MEASUREMENT OF SOUND INTENSITY AND SOUND POWER

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Measurement of Sound Intensity and Sound Power

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Abstract

In this report the concept of a measurement technique for calculating sound intensity in the frequency domain is discussed and also how such a measurement system can be implemented in practice by using a frequency domain analyser. The technique described employs a dual-channel FFT analyser to obtain a cross power spectrum from the two microphones from which sound intensity is calculated . This approach enables a general-purpose FFT analyser together with a micro-computer to perform the function of a dedicated sound intensity analyser. The application of sound intensity measurement technique in sound power determination of a reference source is presented.

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Measurement of Sound Intensity and Sound Power

1. Introduction

This report describes a new and practical method for measuring and analysing the noise signature caused by air-borne and structure-borne noise. If the sound intensity of noise signatures can be measured, it is then possible to identify and minimize the average acoustic spectrum and emission of the Navy's surface ships and submarines.

Conventional techniques for measuring sound power [ref.5,6], or the transmission loss of sound-absorbing materials, require special facilities such as anechoic or reverberant chambers. This report deals with a measurement technique for sound intensity that is an attractive alternative to these conventional techniques.

Measuring sound power by means of sound intensity has a number of advantages including the ability to locate the sources and sinks of sound, to determine sound power from a source in situ even in a noisy machinery room, and the ability to map the intensity of the sound source. These cannot be done by the traditional techniques except under controlled acoustic environment.

H.F. Olson laid down the theoretical background for intensity measurements in 1932 [ref.1] but it was not until the 1970s that the electronic instruments required for a reliable measurement of sound intensity became available [ref.5]. A sound intensity measurement system comprises:

1. An intensity probe for sensing the sound signal

Currently there are two categories of probe in widespread use. The "p-u" probe combines a pressure transducer with a particle velocity transducer. The "p-p" probe is made up of two matched microphones (pressure transducers) separated by a spacer for measuring sound pressure and particle velocity [ref.4]. This report discusses the use of the "p-p" type of probe, upon which the measurement system is based.

2. An analyser for processing the sound signal

The analyser may be one of two types. It may have either digital or analog filters, and operate in the time domain (as do Type 4437 and 2134 Bruel & Kjaer sound intensity analysers); or it may be a dual channel FFT analyser which operates in the frequency domain of the sound signals [ref.10].

The former are faster, have real-time processing, and produce output in the octave or fractional octave frequency bands that are frequently used in acoustic measurements. However, if the analysis function can be performed on a general purpose FFT analyser, it has the important advantage of eliminating the need for an expensive and limited piece of equipment. This report describes how a dual channel FFT analyser can be used to determine sound intensity, by taking the cross power spectrum from two microphones.

2. *Sound intensity and its applications*

Sound intensity describes the rate of energy flow (ie. the power flow) per unit area at a point in space. In the SI unit system, the unit for Sound Intensity is watts per square metre.

In contrast to sound pressure which is a scalar quantity, sound intensity is a vector quantity as it has both direction and magnitude. Usually, sound intensity is measured in the direction normal to the surface through which there is a net flow of sound energy.

2.1 *Sound Power and Sound Pressure*

Sound power can be considered as the strengh of the source which gives rise to a sound pressure in space. The cause of noise is sound power; what we hear is its effect, sound pressure.

Sound power is virtually independent of the environment. A five watt source will always give an energy output of five watts; it does not matter if the source is placed in a large or small room, or if there is another source present.

Sound pressure, on the other hand, is a quantity that does depend on the acoustic environment; on the distance from the point of measurement to the source, on the size of the room in which the sound source is placed, on the sound absorption coefficients of surrounding surfaces, and so on [ref.6]

Because of its independence from the acoustic environment, sound power is a good descriptor of the source strength whereas sound pressure, a quantity that relates directly to hearing damage and noise annoyance, is a good descriptor for the effects of sound on people.

2.2 *Applications of Sound Intensity Measurements*

2.2.1 *Sound Power Determination*

In determining sound power radiated from a source, a surface enclosing the source is defined as the control surface. At this surface, the sound intensity is measured in the direction normal to the surface and the total flow rate of energy outward is determined.

Before the development of measurement techniques for sound intensity, the sound power of a source was usually calculated from sound pressure measurements. These measurements need to be made within special structures with known acoustic properties, such as anechoic or reverberant chambers. Such structures are quite costly, and the sound source being measured must first be removed from its normal working environment [ref.5,6].

On the other hand, sound intensity can be measured in virtually any environment. This allows the measurement to be done on-site. By using sound intensity measurements on a control surface as described above, the sound power of a given noise source can be determined even in the presence of other radiating sources.

Theoretically, background noise will have no effect on the measurement of sound power because sound intensity is a vector quantity. Background noise is caused by sources outside the control surface, and so, according to Gauss' theorem [ref.2], the net flow of background noise through the control surface is zero. (This applies only to a stationary background noise and where there is no sound absorption materials inside the control surface.)

In practice, a sound field generally consists of active part (free field plane wave), reactive part (standing wave) and diffuse part (reverberant field) [ref.12] . A sound intensity measurement system only responds to the active part. When sound intensity is measured in the presence of a strong extraneous background noise and/or in a highly reverberant (diffuse) environment, the random errors and the phase mismatch error will become significant hence making the measurement results inaccuracy. However, providing the background noise is time stationary, measurements can be made to an accuracy of 1 dB even when the background level exceeds the source level as much as 10 dB [ref.6 p.22].

2.2.2 *Intensity Mapping*

To perform intensity mapping, the surface area of interest is first subdivided into a grid and the intensity over each point on the grid is measured. The data obtained is then further processed so that maps of intensity can be computed and plotted out across the entire grid for each frequency band of interest. In this way the precise area of the dominant contribution of noise can be determined.

Since intensity is a vector quantity, it is possible to locate the sound sources and sinks by mapping the source area; a positive intensity indicates a source, and a negative intensity indicates a sink. It is quite possible to find a source next to a sink on the same machine [ref.2].

2.2.3 *Sound Transmission Loss (Reduction Index)*

While the conventional procedure for the measurement of sound transmission loss requires the test speciment to be placed between two reverberant rooms (called a "transmission suite"). The measurement of sound intensity needs only one reverberant room [ref.2,7]; in this procedure the source is placed in a reverberant room to provide a diffuse incident field, and the transmitted power is measured using sound intensity technique.

2.2.4 *Source Ranking*

A source within a complicated structure may radiate sound in some components and absorb sound in others. In order to effectively reduce the noise level of this type of source it is necessary to rank the noise level for each of the source components individually and then focus on the source component that makes a dominant contribution to the total noise level. This makes the measurement of sound intensity a powerful tool because one can define a measurement surface that encloses the component of interest, and treat all other noise- radiating components as background noise as long as the noise is stationary. Further, the total sound power can be calculated simply by adding the partial sound powers from all the components that radiate noise [ref.8].

3. *Calculation of sound intensity*

In general, the component of intensity in the r-direction is defined as the amount of energy passing through an unit area per unit of time:

$$I_r = \frac{E_r}{At} \qquad (1)$$

where E_r, A and t are the energy, the area and the time (in seconds).

In acoustics, energy E_r is the work done by the sound field on the air particles causing them to move:

$$E_r = \text{Work} = Fd_r = \frac{FAd_r}{A}$$

where F and dr are the force and the distance.

since F/A is the sound pressure p, we have:

$$E_r = p.A.d_r \qquad (2)$$

Therefore to describe intensity (2) is substituted into (1) :

$$I_r = \frac{pAd_r}{At} = \frac{pd_r}{t}$$

$$I_r = pu_r \qquad (3)$$

since $u_r = dr / t$ is the air particle velocity in the r-direction.

Equation (3) above is the expression for an instantaneous intensity at a point r in space. For the mean intensity we have:

$$\langle I_r \rangle = \overline{pu_r} \qquad (4)$$

where the $\overline{\qquad\qquad}$ indicates time averaging.

In three dimensions, the Intensity vector can be expressed as:

$$\langle I \rangle = \overline{pu} \qquad (5)$$

4. *The Two Microphone Method For Practical Sound Intensity Measurements*

Equation (5) shows that sound intensity is the time averaged product of the sound pressure and air particle velocity at a point in space. In principle, a sound intensity measuring device should consist of transducers for the detection of the air particle velocity and the sound pressure signals (these transducers are associated in an intensity probe). The signals from the transducers are then multiplied and time averaged to determine the mean sound intensity in the direction of the probe axis.

Currently, two methods are widely used for practical measurements of sound intensity. The first method uses a particle transducer and a sound pressure transducer (the p-u probe). The second method employs two sound pressure transducers (the p-p probe). In the latter method, the particle velocity is determined from the spatial pressure gradient via the Euler equation, using a finite difference approximation, while the pressure is approximated as the average of the two transducer pressures. The approximations involved in the p-p probe are discussed below.

4.1 *The Estimator for Particle Velocity* ($\hat{u}_r$)

According to Newton's second law of motion:

$$F = ma \qquad (6)$$

Applying this law to a unit volume of air yields the Euler equation:

$$\rho \frac{\partial \mathbf{u}}{\partial t} = - \nabla p \tag{6a}$$

Integration (6a) with respect to time will give the air particle velocity:

$$\mathbf{u} = -1/\rho \int \nabla p \, dt \tag{7}$$

where ρ is the density of the air, $\mathbf{u}$ is the air particle velocity and ∇p is the pressure gradient at a point in space. Then from (7) the component of $\mathbf{u}$ in the r direction is given by:

$$u_r = -1/\rho \int (\partial p/\partial r) \, dt \tag{8}$$

By using the finite difference approximation method, the pressure gradient $\partial p/\partial r$ can be estimated in practice by measuring the pressures p_a and p_b at two closely spaced points separated by a distance Δr :

$$\frac{\partial p}{\partial r} = \frac{p_b - p_a}{\Delta r} \tag{9}$$

Note that this approximation is valid only if Δr is small compared with the shortest wave lengths in the measured sound field.

