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A Broadband Hybrid Magnetostrictive/ Piezoelectric Transducer Array

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ATILA computes structural and acoustic coupled problems specifically for sonar transducers.

Surface ship sonar systems now in development for future Navy use will utilize more frequency bandwidth than current systems do. The Navy is currently developing new transduction materials in an effort to develop new sonar projectors that operate over greater frequency bandwidths, with greater source levels and smaller volume to meet this need. A unique broadband Tonpilz-type transducer, the Hybrid Magnetostrictive/Piezoelectric Transducer (MPT), is currently in development at the Naval Undersea Warfare Center (NUWC) Division, Newport, RI, for surface ship and submarine

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Comparison of Assumptions in the Computation of Short-Circuit Forces in Transformers

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Finite element methodology is appropriate for computing the winding forces in distribution transformers.... A 3D analysis is necessary to compute the end forces outside the window.

During the operation of a transformer, electromagnetic forces are generated in both the radial and axial directions. When the electrical centers of the windings are aligned, the net force in the axial direction is zero. However, if there is a misalignment of the electrical centers, axial forces act in opposite directions in the low and high voltage windings. Under short-circuit conditions, these forces can become substantial enough to cause axial displacement of the low voltage (LV) and high voltage (HV) windings relative to each other. This failure mode is commonly referred to as telescoping.

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INSIDE

From the Editor...

Fifteen and counting: The joys of adolescence

We're 15! Magsoft Corporation celebrated its 15th year in business at our 2001 Users Meeting in Saratoga Springs, June 14 and 15. We now enjoy all the characteristics of a typical teenager:

Intensity, energy and maturity

The Users Meeting provided a varied program of

- instruction (a primer in dielectric design, FEA analysis of torque in rotating machines)
- introduction to new products (WINSPEED and Motor-CAD)
- previews of the new features and capabilities in Flux2D 7.6
  - axiperiodic model in magnetostatics
  - Park model for circuit coupling in magnetostatics
  - superconductivity model
  - ability to import objects in Preflu2D multiparametric analysis and postprocessing and
- new features in Flux3D 3.3
  - parametric analysis for materials, charge density and geometric properties
  - coils in series or in parallel nonlinear
  - magnetoharmonics linear surface impedance (analytical solution)
  - input of 10 user coefficients in user defined material properties
  - expanded circuit connections in 3D, including external link to Simulink
- applications ranging from a bus bar design tool dedicated to optimization to 3D transient magnetic modeling of braking torque in a rotating conducting disk.

Capacity for fun

The intrigue! The suspense! The drama!

Our users would have held their own against any teens during Thursday evening's *divertissement*: A murder-mystery dinner theatre at the Good Times Restaurant in Ballston Lake.

Your editor's limited theatrical experience taught her one classic lesson: the quality of any performance depends on a receptive and appreciative audience. This particular drama depended on active participation from the audience. Well, based on that, the performance was phenomenal, because our users have to be the best audience ever. The flamboyant Captain, the woman scorned, the gangster, the doctor, the private eye, "The Flux People," "The Pink Ladies," "Hot'n'Spicy", and a heartbreakingly earnest little messenger are sure to be such stuff as dreams are made on (not to mention tell-all, scandal-mongering memoirs).

Anticipation of big changes

Like any fifteen-year-old, we're also facing big changes. Besides increasing the capabilities of our Flux tools, such as new formulations in transient magnetics, and a 3D circuit equation coupling for solid conductors, we're implementing a whole new command language (in Python) and "changing the whole look of the software," according to Xavier Brunotte, Head of Software Development.

Growth spurts

Every teenager goes through growth spurts, and our network of distributors has grown recently, too. We're happy to welcome new partners in the USA, as well as in the UK, Finland, Germany, Italy, Bulgaria, Croatia, Japan, Singapore and Indonesia, and India. Look out, world!

