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PROCESSING AND ANALYSIS TECHNIQUES FOR SOUND INTENSITY MEASUREMENTS

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ABSTRACT

New applications and processing techniques have been developed for the acoustic intensity analysis field within the recent years. Both measurement devices and data analysis techniques have been enhanced to increase the user capability and flexibility for dealing with the noise analysis problems of identification, quantification, correlation and correction.

By utilizing the latest Genrad computer aided data acquisition system, the user has total access to a three dimensional acoustic data base for analysis of complex sound problems. Special analysis techniques are available for both on or off line processing of sound intensity data from 1, 2 or 3 dimensional acoustic acquisition, as well as from velocity or extended frequency bandwidth measuring probes.

INTRODUCTION

The sound intensity calculational techniques have been implemented on a variety of instruments, but an integrated system application of the intensity technique offers more functional freedom and expandable processing operations. This paper deals with a brief background of the system implementation of sound intensity methodology and its general application.

BACKGROUND

Classical Two Microphone Method

A formal derivation of the various formulations of the intensity techniques will not be presented herein. Such presentations are well documented by several authors (*) and to reproduce such efforts is not warranted within the scope of this document. Instead, a brief review will suffice to anchor the intensity concept for future discussion in this paper.

Basically, the acoustic power emitted by a source is defined as the surface integral of the sound intensity, I, over an area of emission generally enclosing the source.

$$W = Ids \qquad (1)$$

In addition, the acoustic intensity as defined by the product of acoustic pressure and velocity.

$$I = PU \qquad (2)$$

Hence the measurement of intensity requires a measurement of acoustic pressure as well as acoustic velocity. Since acoustic pressure is a fairly simple measurement, an often employed approximation was used to relate the acoustic pressure and velocity in far field (no reflecting surfaces) conditions. Based on simple characteristic acoustic impedance, a simple relationship is found:

$$P/U = \rho c \quad (3)$$

where ρ = air density
c = speed of sound

This equation can be utilized in equation 2 to solve for the intensity.

$$I = \frac{P^2}{\rho c} \quad (4)$$

However, the free field requirement is a fairly severe restriction due to the test facilities involved, and it also is difficult to assess relative source strengths without time consuming (and often inaccurate) techniques of lead wrapping.

Alternate formulations to equation (3) are available under fairly reasonable assumptions that also relate pressure and velocity of plane waves. The end result of these formulations is the velocity of the plane wave elements which can be determined through a differential pressure measurement. This differential pressure measurement is supplied by a finite difference approximation utilizing two pressure tranducers (i.e. microphones) separated by some distance R. Solving the differential equations in the Fourier domain yields the intensity formulation based on the cross power spectrum between the two microphone measurements.

$$I_r = \frac{1}{\rho\,\delta r} E\{\int \mathrm{IMAG}\,(\pi f)^{-1}(P_1 \cdot P_2^*)\,df\} \quad (5)$$

where P_1, P_2 are the two pressure measurements and * denotes complex conjugate

and δr = spacing between the pressure probes.

Implementation of equation (5) on multiple channel spectrum analyzers is fairly straight forward. Generally, the primary usage differences lie in compensating for residual errors and post-processing capabilities.

IMPLEMENTATION CONSIDERATIONS

Approximation Errors

The cross spectral formulation basically provides a velocity calculation by obtaining the frequency distributed phase shift between two measurement points in the path of a progressive plane wave. For wave lengths on the order of the microphone spacing, the error associated with the finite difference approximation can become significant due to the large phase shift. Hence, both the maximum frequency and microphone spacing are normally "related" in the sense that selection of these parameters are done to minimize errors in the intensity calculation in the upper frequency ranges.

The expected phase shift is plotted for two microphone spacings in Figure 1.