Substituting equation (9) into equation (8) the estimator $\hat{u}_r$ for the particle velocity [ref.5] is:

$$\hat{u}_r = \frac{-1}{\rho \Delta r} \int (p_b - p_a) dt \tag{10}$$

4.2 *The Estimator for Sound Pressure* $(\hat{P}_r)$

Using a system of two microphones for estimation of $\hat{u}_r$ above, the sound pressure p can be estimated as the average of the pressure p_a and p_b. Hence:

$$\hat{P}_r = \frac{p_b + p_a}{2} \tag{11}$$

4.3 *The Estimator for Sound Intensity* ($\hat{I}_r$)

Finally, the estimated sound intensity in the r-direction , $\hat{I}_r$ is given by:

$$\hat{I}_r = \frac{-(P_b + P_a)}{2\rho\Delta r}\int (P_b - P_a)dt \qquad (12)$$

Note that equation (12) is used in the analog signal processing analyser in the calculation of intensity.

In the frequency domain, the estimated sound intensity $\hat{I}_r$ can be calculated from the imaginary part of the cross power spectrum, G_{ab}, of the signals from the two microphones [ref.1]

$$\hat{I}_r = \frac{-1}{2\pi f\rho\Delta r}\int_0^\infty \mathrm{Im}[G_{ab}(f)]df \qquad (13)$$

This applies to an ideal continuous frequency spectrum. In practical measurement and analysis a narrow-band frequency, dual channel FFT analyser can be used for calculating the intensity. In such cases, the equation (13) becomes:

$$\hat{I}_r = \frac{-1}{2\pi f\rho\Delta r}\sum_{n=1}^{N}\frac{\mathrm{Im}[G_{ab}(n\Delta f)]}{n\Delta f} \qquad (14)$$

where N is the number of spectral lines in the cross power spectrum and Δf is the frequency increment (resolution) between the spectral lines.

5. *Sound Intensity Measurement System*

A practical system for sound intensity measurement, using the frequency domain analysis derived above, is described below. The system comprises:

- P-P type sound intensity probe (Bruel & Kjaer type 3520).
- A phase matched microphone pair (Bruel & Kjaer type 4183).
- Dual channel FFT analyser (Ono Sokki CF-350).
- A microcomputer for post processing of data.

The sound intensity probe (type 3520) operates with a pair of microphones (type 4183) separated by a solid spacer (see Appendix 1(A)). The 4183 consists of two phase-matched and amplitude matched, prepolarised microphones which feature special phase-corrector units. These microphones are used to measure the sound pressures Pa and Pb at two closely spaced points and the spacer provides Δr, the separation distance between these two points.

The Ono Sokki CF-350 FFT analyser is used to convert the time domain into the frequency domain by taking a Fourier Transform of the output signals from the two microphones. It then produces and stores the cross spectrum of the two signals for each point of measurement.

A microcomputer is used for interfacing and processing the cross spectrum data obtained from the Ono Sokki CF-350.

A schematic diagram of this sound intensity measurement system is presented in Figure 1. The photographs of the complete system are shown in Appendix 1(C). The limitations of this system are discussed in section 9.

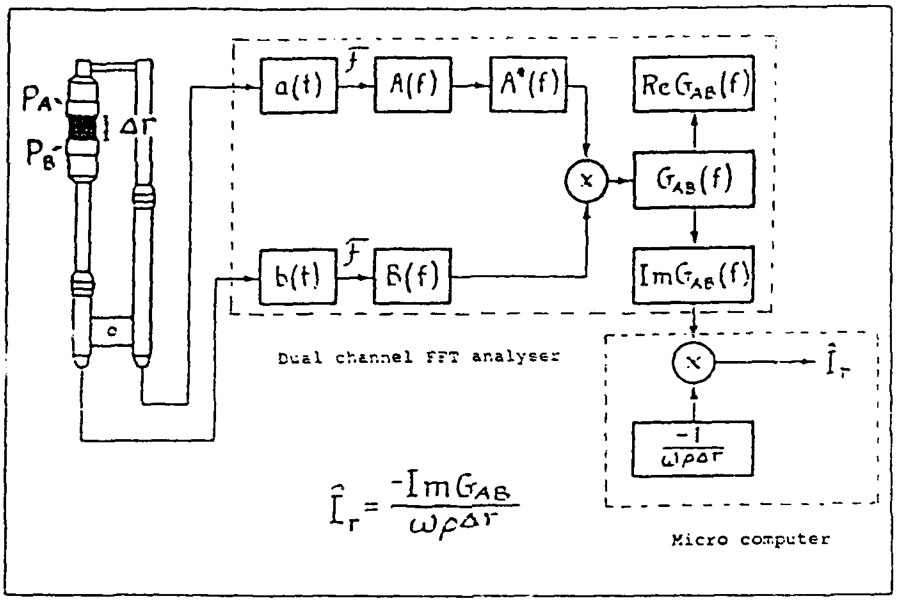


Figure 1: *Schematic diagram of a sound intensity measurement system.*

6. *Computer Program For Calculation Of Sound Intensity From Cf-350 Fft Analyser Data*

From equation (14), the sound intensity at a point r in space can be deduced from the cross spectrum of the two microphones (intensity probe) using a dual channel FFT analyser.

A computer program has been developed for processing sound intensity measurement data (in the form of cross spectrum) using the programming language ASYST. The program performs the following functions:

(1) It interfaces with the Ono Sokki (CF-350) dual channel FFT analyser via a GPIB board. This enables the reading of cross spectrum data from the analyser block memory into the PC. Note: each cross spectrum corresponds to a measurement point on the control surface.

(2) It calculates the sound intensity from the cross spectrum. The calculation is based on equation (14) of section 4.3 and the computed intensity represents the component which is normal to the measurement surface (also the direction of the probe axis).

(3) It provides post processing of sound intensity data such as:
- Calculation of total radiated power by integrating of partial sound powers (from sub-areas of the control surface).
- 3-dimensional plotting of intensity distribution over the area of the measurement surface, and
- Third octave band analysis of the power radiated from the control surface.
  Note: the formation of third octave bands from narrow bands (spectrum lines) includes Hanning window compensation.
  The method used is based on that of the CF-350 analyser.

(4) It allows the user to re-execute the program for another set of data.

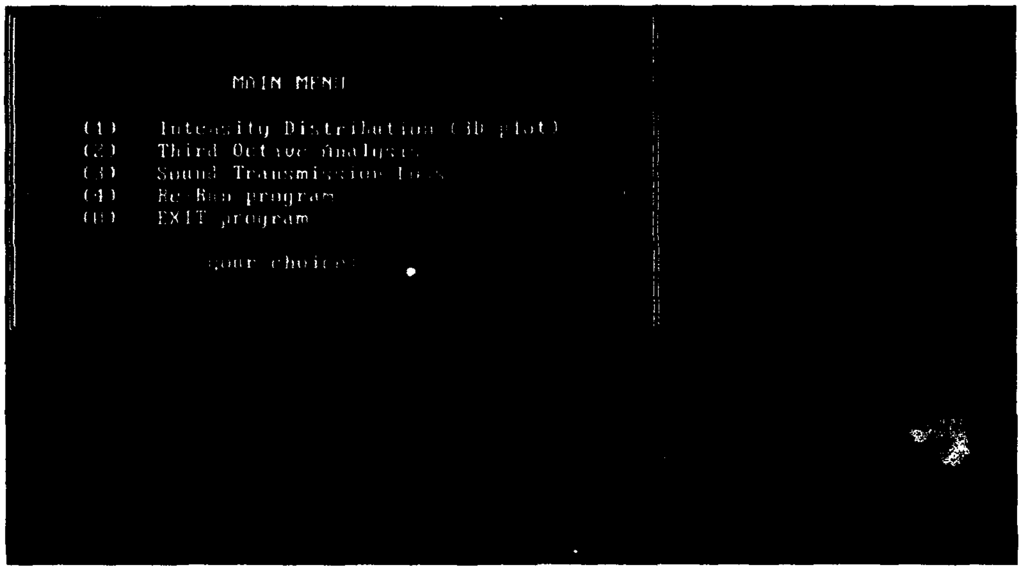
(5) It provides print-out functions for all plots and result listings.

Some of the program features are:

- menu selection for driving the program as shown in Figure 2,
- screens for data entry. Usually there is a brief description about the process and types of data to be input (Fig.3),
- status of current process, instructions for loading of data etc. (Fig.4),
- in third octave band analysis, the program displays the centre frequency, band number, and band value both in engineering units and in dB (with reference to 10E-12 W) (Fig.5),

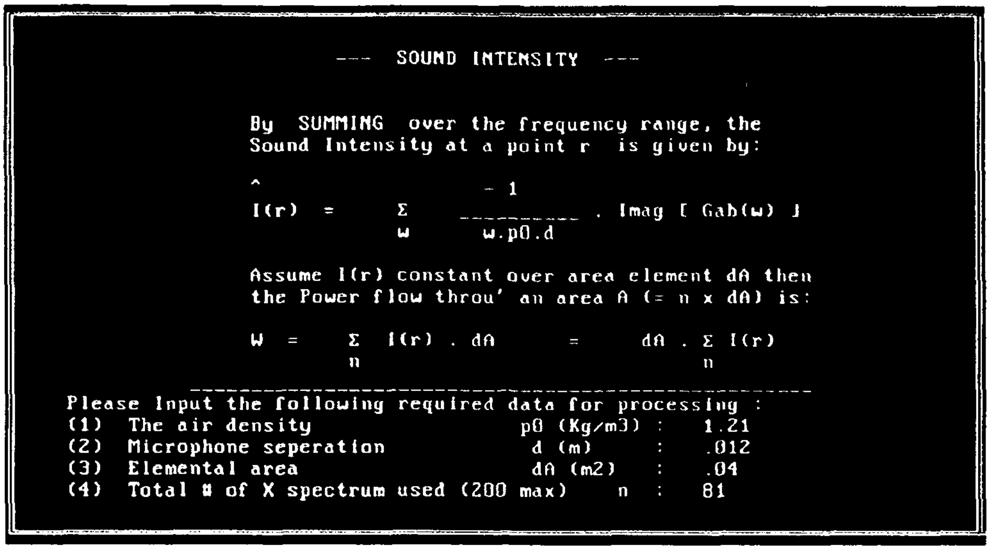
- a 3-dimensional plot of sound intensity distribution (intensity map) over a quasi-surface area as shown in Figure 6,

- a sample histogram plot of analysis results in third octave band, as is shown in Figure 7.