Grounded in a strong family

If any teenagers can be described as "well-adjusted," it will be the lucky girls or boys who can rely on support and guidance from their parents and friends. We're lucky to have a group of users that's amazingly like a healthy family: warm, courteous, loyal, and supportive. Our users have the graceful ability to advise and criticize frankly, but always with our mutual best interests at heart.

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Piezoelectric Transducer

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sonar applications. This transducer combines the high-strain magnetostrictive transduction material Terfenol-D with the current fleet transduction material of lead zirconate titanate piezoelectric ceramic. The result of combining the two driver materials is an increase in bandwidth from the traditional Tonpilz of 40% to near 100%. An additional benefit of using the Terfenol-D driver material is that its inherent lower sound speed permits a lower resonance frequency within a preset driver length, which leads to a significantly increased source level needed at lower frequencies.

A single proof-of-concept hybrid prototype transducer was designed, fabricated, and tested from 1997 to 1998, funded by the Office of Naval Research. This element demonstrated an increased bandwidth over the existing surface ship array transducer elements and an increased source level at the low-frequency end of the operating band. The empirical evaluations of the hybrid transducer element also demonstrated that it is capable of producing broadband acoustic energy at the required source levels over the wide frequency bandwidths that future sonar systems will require. The current task comprises the design, fabrication, and testing of a 4×4 element array of hybrid transducer elements.

The hybrid transducer is a mechanical series arrangement of magnetostrictive and piezoelectric sections, which are rigidly attached together with a center mass between the two materials and a tail and head mass (radiating piston) at opposite ends. This method creates a double-resonant (three-degree-of-freedom mass-spring-mass-spring-mass system) transducer, in which the piezoelectric section controls the upper resonance and the magnetostrictive section controls the lower resonance. Optimum bandwidth is achieved by designing the central mass to be 2 times greater than the head mass, and the tail mass to be 2.5 times that of the head mass, thereby optimally reducing the lower resonance frequency. This current hybrid design is a departure from the earlier hybrid design in which the transducer was a double-

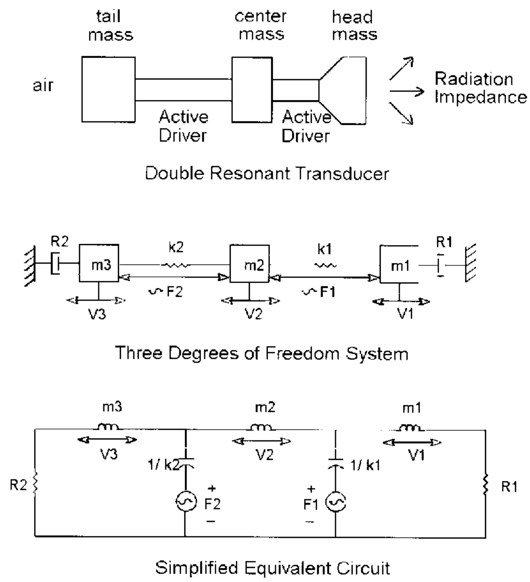


Figure 1.
Simplified equivalent circuit for a double-resonant transducer

ended radiator capable of producing unidirectional beam patterns from either end (Terfenol-D side or ceramic side) and produced a front-to-back acoustic ratio greater than 15 dB under array loaded conditions. In the former design, the center mass was twice the weight of the head masses, and the stiffnesses of the Terfenol-D driver and the ceramic stack were the same.

The hybrid transducer operation can be described by a simplified equivalent circuit of three masses, two stiffnesses, and two driving force functions, as shown in Figure 1. This simplified equivalent circuit of lumped parameters makes it easy to analyze and describe the model. This device creates a

