ANALYSIS OF A BARREL-STAVE FLEXTENSIONAL TRANSDUCER USING MAVART™ AND ATILA FINITE ELEMENT CODES

Richard A.G. Fleming[1], Mark Kwiecinski[2], and Dennis F. Jones[1]
[1]DRDC Atlantic, PO Box 1012, Dartmouth, Nova Scotia, CANADA, B2Y 3Z7

ABSTRACT

A small barrel-stave flextensional transducer, designed and tested at Defence Research and Development Canada – Atlantic (DRDC Atlantic), is a candidate source for underwater coastal surveillance and acoustic communications applications. This high-power transducer (in excess of 190 dB re 1 μPa @ 1 m) has an outside diameter, length and mass of 5.7 cm, 12.7 cm, and 1.1 kg, respectively. The measured fundamental flexural resonance frequency was 1.8 kHz with a transmitting voltage response of 118 dB re 1 μPa/V @ 1m and an omnidirectional radiation pattern. Two computer models were developed for this transducer using finite element codes MAVART™ (Model to Analyze the Vibrations and Acoustic Radiation of Transducers) and ATILA (Analysis of Transducers by Integration of Laplace equations). Comparisons are made between the calibration measurements and the model predictions. [[2]Summer student supported in part by Sensor Technology Limited.]

SOMMAIRE

Un petit transducteur flextensionnel à douves, conçu et mis à l'essai à Recherche et développement pour la défense Canada – Atlantique (RDDC Atlantique), est une source possible pour des applications de surveillance côtière sous-marine et de communications acoustiques. Ce transducteur de grande puissance (supérieure à 190 dB, rapportée à 1 □Pa à 1 m) a un diamètre extérieur de 5,7 cm, une longueur de 12,7 cm et une masse de 1,1 kg. La fréquence fondamentale de résonance en flexion mesurée était de 1,8 kHz avec une réponse en tension d'émission de 118 dB, rapportée à 1 □Pa/V à 1 m, et un diagramme de rayonnement omnidirectionnel. Deux modèles informatisés ont été élaborés pour ce transducteur à l'aide des codes à éléments finis MAVART™ (modèle pour analyser les vibrations et le rayonnement acoustique de transducteurs) et ATILA (analyse de transducteurs par intégration d'équations de Laplace). Des comparaisons sont effectuées entre les mesures d'étalonnage et les prédictions à partir des modèles. [[2]Stagiaire d'été rémunéré en partie par Sensor Technology Limited.]

1. INTRODUCTION

The Class I barrel-stave flextensional transducer is capable of low frequency operation in a relatively small package [1]. This transducer is composed of the five basic components shown in Fig. 1: a driver consisting of sixteen piezoelectric washers, two glass ceramic insulators, two stiff carbon steel endplates, a set of six aluminum staves, and a central stainless steel stress rod. With longitudinal piston motion of the driver, the endplates displace axially causing the staves to flex in the radial direction. Since the staves are curved, the relatively small driver displacements are transformed into larger stave displacements [2].

Much of the design and development of the barrel-stave transducer has been accomplished through the use of finite element modeling, reducing costs and prototype turnaround times. At DRDC Atlantic, transducer modeling has made extensive use of the MAVART™ (**M**odel to **A**nalyze the **V**ibrations and **A**coustic **R**adiation of **T**ransducers) and ATILA (**A**nalysis of **T**ransducers by **I**ntegration of **LA**place Equations) finite element codes.

MAVART™ is a finite element code under development at DRDC Atlantic for transducer design since 1976. This coupled-physics code makes it possible to model and analyze the electro-mechanical-acoustic interactions of piezoceramic- and electrodynamic-driven transducers in fluid media. In MAVART™, the coupling of elastic and electrical fields is carried out by augmenting elastic matrix variables with constituitive relations for the driving materials. The surrounding fluid is modeled similarly with the nodal pressures becoming the finite element variable. The Helmholtz integral is used to determine the effect of the infinite fluid force on the finite-element-modeled fluid. All variables are assumed to vibrate sinusoidally at the selected frequency. The complex solution consists of fluid node pressures, voltages at nodes on the drive elements and displacements of solid element nodes. These solutions are post-processed into stresses and strains, far-field transmitting responses, hydrophone sensitivities, directivity indices, electrical admittances, and fluidic pressure gradients [3]. MAVART™ presently exists in 2D, 3D and magnetic versions. Geometry construction of finite element models is carried out using the DRDC Atlantic-developed ModelMaker™ add-on for Mathematica® [4].