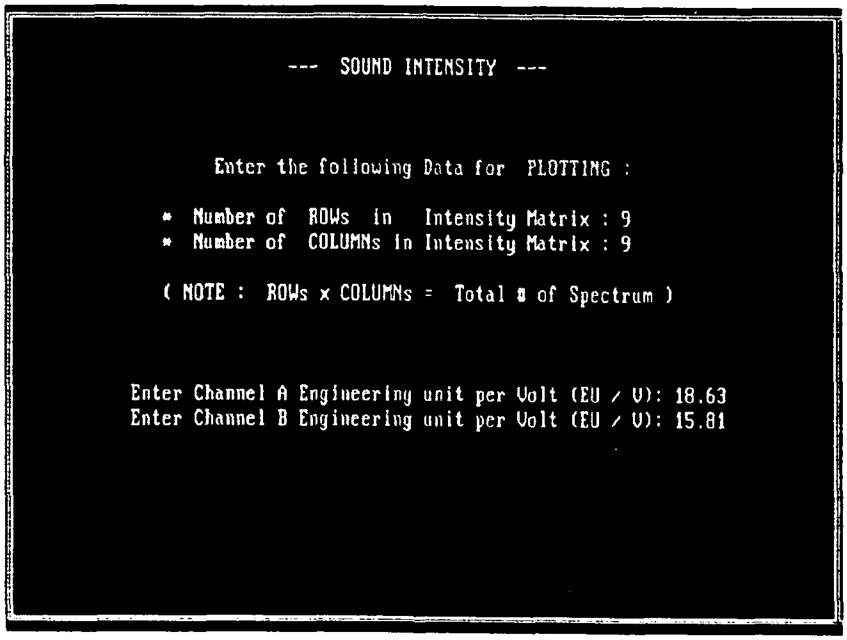
```
              MAIN MENU

(1)    Intensity Distribution (3D plot)
(2)    Third Octave Analysis
(3)    Sound Transmission Loss
(4)    Re-Run program
(0)    EXIT program

            your choice:
```

Figure 2: *Menu selection for driving the sound intensity program.*



```
                    ---  SOUND INTENSITY  ---

               By  SUMMING  over the frequency range, the
               Sound Intensity at a point r  is given by:

               ^                 - 1
               I(r)  =     Σ    __________ . Imag [ Gab(w) ]
                           w      w.p0.d

               Assume I(r) constant over area element dA then
               the Power flow throu' an area A (= n x dA) is:

               W  =    Σ  I(r) . dA      =     dA . Σ I(r)
                       n                            n
           -----------------------------------------------------
     Please Input the following required data for processing :
     (1)  The air density                  p0 (Kg/m3) :   1.21
     (2)  Microphone seperation             d (m)     :   .012
     (3)  Elemental area                    dA (m2)   :   .04
     (4)  Total # of X spectrum used (200 max)    n   :   81
```

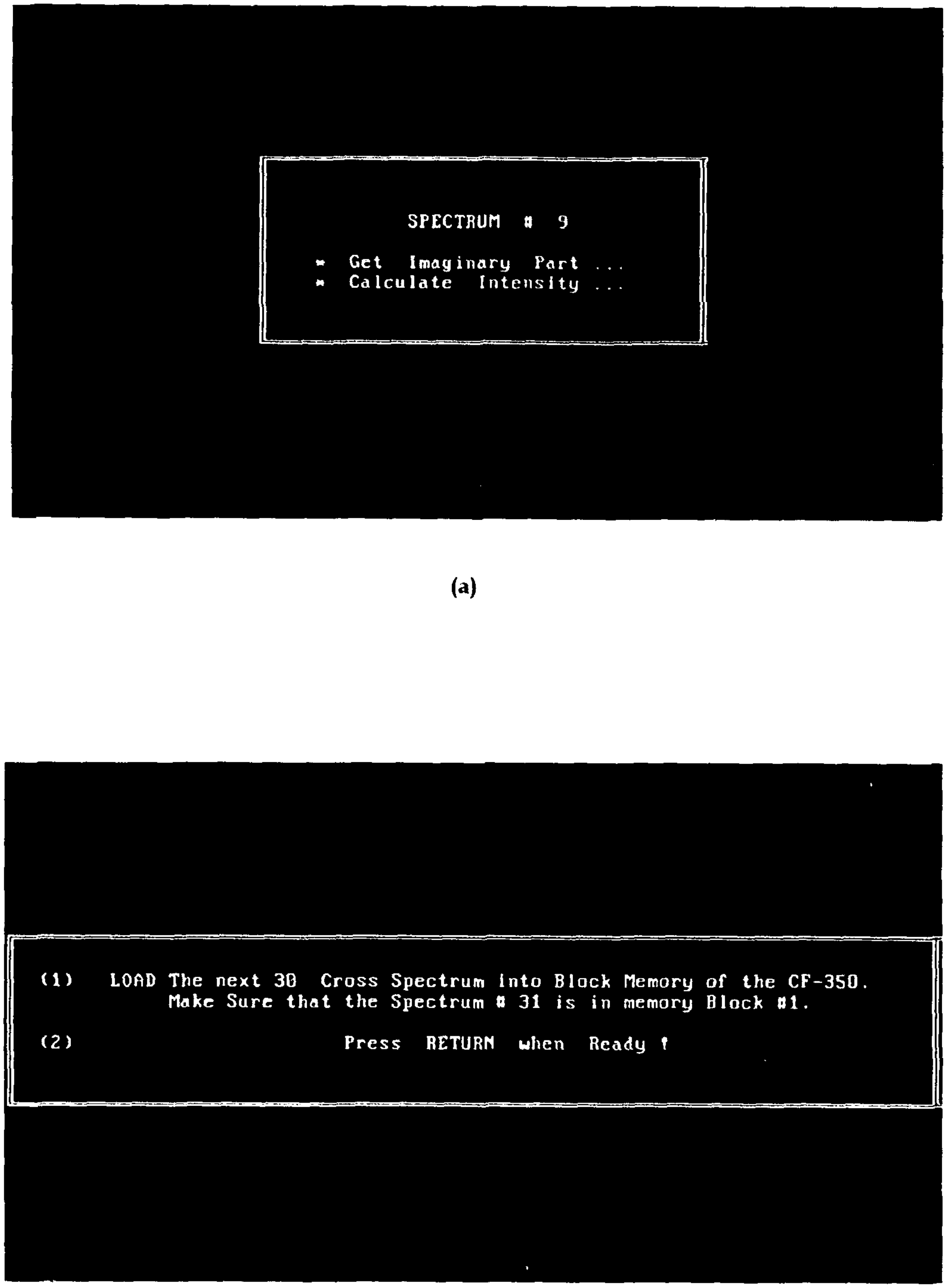
(a)



```
                    ---  SOUND INTENSITY  ---


              Enter the following Data for  PLOTTING :

        *  Number of  ROWs  in   Intensity Matrix : 9
        *  Number of  COLUMNs in Intensity Matrix : 9

        ( NOTE :  ROWs x COLUMNs =  Total # of Spectrum )


     Enter Channel A Engineering unit per Volt (EU / V): 18.63
     Enter Channel B Engineering unit per Volt (EU / V): 15.81
```

(b)

Figure 3 (a&b): *Screens for data entry. Usually there is a brief description of the process and types of data to be input.*



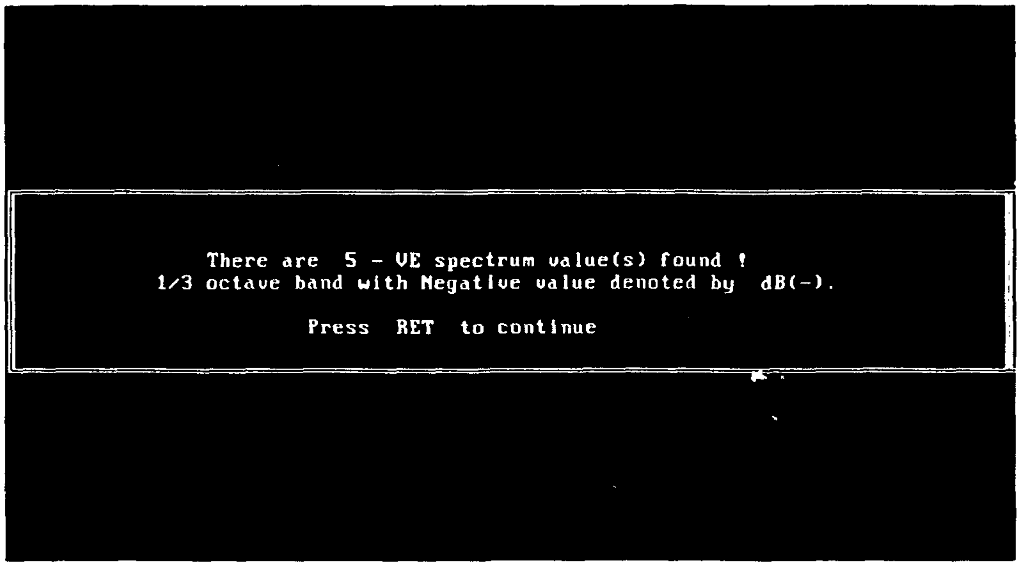
```
SPECTRUM # 9

* Get Imaginary Part ...
* Calculate Intensity ...
```

(a)

```
(1)   LOAD The next 30  Cross Spectrum Into Block Memory of the CF-350.
           Make Sure that the Spectrum # 31 is in memory Block #1.

(2)                      Press  RETURN  when  Ready !
```