Figure 2.
Simplified approach to the double-resonant system

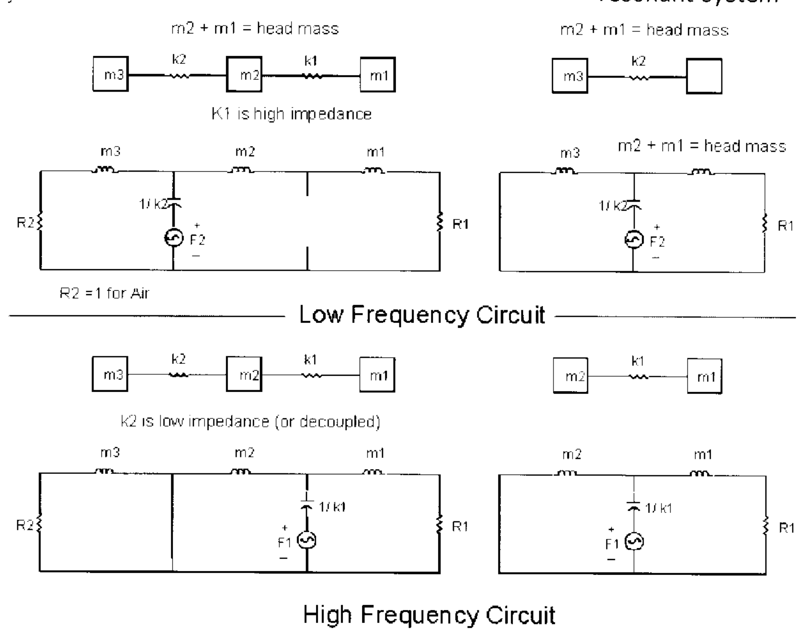
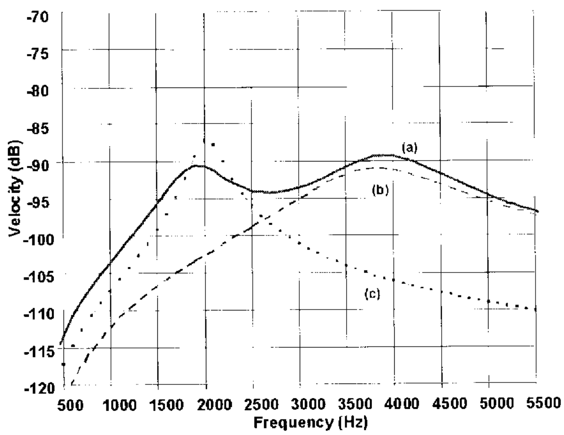


Figure 3.
Head mass velocity response of
(a) complete circuit,
(b) high-frequency circuit, and
(c) low frequency circuit



double-resonant transducer in which the piezoelectric section controls the upper resonance and the magnetostrictive section controls the lower resonance. Stiffness k1 represents the piezoelectric stack driver, and stiffness k2 represents the magnetostrictive driver. The masses are the tail mass, center mass, and head mass. The head mass radiates the acoustic energy into the medium.

The two resonances of the system can be described by the two equivalent circuits, one at low frequency and the other at high frequency, as shown in Figure 2. At low frequencies, stiffness k1 essentially becomes a high impedance, i.e., stiffness being inversely proportional to frequency. This makes a mechanical short circuit or an equivalent electrical open circuit to the system. This creates a resonant system that is controlled by the head mass m1 and center mass m2 lumped together, resonating with active driver k2 and tail mass m3. At high frequency, magnetostrictive section k2 decouples from the system, creating a mechanical open circuit or electrical short circuit, i.e., stiffness being inversely proportional to frequency. This allows the upper resonance to be controlled by the head mass m1, piezoelectric driver k1, and center mass m2.

The head mass velocity frequency response for the individual circuits of Figures 1 and 2 is shown in Figure 3. Response (a) is the complete equivalent circuit; response (b) is the high-frequency circuit; and response (c) is the low-frequency circuit. The dual active sections, i.e., magnetostrictive and piezoelectric, have several distinct advantages:

(1) Because the active components of the transducer are both inductive and capacitive in nature, the two sections can electrically tune each other.