Beginning in the late 1970s, the finite element model ATILA was developed by researchers in France at the Institut Supérieur d'Electronique du Nord in collaboration with the Centre d'Etude et de Recherche de Détection Sous-

Marine. Although the program was originally intended as a design tool for sonar transducers, ATILA has been used to study many types of active and passive mechanical structures in any type of acoustic fluid media. ATILA can handle 2D and 3D problems as well as elastic, piezoelectric, magnetostrictive, and electrostrictive materials [5–6]. Elastic and electroacoustic quantities calculated by ATILA include displacement fields, stress fields, near-field and far-field pressures, electrical impedances, transmitting voltage and current responses, open circuit voltage receiving sensitivities, and beam patterns.

In this paper, 2D MAVART™ and ATILA finite element models were developed for the barrel-stave transducer. Measured fundamental flexural and longitudinal resonance frequencies were matched using several geometric and material approximations. Measured response levels were achieved by using damping in the models. This is the first time that finite element modeling results of this barrel stave transducer have been published in the open literature.

2. Transducer Component Dimensions

The dimensions of the main components of the barrel-stave flextensional transducer shown in Fig. 1 are given in this section. The driver consists of a ring-stack of sixteen piezoceramic lead zirconate titanate washers poled through the thickness and connected in parallel electrically. Each washer has an outside diameter of 30 mm, an inside diameter of 7 mm, and a thickness of 5.6 mm. At each end of the piezoceramic ring-stack is a machinable glass ceramic insulator with the same diameters as the washers but a thickness of about 6 mm.

Figure 1: Barrel-stave flextensional transducer components clockwise from upper right: sixteen piezoceramic washers, two ceramic glass insulators, two hexagonal endplates, six concave aluminum staves (the two shown separately are 12.7 cm long), and a stress rod located along the axis of the transducer.

Two hexagonal endplates are bonded to the insulators. The carbon steel endplates have a 7-mm-diameter hole in the center (to allow the stress rod to pass through), an edge length of 27 mm, and a thickness of 12.5 mm. A 4.8-mm-diameter stainless steel stress rod is used to apply a compressive bias to the ring-stack. Six concave aluminum staves are bonded and bolted to the sides of the hexagonal endplates. The staves are 12.7 cm long, have a maximum thickness of 5 mm, and a radius of curvature of 20.0 cm. Since this transducer's shape is fully described over 1/nth of its circumference, it is said to have n-fold symmetry. In the case of this projector, since its geometry is fully described over 1/6th of its circumference, it is 6-fold symmetric.

3. Finite Element Models

Two finite element models were developed using the transducer design codes MAVART™ and ATILA. The first author used the former code, the other two authors the latter. Apart from transducer dimensions and material properties, the models were developed independently. A 2D barrel stave model was developed in 1996 at DRDC Atlantic and analyzed in MAVART but the analysis was confined to the first resonance and described a different version of the barrel stave projector [7].

3.1. MAVART™ barrel-stave transducer model

The barrel-stave flextensional transducer geometry and mesh were generated using the ModelMaker™ [8] add-on to Mathematica®. As seen in Fig. 2, the single quadrant model was composed of 342 quadratic elements (Table 1) with 1321 nodes. The elements included quadrilateral axially-poled piezoceramic elements, quadrilateral solid elements, fluid-to-solid elements, fluid elements and fluid-to-fluid infinite elements. Air was modeled in the volume between the inside of the stave material and the outside of the driver.

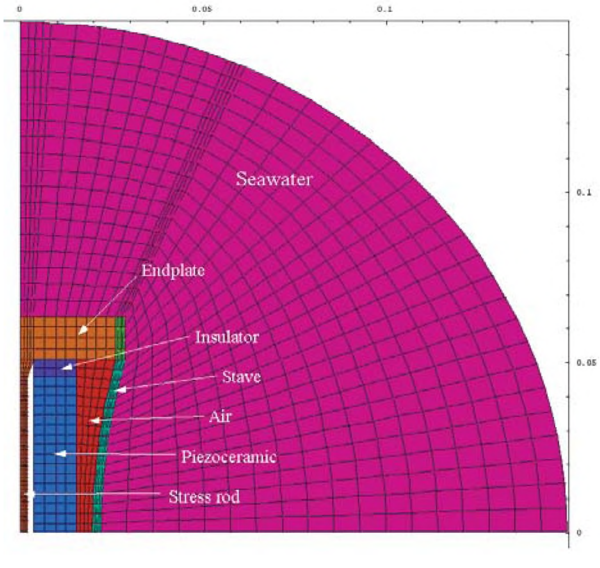


Figure 2: 2D MAVART™ barrel-stave transducer model.