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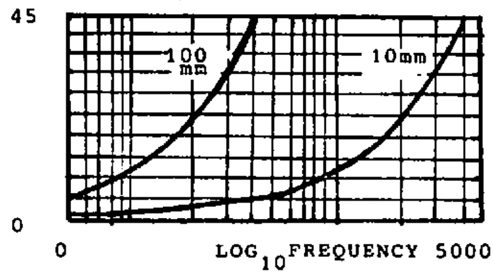

Figure 1 Phase Shift due to microphone spacing

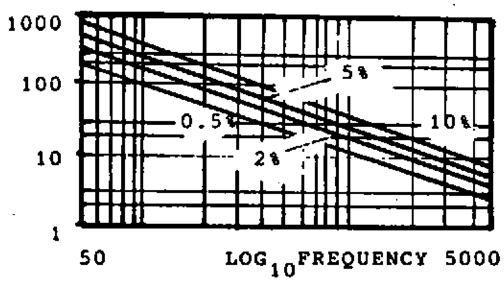

Figure 2 Phase error due to finite difference approximation

One should select microphone spacing based on the required maximum frequency range and acceptable (measurable) phase shift. An upper limit to the acceptable phase shift can be related to the error in the finite difference approximation with only two measuring points. The maximum expected error is plotted in Figure 2.

For example, choosing an upper frequency of 3000 hz and a spacing of 10 mm yields a phase shift (from Figure 1) of about 32. From Figure 2, this phase shift and frequency can be expected to contain about a 5% error in the intensity measurement. As a guideline, intensity surveys should not exceed a 5-10% error due to phase shift errors as a usable upper limit which corresponds to a 30 to 45 degree phase shift.

Measurement Phase Errors

Another possible source of intensity estimation error is the residual (or relative) phase shift differences between the two microphone transducers and associated signal conditioning electronics. This error is ually fixed due to hardware characteristics and not a function of microphone spacing. Generally this error becomes significant at low frequencies due to the inherently small phase angles being measured. Several techniques are available to minimize this fixed-bias error:

1. limit low frequency range of calculations
2. phase match all components as best as possible
3. mechanically switch instrumentation and double average out errors
4. compensate complex cross-spectrum for fixed-bias phase errors

STANDARD CONFIGURATION

System implementations of the intensity technique have usually been limited to single dimensional acquisition primarily due to A/D and post processing system limitations in a reasonably portable equipment configuration. With the advent of the 2515, high quality A/D and processing power are now available in a field portable unit. The basic analysis range can cover 40 to 10240 hertz in 8 binary steps. This acquisition bandwidth can be located anywhere within the 25k hertz input range. Spectra acquired by the intensity software package can contain from 80 to 1280 spectral lines of resolution under user control. The data results (sound pressure levels as well as intensity and overall power levels) may be digitally A-weighted. Display formats include both narrowband or synthesized 1/3 octave presentations with user selectable (or autoranged) limits.

Compensation Functions

Errors in the intensity measurements can be minimized via several alternatives. The most common is to utilize a measured phase compensation function which extracts the residual phase measurement errors from the system calculated intensity functions. This compensation function may include the microphone effects if the proper calibration equipment is available. In addition, the user has the option to bypass all compensation if desired.

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The finite difference approximation error can also be reduced under certain testing conditions. For applications where the intensity measurement is sufficiently removed from the source, the 2 point difference approximation may be enhanced to increase the useable frequency range of the analysis. This amounts to increasing the upper phase angle measurement limit from 45 degrees (as mentioned earlier) to 60-70 degrees.

Data Base Generation

The data base generation can be accomplished with any of the intensity probe options. At present, the user has available single or multi-dimensional 2 microphone probes as well as a velocity probe which measures the acoustic velocity (as opposed to approximation by finite pressure differentials). In addition, a multi bandwidth probe is supported which allows simultaneous acquisition of 2 bandwidths of intensity measurements thereby extending the useable frequency range of the overall analysis. This configuration requires 3 microphones with 2 different spacings. Multi-bandwidth processing is particularly useful for overall power summations where low frequency power noise (e.g. due to low RPM sources) is as important as high frequency (e.g. due to structural vibration of components) emitted energy.