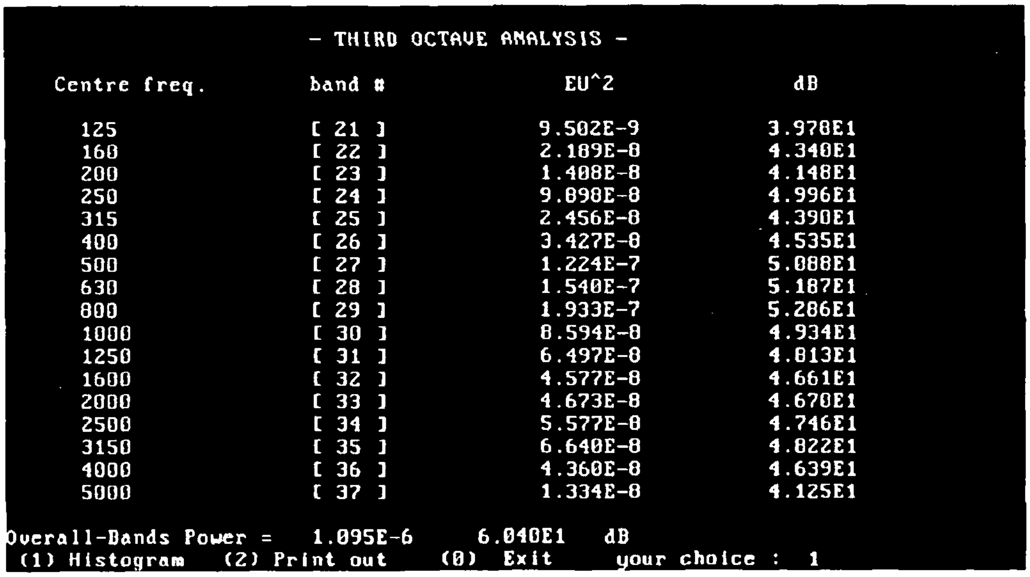
(b)

Figure 4: *(a) Status of the current process. (b) Instructions for loading of data into the FFT analyser.*



```
There are  5 - VE spectrum value(s) found !
1/3 octave band with Negative value denoted by  dB(-).

          Press  RET  to continue
```

(a)



```
                         - THIRD OCTAVE ANALYSIS -

   Centre freq.          band #             EU^2              dB

     125                [ 21 ]            9.502E-9          3.978E1
     160                [ 22 ]            2.189E-8          4.340E1
     200                [ 23 ]            1.408E-8          4.148E1
     250                [ 24 ]            9.898E-8          4.996E1
     315                [ 25 ]            2.456E-8          4.390E1
     400                [ 26 ]            3.427E-8          4.535E1
     500                [ 27 ]            1.224E-7          5.088E1
     630                [ 28 ]            1.540E-7          5.187E1
     800                [ 29 ]            1.933E-7          5.286E1
     1000               [ 30 ]            8.594E-8          4.934E1
     1250               [ 31 ]            6.497E-8          4.813E1
     1600               [ 32 ]            4.577E-8          4.661E1
     2000               [ 33 ]            4.673E-8          4.670E1
     2500               [ 34 ]            5.577E-8          4.746E1
     3150               [ 35 ]            6.640E-8          4.822E1
     4000               [ 36 ]            4.360E-8          4.639E1
     5000               [ 37 ]            1.334E-8          4.125E1

Overall-Bands Power =    1.095E-6      6.040E1    dB
 (1) Histogram    (2) Print out     (0) Exit      your choice :  1
```

(b)

Figure 5: *(a) A message to show information about the negative intensity contained in the data. (b) The centre frequencies, band numbers and the band values are displayed both in engineering units and in dB (ref. 10^{-12} W)*

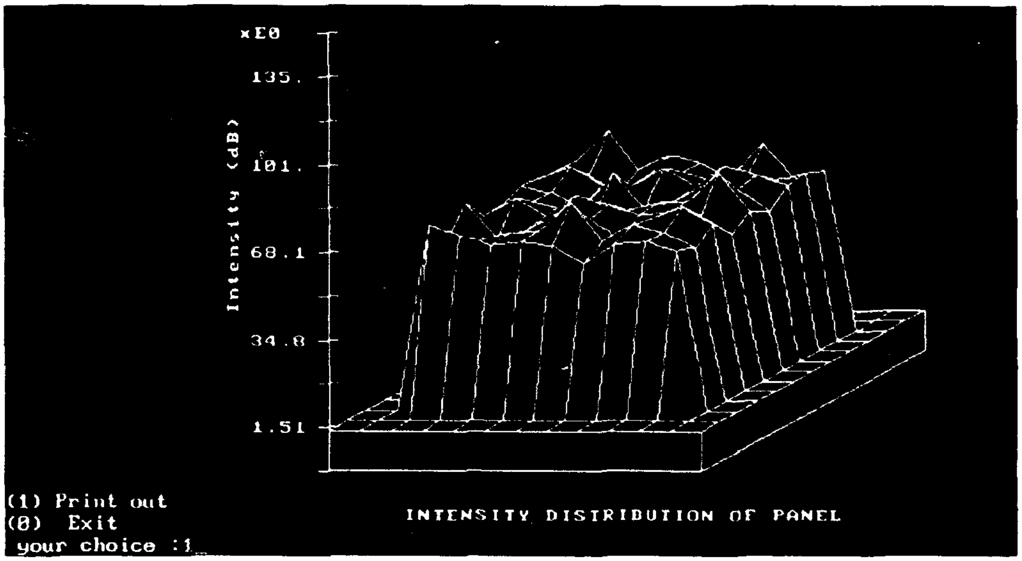


Figure 6: *A 3-dimensional plot of sound intensity distribution (intensity map) over the measured surface.*

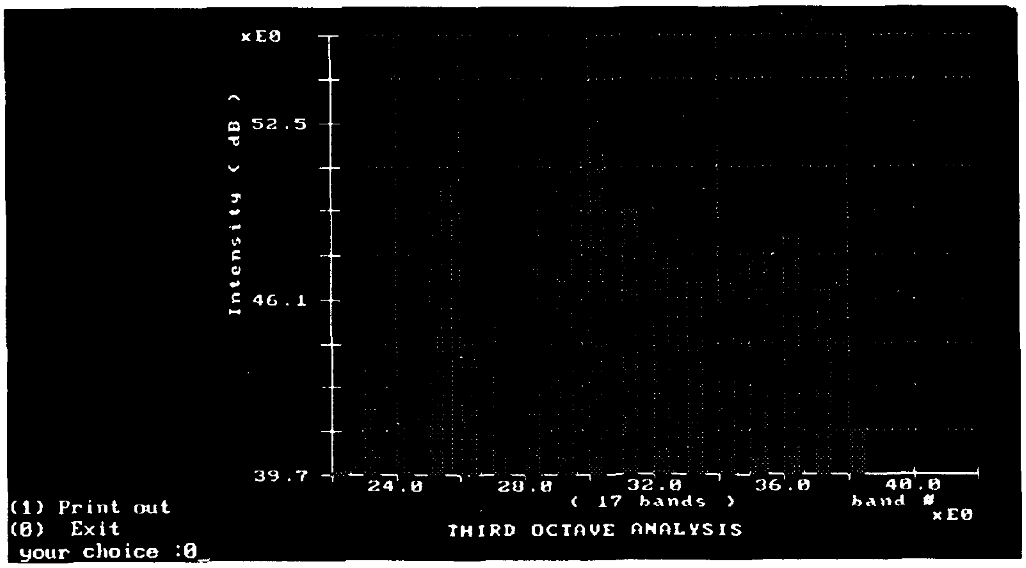


Figure 7: *A histogram plot from a third octave band analysis results.*

7. Errors In The Estimation Of Sound Intensity With P-P Type Intensity Probe

7.1 Finite Difference Approximation Error

As described in section 4, to estimate the air particle velocity, the pressure gradient $\partial p/\partial r$ has been approximated by $\Delta p/\Delta r$ using a finite difference method. This approximation is valid when Δr is small compared to the shortest wavelength in the sound field to be measured. At high frequency, when the corresponding wavelength is small compared to the effective microphone separation then $\partial p/\partial r \neq \Delta p/\Delta r$ and the estimate of intensity, I, will become inaccurrate.

For a particular microphone separation, Δr, there will be an upper frequency limit of the measurement system beyond which results may be inaccurate. As an example, the upper frequency limits for the standard microphone separations of the Bruel & Kjaer sound intensity probe beyond which the error is greater than 1 dB are (assuming plane wave along the probe axis [ref. 9 pp.13]) :

Δr (mm)	f max. (kHz)
6	10
12	5
50	1.2

From the table above we can see that if a smaller spacer is chosen, the upper frequency limit of the system can be increased. For an error within 1 dB, the smallest wavelength measured in the sound field should be at least 6 times the microphone spacer Δr.

7.2 Probe Diffraction Error

Due to the presence of the probe, the sound field will be distorted by diffraction and there will be variations in the sensitivity and acoustical separation of the microphones [ref.9 pp12]. This places an upper frequency limit on practical probes. Usually the evaluation of probe diffraction characteristics is carried out by the manufacturer and the probe frequency limit is stated with the hardware.

7.3 *System Phase Mismatch Error*

7.3.1 *System Phase Mismatch*

It can be shown that the intensity measured at a point in the sound field is directly related to the phase difference Φ_{ab} detected (by the system) between the two microphones of the sound intensity probe. Ideally, this phase angle should purely be the phase change of the sound field pressure across the two microphones of the probe. In practice, there always exists a phase mismatch in all sound intensity measurement systems. This system phase mismatch is the combined effect of:

- phase mismatch between the two microphones of the probe,
- phase mismatch between channels of the analyser.

Hence in an actual measurement, the phase difference Φ_{ab} detected between the two microphones is the sum of the actual phase change of the sound field and the system phase mismatch.

For a measurement to be accurate, the system phase mismatch must be kept small. This can be achieved by using an analyser with two highly phase matched channels. Also the probe should only employ a phase matched microphone pair, such as those especially designed for sound intensity measurements.

