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Low-Frequency Underwater Flex-Beam Transducer

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13. ABSTRACT *(Maximum 200 words)* Acoustic sources that operate at frequencies below 1000 Hz are usually very large if they are required to generate sound power greater than one acoustic watt. Certain naval requirements call for compact low-frequency narrow band acoustic sources. The Naval Research Laboratory's Underwater Sound Reference Detachment has developed a unique underwater acoustic source with the capability of producing high acoustic levels in a small package at a fraction of the cost of comparable transducers. Several prototype transducers have been constructed which feature a fixed-free beam excited in flexure. The basic component, referred to here as a "paddle," comprises a steel beam sandwiched between two piezoelectric ceramic plates and connected to a support base. One transducer prototype includes two such paddles attached to a common base in a "U" configuration and electrically driven in phase. This assembly is housed in an oil-filled, thin elastomeric sleeve attached to circular endcaps. An additional feature of the device is an air-filled bladder mounted between the two paddles which acts as an acoustic pressure release surface, thereby reducing the stiffness of the internal cavity. The measured free-field performance of this simple device gives a peak transmitting voltage response of 120 dB re 1 μPa/V at 1 m at a frequency of 355 Hz.

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LOW-FREQUENCY UNDERWATER FLEX-BEAM TRANSDUCER

INTRODUCTION

Acoustic transducers that can produce high-power, low-frequency sound in the ocean are typically characterized by large size and weight. It is desirable to be able to generate hundreds of watts of acoustic power at frequencies below 1000 Hz with a device that is small enough to be deployed from an aircraft, surface vessel, or submarine. One way to meet both the power and size requirements is to design an array that is made up of multiple small narrow band sources, each having a slightly different characteristic frequency, assembled in a modular configuration. Such a source array would be compact and have high-power output and a broad effective bandwidth. The new transducer concept described in this report takes advantage of a unique geometry that provides both considerable radiating area and large volume displacements in a compact configuration.

The featured geometry is a flexurally excited fixed-free beam. Based on this simple driving mechanism, the development and analysis of transducer prototypes is presented here. A single flex-beam prototype was designed and constructed based on the result of a preliminary analysis which used a finite element model. Testing of this single-beam prototype enabled the advancement of the numerical model to comprehensively analyze the behavior of a two-beam array. The initial analysis of the two-beam array was performed for in-air conditions and then the water loading was incorporated. Comparisons of in-water tests made at the USRD Lake Facility were made with the results from the coupled radiation finite element model. This report presents suggestions for alternative designs and limitations of the existing prototype.

CONCEPT

The basic operating principle of this new sound source is to drive flexurally a fixed-free beam by using piezoelectric ceramic plates attached to the beam and excited in the 31-mode (Fig. 1). This mode of operation has the advantage of giving the lowest modal resonance for a specific beam length [1]. A transducer developed with this concept has a low resonance frequency (below 1000 Hz) and has a relatively high efficiency compared with similar compact, low-frequency transducers.

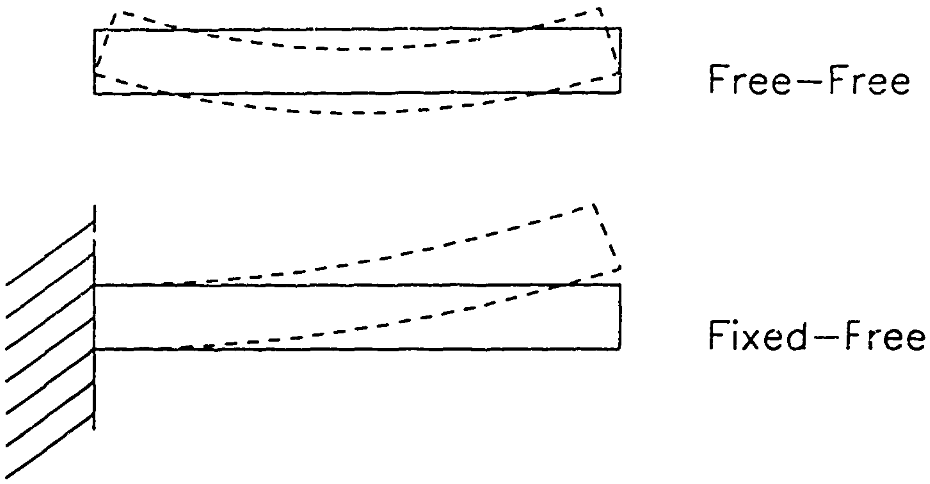

Fig. 1 - Fundamental modes of beam configurations.

Design of Single Flex Beam

After some preliminary numerical modeling, a composite beam configuration was designed and constructed utilizing the fixed-free beam concept described above. The basis of the design is a beam driven at the fundamental mode of vibration by piezoelectric plates attached to both sides of the beam to provide a push-pull mode of operation. This beam configuration, hereafter referred to as a "paddle," is illustrated in Fig. 2.