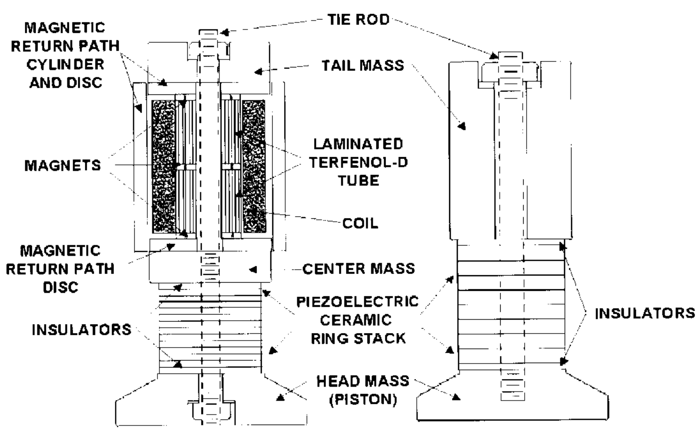
(2) Another advantage of using the combined magnetostrictive and piezoelectric driving arrangement is its ability to prevent a deep null in the response between the two resonances, because of the intrinsic electromechanical 90° phase shift between the two materials. Figure 3 shows the advantage of this phenomenon.

(3) Another advantage of using Terfenol-D is its ability to produce the greater displacements needed at the lower resonant frequency for a given length requirement.

(4) Being magnetostrictive, Terfenol-D also has the advantage of a 6-dB/octave slope below resonance (unlike piezoelectric ceramic, which is 12-dB/octave in the transmitting response).

The hybrid transducer prototype designed and fabricated at NUWC Division, Newport is shown in Figure 4a. The transducer is composed of two single Terfenol-D drive rods manufactured by Etrema Products, Inc., Ames, Iowa. Each drive rod contains a hole through its center for the stress rod and is interlaced with samarium cobalt magnets that magnetically bias the Terfenol-D to 60 kA/m (750 Oe). Both the Terfenol-D rods and magnets were laminated to reduce eddy currents. The magnetic circuit is comprised of pole piece

Figures 4a and 4b.
Sketches of broadband hybrid MPT transducer and conventional Tonpilz transducer



4a. Hybrid 4b. Conventional

discs on each end of the Terfenol-D magnet assembly and an external magnetic cylinder made of a high-permeability, high-resistivity, high-saturation powered metal T2 (manufactured by Etrema Products, Inc.), which provides the magnetic field return path. In the development phase of the hybrid transducer, a dual-leg Terfenol-D design was also fabricated. This design had dual Terfenol-D drive rod assemblies in parallel each with its own coils and coupled by the high-permeability T2 material in the form of a bar on the top and bottom to form a closed magnetic return with no air gaps. For comparison with the hybrid transducer, a sketch of conventional sonar transducer design of the same size and weight is shown in Figure 4b. The current hybrid transducer has a 363 cm^2 (56.25 $in.^2$) radiating face (piston), is 40.6 cm (16 in.) long, and weighs 29.5 kg (65 lb.) without the underwater housing. It is 55.9 cm (22 in.) long and 40 kg (88 lb.) with the underwater housing.

Extensive electrical, magnetic, and acoustical measurements were performed on both single-leg and dual-leg transducer designs. The acoustical measurements were conducted at a 100-foot depth at NUWC Division Newport's Seneca Lake Sonar Test Facility in April and July 1998. Figure 5 shows the measured transmitting voltage responses of the hybrid broadband single-leg transducer design and a conventional Tonpilz sonar transducer of the same size and weight, without tuning or step-up transformer.

The magnetostrictive section of the hybrid transducer controls the lower resonance, at 1.8 kHz. The higher resonance is at 3.5 kHz and is controlled by the ceramic stack section. Both hybrid designs (i.e., single-leg design and dual-leg design) produced similar transmitting voltage responses. As a result of the added magnetostrictive portion of the hybrid transducer, the hybrid transducer produces 10 dB to 20 dB more response than the conventional transducer below 2.25 kHz. If one were to design a conventional Tonpilz transducer to resonate at 1.8 kHz with the same mechanical quality factor, the transducer would be at least 50% longer in length.

