Triply Resonant Broadband Transducers

Stephen C. Butler
Naval Undersea Warfare Center Division Newport
Transducer Development and Support Branch
Newport, RI 02841

Abstract- The Navy's current emphasis on broadband sonar signal processing and frequency agility has prompted the need for new classes of broadband sonar transducers that can transmit these complex signals. The design approaches used are based on the longitudinal vibrator tonpilz type double resonant sonar transducer development that began with the "Rodrigo" type design (named after the pioneer of such design) also commonly referred to as "double head mass" transducer by the British naval community. This design is a series mechanical arrangement of an inactive compliant material such as aluminum or composite polymer material that is sandwiched between a central mass and head mass (radiating piston) and active driver material such as piezoelectric ceramic stack or magnetostrictive rod sandwiched between the central mass and a tail mass. This method creates a double resonant three-degree-of-freedom (i.e. mass-spring-mass-spring-mass system) transducer, which offers greater bandwidth than conventional tonpilz transducer designs. These designs can be expanded by the addition of other series resonators (mass-spring) to produce triple resonant transducer (TRT) or higher order multiple resonant transducer (MRT) devices. Several prototype transducer elements designs were fabricated at the Naval Undersea Warfare Center that demonstrated proof of concept by generating three resonances at 15, 25 and 35 kHz. The theory of operation, modeling approaches, fabrication technique and test results will be presented.

I. INTRODUCTION

The Navy's current emphasis on broadband sonar signal processing and frequency agility has prompted the need for new classes of broadband sonar transducers that can transmit these complex signals. The design approaches used are based on the longitudinal vibrator tonpilz type double resonant sonar transducer development that began with the "Rodrigo" type design[1] (after the pioneer of such design) also commonly referred to as "double head mass" transducer by the British naval community[2,3]. This design is a series mechanical arrangement of an inactive compliant material such as aluminum or composite polymer material that is sandwiched between a central mass and head mass (radiating piston) and active driver material such as piezoelectric ceramic stack or magnetostrictive rod sandwiched between the central mass and a tail mass, as shown in figure 1. This method creates a double resonant three-degree-of-freedom (i.e. mass-spring-mass-spring-mass system) transducer, which offers greater bandwidth than conventional tonpilz transducer designs, as shown in figure 1. By replacing the inactive compliant section by an active drive material, see figure 2, the acoustical output power capabilities are enhanced, as reported by S. Thompson doubly resonant wideband transducer design[4,5] and J. Butler Hybrid magnetostrictive-piezoelectric transducer design[6,7]. Both these designs have been shown to operate very successfully producing flat transmitting bandwidths of one to two octaves. These designs can be expanded by the addition of other series resonators (mass-spring) to produce triple resonant transducer (TRT) or higher order multiple resonant transducer (MRT) devices.

Two high-frequency triply resonant transducer (TRT)[8,9] designs are being investigated at the Naval Undersea Warfare Center Division Newport (NUWC). Both transducer designs borrow their technologies from the previous double resonant transducer designs of the Hybrid transducer, Doubly Resonant transducer (DRT)[10], and Rodrigo transducers. The first design (Design I) is Rodrigo-type design with the addition of another mass-spring resonant system the second design (Design II) is a Rodrigo-type configuration with a quarter-wave matching layer of Lucite on the radiating face, both are shown in figure 3.

II. THEORY OF OPERATION

The Triple Resonant Transducer design I (see figure 4) is a mechanical series arrangement of a tail mass (m1), piezoelectric ceramic stack (C1), center mass (m2), compliances (C2), center mass (m3), compliance (C3) and a acoustic radiating head mass (m4). This method creates a triple-resonant (mass-spring-mass-spring-mass-spring-mass-system) transducer, in which the inactive compliances sections control the upper resonances and the piezoelectric stack section controls the lower resonance. Optimum bandwidth is achieved in this design when the center mass (m2) and tail mass (m1) are equal, the center mass (m3) and head mass (m4) being equal and half the weight of the tail mass and all compliance C1, C2 and C3 are equal.

The transducer operation can be described by the

0-7803-7535-1/$10.00©2002 IEEE

simplified mechanical circuit representation or by its equivalent analog electrical lumped circuit representation of four masses, three compliances, and a driving force function, as shown in figure 4. This simplified equivalent circuit of lumped parameters makes it easy to analyze and describe the model.