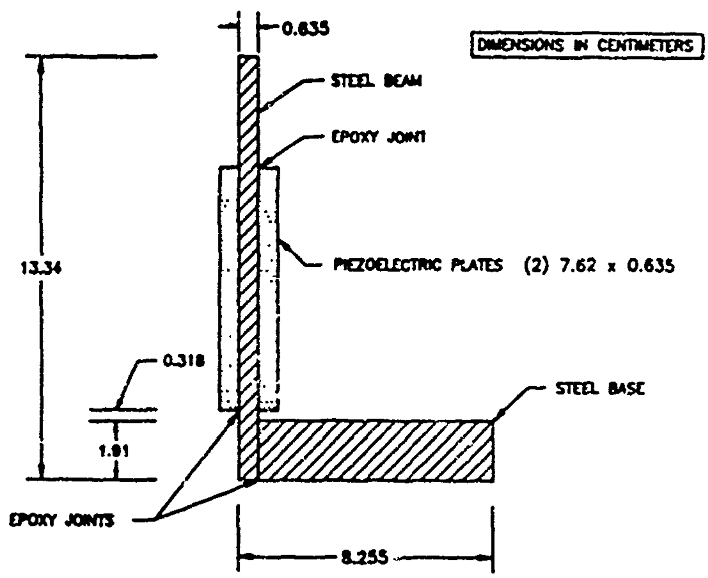

Fig. 2 - Cut-away view of a single flex-beam configuration.

The piezoelectric plates are thickness poled and are used in the transverse mode of operation; that is, the plates are driven so that one plate is increasing in length on one side of the beam while the opposite piezoelectric plate is driven so that it is contracting in length. The combined drive of the opposing piezoelectric plates produces a bending moment in the beam. The piezoelectric plate dimensions were chosen to fit within the overall geometry constraints of the transducer. The ceramic thickness was chosen to accommodate the necessary high voltage. For PZT-4, the maximum safe electric field is 1 kV per 0.254 cm of ceramic thickness in the poling direction [2]. For the 0.00635 m (0.25 in.) thick ceramic used in the design this would allow a 2500 V continuous drive. The entire steel beam is sandwiched between two shorter piezoelectric plates. According to Woollett [3], about 60% of a fixed-free beam length is capable of efficiently being driven to produce the bending moment. Additional ceramic would not significantly contribute to the motion although would be expending energy and thus lowering the overall efficiency. The laminated beam is attached to a steel base whose dimensions were configured to provide an effective inertial mass.

Analysis of Single Flex Beam

The analysis performed on the single paddle was done in a step-by-step procedure; that is, a different numerical model was developed for each stage of the transducer assembly in order to identify any inaccuracies in the analysis.

The first model included only the "L-shaped" steel beam and steel base as shown by the hatched areas in Fig. 2. An in-air modal analysis was performed using the ATILA [4] linear finite element code. The modal frequencies obtained from this model were compared to those obtained experimentally by mechanically exciting the base-beam assembly. Since there was good agreement between the experimental and numerical results, it was concluded that both the steel material properties were accurate and the mesh density for the finite element model was adequate.

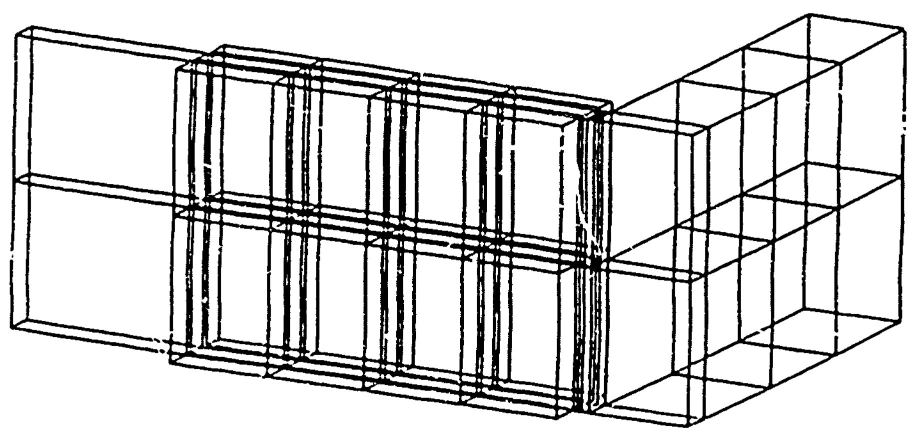

Fig. 3 - Three-dimensional finite element mesh of a single flex-beam.

