A UNIDIRECTIONAL FLEXTENSIONAL TRANSDUCER FOR SINGLE ELEMENT AND ARRAY APPLICATIONS

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1. Introduction

Class IV flextensional transducers are normally omnidirectional (± 3 dB) since they are usually small compared to the wavelength of sound in the surrounding water medium and because most of the radiating surface is in phase. This omnidirectionality creates a significant problem in achieving planar or line flextensional transducer arrays that are to radiate in only one direction. The use of large heavy baffles behind the array or an additional array phased at ninety degrees and one quarter wavelength behind the primary array are two possible solutions. Unfortunately, these solutions can lead to doubling the cost and/or size of the array. An alternative solution is to drive the Class IV flextensional transducer into a directional mode of operation.[1] This directional operation is quite different than the hybrid magnetostrictive/piezoelectric directional transducer that has been discussed elsewhere.[2] We present here two methods of drive, displacement and pressure field, which can be used to achieve directionality in Class IV flextensional transducer under either array or single element applications respectively. We first review the condition for displacement drive directionality[3] and then introduce the condition for pressure field single element directionality.

2. Theory of operation

The directional flextensional transducer achieves directionality by combining the shell quadrupole mode with a shell/stack dipole mode. In one means of excitation the two modes are driven together to create a displacement reduction on one surface and enhancement on the opposite surface. This case allows potentially unidirectional operation from planar arrays and modest directional operation for a single element. In the second means of excitation the two modes are driven to create a pressure reduction in one direction and a pressure enhancement in the other direction. This second case allows unidirectional operation from a single element or a line array of elements.

The unidirectional mode is achieved by simultaneously exciting the flextensional transducer into its fundamental quadrupole mode (which is essentially omnidirectional) and also into its fundamental dipole mode. Consider Fig. 1 which illustrates the combination of these two modes yielding a directional mode where the motion of one side is enhanced while the motion of the opposite side is essentially canceled. The excitation of the dipole mode is accomplished by driving the piezoelectric stack into an inextensional bending mode which causes the shell to move in an oscillatory way as a reaction to the stack bending motion. The stack bending mode is excited by dividing the stack into two separate electrical parts and driving them out of phase to cause bending. This dipole mode is illustrated in the center figure. The conventional nearly omnidirectional quadrupole mode is excited by driving the two sides of the stack in phase and is shown in the first figure. The combined directional results is illustrated in the last figure.

A finite element model of a practical transducer operating in the quadrupole and dipole modes is shown in Fig. 2. This transducer is a modified 3.25 kHz BAeSEMA flextensional transducer[4]. A photograph of the striped driving stack is shown in Fig. 3 and the complete transducer is shown in Fig. 4 illustrating the position of two accelerometers on the inside of the two major radiating surfaces.

The drive scheme is illustrated in Fig. 5 showing two halves of a drive stack assembly. To excite the quadrupole mode we would put equal polarity values $+E_q$ on side A and $+E_q$ on side B of the stack. To excite the dipole mode we would put opposite polarity values such as E_d on the left and $-E_d$ on the right side. We would sum these both modes to obtain the directional mode. In this case with E_A the total voltage on side A and E_B the total voltage on side B we would have

$$E_A = E_q + E_d \quad \text{and} \quad E_B = E_q - E_d$$

For the simple case where E_d is set equal to E_q we would have $E_A = 2E_q$ and $E_B = 0$. In this case only one half of the ceramic stack would be driven. This would assume equal drives would yield equal displacement amplitudes. If the displacement of the dipole mode was twice as much at resonance due to a higher Q, the dipole drive voltage should be reduced to $E_d = E_q/2$ yielding the drive condition $E_A = (3/2)E_q$ and $E_B = E_q/2$ or the condition $E_A/E_B = 3$.

For the most effective operation the directional flextensional transducer is designed so that the transducer dipole mode resonates in the vicinity of the transducer quadrupole mode resonances. Since the dipole and quadrupole amplitudes and phase may not be the same at the desired operating frequency, the dipole mode may require a different drive condition to attain reduced motion on one surface. Moreover, if the desire is to attain a deep pressure null on one side an additional 90^0 phase shift may be required to compensate for the quadrature related radiation characteristics of a dipole and monopole sources.

If planar array operation is desired then the cancellation of the displacement on one surface (say the back surface) should be the goal. However, for a single element or line array stationary motion on one surface may not be sufficient for directionality since the front surface radiation may be diffracted around to the back as a result of the small size of the element. In this case the goal should be the cancellation of the pressure in the back directions. Since the dipole mode is normally 90^0 out of phase with the omnidirectional mode at low frequencies, an additional 90^0 phase shift [or operator $j = (-1)^{1/2}$] on the dipole mode should accomplished the desired results. If in addition to this, the dipole mode operates with twice the output (due to a higher Q as a result of the lower radiation loading) the drive condition for pressure cancellation would be $E_d = jE_q/2$ yielding $E_A = E_q(1 + j/2)$ and $E_B = E_q(1 - j/2)$ or $E_A/E_B = 3/5 + j4/5$ yielding and amplitude ratio of unity and phase angle difference between stack sides A and B given by 53^0. The corresponding condition for displacement cancellation was shown earlier to be an amplitude ratio of 3 with no phase difference between the two sides.