The Triple Resonant Transducer design II (see figure 5) is also a mechanical series arrangement of a trail mass (m1), piezoelectric ceramic stack (C1), center mass (m2), compliances (C2), head mass (m3) and a compliance (C3) and mass (m4) for the quarter wave matching layer. This method also creates a triple-resonant transducer, in which the inactive compliance section control the upper resonance and the piezoelectric stack section controls the lower resonance and the quarter matching layer controls the center frequency. Optimum bandwidth is achieved in this design when the center mass (m2) and tail mass (m1) are equal, and head mass (m3) and matching layer mass (m4) being one-half the weight of the tail mass and compliance C1and C2 equal and the quarter wave matching layer compliance C3 being twice that of C1 or C2. This transducer design operation can also be described by the simplified equivalent electrical lumped circuit representation of four masses, three compliances, and a lumped transmission "T" network line describing the quarter wave matching layer, as shown in figure 5.

The masses and compliances in both designs are adjusted so they produce same three resonant frequencies, table I lists the values of the masses and compliances.

Table I. Mass and Compliance Values.

Design	I	II
m1 (kg)	0.025	0.03
m2	0.025	0.03
m3	0.015	0.015
m4	0.015	0.015
C1 (m/N)	4 x 10^-9	4 x 10^-9
C2	4 x 10^-9	4 x 10^-9
C3	4 x 10^-9	8 x 10^-9

Using values in table I and applying a force of 1 Newton to the equivalent circuits of figures 4 and 5 the relative piston velocity (v) through the radiation load R (R=1 for air load) was computed for both equivalent circuits and is shown in figure 6. The velocity responses displays the three coupled resonances generated by these multi-degree-of-freedom circuits. A mechanical losses factor of 0.01 was added to all the compliance values to slightly dampen the peaks of the responses.

Triple Resonant Transducer Design I generates three resonances at 15, 25, and 35 kHz. The 15 kHz resonance is generated by the ceramic stack resonating with the tail mass and the two center masses, two G-10 (fiberglass) compliances, and head mass, all acting together as one lumped mass. The 35 kHz resonance is generated by the upper center mass and G-10 compliance resonating with the head mass. The 25 kHz resonance is generated by the lower center mass and G-10 compliance resonating with the upper center mass, G-10 compliance, and head mass, all functioning together as one lumped mass. Triple resonant transducer Design II is also a Rodrigo-type configuration, which uses a quarter-wave matching layer of Lucite on the radiating face. As with Design I, this transducer generates three resonances at 15, 25, and 35 kHz. The 15 kHz resonance is generated by the ceramic stack resonating with the tail mass and the center mass, G-10 compliance, head mass, and Lucite, all functioning together as one lumped mass. The 35 kHz resonance is generated by the center mass resonating both with the G-10 compliance and with the head mass and Lucite acting as one lumped mass. Although the ceramic stack is essentially decoupled from the transducer, it still acts as a driving force for this mode. The 25 kHz resonance is generated by the Lucite quarter-wave matching layer, providing the proper impedance transformer. Lucite was chosen as the matching layer because its characteristic impedance (ρ-c) is close to that of water and its mechanical loss is well known.

III. DESIGN AND FABRICATION

Photographs of the Triple Resonant Transducer prototypes that were designed and fabricated at NUWC Division Newport are shown in figure 7. Transducer Design I is composed of 12 piezoelectric Navy type III (PZT-8) ceramic rings 2.032 mm (0.08 inches) thick electrically connected all in parallel with insulating rings on the ends, tungsten tail mass, two tungsten center masses and an aluminum head mass separated by two G10 washers. A steel bolt is used to maintain a preload of 41.4 MPa (6000 psi) on the ceramic stack and G10 washers, preventing the ceramic from going into tension under high driver conditions. The transducer is 6.6 cm (2.6 in) in height with 2.54 cm x 2.54 cm (1 in x 1 in) radiating face and weighs 110 grams. Transducer Design II is composed of 10 piezoelectric Navy type III (PZT-8) ceramic rings 2.54 mm (0.10 inches) thick that are electrically connected in parallel with insulating rings on the ends stack, tungsten tail mass, tungsten center mass and an aluminum head mass separated by one G10 washer. The Lucite matching layer face is 1.8 cm (0.71 in) high, its sound speed is 1800 m/s and generates a quarter-wave resonance at 25 kHz. A titanium bolt is used to maintain a preload of 41.4 MPa (6000 psi) on the ceramic stack. The transducer is 7.62 cm (3 in) in height with a radiating face of 2.54 cm x 2.54 cm (1 in x 1 in) and weighs 122 grams.