Next, the piezoelectric ceramic plates were added to the model. The finite element mesh of this "paddle" assembly is shown in Fig. 3. Note that the adhesive layers between the plates and the beam were assumed to be ideal, infinitesimally thin bonds. The fundamental resonance frequency obtained from this model is 1150 Hz. Unfortunately, the electromechanical resonance frequency measured on the bench (934 Hz) did not match the numerical results. It was believed that this discrepancy was due to either the elasticity of the adhesive layer or inaccurate material properties of the piezoelectric ceramic. Therefore, a finite element model was developed for the piezoelectric plates alone. For this case, there was good agreement between the experimental and numerical resonance frequencies. This implies that the adhesive layer produces most of the difference in the measured and numerical resonance frequencies of the single flex-beam "paddle." A choice at this point could be to extend the finite element ATILA model to include a thin adhesive layer. However, current ATILA array dimension values were not sufficient to allow a full three-dimensional finite element model of the single paddle with the adhesive layer while retaining 4 to 1 aspect ratio for finite elements. (The aspect ratio is the length of the longest side to the shortest side of the finite element.) Aspect ratios larger then 4 to 1 can lead to numerical inaccuracies. As an alternative, a two-dimensional plane strain model was developed for the paddle with the adhesive layer. The validity of this approach was supported by good agreement between the two-dimensional plane strain model and the full three-dimensional model when no adhesive layer was included. This agreement showed that the in-plane motion can be ignored for the modes of interest. The two-dimensional model with the adhesive layer is shown in Fig. 4. The resultant resonance frequency for this two-dimensional model is 1068 Hz. Again, this frequency did not agree favorably with the experimental resonance frequency of 934 Hz. It was then hypothesized that the differences in these frequencies could be due to the nonuniformity of the adhesive layer. The finite element model had been developed assuming a uniform thickness. To test this theory, another single paddle was constructed with both surfaces of the steel beam ground flat to assure a uniform adhesive layer. This resulted in a significantly stiffer structure with a measured resonance frequency of 1071 Hz which agrees well with the finite element results of 1068 Hz.

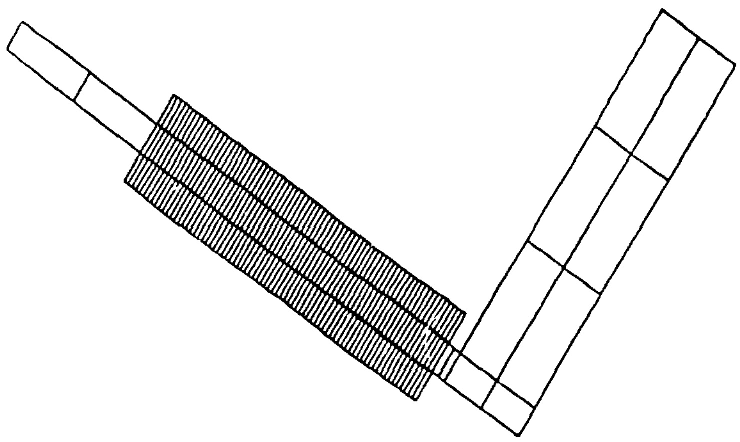

Fig. 4 - Two-dimensional finite element mesh of a single flex-beam including the adhesive layer.

Design of Two-Paddle Array

Figure 5 is a diagram of the two-paddle array which includes two "L-shaped" paddles in an opposing configuration. This nearly closed configuration was chosen so as to transfer the oil acoustic shunting from the outer to inner areas. Acoustic shunting reduces the amount of acoustic energy that is radiated to the medium. The two side plates provide mechanical support for the paddle assembly and also act as baffles to block the acoustic path from the exterior to the interior of the assembly. Fine tuning of the paddle assembly can be performed by optimizing the spacing between the paddle assemblies to allow maximum acoustic baffling with minimum viscous losses. Smaller spacing increases the amount of acoustic energy radiated but also increases losses due to the viscosity of the fill fluid.