3. Measured results

The in-air quadrupole 4.7 kHz resonant frequency and dipole 3.6 kHz resonant frequency resulted in an in-water essentially single directional mode resonant frequency of 3.25 kHz for the BAeSEMA transducer. We first consider the case for canceled displacement where only one side of the stack is driven and no phase shift is introduced and equal displacements are assumed.

The measured acceleration response for the two surfaces under water loaded conditions is shown in Fig. 6 illustrating a maximum front to back displacement ratio of 30 dB in the vicinity of resonance. In Fig. 7 we show the transmitting voltage response for the element set in a four by three foot (1.22m x 0.91m) pressure release baffle showing a front to back ratio of 15 dB at resonance. The baffle was also modified to extend only above and below the transducer to simulate the limited baffle conditions for a line array of five elements. These measured TVR results are shown in Fig. 8 illustrating a front to back ratio of 10 to 8 dB across the band. The measured mechanical Q from this curve is approximately 3. The coupling coefficient for the transducer in this mode was found to be 20% with an efficiency of 80%.

The transducer was also driven with an additional phase shift to provide cancellation in the pressure field as opposed to cancellation of the vibrating surface as illustrated above. In the new case additional amplitude compensation was necessary to account for the higher output of dipole mode at resonance. The single element optimized results are shown in Fig. 9 illustrating a front to back ratio of over 40 dB at 3.5 kHz for the dipole mode driven at amplitude 0.45 and a phase 70^0 relative to the quadrupole mode. This drive condition also yields a TVR output increase of 2 dB in the vicinity of resonance and an improved power handling capacity since both sides of the stack are now being driven. The dipole and quadrupole amplitude and phase conditions were also optimized for maximum front to back ratio at other frequencies. The corresponding optimized drive beam patterns are shown in Fig. 10 at 2.5, 3.0, 3.5 and 4.0 kHz.

4. Modeling

A number of tools have been used to model this transducer. The Class IV computer design/analysis program FLEXT[5] has been updated to now include the electrical excitation of this dipole mode and this model has been used, in part, to design a new directional transducer specifically designed for directional mode operation at 900 Hz. Since the desire is to attain in-water loaded dipole and quadrupole resonance at nearly the same frequency (900 Hz), we have also utilized the piezoelectric and acoustical options of the ANSYS[6] finite element program.

In Fig. 11 we show computed ANSYS results for both displacement and pressure cancellation for the new 900 Hz design. The top figure is the case of displacement cancellation showing a smaller front to back ratio below resonance due to back diffraction. However, because of self shielding, there is an improved ratio above resonance. Here the quadrupole is driven at one volt and the dipole mode is driven at one-half volt to compensate for the higher Q of this mode. One part of the stack is driven at 1.5 v and the other part is driven at 0.5 v. The lower illustration is for the same Q conditions but with the dipole additionally phase shifted by 90^0. This yields identical stack sectional voltage magnitudes and a phase shift of 53^0 as discussed earlier. As seen, this condition yields greater output and an improved front to back ratio below resonance. As suggested by the two curves of Fig. 11 a reduction in phase difference above resonance would yield improved front to back ratios above resonance. The program CHAMP[7] (a derivative of CHIEF) was also used to obtain the beam patterns for a single element and also a linear array of four elements under the 90^0 phase shifted condition. These results are illustrated in Fig. 12.

5. Summary and conclusions

A directional Class IV flextensional transducer which can be operated in either displacement or field pressure canceling modes has been described. The transducer uses both the conventional quadrupole mode which is excited by the extensional motion of the piezoelectric stack and a body dipole mode which is excited by the inextensional bending mode of the stack. The piezoelectric stack is striped so that both sides may be separately energized to excite both modes. The displacement drive condition is the preferred choice for unidirectional planar array applications. The phase shifted pressure drive condition is the choice for single element or line array applications. This choice yields not only a large front to back ratio but also a 2 dB increase in source level and greater power capacity since both sides of the stack are simultaneously driven.

6.0 References

[1] J.L. Butler, "Directional Flextensional Transducer," U.S. Patent 4,754,441 (28 June 1988).

[2] J.L. Butler, A.L.Butler and S.C. Butler, "Hybrid magnetostrictive/piezoelectric Tonpilz transducer," J. Acoust. Soc. Am. 94 , 636-641 (1993).

[3] S.C. Butler, A.L. Butler and J.L. Butler, "Directional flextensional transducer,"J. Acoust. Soc. Am. 92 , 2977-2979 (1992).

[4] J.R. Oswin, "The acoustic performance of a high power flextensional transducer," Report TR.5022, BAeSEMA, Filton (FPC 087), Bristol BS127QW, England.

[5] J.L. Butler, T.J. Peirce and J. Lindberg, "A desktop computer program for a flextensional transducer," Proc. I.O.A, Vol 9 Part 2 (1987) pp 31-41.

[6] ANSYS, Inc., 210 Johnson Road, Houston, PA 15342

[7] CHAMP, Image Acoustics, Inc, Cohasset MA 02025, USA.