IV. MODEL AND TEST RESULTS

Both plane wave equivalent circuit models and finite element models were used to aid in design of the Triple Resonant Transducers. The plane wave model program, TRN[11], is composed of cascading two-port transmission line networks, lumped elements and piezoelectric elements. The plane wave model calculates transmitting responses, receiving responses, electrical input impedance, mechanical impedance at various ports, directivity index, and the transducer ABCD matrix values, for a piston in a rigid baffle. The plane wave equivalent circuit representation of the triple resonant transducer is shown in figure 8. Each of the numbered ports represents a section and corresponding piece parts of a two-port plane-wave element. The solid lines are interconnects between the sections, and the broken lines are disconnects. Z_r is the radiation impedance function for a baffled piston in water. Z_t is the tail impedance port, which is set to a small value in order to represent a pressure release boundary (i.e., air). Z_n is a nodal impedance port used for nodally mounted transducers and is not used here. Z_e represents the electrical input impedance port to piezoelectric ceramic stack section 19.

The finite element program used is ATILA[12], which 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 also calculates electromechanical characteristics such as resonance and antiresonance frequencies, effective coupling coefficient, electrical impedance, capacitance (or inductance), beam patterns, transmitting responses, receiving responses, and directivity indexes. The acoustical measurements were conducted at NUWC Division Newport's Acoustic Open Tank Measurement Facility (AOTF) in April 2002 at a test depth of 2.3 m and separation distance of 2 m. The measurements were made using standard gated pulse techniques. The gated receive signals were measured at the steady-state portion of the signal and were free of interference reflections.

The in-air measured electrical conductance for both designs are shown in figures 9 and 10 using an HP4194A impedance analyzer. Comparison of the measured in-air electrical conductance with the plane wave circuit model of Design I is extremely accurate. The measured conductance responses of Design II shows comparison of a solid Lucite face with a diced Lucite face on the transducer. As shown the diced face removed the lateral modes of the solid Lucite block, which is evident from the three response peaks of the diced face in figure 10. A photograph of the solid and diced Lucite face is shown in figure 11. A comparison of the transmitting voltage response of Design I for measured, plane wave circuit model and finite element model are shown in figure 12 and electrical impedance magnitude in figure 13. A comparison of the transmitting voltage response of Design II for measured, plane wave circuit model and finite element model is shown in figure 14 and electrical impedance magnitude in figure 15.

The transducer design was configured into a 16-element planar array model to allow investigation of element interactions under array loading conditions at both low and high frequencies. The 16-element array configuration was chosen for its successful comparison of measured and modeled results in the hybrid magnetostrictive/piezoelectric transducer 16-element array study[13] and for its simple symmetric geometry. The mathematical model used for the array is based on Pritchard's interaction theory for pistons in a rigid baffle[14]. Generated from the TRN model, ABCD parameters that describe the electromechanical transfer function of a single-element transducer were used in the calculations. The model predicts transmitting responses, receiving responses, beam patterns, acoustic velocities, and input impedance for the individual array elements, as well as for the whole array. The array configuration is a 4 x 4 planar array with element center-to-center spacing of 26.2 mm, is shown in figure 16. Figure 17 shows the modeled transmit voltage responses of both designs compared with a traditional Tonpilz transducer of approximately the same size.

Transducer Design II has a flat operating transmitting response band from 13 kHz to 45 kHz, a bandwidth (Δf) of 32 kHz. For a 25 kHz center frequency the relative bandwidth $\Delta f/fc$ (ratio of bandwidth to center frequency) is 1.3 or 130%, which is 2.5 times that of a traditional tonpilz transducer. Both Designs produce 15dB greater response levels at 14 kHz than the traditional tonpilz transducer. Transducer Design I response should be "broader" in practice since not all the mechanical losses were accounted for in that model.