The data base is maintained in full 3 dimensional format thereby allowing component as well as vector display and power summation analysis.

The multi-channel acquisition necessary for any of these approaches is supported by appropriate graphic displays. Figure 3 shows four channels time data, Figures 4 and 5 show 3-axis spectral and coherence functions. Multidimensional phase compensation functions are shown in Figure 6, and the multidimensional frequency content in terms of bands is shown in Figure 7. A three-dimensional vector scan is shown in Figure 8. Figures 9 and 10 show intensity characteristics.

A COMPARISON OF SINGLE-AXIS AND MULTI-AXIS INTENSITY MEASUREMENTS

To compare the results of single and multi-axis intensity studies a series of measurements was conducted on a flat surface containing a 'hot spot' from which the majority of the sound was radiating. The location of the 'hot spot' was not accurately known - neither were the radiation and directivity characteristics of the surface. However, being a flat symmetrical surface the intensity measurements would normally be made also on an imaginary flat control surface above the radiating object. This method for the single-axis probe assumes the intensity vectors are normal to the control surface with the limitation that any non-normal intensity vectors will only contribute a component of the total vector in the chosen measurement direction.

Two probe types were used in creating a data base for subsequent analysis; a single-axis probe to measure the normal and components of non-normal intensity vectors and a multi-axis probe to measure

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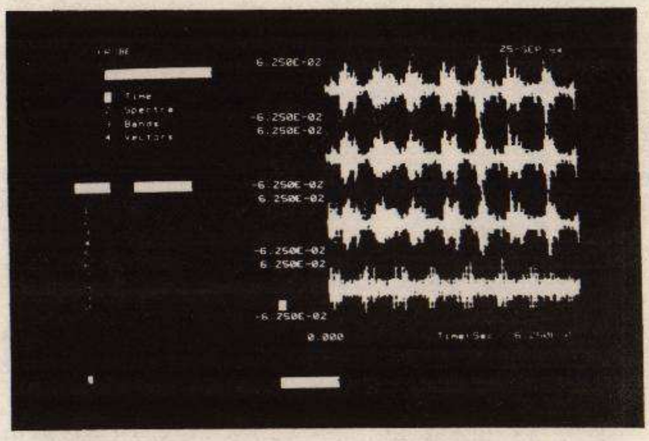

Figure 3 Time domain display

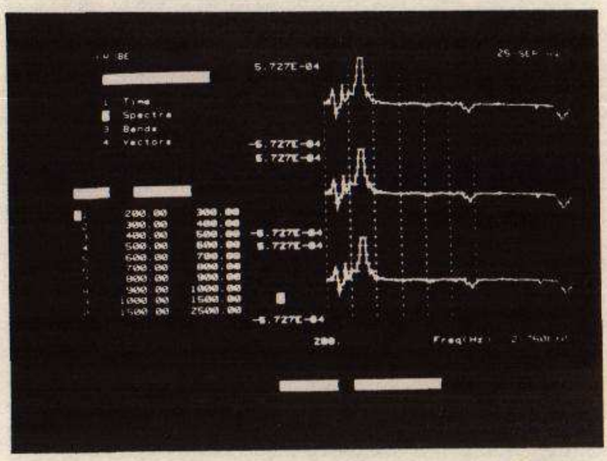

Figure 4 Spectral display

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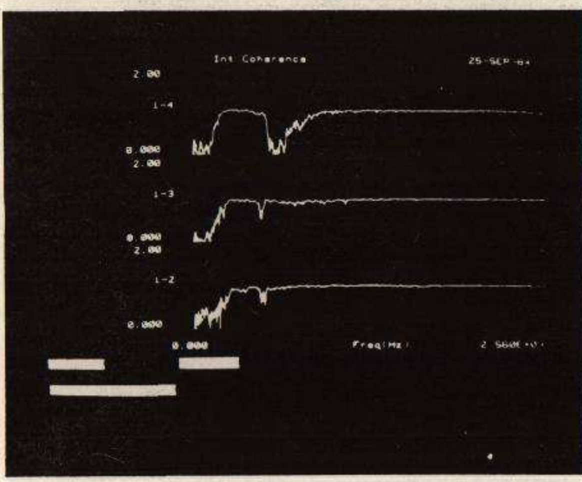