7.3.2 *Phase Mismatch and Error at Low Frequency*

For the error due to phase mismatch, in the estimate of intensity I, to be negligible the phase change of sound pressure across the microphones must be many times larger than the system phase mismatch. This is analogous to the signal to noise ratio in an electrical system. Consequently the effect of system phase mismatch is most critical for small microphone spacings and at low frequency since the sound field phase change is small in these cases [ref.4 p.115].

To reduce the effect of phase mismatch at low frequency a larger spacer can be used, but this reduces the system upper frequency limit, as shown in section 7.1. Therefore at low frequency a large spacer should be used and at high frequency a small spacer is preferred.

Hence in a sound intensity measurement system, for a chosen Δr there is a low frequency limit beyond which the error due to system phase mismatch is unacceptable in the estimate of I.

7.3.3 *Phase Mismatch and The Pressure-Residual Intensity Index*

If a sound wave is incident at 90° to the probe axis, the two microphones are exposed to the same sound signal . In this case the field pressure phase difference across the microphones is zero and any phase difference detected is the system phase mismatch. The intensity corresponding to this phase mismatch is called the residual intensity. The residual intensity depends on both the magnitude of the system phase mismatch and the sound pressure at the microphones. It can be shown that for a chosen microphone spacing Δr and at a given frequency, f , the difference between pressure level and residual intensity level is unchanged. This level difference is defined as the pressure-residual intensity index δ_{pI0}:

$$\delta_{pI0} = L_{p(90)} - L_{Ires(90)} \tag{15}$$

where $L_{p(90)}$, $L_{Ires(90)}$ denote the sound pressure level and its corresponding residual intensity level when the sound wave is 90° to the probe axis.

The pressure-residual intensity index describes the phase mismatch characteristics of a particular measurement system.

Note: One way to measure the pressure-residual intensity index δ_{pI0} is to use an acoustic coupler where a plane wave incident at 90° to the probe axis can be simulated.

7.4 *Air Flow Disturbance*

The disturbance caused by an air flow can contaminate the signals from sound intensity probes [ref. 4 p.124]. Therefore windscreens should always be used for an outdoor measurement or where there is an air flow within the vicinity of the measurement surface.

7.5 *Random Error*

If the sound field is contaminated with extraneous noise source(s) and/or high diffuse background noise the random error in the estimate intensity can be severe. It has been shown by Gade [ref. 12] that in a partially diffuse sound field the random error depends on the BT-product and the field measured pressure-intensity index, δ_{pI}. For a measurement, if the value of δ_{pI} is large then the averaging time T must increase in order to reduce the random error in the measured intensity.

Note: BT-product is the product of the frequency bandwith B and the averaging time T.

7.6 *Other Errors*

If the output of the sound source is not stationary with time or extraneous noises are transient then there will be an error in the intensity measured.

8. Pressure-Intensity Index And The System Dynamic Capability

8.1 Pressure-Intensity Index

The pressure-intensity index is defined as:

$$\delta_{pI} = L_p - L_{\hat{I}} \tag{16}$$

where L_p is the pressure level, and $L_{\hat{I}}$ is the measured intensity level at the point of measurement.

δ_{pI} is a measure of the ratio between the true free field intensity I to the measured intensity $\hat{I}$, in dB [ref. 4 p.117]. Therefore δ_{pI} should be as small as possible so that $\hat{I} \approx I$. A small measured intensity $\hat{I}$ will correspond with a large value of δ_{pI}. If $\hat{I}$ is small enough, the error due to system phase mismatch will become significant, hence making the measurement inaccurate.The effect of phase mismatch error on the measured intensity is determined by the pressure intensity index δ_{pI} and the system dynamic capability L_d (to be discussed later). Beside this, the random error in the estimate intensity is also dependent on the δ_{pI} [ref. 4 pp.138,140 ; ref.12 p.15]. A large value of δ_{pI} will correspond with a high level of difficulty in making an accurate measurement of sound intensity.

The δ_{pI} can be reduced by placing the probe closer to the source to improve the signal to noise ratio or placing sound absorption materials around the walls (outside the measurement surface) to reduce the reflections of sound waves at the boundaries etc.

8.2 System Dynamic Capability

For the measured intensity to have a reasonable level of accuracy, the actual phase change of the sound field across the microphones must be large compared to the system phase mismatch. This is equivalent to the pressure-residual intensity index δ_{pI0} being much larger than the pressure-intensity index δ_{pI}. For an accuracy in the measurement of intensity to within 1 dB and 0.5 dB the field measured δ_{pI} must be smaller than (δ_{pI0} - 7) dB and (δ_{pI0} - 10) dB respectively. From this, the system dynamic capability L_d is defined as:

$$L_d = \delta_{pI0} - K \tag{17}$$

where K is a constant which is dependent on the level of accuracy to be achieved (eg. 7 dB, 10 dB for an accuracy of ± 1 dB, ± 0.5 dB respectively) .
The field measured δ_{pI} must not exceed the level indicated by L_d in order to achieve the level of accuracy proposed by the constant K. Usually the phase mismatch error is significant at low frequency. The frequency in which $L_d \leq \delta_{pI}$ is regarded as the low frequency limit of the system.

9. *Evaluation Of System Performance*

Following is a description of the limits and capabilities of the system configuration as described in section 5 (Sound intensity measurement system).

(1) High frequency limit

The Bruel & Kjaer intensity probe type 3520 together with the phase matched microphone pair type 4183 (12 mm and 50 mm spacers) has an upper frequency limit of 5 kHz [ref. 14]. This determines the 5 kHz upper frequency limit for the measurement system as a whole.

(2) The Processor Real Time Analysis

The Ono Sokki dual channel FFT analyser (CF-350) can operate at a frequency range up to 40 kHz. For real time analysis, 2 kHz is the range limit.

(3) The Processor (CF-350) Channel Phase Mismatch

By feeding common electrical signals to the CF-350 channel inputs, the phase mismatch between the two channels of the CF-350 has been evaluated using the phase part of the cross spectrum (or transfer function). It was found that for a 5 kHz frequency range and a frequency resolution of 12.5 Hz (400 line spectrum) the CF-350 has a typical phase mismatch which was less than or equal to ± 0.2° between its two channels (random signal inputs with 1024 times of averaging).

(4) The Microphone pair (4183) Phase Mismatch

Typically the type 4183 has a phase match which is better than 0.2° from 40 Hz to 700 Hz and it is better than $(f / 3500)^\circ$ for frequency f up to 5 kHz [ref. 14]. The calibration of the phase part (supplied by the manufacturer) for the microphone pair which is used in our system is shown in the Appendix 1(B).

(5) System Pressure-Residual Intensity Index and Dynamic Capability

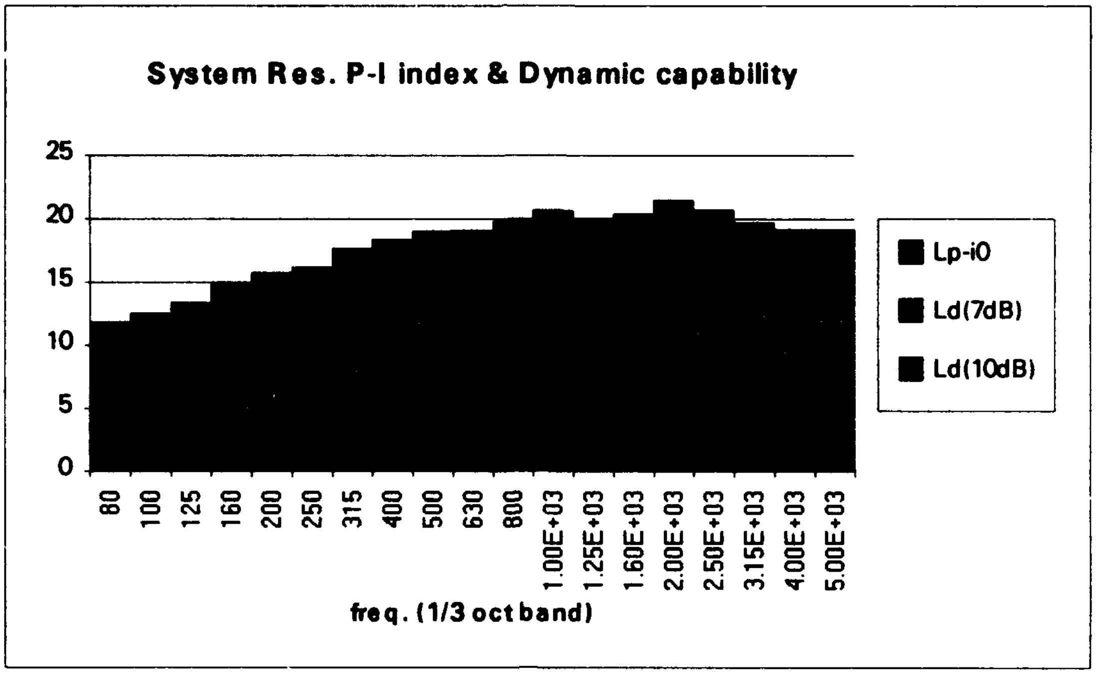
Once sound intensity calibration has been completed, the type 3541 Bruel & Kjaer sound intensity calibrator can be used for measurement of the system pressure-residual intensity index. In the acoustic coupler chamber (UA 0914), the two microphones of the probe are exposed to the same source of pink noise (ZI 0055). The pressure-residual intensity index can be computed by subtracting the detected residual intensity level from the sound pressure level at the two microphones.

Figure 8 gives typical pressure-residual intensity indices of the system with the microphone pair type 4183, a 12 mm microphone spacer, and a frequency range of

0 - 5 kHz. The dynamic capability of the system with K = 7 dB and 10 dB are also presented in this figure.