The dimensions of the piezoceramic ring-stack washers, insulators, endplates and most of the stress rod were the same as those in the actual projector (Section 2). The transition of the stress rod diameter to the larger endplate inside diameter was varied to retain topological congruence. The outside diameter of the endplate (assumed to be circular) was the difference between the stave thickness and the outside diameter of the transducer. The stave thickness was set at 2.5 mm instead of the crescent-shaped cross-section of the actual stave. The aluminum at the stave/endplate intersection was modeled as isotropic as there is no appreciable movement here, relative to the endplate.

The material matrix of the aluminum used for the staves had to account for the fact that the model could not include the inter-stave slots or variation in stave wall thickness over the transducer's circumferential direction. This deviation from a truly isotropic stave material was necessary to give the finite element model its ability to breath and radiate sound in a manner similar to the actual transducer. Both material damping and a fictitious transversely isotropic aluminum were selected so that the first resonance of the model matched that of the measured values in both frequency and TVR. The tangential stiffness of the transversely isotropic aluminum used in the stave was reduced by a factor of 155.

3.2. ATILA Barrel-stave Transducer Model

A 2D finite element grid was used to model the barrel-stave flextensional transducer with ATILA. Using appropriate displacement boundary conditions along the central axial and radial planes, symmetry in both the longitudinal and circumferential directions reduced the problem to solving the one-quarter cross-section shown in Fig. 3. In total, the model consisted of 1688 elements and 3617 nodes. A breakdown of the elements by material type is given in Table 1. Quadrilateral elements were used for the solid materials and triangular elements for the seawater, the latter elements created using ATILA's automatic mesh generator.

The hexagonal endplates were modeled as circular plates by assuming that their cross-sectional areas were identical. The aluminum staves were assumed to have a constant thickness of 2.54 mm instead of a crescent-shaped cross-section. The curved portion of the staves was assumed to be a fictitious transversely isotropic aluminum with the hoop (tangential) compliance increased by a factor of 210. Damping was included in the ring-stack to achieve the best fit to the experimentally determined TVR level at the fundamental flexural resonance.

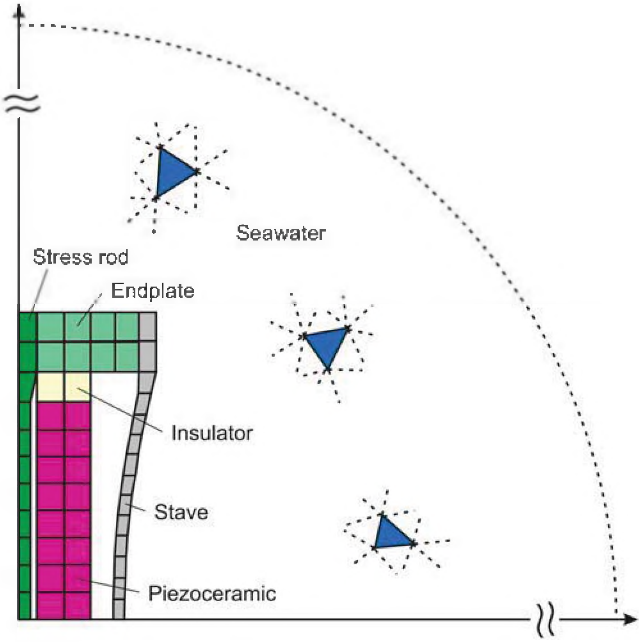


Figure 3: 2D ATILA barrel-stave transducer model.

Table 1: MAVART™ and ATILA element comparisons.

Number of Elements		
Material	MAVART™	ATILA
Stress rod	44	11
Piezoceramic	16	16
Insulator	2	2
Endplate	12	8
Stave	22	14
Air	37	0
Seawater	209	1637

4. Results

Post-processing of the finite element models yielded transmitting voltage responses (TVRs) in both the axial and radial directions, as well as directivity patterns near the first and second resonance frequencies.