Figure 5 3-axis Coherence

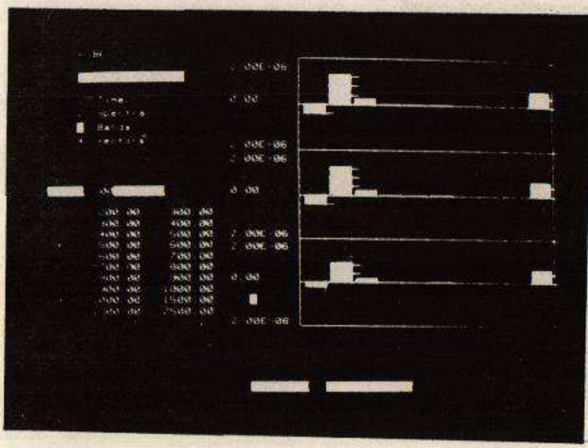

Figure 6 Intensity in predefined bands

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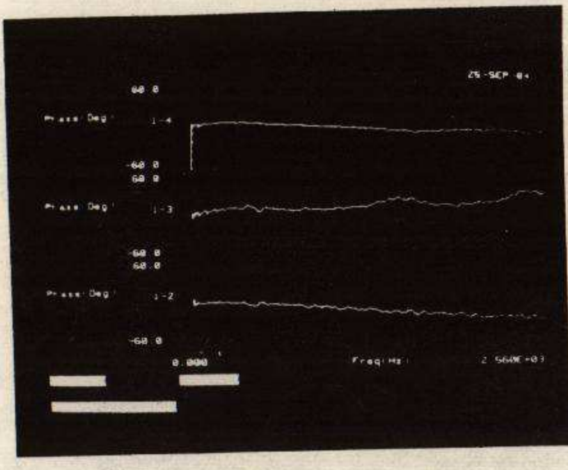