VI. SUMMARY

This paper is an overview of the development of novel broadband triply resonant transducers that were designed and built at NUWC Division Newport, and presents theory of operation, design, fabrication and test results. The transducer designs use multiple passive components (masses and compliances) added to a conventional type Tonpilz transducer to produce triply resonant transducer devices. The designs have the ability to produce lower frequency capabilities from a small package (Element Size), than current traditional tonpilz transducer of the same size and weight. The increase in operating bandwidth is achieved without using exotic expensive transduction materials, making the designs cost effective. These Triple Resonant Transducers provide 5 kHz to 10 kHz increase in bandwidth at the low end of the band over a traditional Tonpilz transducer and have a broadband operating bandwidth from 13 kHz to 37 kHz.

ACKNOWLEDGMENT

The author would like to thank Jan F. Lindberg of the Office of Naval Research for his support on this project and to the technical staff at the Naval Undersea Warfare Center. This work was sponsored by the Office of Naval Research, (S&T) Science & Technology program.

REFERENCES

1. G. C. Rodrigo and M Redwood, "Analysis and Design of Piezoelectric Sonar Transducers," Department of Electrical and Electronic Engineering Queen Mary College, London, UK, Phd Thesis August 1970.
2. A. G. Elliott, "The design of a high power broadband noise source," Proceedings of the Institute of Acoustics Vol. 12 Part. 4 1990 Sonar Transducers for the Nineties, pp 126– 32, Birmingham, UK, December 1990.
3. R. F. W. Coates, "The Design of Transducers and Arrays for Underwater Data Transmission," IEEE Journal of Oceanic Engineering, Vol. 16, No. 1, January 1991.
4. S. C. Thompson, "Broadband Multi-Resonant Longitudinal Vibrator Transducer," U. S. Patent 4,633,119, December 1986.
5. S. C. Thompson, M. P. Johnson, E. A. McLaughlin and J. F. Lindberg, "Performance and Recent Developments with Doubly Resonant Wideband Transducers," Proceedings of the Third International Workshop Transducers for Sonics and Ultrasonics, Orlando, Florida, U.S., May 1992.
6. J. L. Butler and A. E. Clark, "Hybrid Piezoelectric and Magnetostrictive Acoustic Wave Transducer," U.S. Patent 4,443,731, 17 April 1984, and "Hybrid Transducer," U.S. Patent 5,047,683, 10 September 1991.
7. S. C. Butler and F. A. Tito, "A Broadband Hybrid Magnetostrictive/Piezoelectric Transducer Array," *OCEANS 2000 MTS/IEEE Conference Proceedings*, vol. 3, session 8, Providence, RI, 11-14 September 2000, pp. 1469-1475.
8. S. C. Butler, "Development of a High Power Broadband Doubly Resonant Transducer (DRT)," NUWC-NPT Technical Memo 01-112, Naval Undersea Warfare Center Division, Newport, RI. November 2001
9. S. C. Butler, " High Frequency Mutli-Resonant Broadband Transducer Development at NUWC," *UDT 2002 Undersea Defence Technology Conference Proceedings*, session 6A.2, 18 – 20 June, 2002, La Spezia, Italy.
10. S. C. Butler, "Development of a High Power Broadband Doubly Resonant Transducer (DRT)," *UDT 2001 Undersea Defence Technology Conference Proceedings*, session PII.5, 30 October–1 November, 2001, Waikiki, HI.
11. "TRN System Users Manual," Version TRN 5.0, Naval Undersea Warfare Center, Newport, RI, October 1988.
12. ATILA, Magsoft Corporation, Troy, NY 12180.
13. F. A. Tito and S. C. Butler, "4 x 4 Array Test Summary for a Broadband Hybrid Magnetostrictive/Piezoelectric Transducer," NUWC-NPT Technical Memo 02-002 (in preparation), Naval Undersea Warfare Center Division, Newport, RI.
14. R. L. Pritchard, "Mutual Acoustic Impedance Between Radiators in an Infinite Rigid Plane," *Journal of the Acoustical Society of America*, vol. 32, June 1960.