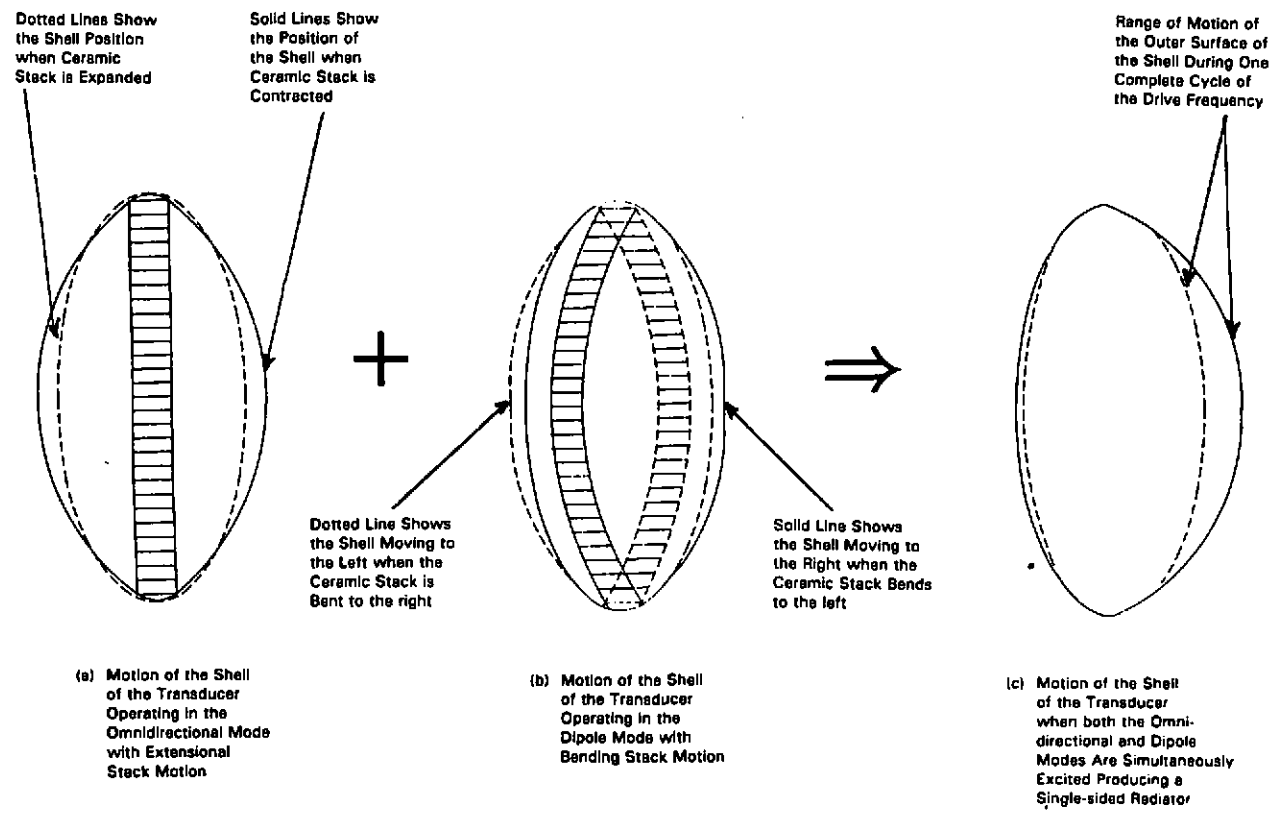


Fig. 1 Schematic representation showing how the motion of the outer surface of the shell of a Flextensional Transducer when operated simultaneously in the omnidirectional and dipole modes of vibration will superimpose to produce a Single-sided Radiator