Both finite element models' predictions of performance both in TVR (see Figs. 4 and 5) and directivity pattern (see Figs. 6 and 7) are in good agreement especially near the first two resonances.

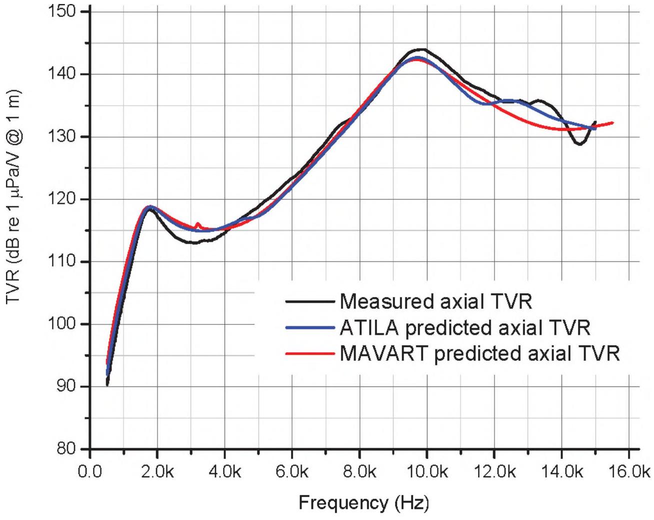


Figure 4: Measured versus modeled axial TVRs.

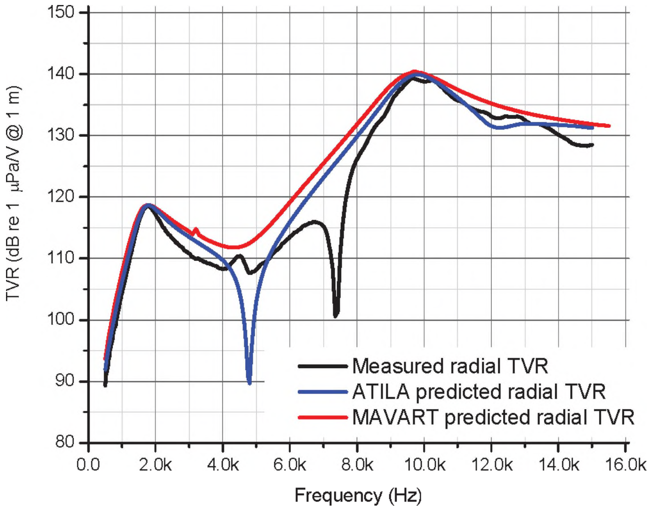


Figure 5: Measured versus modeled radial TVRs.

Variations in radial TVR levels between predictions and measured data in the 3–8 kHz band may be due to 3D effects not be fully described in a 2D model or to the presence of the waterproof rubber boot material covering the projector which was not modelled. The difference in transversely isotropic aluminum stiffness ratio between models or the presence of air inside the projector in the MAVART™ model may explain the inter-model radial TVR discrepancy. Further investigation into these disparities is under way with the added benefit of a new single-fold segment 3D model of this transducer.

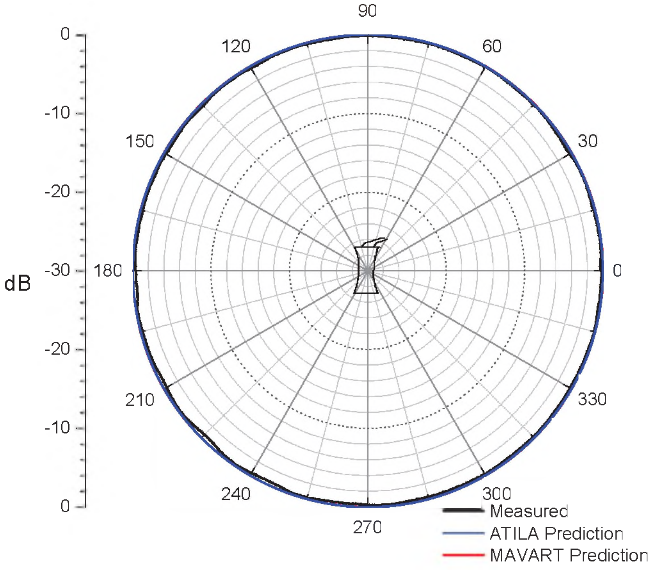


Figure 6: XZ directivity pattern at 1.5 kHz.