Figure 7 3-axis phase compensation values

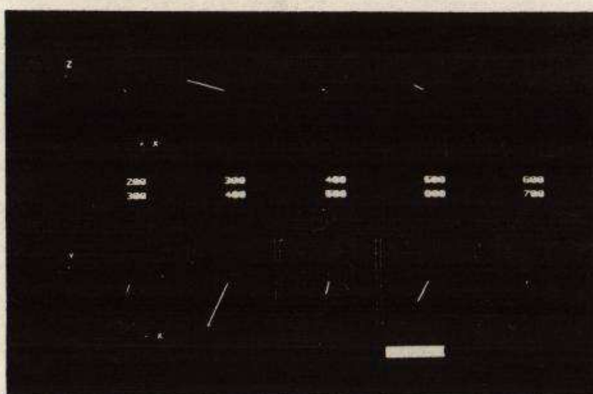

Figure 8 3-axis banded vector scan

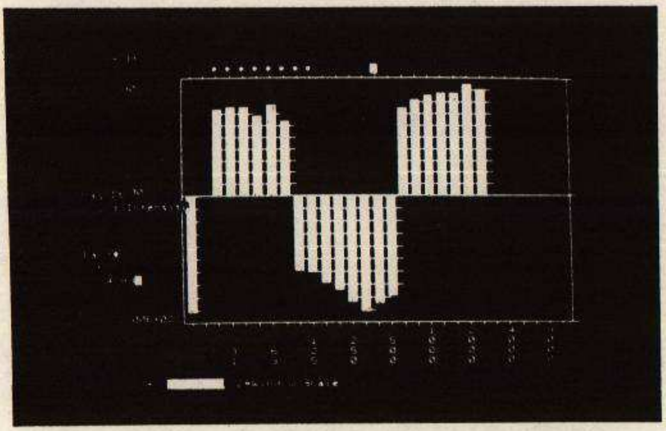

Figure 9 Positive and negative intensity in bands

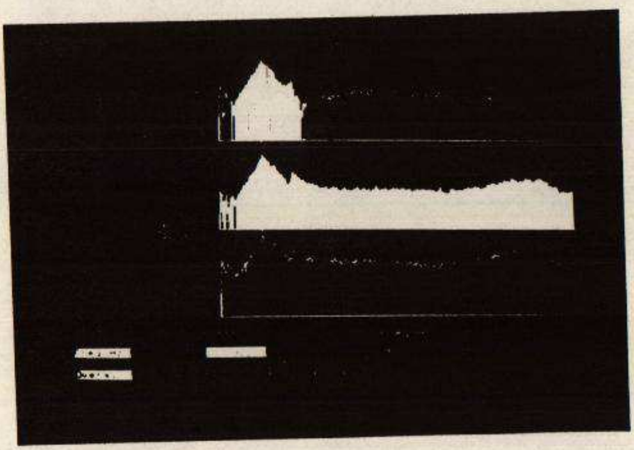

Figure 10 3-axis intensity results

the total intensity vector.

The radiating surface and measurement locations are shown in Figures 11 and 12. The probes were mounted on a tripod to ensure accurate location and good repeatability of results.

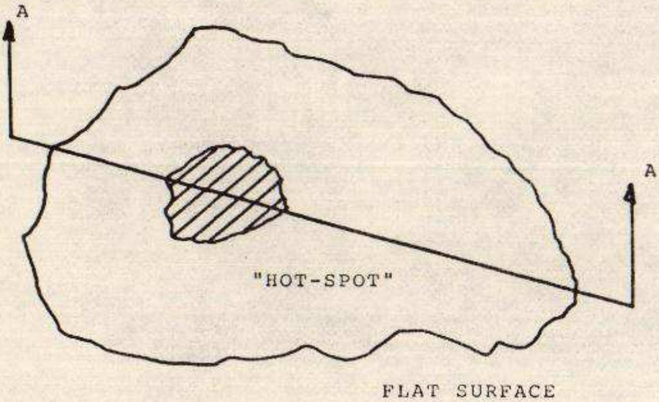

Figure 11

A band width of 248 Hz to 2560 Hz was chosen to minimise low-frequency phase errors and linear interpolation errors for the probe spacing used. A large averaging period was also chosen to minimise statistical errors. The sound emitted by the test object is close to white noise, having a flat spectrum across the frequency range of interest.