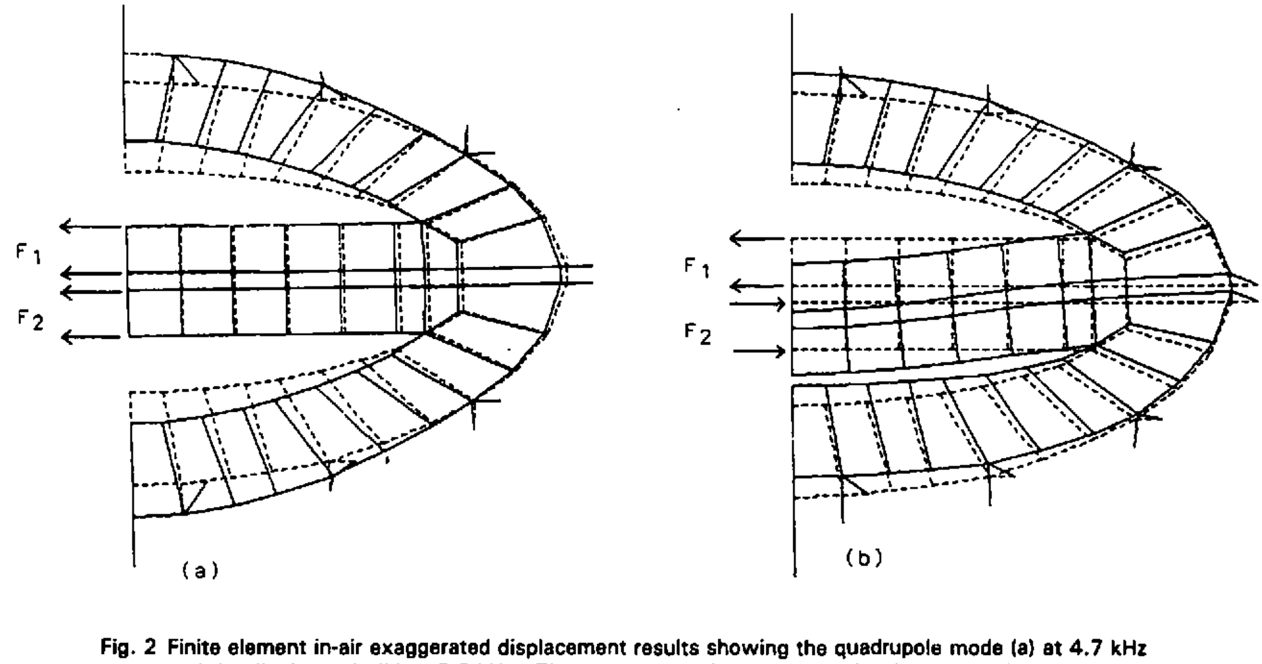


Fig. 2 Finite element in-air exaggerated displacement results showing the quadrupole mode (a) at 4.7 kHz and the dipole mode (b) at 3.6 kHz. The neutral state is represented by the dashed lines.

A UNIDIRECTIONAL FLEXTENSIONAL TRANSDUCER

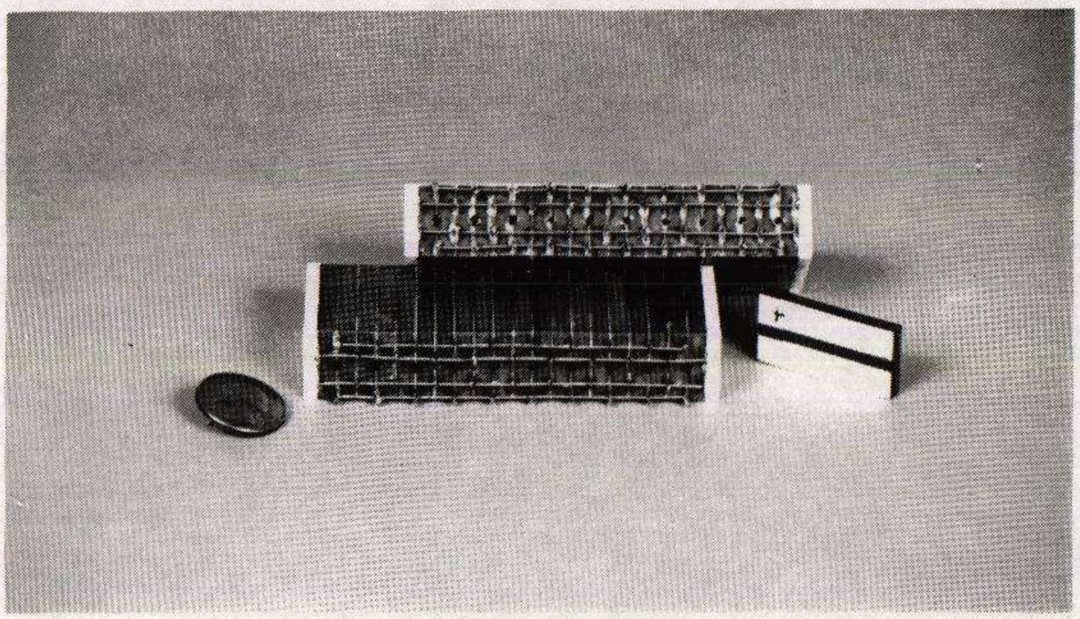


Fig. 3 Photograph showing a striped PZT-8 ceramic plate and the entire Stack Assembly used in the Massa TR-1420 Directional Flextensional Transducer