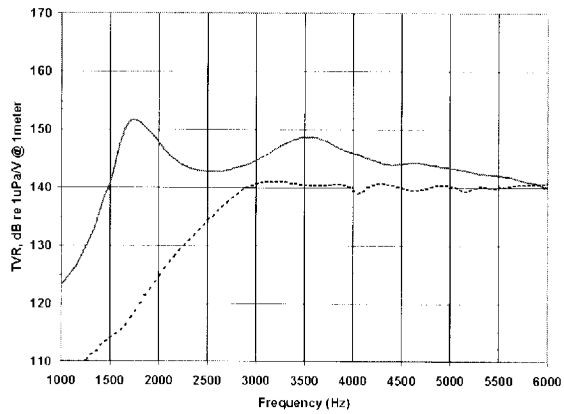
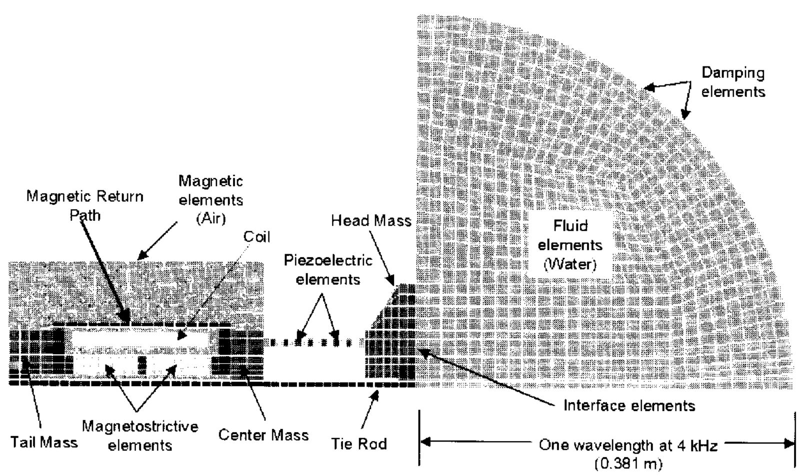


Figure 5.
Measured transmitting voltage responses (TVR) of hybrid transducer (solid line) and conventional Tonpilz transducer (dashed line) of same size and weight

The finite element program ATILA contains elastic, piezoelectric, magnetostrictive, magnetic and fluid material elements in two and three dimensions. This finite element program computes structural and acoustic coupled problems specifically for sonar transducers. The program calculates such electromechanical characteristics as resonance and antiresonance frequencies, effective coupling coefficient, electrical impedance, capacitance (or inductance), beam patterns, transmitting responses, receiving responses, and directivity indexes. The ATILA finite element model mesh of the hybrid transducer is shown in Figure 6.

The model is axisymmetric around the horizontal axis, and the fluid radius is 0.381m (15 in.). The model considered far-field radiation conditions using the dipole damping non-reflecting elements on the far side radius of the fluid. Each piece in the magnetostrictive section of the model is

Figure 6.
In water finite element axisymmetric model from ATILA



enclosed by magnetic finite elements on top of the structural elements and assigned a magnetic permeability value of the materials in order for magnetic flux lines to be calculated. The active material properties used in the model are listed in Table 1. These material properties were based upon measurement of the Terfenol-D drive rods and curve fitting to the data.

TABLE 1: Active Material Properties

Terfenol-D Section	Ceramic Section Navy Type III (Plus glue joints)
Y_{33}^H = 29.4 GPa	Y_{33}^D = 87.1 GPa
Y_{33}^B = 47.3 GPa	Y_{33}^H = 57.1 GPa
k_{33} = 0.615	k_{33} = 0.586
μ_{33}^T/μ_0 = 5.34	$\varepsilon_{33}^T/\varepsilon_0$ = 1118
μ_{33}^S/μ_0 = 3.32	$\varepsilon_{33}^S/\varepsilon_0$ = 734
$d_{33} = 9.29 \times 10^{-9}$ m/A	$d_{33} = 250 \times 10^{-12}$ m/V
ρ = 9250 kg/m^3	ρ = 7600 kg/m^3

A comparison of the transmitting voltage response of the single element hybrid transducer for the measured, plane wave circuit model and the ATILA finite element model is shown in Figure 7. The disagreement between the measurement and the models at 1000 Hz is the result of the model's baffled piston condition, which does not account for acoustic diffraction effects.