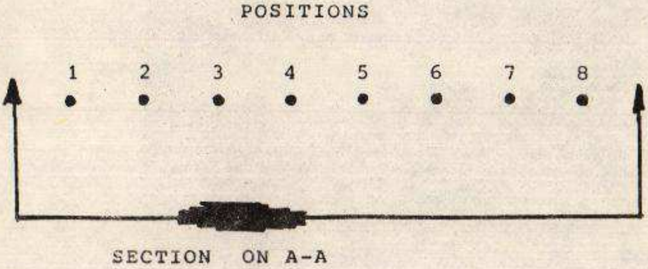

Figure 12

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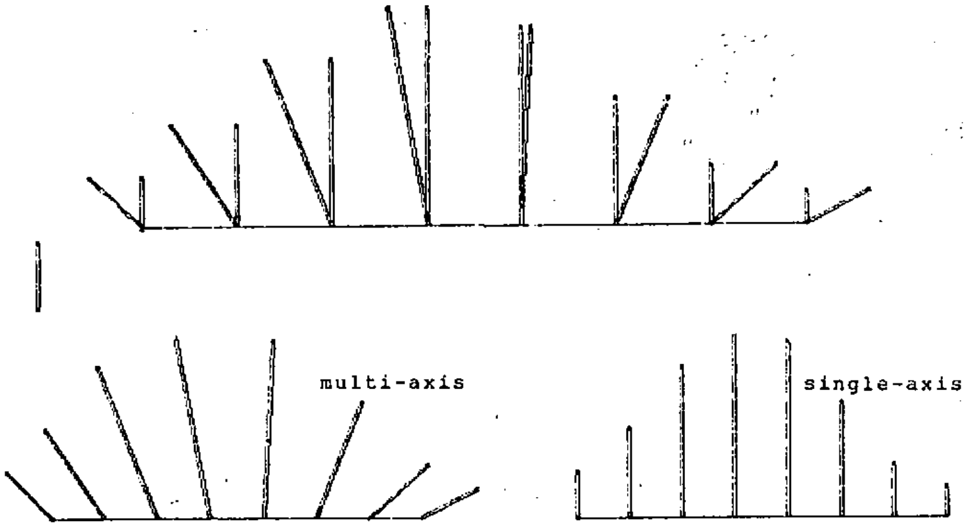

Figure 13 Single- and multi-axis results

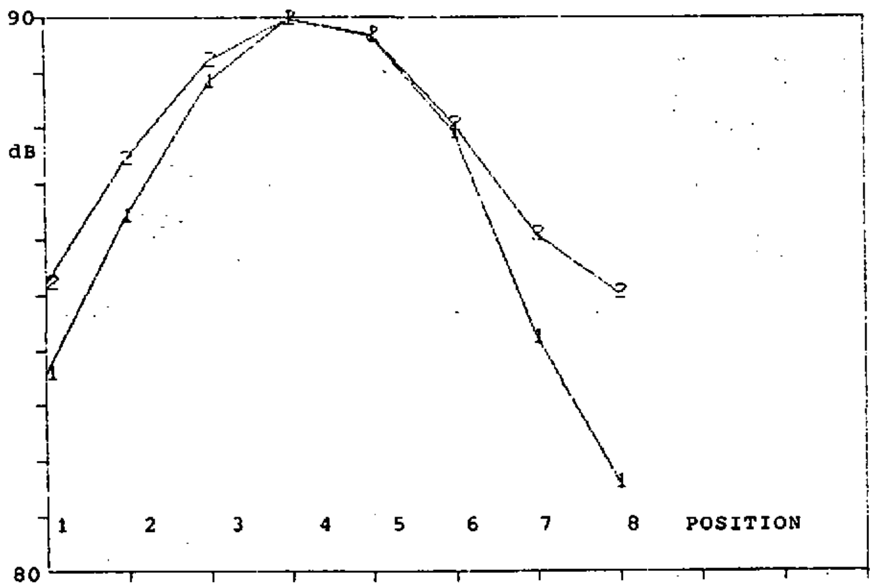

Figure 14 Comparison of single- and multi-axis results

Intensity Results

Table 1 below compares the single-axis and multi-axis data showing that the greatest error occurs at position 8, which is located farthest from the hot spot and where the vector has a large Y axis component. A graphical comparison of the results is shown in a vector plot in Figure 13 and level V position plot in Figure 14.

Data from Section AA

Intensity $/M^2$

Position		1	2	3	4	5	6	7	8	TOTAL
1 Axis	dB	83.68	86.66	88.91	90.05	89.68	87.74	84.33	81.68	96.46
Multi-Axis	dB	85.25	87.44	89.23	90.12	89.69	88.08	86.10	85.03	97.03
Error	dB	1.57	0.78	0.32	-	-	0.34	1.77	3.35	0.57

Table 1.

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The source dimension in relation to the total surface is approximately 1:2. Should this ratio be larger 1:4 or 1:5 then a greater Y axis component will be present and the difference between the two measurements will be greater.