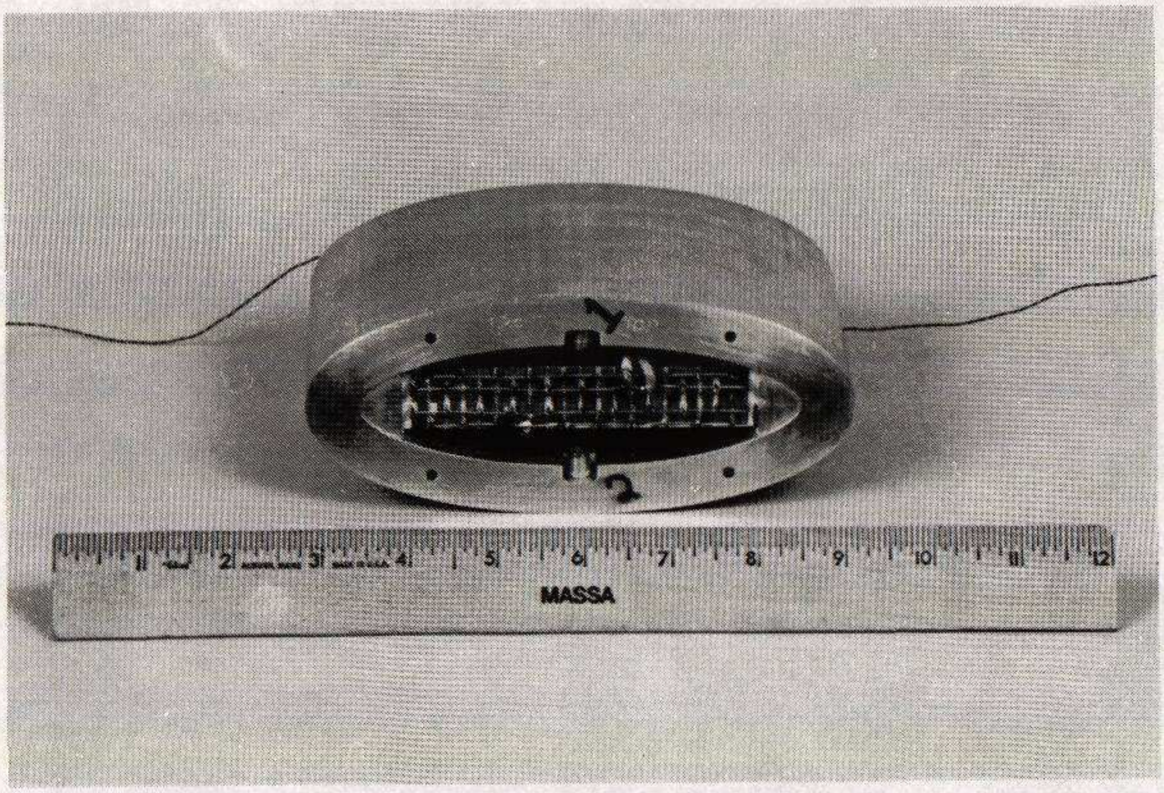


Fig. 4 Photograph of the subassembly of the Massa TR-1420 Directional Flextensional Transducer showing the Shell, the Ceramic Driver Assembly, and the Accelerometers mounted into the Shell

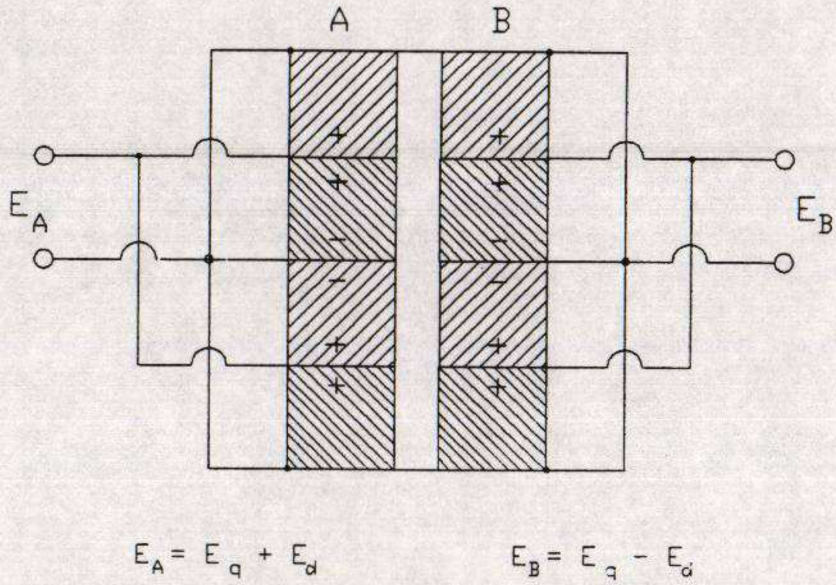


Fig. 5 Example of an electrical drive arrangement for the simultaneous excitation of the quadrupole and dipole modes.

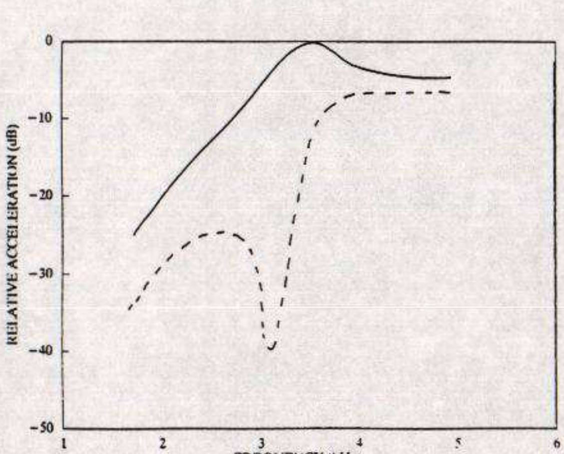


Fig. 6 Measured in-water acceleration response on the two sides A (solid line) and B (dashed line) of the shell, with the stack driven in the directional mode

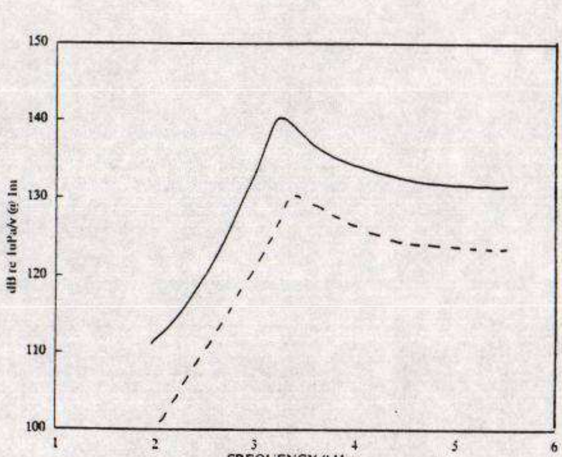


Fig. 7 Measured in-water transmitting voltage response of directional mode with the element set in a pressure release baffle for side A (solid line) and side B (dashed line)