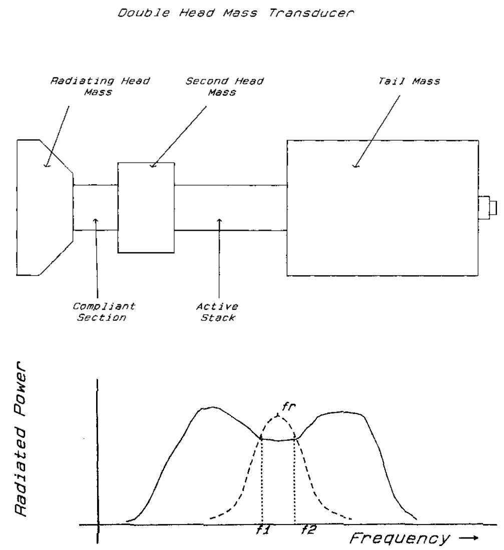

Fig. 1. “Rodrigo” type doubly resonant transducer design.

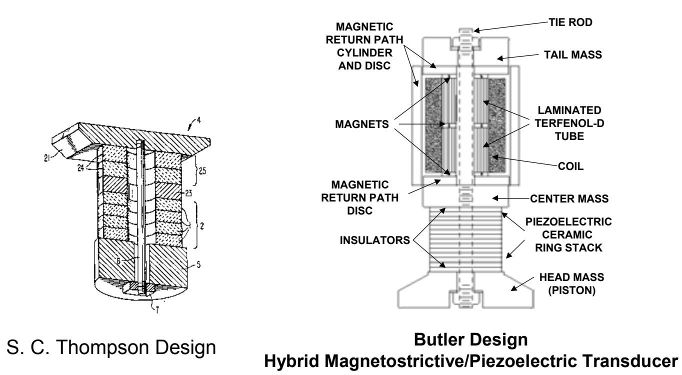

Fig. 2. Thompson doubly resonant wideband transducer design and Butler Hybrid magnetostrictive-piezoelectric transducer design.

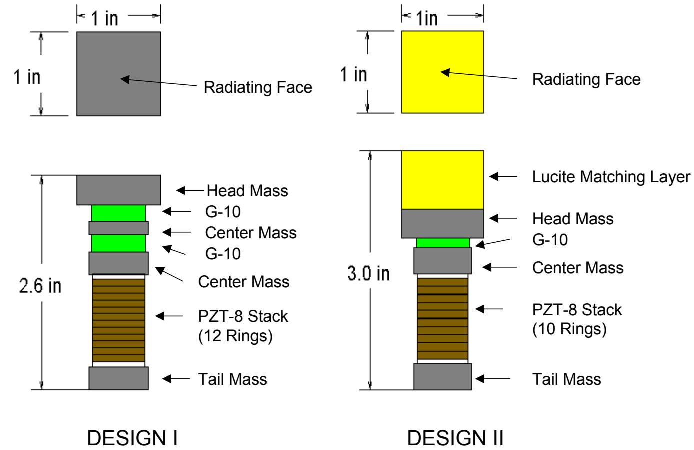

Fig. 3. Sketch of NUWC Triple Resonant Transducer (TRT) Design I and Design II.

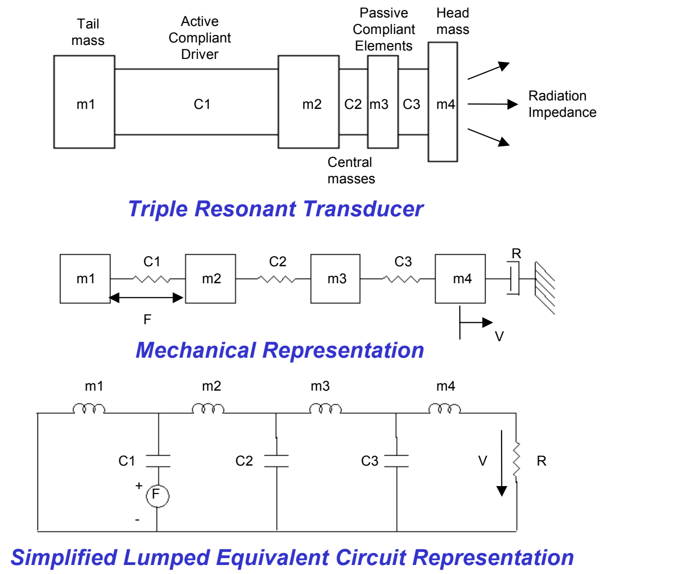

Fig. 4. Simple Equivalent Circuit for the Triple Resonant Transducer design I.