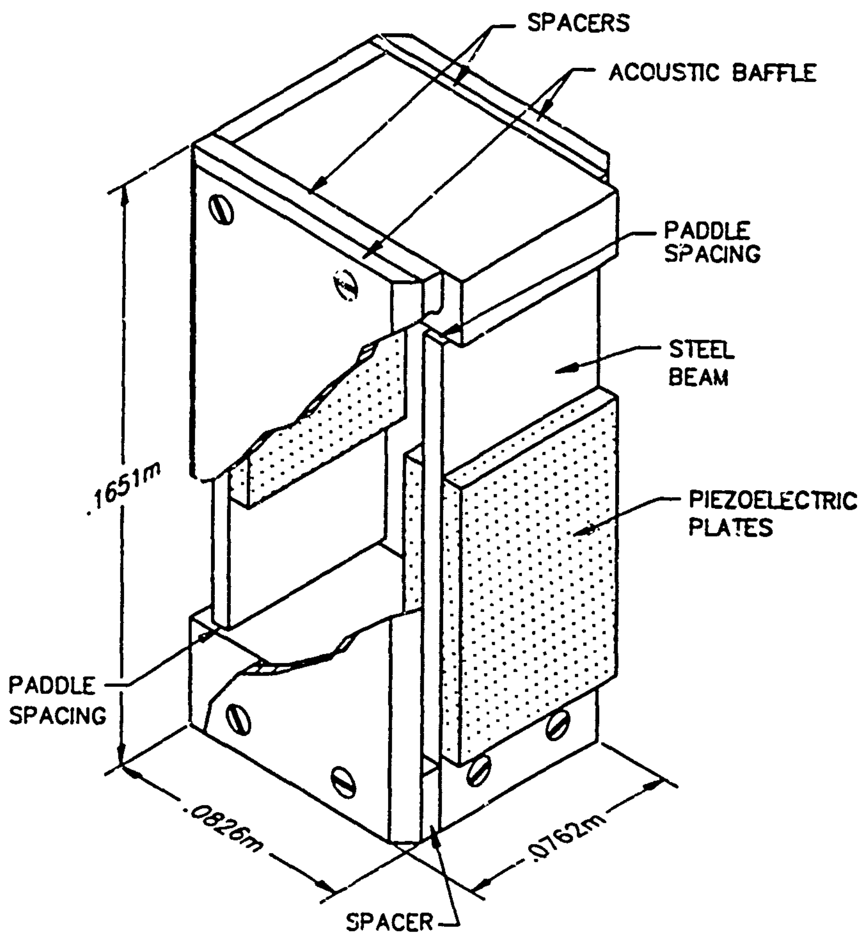

Fig. 5 - Two paddle array.

Analysis of Two-Paddle Array

The analysis of the two-paddle array included both in-air and in-water results. First, a three-dimensional finite element model was developed, again omitting the adhesive layer because of the mesh size limitations in ATILA at that time. Mode shapes computed by the numerical model are shown in Figs. 6

and 7. Figure 6 is the first coupled mode and was computed to be at 556 Hz. The second mode (Fig. 7) computed at 626 Hz is a dipolor mode which is not excited when the transducer is driven electrically. This dipolar mode is presented only because it also was used to compare to the results obtained from the experimental modal analysis procedure.

Results from the experimental modal analysis showed the first mechanical resonance was at 434 Hz, while the second mechanical resonance occurred at 508 Hz. The difference between the experimental data and the numerical results can be attributed to the absence of the adhesive layer in the numerical model.

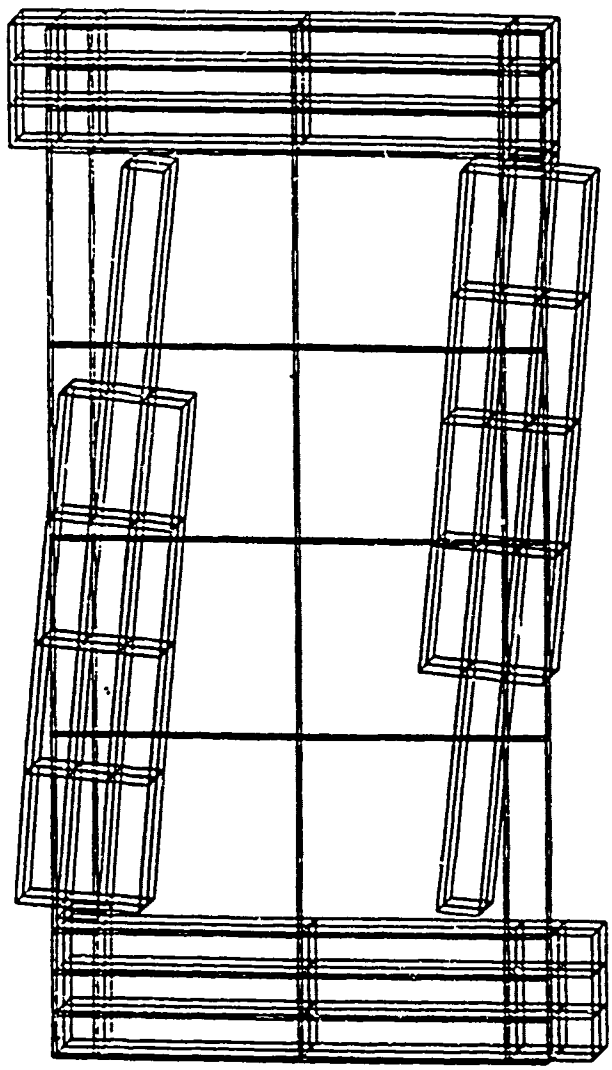

Fig. 6 - First electrically coupled mode generated by the ATILA finite element program.