A UNIDIRECTIONAL FLEXTENSIONAL TRANSDUCER

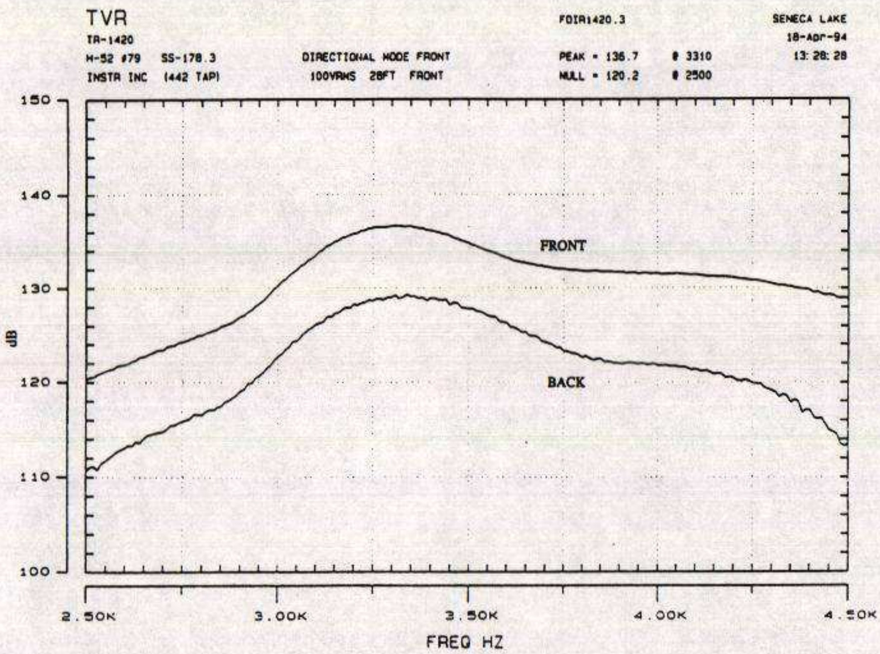


Fig. 8 Measured front and back TVR of the Massa TR-1420 Directional Flextensional Transducer with one side of the ceramic stack driven

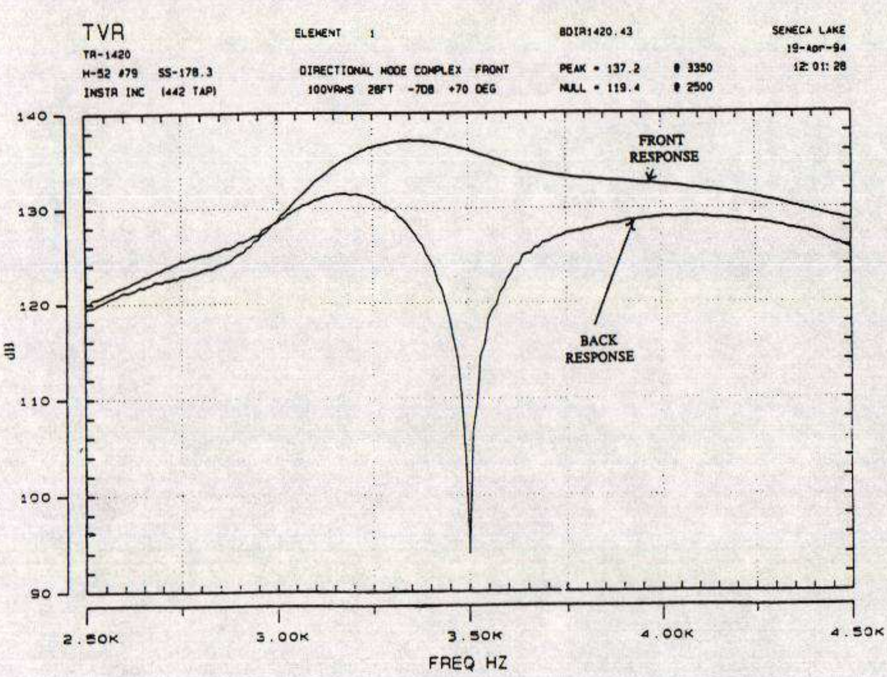


Fig. 9 Measured front and back TVR of the Massa TR-1420 Directional Flextensional Transducer with each ceramic section driven with a constant 70° phase shift