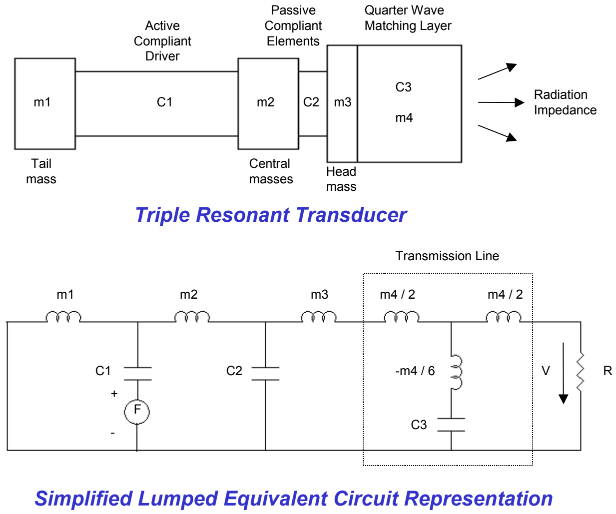

Fig. 5. Simple Equivalent Circuit for the Triple Resonant Transducer design II.

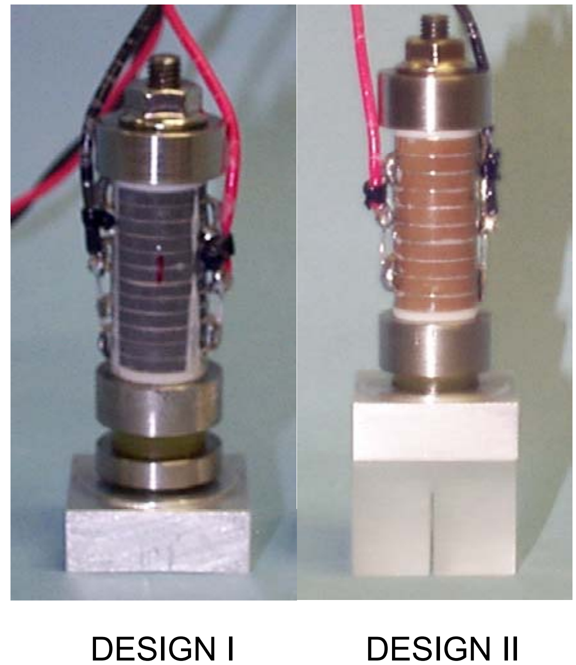

Fig. 7. Photograph of Triple Resonant Transducer (TRT) Design I and Design II, Fabricated at NUWC.

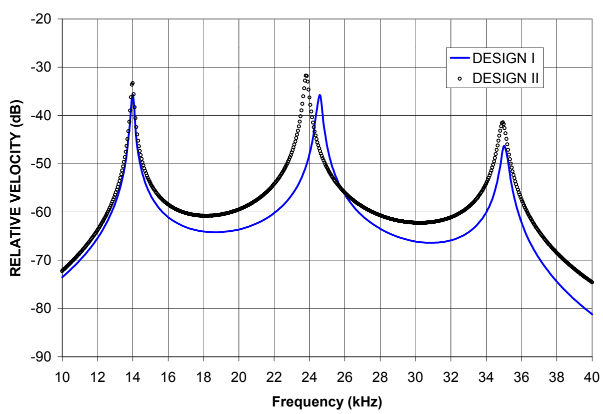

Fig. 6. Head mass velocity response for both circuit models.

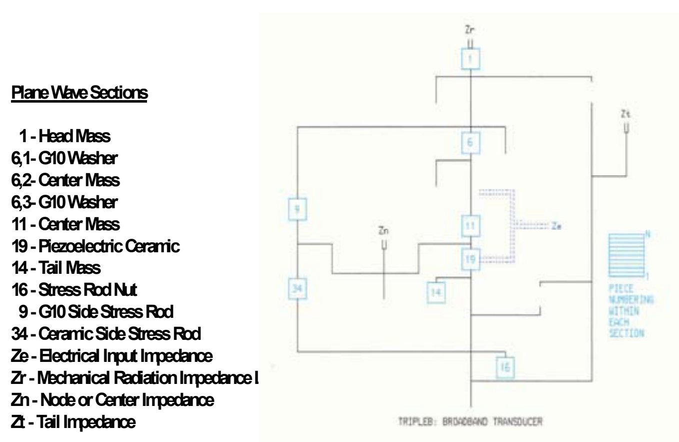

Fig. 8. Plane wave model circuit model for design I.

