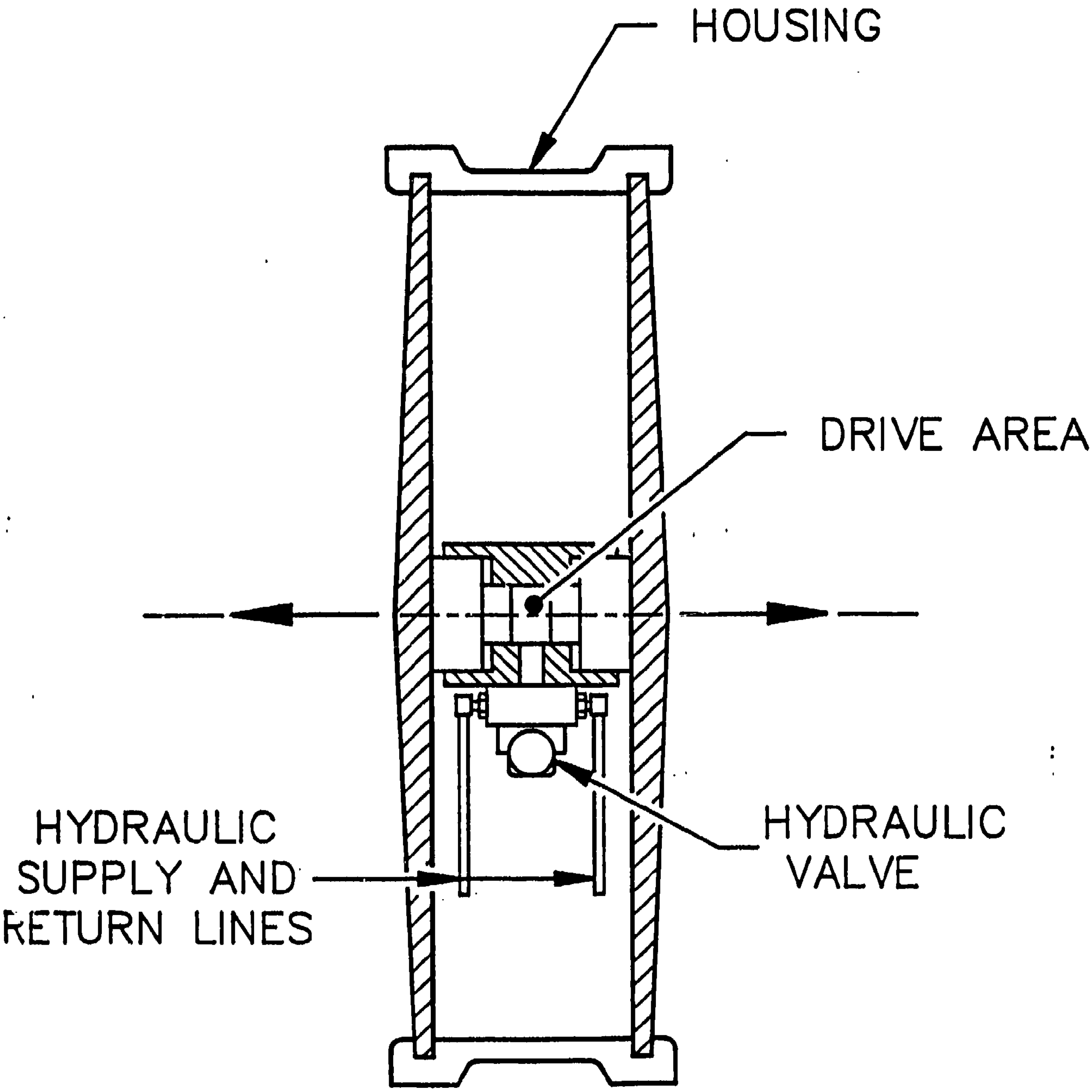

Fig. 9. Hydraulically actuated transducer.