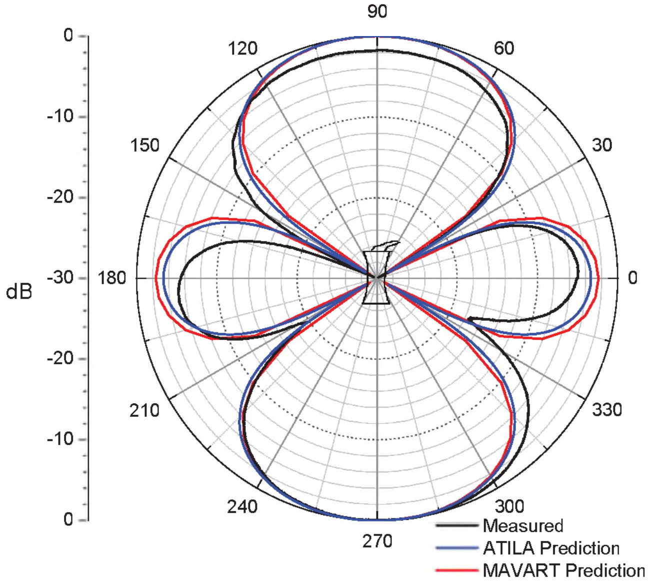


Figure 7: XZ directivity pattern at 9 kHz.

The 2 dB asymmetry seen the projector's measured endfire directivity pattern at 9 kHz is due to the presence of the wiring and waterproofing on one end of the transducer (see Fig. 7). Note also that the measured directivity pattern at 9 kHz is rotated counter-clockwise a few degrees. The modelled response pattern shape at 9 kHz is consistent over all angles. The level disagreement seen in the x-direction between the measurement and model may be due to boot material losses or 3D stave effects.

As can been seen in the results, these models make it possible to quickly model the fundamental performance of this 6-fold symmetric barrel-stave transducer and aid in its further development.

5. REFERENCES

[1] Jones, D.F. and Lindberg, J.F. (1995). Recent transduction developments in Canada and the United States. Proceedings of the Institute of Acoustics, 17(3), 15–33.

[2] Jones, D.F. (1989). Low-frequency flextensional projectors. Proceedings of the Annual Meeting of the Canadian Acoustical Association, Edited by A.J. Cohen, 18–23.

[3] Armstrong, B.A. and McMahon, G.W. (1984). Discussion of the finite-element modeling and performance of ring-shell projectors. IEE Proceedings, Vol. 131, Part F, No. 3, 275–279.