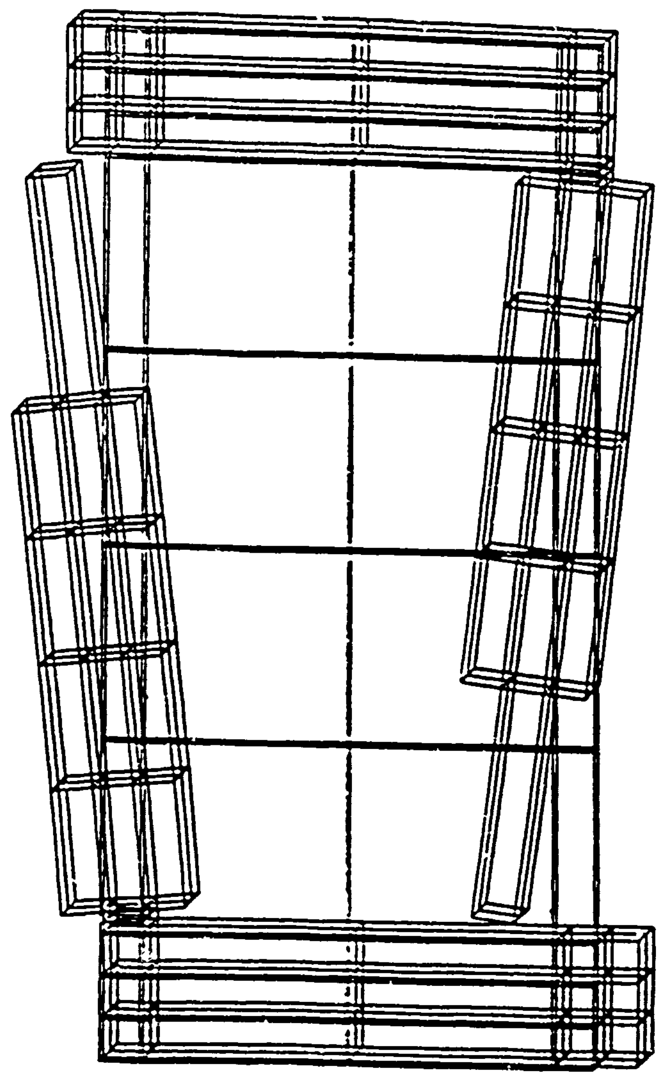

Fig. 7 - First mechanical mode generated by the ATILA finite element program.

The complete prototype two-paddle transducer is shown in Fig. 8. An air-filled bladder is mounted between the two paddles to provide an acoustic pressure release surface, thereby increasing the compliance of the internal cavity. A thin elastomeric sleeve is attached to the circular endcaps and the entire assembly is filled with an oil such as castor oil or Fluorinert (FC-43).