Sound Power Results
The intensity levels converted to sound power levels by application of a factor for the area at each measurement location. The increase in error results from a higher area weighting applied to locations at a larger radius. Table 2 lists the sound power levels for each probe type and Figure 15 shows the results graphically.

Sound Power radiating in a Positive x direction

Position		1	2	3	4	5	6	7	8	TOTAL
1 Axis	dB	74.10	75.62	75.65	72.01	71.62	74.48	73.28	72.09	82.89
Multi-Axis	dB	75.63	76.39	75.96	72.08	71.65	74.81	75.05	75.44	83.94
Error	dB	1.53	0.77	0.31	-	-	0.33	1.77	3.35	1.05

Table 2.

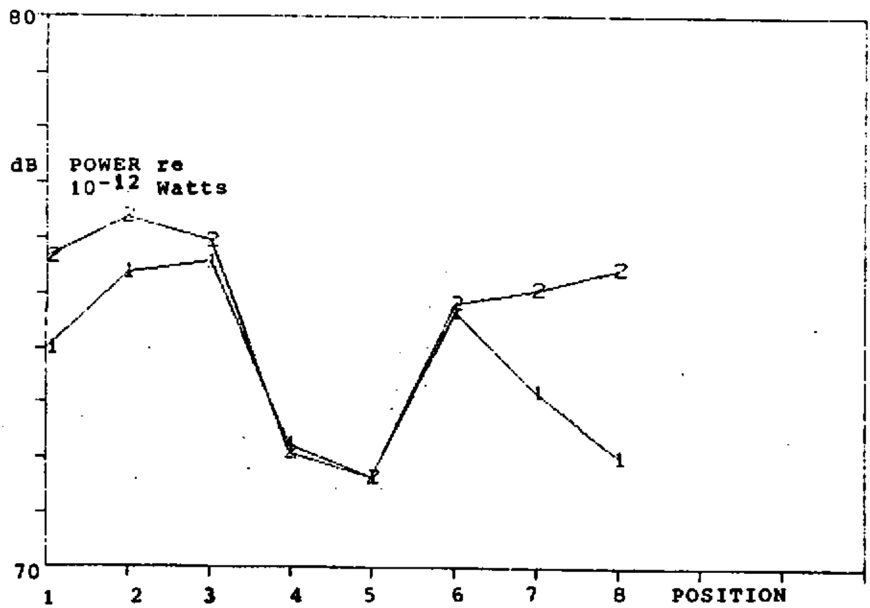

Figure 15

Repeatability

Errors due to statistical and positioning elements have been minimized for the test and to check on repeatability of results the survey was conducted twice using exactly the same setup and parameters.

1 Axis Measurements

Position										
Survey #1	dB	83.56	86.42	88.83	90.27	89.68	87.93	84.23	81.60	96.49
Survey #2	dB	83.68	86.66	88.91	90.05	89.68	87.74	84.33	81.68	96.43
Error	dB	0.12	0.24	0.08	0.22	-	0.19	0.10	0.08	0.06

Table 3.

CONCLUSIONS

Most applications generally deal with locating a troublesome noise source and then quantifying its magnitude and distribution. After this has been accomplished, the task of eliminating or quieting the source is generally undertaken. Without detailed knowledge of the noise source location and form of the emitted intensity sound fields, it may be difficult to obtain consistent results from simple single-axis acquisition due to variance of sound field distributions.

To obtain accurate intensity data from 1 axis probes in many instances requires prior knowledge of the vector direction. Although this may be possible in some circumstances when testing simple objects it becomes impractical in more complex acoustic fields where vector directions will vary with position and frequency.

The multi axis probe allows 2 and 3 dimensional acoustic studies to be performed with improved accuracy and test time as well as performed with improved accuracy and test time as well as providing a method for source location, determination of radiation coefficients and reflection angles, insertion loss, transmission loss and vector streaming.

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