Frequency (Hz)	δ_{pI0}	L_d K=10 dB	L_d K=7 dB
80	11.837	1.837	4.837
100	12.535	2.535	5.535
125	13.369	3.369	6.369
160	14.783	4.783	7.783
200	15.775	5.775	8.775
250	16.174	6.174	9.174
315	17.676	7.676	10.676
400	18.356	8.356	11.356
500	19.023	9.023	12.023
630	19.105	9.105	12.105
800	19.722	9.722	12.722
Frequency (kHz)			
1.0	20.68	10.68	13.68
1.25	20.042	10.042	13.042
1.6	20.351	10.351	13.351
2.0	21.461	11.461	14.461
2.5	20.713	10.713	13.713
3.15	19.708	9.708	12.708
4.0	19.191	9.191	12.191
5.0	19.169	9.169	12.169

(a)



(b)

Figure 8: *The* δ_{pI0} [1] *and* L_d *for K= 10, 7 dB of the system.*
(a) Numerical values. (b) Graphical presentation.

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[1] Note: since the option for calculation of pressure-residual intensity index is not yet available with the current version of sound intensity program the mean pressure level has been obtained manually from the CF-350 then substracted by the residual intensity level which is calculated from the sound intensity program.

10. Procedures For Calibration Of The System

For reliable results, a sound intensity measurement system should be calibrated properly before any measurements are made. The intensity can be calibrated in an anechoic chamber, a plane wave tube or an acoustic coupler. At MRL the measurement system is calibrated with the Bruel & Kjaer sound intensity calibrator type 3541. This type of calibration is carried out in an acoustic coupler where sound waves of both 0° and 90° incidence to the probe axis can be simulated. These allow us to calibrate both pressure and sound intensity sensitivities of the system and also allow the measurement of system pressure-residual intensity index, δ_{pI0}.

Following is an outline of the procedure for calibration of the system, with respect to the calibrator type 3541 mentioned above. For further details such as the calculations of the correction terms for the actual ambient conditions, operation of the CF-350 etc., the reader is referred to the manuals of the corresponding instruments.

10.1 Pressure Calibration

1. Calculate the correct pressure value given by the calibrator under the actual ambient conditions of the measurement. This is done by applying the correction terms (specified in the instruction manual) to the reference pressure stated in the calibration chart of the pistonphone.
2. Set the CF-350 to operate at 500 Hz frequency range and 2 volts amplitude range for both channels.
3. Set the CF-350 to operate on third octave band mode.
4. Insert the microphones into the coupler ports which are intended for pressure calibration. This enables the microphone pair to be exposed to the same sound signal from the source.
5. Place the pistonphone type 4228 on the coupler and turn it on. This gives a reference signal of X Pa (Y dB ref 20 μ Pa) at 251.25 Hz inside the coupler chamber. Where X and Y are the corrected values of the reference signal calculated in step 1.
6. Set the CF-350 to display the power spectrum of channel A and move the cursor to the 250 Hz peak.
7. Use the soft key [SP/EU] of the CF-350 to set the sensitivity for channel A so that the current cursor corresponds to X Pa. A value will be assigned to the EU/V on the screen, this is the sensitivity factor for channel A.
8. Set the CF-350 to display the power spectrum of channel B, move the cursor to the 250 Hz peak then set the channel B sensitivity similarly to step 7 above.

10.2 Intensity Calibration

1. For the particular microphone spacing at the probe, calculate the correct intensity level given by the calibrator, under the actual ambient conditions. Here, correction terms (specified in the instruction manual) are applied to

give the values appropriate to the ambient conditions rather than reference conditions assumed (stated in the calibration chart of the pistonphone).

2. Set the CF-350 to operate at 500 Hz frequency range and 2 volts amplitude range for both channels.
3. Set the CF-350 to display the cross power spectrum .
4. Insert the microphones into the coupler ports which are intended for intensity calibration. This enables the sound source to simulate a plane wave which is 0° incident on the probe axis.
5. Place the pistonphone type 4228 on the coupler and turn it on.
6. Run the program for sound intensity calculation.
7. Choose third octave analysis option from the program main menu to display the calculated data in third octave band.
8. Check if the intensity measured by the system at the 250 Hz band is matched with the corrected intensity calculated in step 1.

10.3 *Measurement of Pressure-Residual Intensity Index* δ_{pI0}

1. Set the CF-350 to operate on frequency range of interest and adjust amplitude range of both channels to give the optimum signal to noise ratio.
2. Set the CF-350 to display the cross power spectrum and set the number of averaging N (≈ 512 - 1024).
3. Insert the microphones into the coupler ports which are intended for sound pressure calibration. This enables the sound source to simulate a plane wave which is 90° incident on the probe axis.
4. Place the source of pink noise ZI 0055 on the coupler and turn it on.
5. Start the averaging process for measurement of cross spectrum across the microphones until it finishes.
6. Run the program for sound intensity calculation. When asked, input the microphone spacing to be used with the probe and all other required parameters.
7. Choose third octave analysis option from the program main menu to display the calculated data in third octave band. This is the residual intensity spectrum of the system with respect to the pressure produced by the broad band sound source ZI 0055.
8. Display either power spectrum of channel A or B in third octave band. The reading dB value on the CF-350 is referenced to 1Pa. Add 94 dB to this value to obtain the sound pressure level with reference to 20 μ Pa. For each frequency band, subtract the residual intensity level from the pressure level. This level difference between sound pressure level and residual intensity is the pressure-residual intensity index δ_{pI0}.

11. *Sound Power Determination Of A Reference Source*

To show the application of sound intensity measurement in sound power determination, the sound power output from a reference source (Bruel & Kjaer type 4205) has been measured using the intensity measurement system in the configuration which was described in section 5 (Sound intensity measurement system).

The power output of the sound source type 4205 can be varied continuously between 40 and approximately 100 dB re 1 pW. The output level can be broad band pink noise from 100 Hz to 10 kHz range or octave band filtered noise by using one of the 7 built-in octave band pass filters. Because the upper frequency limit of the system is 5 kHz, we cannot use the reference output given by the broad band pink noise. Instead, the octave band pass filters (from 125 Hz to 4 kHz centre frequency) were used to give a nominated output of 85 dB re 1 pW from each band.

(1) **Equipment used**

- The intensity measurement system consists of a microcomputer to run the sound intensity program, the CF-350 dual channel FFT analyser, a Bruel & Kjaer sound intensity probe type 3520, a phase matched microphone pair type 4183 with a 12 mm or 50 mm spacer.

- The sound power source type 4205 consists of two separate units: the generator, containing all the controls, filters, amplifiers, level meter etc. and the sound source HP 1001 containing two loud speakers with the associated crossover networks.

(2) **Calibration of the equipments**

- The source type 4205 has been calibrated according to the procedures described in its instruction manual. Due to the equipment availability the source type 4205 has been calibrated using the Bruel & Kjaer real time frequency analyser type 2144 and one of the microphone from the probe.

- The sound intensity measurement system has been calibrated for both sound pressure and intensity sensitivities according to the procedures described in section 10 (system calibration procedure) using the Bruel & Kjaer sound intensity calibrator type 3541.

(3) **The measurement surface and the environments**

The measurement has been carried out in a room of 8.0 × 8.0 × 3.6 m approximately. The floor and the ceiling are rigid concrete, and the floor is tiled with vinyl sheet. The room also contains some timber cabinets, equipments etc.

There was a low level of background noise during the measurements. This was the fan noise from the corridor outside.

The measurement (control) surface is an imaginary cube of dimensions 1 x 1 x 1 m . The source was placed on the floor at the center of the cube's bottom face. The sound intensity components normal to its faces was to be measured. Data were taken on all of the cube's faces except the bottom one since it is assumed to be reflecting sound energy back to the volume enclosed by the cube surface.

Each face of the cube was subdivided into a grid of 4 (2 × 2) elements and each had an area of 0.25 m^2 (0.5 x 0.5 m). This makes a total of 20 measurement points over the whole cube. The normal component of sound intensity at the center of each element was measured and the power radiated from each of these elements is given by the product of its area and the normal intensity component. The total sound power radiated from the cube can be calculated by integration of these elemental sound powers.

(4) Measurement settings

Settings of the sound source:

- For each octave band from 125 Hz to 4 kHz , the sound source was set to give an output power level of 85 dB with reference to 1 pW.

Settings of the FFT analyser:

- The engineering unit calibration factors for the two channels were set during the calibration process.

- For each measurement band, the frequency range on the CF-350 was set so that it gave the highest frequency resolution on the cross spectrum between the two channels. In this way we obtained the most number of spectrum lines within the band of interest and consequently the result was more accurate when these lines were grouped to synthesise the corresponding octave band value.

- The Hanning window was used to reduce the leakage effects in the measurement data. During synthesis of the third octave bands the effect of this applied window was compensated for by applying the 0.66 factor described in the CF-350 manual.

- The amplitude range of the cross spectrum was set manually until an optimum signal to noise ratio obtained. The number of averages was set to 256.

(5) Discussion of results

The total sound power radiated from the cube was computed from the intensity measurements over the cube (control) surface as described in (3) above.

The results of the measurement (with a 12 mm microphone spacer) are summarised in Table 1 and Figure 9. More details about the measurements can be found in Appendix 2.