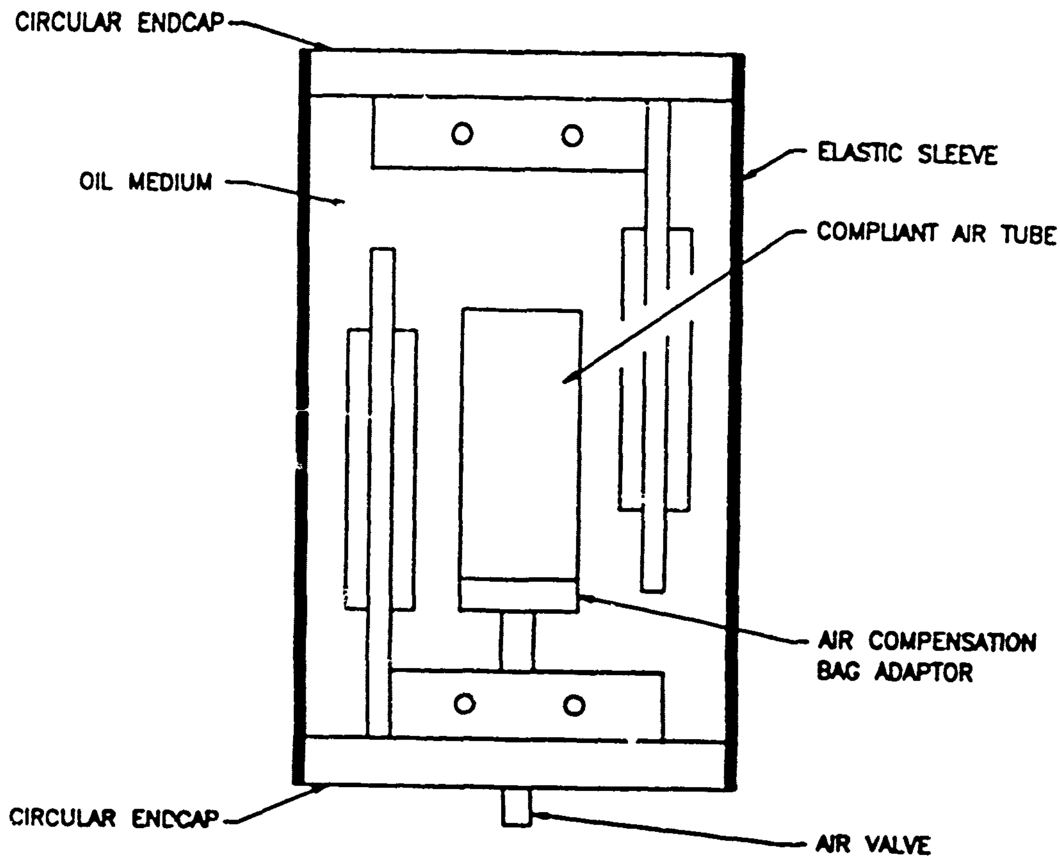

Fig. 8 - Cut-away view of the two-paddle transducer.

A coupled finite-element/boundary-element model was developed to obtain computed transmitting voltage response (TVR) levels for the prototype. The CHIEF [5] boundary-element code was used to model the fluid-loaded surfaces. It should be noted that in order to simplify the water-loaded model the circular endcaps were omitted from the model. Results of in-air electromechanical measurements made on this prototype showed that the addition of the endcaps does not effect the resonance frequency or level.

Figure 9 shows the in-water rigging used to measure the TVR at the USRD Lake Facility. A calibrated USRD type H52 hydrophone was used to measure the TVR of the prototype. To assure a known pressure release volume, an external air-bladder compensation bag was used.

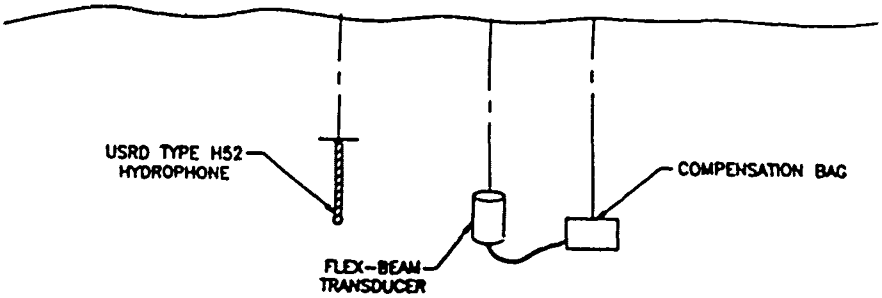

Fig. 9 - In-water rigging setup.

Figure 10 is a comparison of TVR between the numerical and experimental results. The difference in resonance frequencies between the two curves is attributed to the fact that the numerical model did not contain an adhesive layer between the ceramic plates and steel beam. The difference in levels is due to the absence of loss mechanisms such as viscosity of the oil in the model. It should be noted that the experimental curves shown in Fig. 10 represent the highest TVR output which was achieved with the prototype. The oil medium used in this test was Fluorinert (FC-43). Figure 11 is an experimental directivity pattern measured at 360 Hz which is the in-water fundamental resonance of the prototype transducer.

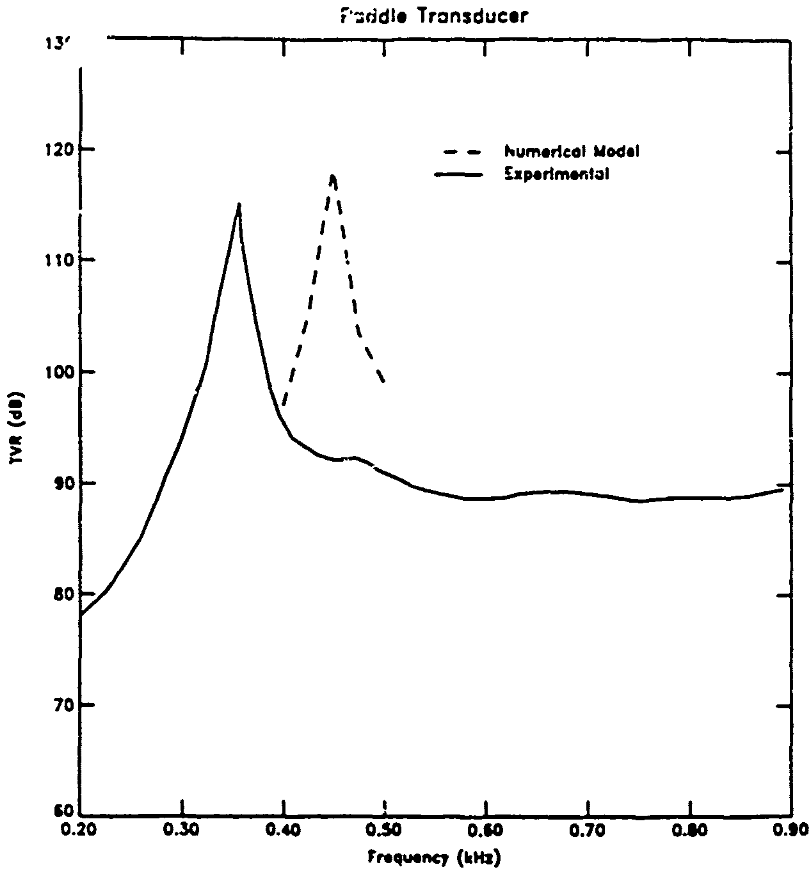

Fig. 10 - Comparison of the TVR between results obtained from the numerical model and the experimental setup.