A UNIDIRECTIONAL FLEXTENSIONAL TRANSDUCER

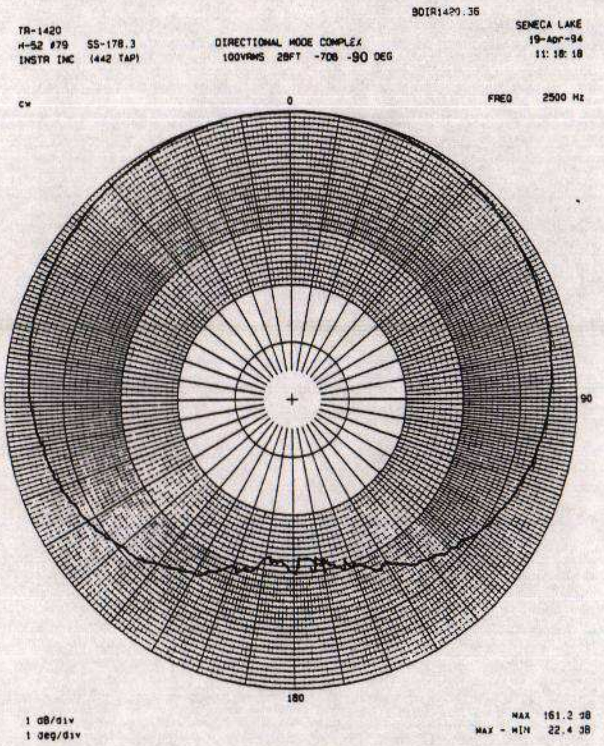


Fig. 10A Measured Horizontal Pattern of the Massa TR-1420 Directional Flextensional Transducer at 2.5 kHz showing a 22.4 dB front/back ratio

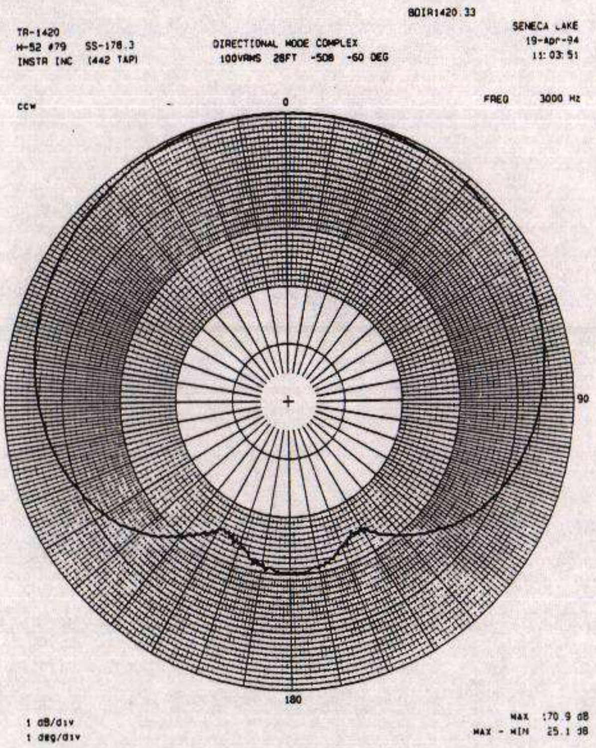


Fig. 10B Measured Horizontal Pattern of the Massa TR-1420 Directional Flextensional Transducer at 3.0 kHz showing a 25.1 dB front/back ratio

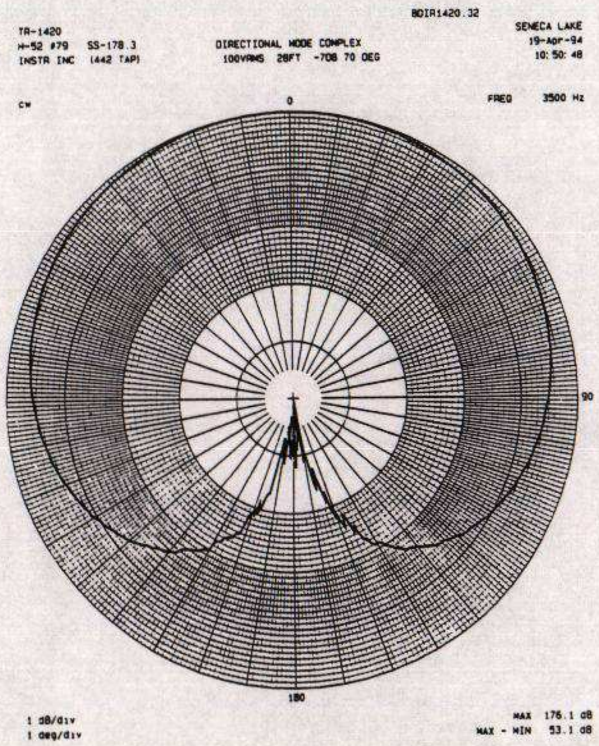


Fig. 10C Measured horizontal pattern of the Massa TR-1420 Directional Flextensional Transducer at 3.5 kHz showing a 53.1 dB front/back ratio