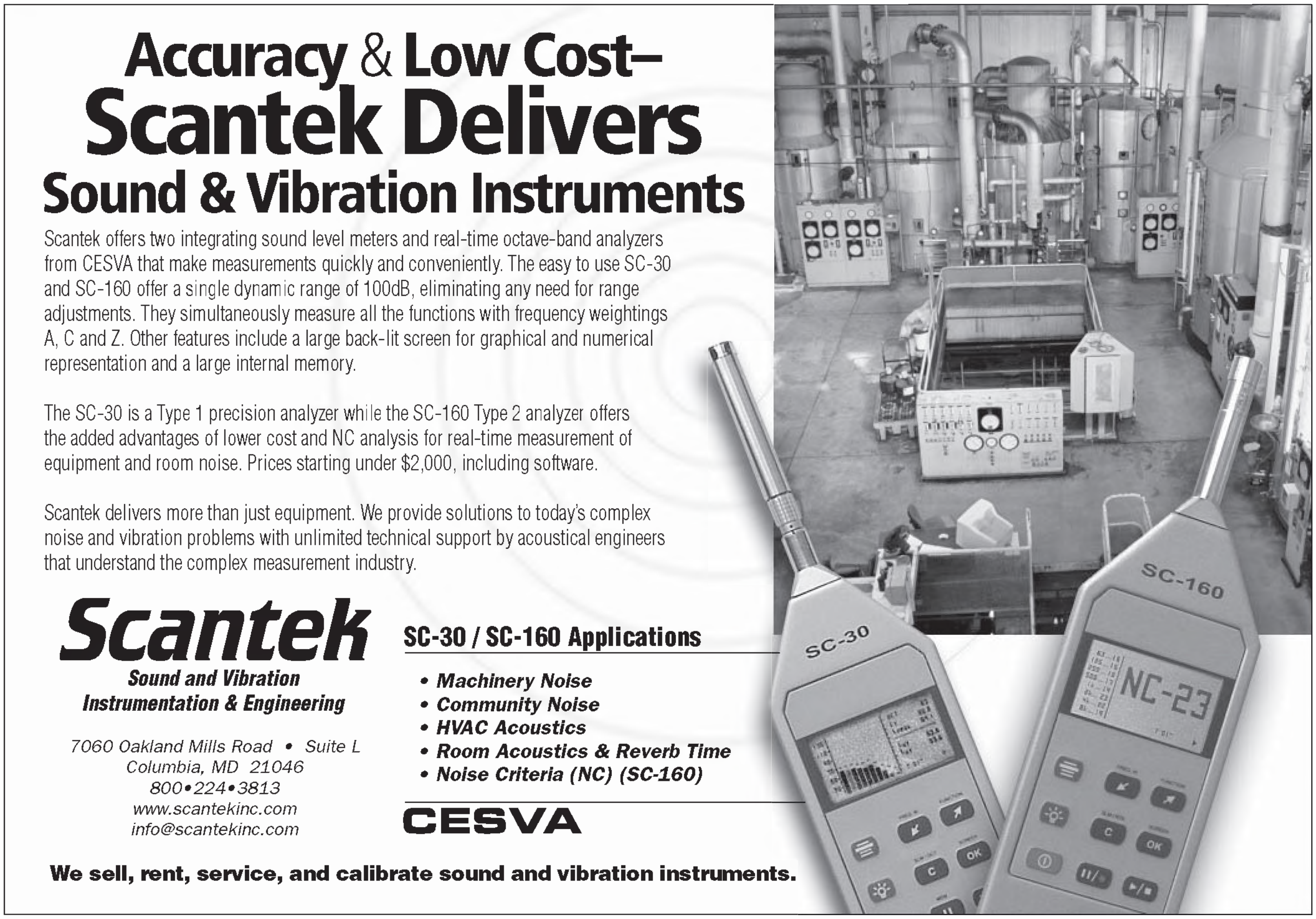
[4] Mathematica®, The Way the World Calculates, http://www.wolfram.com/products/mathematica/index.html

[5] Welcome to Micromechatronics Inc. - ATILA FEA, http://www.micromechatronicsinc.com/atilainfo.html

[6] Coutte, J., Dubus, B., Debus, J.-C., Granger, C., and Jones, D.F. (2002). Design, production, and testing of PMN-PT electrostrictive transducers. Ultrasonics 40, 883–888.

[7] McMahon G.W. and Fanning B.L. (1996), Barrel Stave Projector Finite Element Modelling, DREA Contractor Report CR/96/402/EA (Distribution Limited).

[8] Purcell C.J., Building Finite Element Models with Mathematica®, 1997 Mathematica® Developers Conference, Wolfram Research Inc., Champagne, Illinois, http://library.wolfram.com/infocenter/Conferences/229/


Accuracy & Low Cost–
Scantek Delivers
Sound & Vibration Instruments

Scantek offers two integrating sound level meters and real-time octave-band analyzers from CESVA that make measurements quickly and conveniently. The easy to use SC-30 and SC-160 offer a single dynamic range of 100dB, eliminating any need for range adjustments. They simultaneously measure all the functions with frequency weightings A, C and Z. Other features include a large back-lit screen for graphical and numerical representation and a large internal memory.

The SC-30 is a Type 1 precision analyzer while the SC-160 Type 2 analyzer offers the added advantages of lower cost and NC analysis for real-time measurement of equipment and room noise. Prices starting under $2,000, including software.

Scantek delivers more than just equipment. We provide solutions to today's complex noise and vibration problems with unlimited technical support by acoustical engineers that understand the complex measurement industry.

Scantek
Sound and Vibration
Instrumentation & Engineering

7060 Oakland Mills Road • Suite L
Columbia, MD 21046
800•224•3813
www.scantekinc.com
info@scantekinc.com

SC-30 / SC-160 Applications

- *Machinery Noise*
- *Community Noise*
- *HVAC Acoustics*
- *Room Acoustics & Reverb Time*
- *Noise Criteria (NC) (SC-160)*

CESVA

We sell, rent, service, and calibrate sound and vibration instruments.