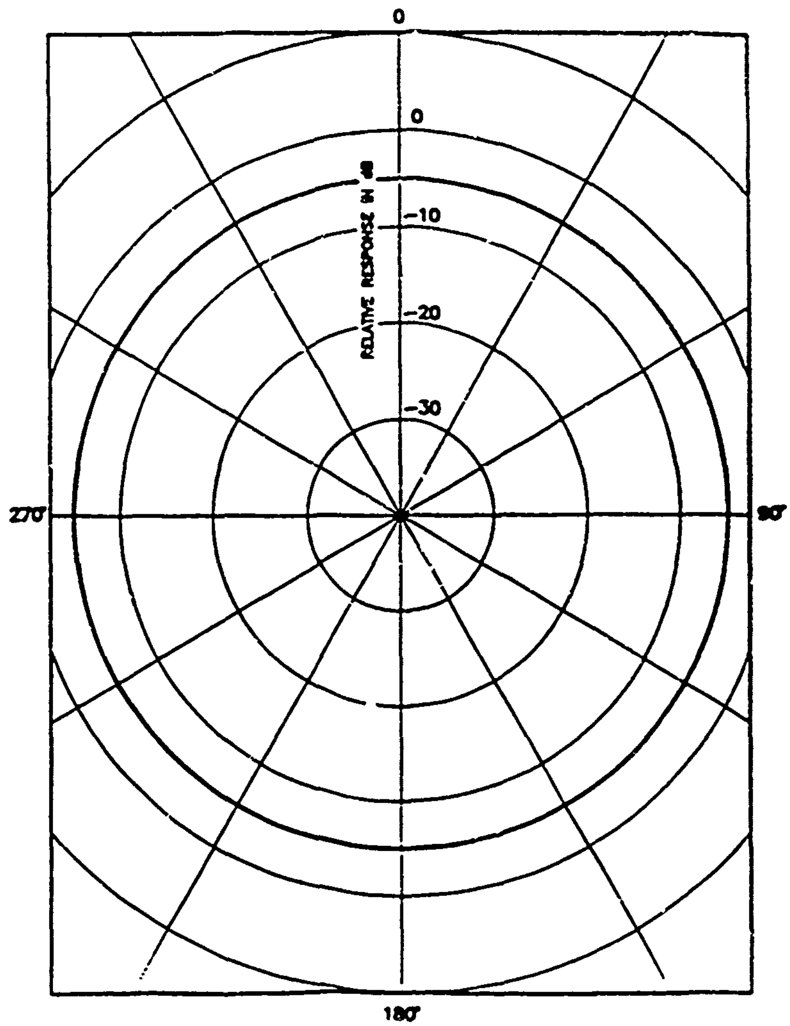

Fig. 11 - Directivity pattern of two-paddle transducer.

LIMITATIONS

A serious limitation of the two-paddle transducer is its nonlinear response with respect to voltage drive level. In order to illustrate this nonlinear behavior, the TVR obtained at several drive levels is plotted versus frequency in Fig. 12. As the voltage increases, the resonance frequency and the level at resonance decrease. Preliminary results indicate that the nonlinearity is due to the adhesive layer between the steel beam and the piezoelectric plates. Currently, various attachment configurations are being examined to minimize the nonlinearity in the frequency range of interest.