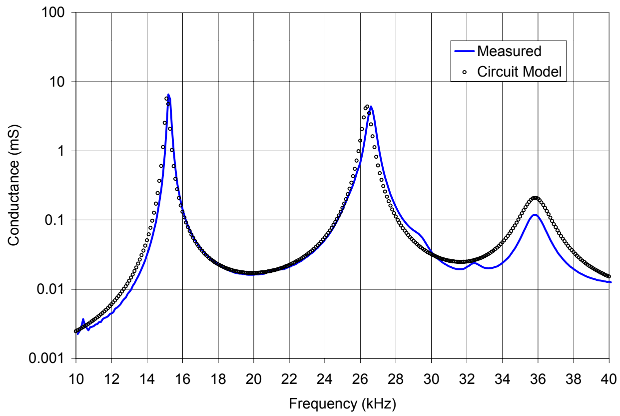

Fig. 9. Modeled and measured in-air electrical conductance of TRT design I.

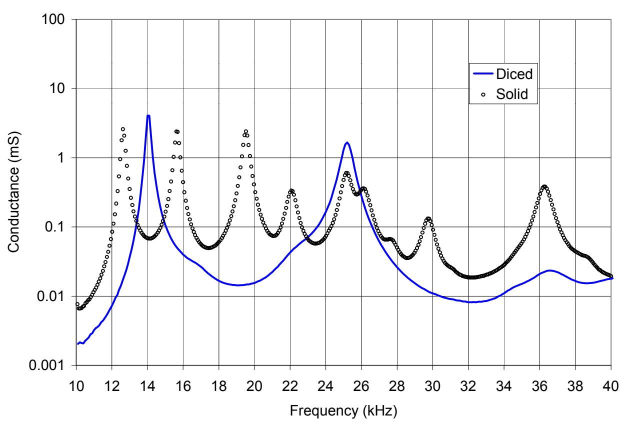

Fig. 10. Measured in-air electrical conductance of design II with solid and diced Lucite Matching Layer.

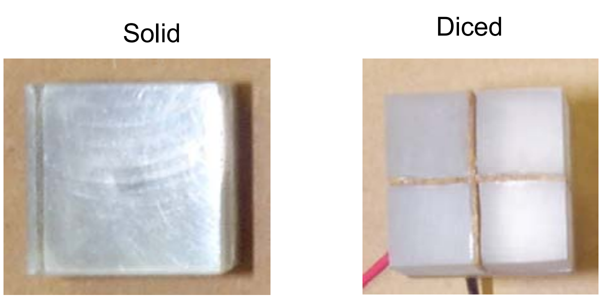

Fig 11. Photograph of Solid Lucite Matching Layer Radiating Face and diced Face.

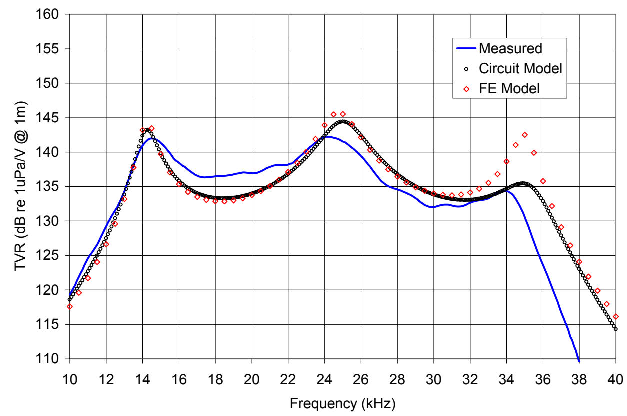

Fig. 12. Modeled and measured Transmitting Voltage Responses (TVR) of TRT design I.

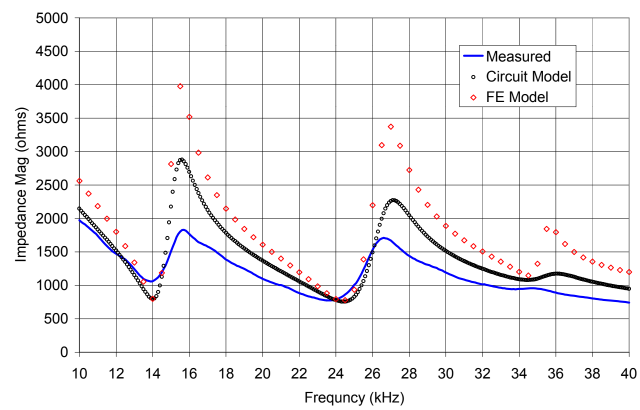

Fig. 13. Modeled and measured electrical impedance magnitude of TRT design I.