The element interactions under array loading conditions were fully empirically evaluated with the 16-element, 4×4 array at the NUWC Seneca Lake Test Facility. The array acoustic loading will flatten the transducers and increase their efficiency over the operating frequency band. The evaluation will also serve as a demonstration for use in a future bow-mounted, broadband sonar system on the new class of Navy destroyers and submarines.

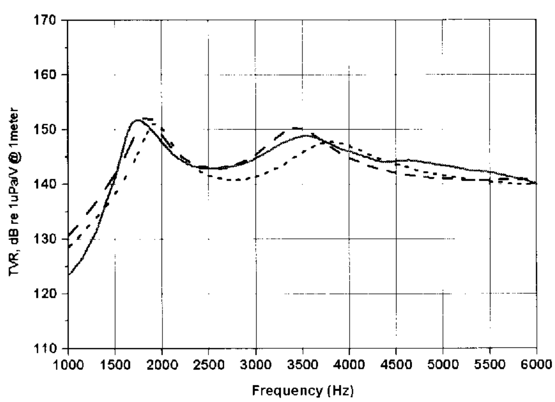


Figure 7.
Hybrid transducer single element transmitting voltage responses (TVR):
measured (solid line),
plane wave circuit model (small dashed line) and
ATILA finite element model (large dashed line)

The acoustical measurements on the array were conducted at a 100-foot depth at NUWC Division Newport's Seneca Lake Sonar Test Facility in June and July 2000. The total array has a weight (elements and array test fixture) of 900 kg (2000 lb.), a center-to-center element spacing of 0.229 m (9 in.), and an aperture of 0.88 m (34.5 in.) by 0.88 m (34.5 in.). The array has a 0.76 packing-factor (PF), which is the ratio of total radiating area of all the pistons faces in the array to the total enclosed area of the array. The array packing-factor effectively modifies the radiation resistance by lowering it, which ultimately affects the electro-acoustic efficiency of the transducer array, because the acoustic output power is the piston velocity squared times the radiation resistance. For this array, the radiation resistance is 24% lower than an ideal array with a PF of 1. Because the transducer housing extended around the head masses, the element-to-element spacing was the closest that could be achieved. Preliminary results indicate that the electro-acoustic efficiency of the hybrid transducer array is 60% at 2 kHz and 70% at 3.5 kHz.

The mathematical model of the array is based on Pritchard's interaction theory for pistons in a rigid baffle. The modeled ABCD parameters from the single element transducer TRN model were used in the array model calculations. The array model provided transmitting responses, receiving responses, beam patterns, acoustic velocities, and input impedance for the individual array elements as well as for the whole array.

Beam patterns were measured at various frequencies from 1000 Hz to 7000 Hz at 0°, 10°, 15°, and 20° steering angles. The measured and modeled transmit beam patterns of the 4×4 element array are shown in Figure 8 for the unsteered condition and in Figure 9 for the steered condition at azimuth angle of 15° at 3 kHz. For this frequency, the measured and modeled total 3 dB beam widths are 25.5° and 27.1°, and steered are 26.0°

and 27.6°, respectively. Measured and modeled side lobe levels are down 13.8 dB at 46° and 12.6 dB at 48°, respectively, from the main lobe. The measured side lobe level was close to that of an ideal line array of 13.5 dB. The array steering was performed by dividing the array into four vertical lines with four elements per line. Each line was driven by a separate power amplifier. The input to each amplifier was supplied with the proper phase shift to each line in the array. The applied phase shift ϕ is related to the steering angle θ_0 by

$$\phi = \left(\frac{360^\circ f}{c}\right) d \sin \theta_0 \qquad (1)$$

where d is the element-to-element separation distance 0.229 m, f is the frequency, and c is the measured water sound speed 1430 m/s. For the 3000 Hz case, the required phase shift for each stave or line was 0°, 45°, 90° and 135°, respectively. All other beam patterns were very symmetrical and were very close to model predictions.