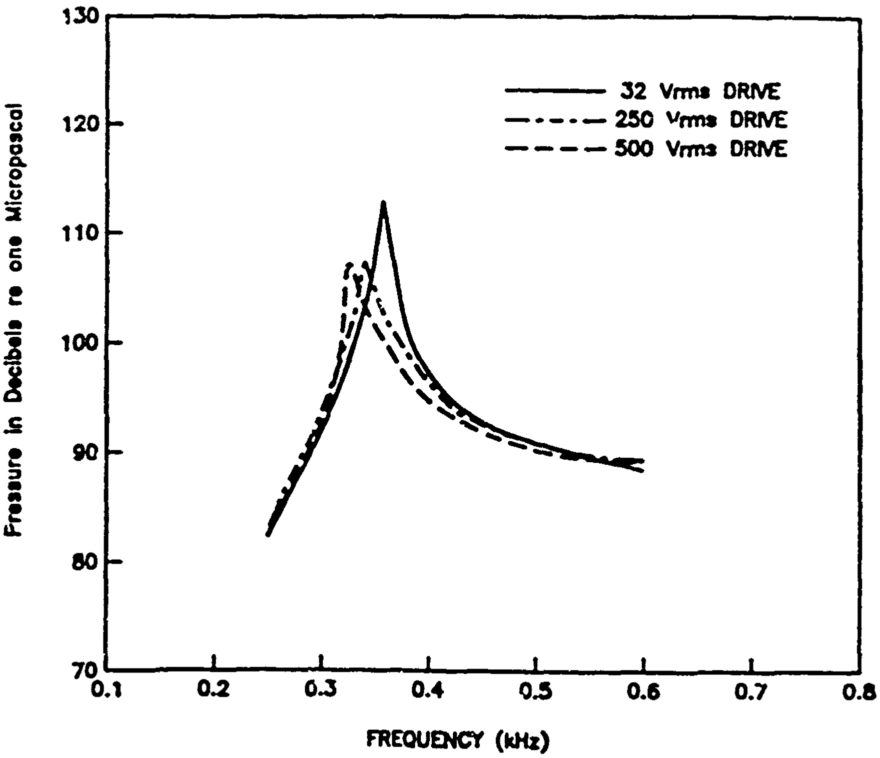

Fig. 12 - Directivity pattern of two-paddle transducer.

ALTERNATIVE CONFIGURATIONS

The basic component of this transducer is the fixed-free beam which provides the low-frequency, high-amplitude motion required to produce high sound levels. Many geometrical configurations are possible using this basic component. As an example, an array of basic paddle assemblies may be arranged in a circular configuration so as to provide increased sound levels at the expense of increased system size. Also, the basic elements may be arranged in a linear array for increased output and to give horizontal spatial directivity. One transducer prototype that is currently being developed is a four-paddle configuration shown in Fig. 13. Alternate materials may be chosen for the fixed-free beam to optimize the resonance frequency to size factor. For example, titanium beams may be used to reduce the weight of the assembly.

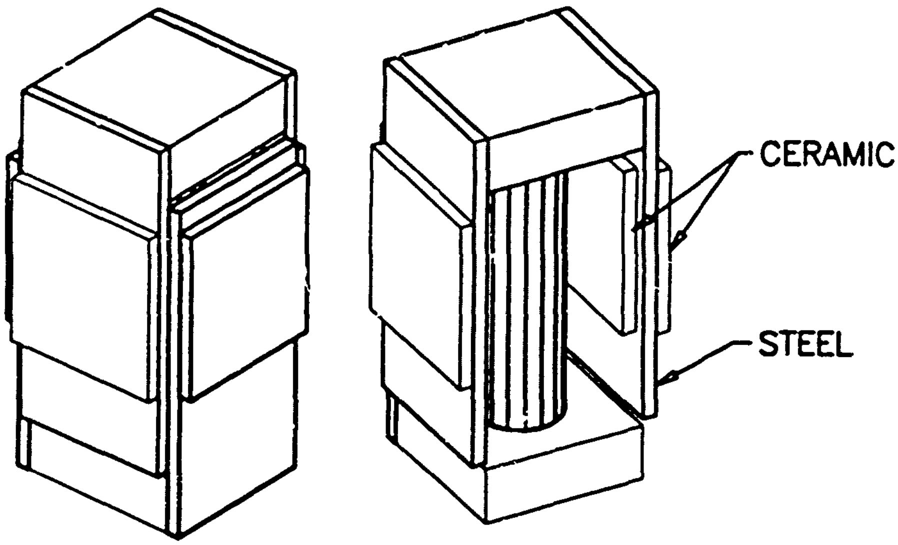

Fig. 13 - Two views of a four-paddle array.

Future work may address increasing the usable bandwidth by stagger-tuning one or more of the paddles. Another area of investigation is the application of the k_{33} mode similar to the "bender bar" concept which would increase the effective coupling and efficiency. The basic transducer may also be modified to work as a Helmholtz resonator by providing an acoustic port to resonate with the enclosed fluid volume. This would eliminate the need for an internal pressure compensation system.

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REFERENCES

1. R.J. Barra, *Geo-Metric Vibration Analysis* (RMS Publishing Company, Baltimore, MD, 1977, pp 88-91.

2. D. Berlincourt and H. H. A. Krueger, "Properties of Clevite Ceramics," TP-226, Clevite Corp., Bedford, OH, 1964.

3. Ralph S. Woollett, "The Flexural Bar Transducer." Naval Underwater Systems Center, New London, CT, 1987, pp 173.

4. "ATILA User's Manual," Institut Superieur d'Electronique du Nord, France, 1991.

5. G.W. Benthien, D. Barach, and D. Gillette, "CHIEF User's Manual," NOSC TR970, Naval Ocean Systems Center, San Diego, CA, Sep 1988.