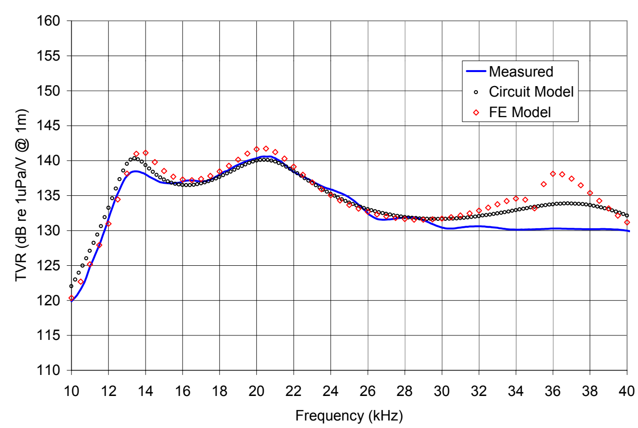

Fig. 14. Modeled and measured Transmitting Voltage Responses (TVR) of TRT design II.

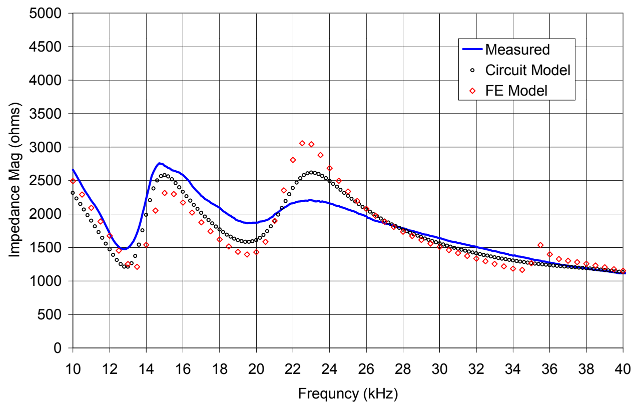

Fig. 15. Modeled and measured electrical impedance magnitude of TRT design II.

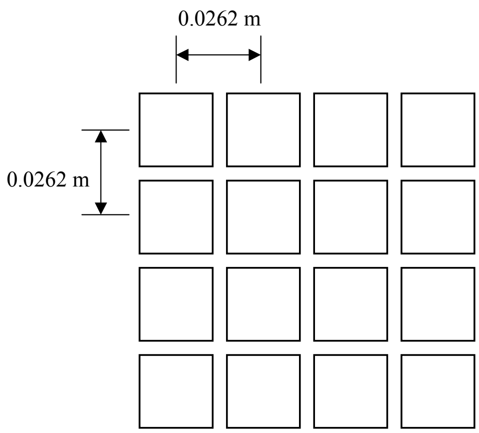

Fig 16. Array 4x4 Element Model Configuration.

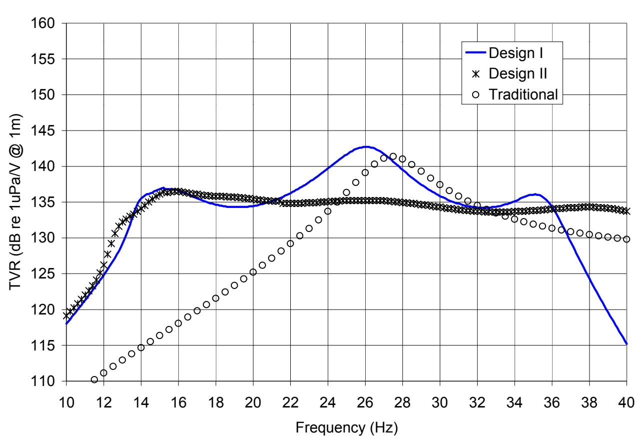

Fig. 17. Modeled Transmitting Voltage Responses comparison of the Triple Resonant Transducers and a traditional Tonpilz transducer, of the same size and weight in 4x4 Array Configuration.