As expected, grating lobes started to appear in the steered beam patterns in the 5 kHz to 6 kHz band. To remove grating lobes in this frequency band, the transducer piston size and element-to-element spacing would have to be smaller. Current arrays that use similar sized transducers are cylindrical in geometry and steered less than 10° in azimuth.

Figure 10 shows the measured array source level with 800 volts rms constant drive on each element compared with model predictions of the array. Peak source levels of 230.5 dB//1uPa-1m were measured at 1830 Hz and 3630 Hz when driven with 900 volts rms and 230.4 dB//1uPa-1m at 3700 Hz when driven with 1500 watts of electrical power into each transducer element. The measured 3 dB bandwidth is 2830 Hz from 1650 Hz to 4480 Hz, ignoring a 4 dB dip between the two resonance frequencies. It is expected that in a much larger full array this dip will be less than 3 dB, because of the increased array acoustic loading. The 6 dB bandwidth is 4300 Hz from 1580 Hz to 5880 Hz. The measured data showed that the array performed as expected across the band and that the responses were linear with increasing drive level across the entire measured band.

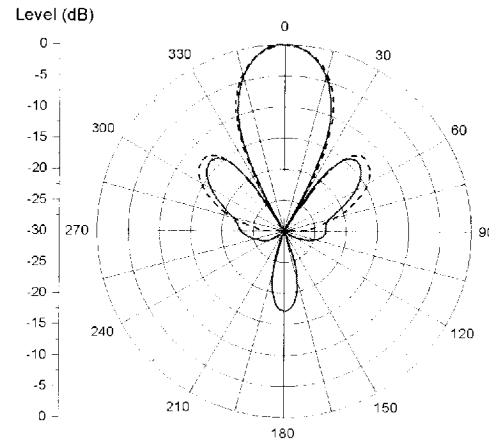


Figure 8.
Hybrid transducer 4 x 4 array transmit beam pattern responses at 3 kHz:
measured (solid line) and
model (dashed line)

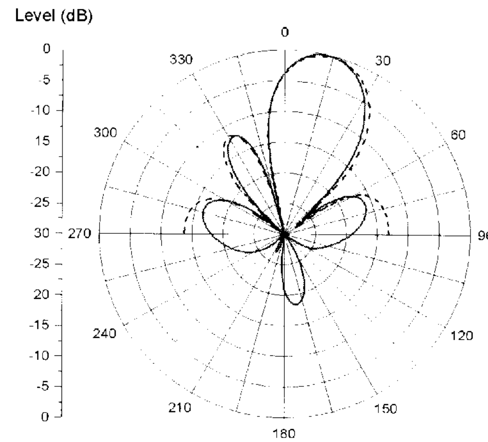


Figure 9.
Hybrid transducer 4 x 4 array transmit beam pattern responses at 3 kHz:
measured (solid line) and
model (dashed line) steered 15 degrees

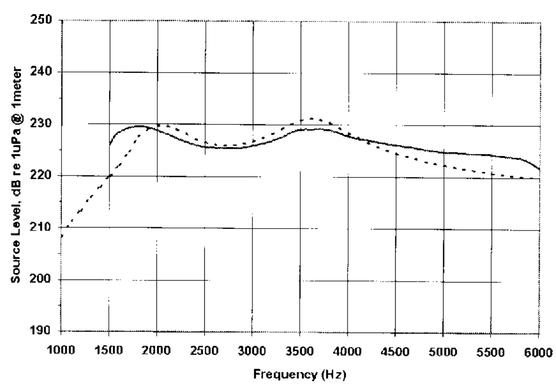


Figure 10.
Hybrid transducer 4 x 4 array 800 Volt source level responses:
measured (solid line) and
array model (dashed line)

ACKNOWLEDGMENTS

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