Microphone spacer Δr = 12 mm

Band freq.	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
L_w (dB)	87.1	85.1	84.6	84.62	84.72	84.1
L_d (10dB)	0.9	7.5	8.2	10.1	12.7	10.0
δ_{pI}	2.4	2.9	3.3	3.2	3.0	3.1

Table 1: *Measurements of the Bruel & Kjaer reference source type 4205 with a nominated level of 85 dB for each octave band from 125 Hz to 4 kHz.*

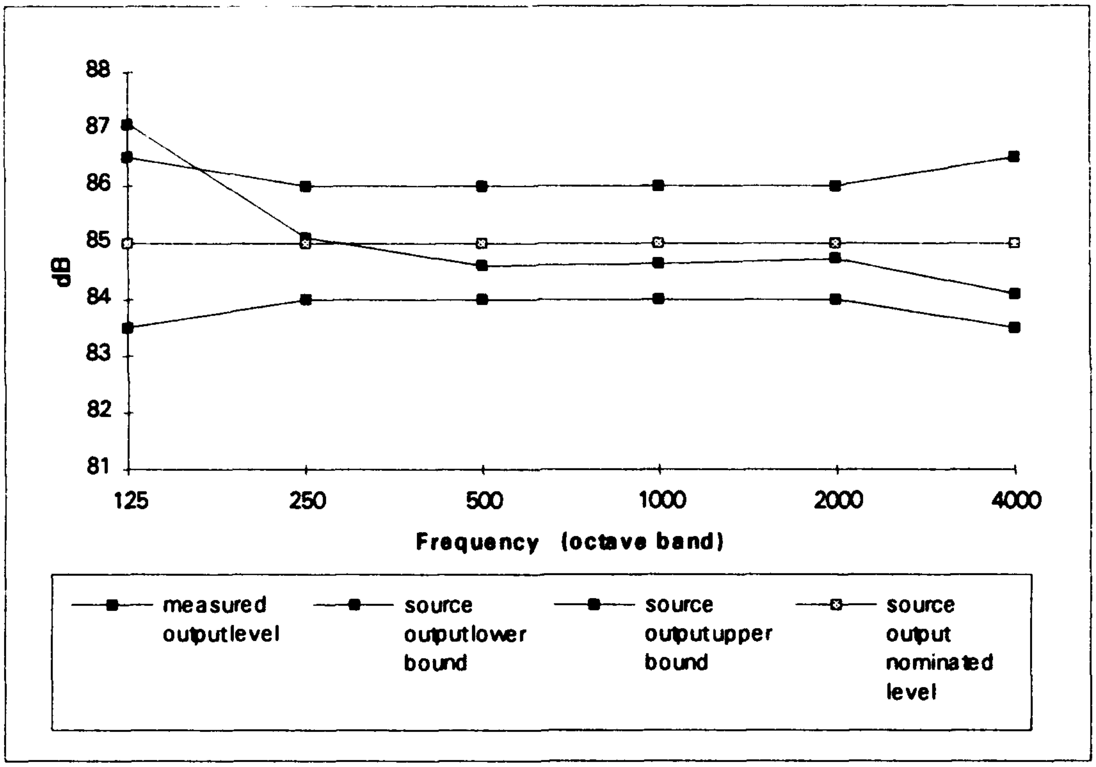

Figure 9: *Sound power measurement of the reference source with 85 dB nominated for each octave band (with a 12 mm spacer).*

From Table 1 we can see that in general, except at 125 Hz and 4 kHz bands, the measured power level is quite close and is less than ± 0.5 dB from the nominated power level (85 dB re 1 pW) . The difference between the measured level and the nominated level is due to the combined effects of :

- Uncertainty in the output level of the reference source. For the output range from 50 - 90 dB, according to the source instruction manual, the accuracy in the power level output of the source is ± 1 dB for octave bands from 250 Hz to 2 kHz and ± 1.5 dB for octave bands outside this frequency range. The uncertainty in the output level of the source was shown in Figure 9 as the output upper and lower bound curves.

- Errors in the estimation of sound intensity using the sound intensity measurement system. These errors are due to the system phase mismatch, random noise, insufficience number of measurement points in the estimation of sound power output etc.

At 4 kHz octave band, the measured level is 0.9 dB below the nominated value. This is due to:

- A large uncertainty in the source output, as mentioned above, for this frequency band (±1.5 dB).

- The upper frequency limit for 4 kHz octave band is 5650 Hz whereas the high frequency limit of the measurement system is 5000 Hz. This leads to the underestimation of the mean pressure and/or the pressure gradient and consequently the intensity is also underestimated [ref. 1, 9].

The main reasons for the difference between the measured level and the nominated level being greatest (2.1 dB) at the 125 Hz octave band are:

- The uncertainty in the source output is large for this frequency band (±1.5 dB).

- The field measured pressure-intensity index for this band is 2.4 dB, whereas the dynamic capability for this frequency band is only 0.9 dB[2], thus in this octave band the field pressure-intensity index exceeds the system dynamic capability[3]. As a consequence, the error caused by the phase mismatch in the

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[2] Note: When a comparison is made between δ_{pI} and L_d, it is imperative that δ_{pI} and L_d originate from measurements made at the same frequency range and then identical frequency resolution. This is achieved by setting an identical range at the CF-350 analyser during the determination of L_d to that used while making the octave band measurements (determination of δ_{pI}).

[3] Note: If the error level of ± 1 dB (instead of ± 0.5 dB) is acceptable in our intensity measurements then the system dynamic capability L_d corresponding to K = 7 dB will have a value of 3.9 dB for the 125 Hz octave band. In this case, the pressure-intensity index δ_{pI} = 2.4 dB becomes well below the L_d value.

measured intensity level can be exceeded ± 0.5 dB (these error bounds are implied by the system dynamic capability L_d with K=10 dB). This could be why there is a fair difference between the two levels if it did not mainly come from the uncertainty of the source output.

To reduce the effect of phase mismatch at low frequency, we repeated the 125 Hz octave band measurement with a 50 mm spacer. In this case the measured output level, L_W, is 86.3 dB, the dynamic capability, L_d, is 7.1 dB and the pressure-intensity index, δ_{pI}, is 3.3 dB (Table 2). Compared with Table 1, we can see that although the pressure-intensity index increased from 2.4 dB to 3.3 dB it is now well below the system dynamic capability which is 7.1 dB. The measured output level for the 125 octave band is now 86.3 dB with the confidence that the phase mismatch error is bounded by ± 0.5 dB. The measurement results corresponding with both 12mm and 50 mm spacers is presented in Figure 10.

Microphones spacer Δr = 50 mm

Band freq.	**125 Hz**
L_W (dB)	86.3
L_d (10dB)	7.1
δ_{pI}	3.3

Table 2: *Measurements of the 125 octave band with a 50 mm microphone spacer.*

Using a larger microphone spacer to improve the measurement results at low frequency is a possibility. There are other methods that can also be used, such as:

- Implementing a computer procedure that will compensate for the system phase mismatch. This helps to increase the system pressure-residual intensity index, δ_{pI0}, and hence the dynamic capability, L_d. The mathematical principle of this phase correction is described in [ref. 4].

- Choosing a smaller measurement cube so that the probe can be placed closer to the sound source. This improves the signal to noise ratio of the measurement and helps to reduce the field measured pressure-intensity index, δ_{pI} .

- Reducing the reverberant component of the sound field under measurement by placing sound absorpbing materials on the walls etc. This will also help to reduce the δ_{pI}.

By manipulation of L_d and δ_{pI} via the methods described above, it is possible to use the 12 mm spacer to measure intensity at relatively low frequency (eg. 125 Hz or lower), as long as we have $\delta_{pI} \leq L_d$. The error level associated with L_d (as determined by K in equation (17)) should also be kept in mind.

The above demonstrates the use of the system dynamic capability, L_d, the field measured pressure-intensity index, δ_{pI} in the evaluation of the sound field quality, and the acceptable level of errors in the measurement of sound intensity.

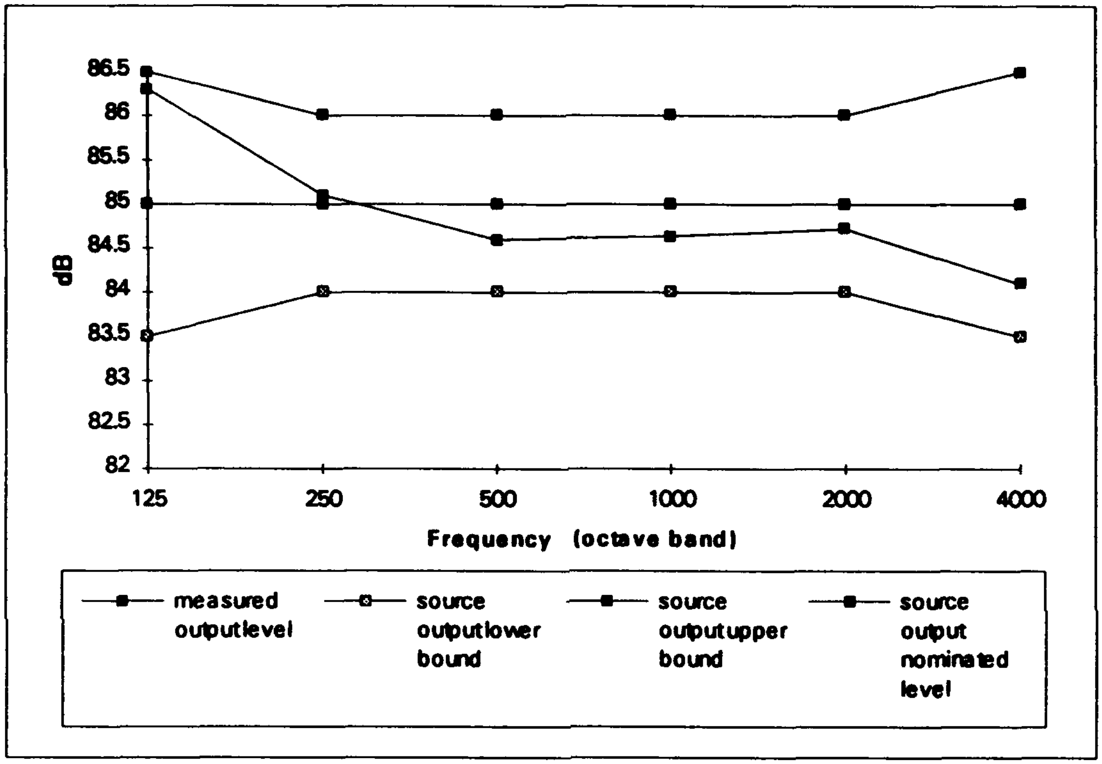

Figure 10: *Final measurement results using both 12 mm and 50 mm spacers.*

12. *Discussion*

One of the advantages of the sound intensity technique is that the sound or noise source of interest can be measured on-site rather than in an anechoic chamber or reverberant room. Apart from the fact that it is more realistic to measure a noise source from its normal radiating environment, the ability of on-site measurement also helps to save the time and effort for the removal and reinstallation of the source. Further, using the sound intensity technique, sound power determination of a noise source can be done even in the presence of other radiating sources as long as these background noises are stationary. These have been demonstrated in our measurements of the reference sound source Bruel & Kjaer type 4205 in section 11 where the measurements were carried out in a normal office space and under the presence of a background fan noise.