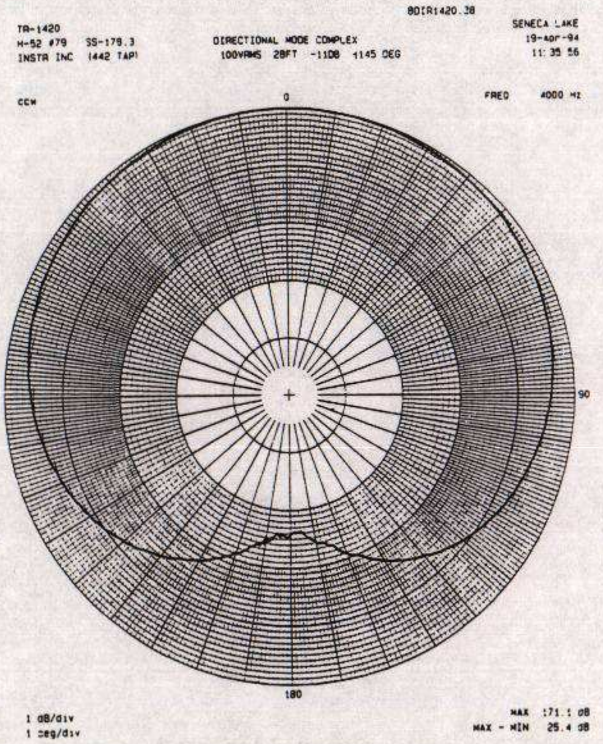
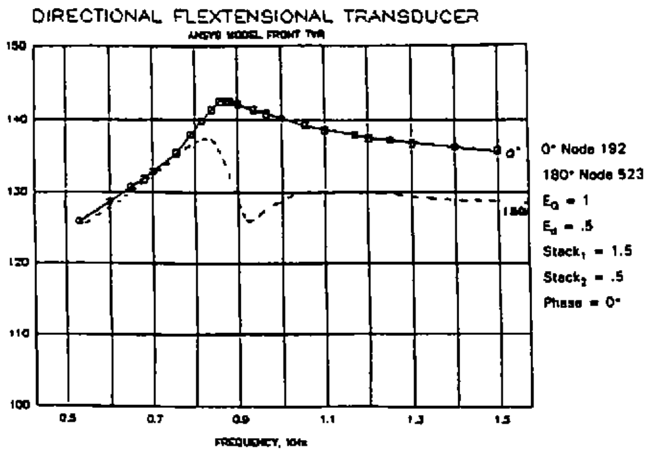
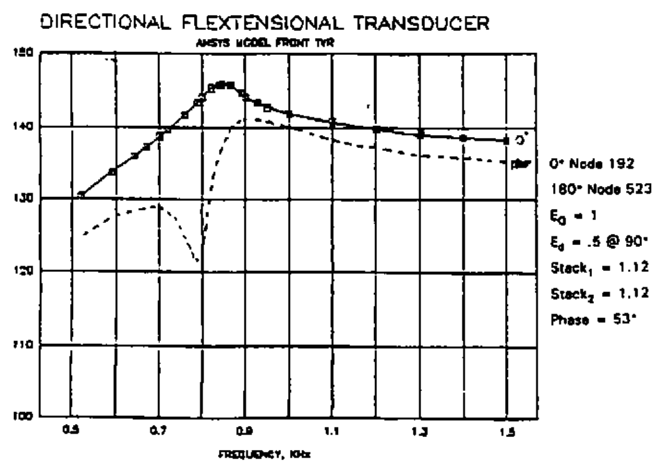


Fig. 10D Measured horizontal pattern of the Massa TR-1420 Directional Flextensional Transducer at 4.0 kHz showing a 26.4 dB front/back ratio



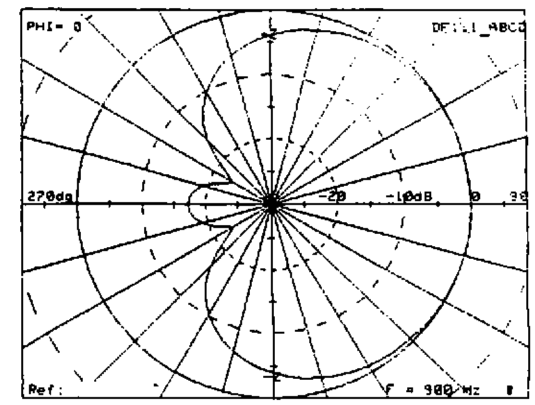
Modeled response curve for displacement cancellation



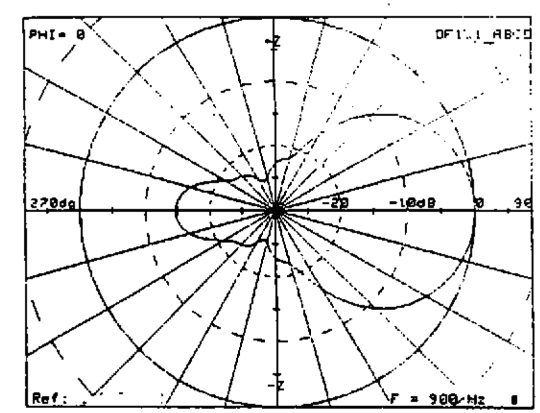
ANSYS Pressure Response

Modeled response curve for pressure cancellation

Fig. 11 Massa TR-1426 Directional Flextensional Transducer modeled front and back TVR



Modeled Massa TR-1426 Single Element
90° Phased Directional Beam Pattern



Modeled Massa TR-1426 Four Element Array
90° Phased Directional Beam Pattern

Fig. 12 Massa TR-1426 Directional Flextensional Transducer modeled beam patterns