Sound intensity is a vector quantity, it has both magnitude and direction. At the point of measurement, a positive intensity indicates the outward flow of sound energy from the surface of consideration while a negative intensity indicates an energy flow in the opposite direction. This enables the locations of the source and sink of a radiating surface to be identified, as a source is indicated by a positive and a sink by a negative intensity. The measurements of sound intensity over a radiating surface also allows the construction of the distribution of sound intensity over this surface. With the aid of these intensity maps it is possible to locate the area(s) of strong noise radiation. Sound intensity technique also has the ability to rank the sound source according to radiated power. This can be done by dividing the source into components, the sound power of each component is determined individually and then compared and ranked in order of sound power.

The sound intensity technique has some disadvantages and limits associated with it. For a measurement system which employs a p-p type probe, there is an inherent systematic error since the air particle velocity and the sound pressure have been approximated by the finite difference method. This was discussed in section 7.1 and this type of error imposes an upper frequency limit to the system for a given microphone spacer of the probe. Measurements attempted beyond this limit will underestimate the true intensity [ref.1]. The error caused by the phase mismatch of the system is important in the sound intensity measurement technique. This type of error is worst at low frequency when the magnitude of the phase mismatch is about the order of the actual sound field phase difference across the two microphones of the probe. Consequently, there is a frequency limit below which the error in the measurement of sound intensity is not acceptable. This low frequency limit is determined by the pressure-intensity index and the system dynamic capability as discussed in section 8.

Finally, for the measurements to achieve a high level of accuracy, a considerable amount of time may be required if the random error in the estimate intensity is to be small. This is particularly true if the FFT method is used.

13. Conclusions

A system has been developed for the determination of the sound power of a source based on the principle of intensity measurement. In this system, data are taken in the form of a cross power spectrum with an FFT analyser. The data are then processed using a micro-computer for intensity calculation and synthesising of third octave band data. By analysing sound signals in the frequency domain, a general purpose dual channel FFT analyser can be used in place of a dedicated expensive sound intensity analyser.

This report has demonstrated, using a reference sound source, that the sound intensity technique can be applied to the measurement of sound power with a reasonable degree of accuracy even under advert conditions including the presence of background noise. Because of this the sound intensity technique can serve as a useful tool to identify the noise emissions of RAN surface ships and submarines in-situ.

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15. *List of Symbols*

$\mathbf{F}$: the force vector in space.

$\mathbf{a}$: the acceleration vector.

E_r : the work done by the sound field in the r-direction.

$\hat{d}_r$: distance d in the r-direction.

A : area of the surface under consideration.

Δr : the separation between 2 points in space. For the sound intensity probe it is the separation between its 2 microphones.

t : the amount of time in seconds.

p : the sound pressure.

p_r : the estimator of p in the r-direction.

p_a , p_b : sound pressures measured at the 2 microphones of the intensity probe.

L_p : the sound pressure level ref. 20 μPa

$L_p(90)$: the sound pressure level when the sound wave is at 90° to the probe axis.

$\mathbf{u}$: the air particle verlocity in space.

u_r : component of air particle verlocity in the r-direction.

$\hat{u}_r$: the estimator of u_r.

$\mathbf{I}$: the sound intensity vector in space.

I_r : component of $\mathbf{I}$ in the r-direction.

$\hat{I}_r$: the estimator of I_r.

$L_{\hat{I}}$: the measured intensity level ref. 1 pW.

L_{Ires} : the residual intensity level ref. 1 pW.

$L_{Ires(90)}$: the residual intensity level when the sound wave is at 90° to the probe axis.

$G_{ab}(f)$: the cross power spectrum between the 2 microphones of the intensity probe.

$\mathrm{Im}\,[G_{ab}(f)]$: imaginary part of the G_{ab}.

ρ : the density of the air.

Δf : frequency increament (resolution) of the cross power spectrum.

N : Number of spectral lines in the cross power spectrum G_{ab}.

k : the wave number.

λ : the wave length of the sound wave.

Φ_{ab} : the detected phase difference between two microphones of the probe.

δ_{pI} : the pressure-intensity index.

δ_{pI0} : the pressure-residual intensity index.

L_d : the system dynamic capability.

Appendix 1

A. *Bruel & Kjaer sound intensity probe type 3520*:

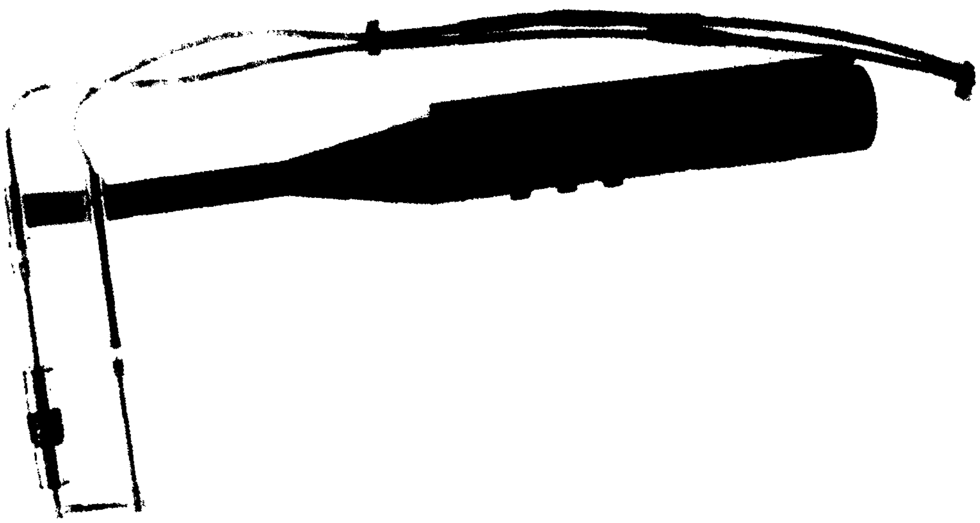


Figure 11: Intensity probe, type 3520 with 12 mm spacer

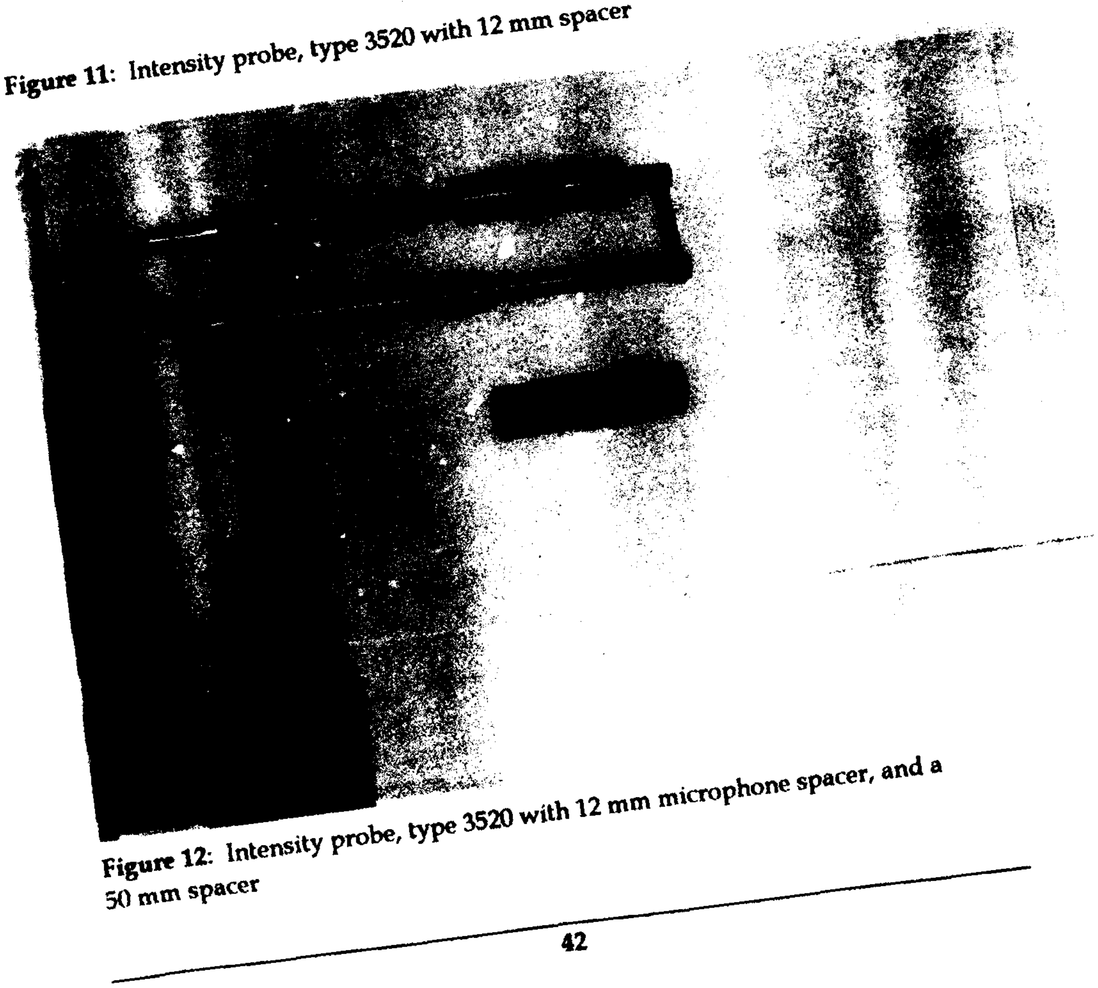


Figure 12: Intensity probe, type 3520 with 12 mm microphone spacer, and a 50 mm spacer

B. The *calibration of the phase part supplied with the microphone pair type 4183*:

- Serial No. 1478121
- Resolution 0.05 deg.

Frequency (Hz)	**Phase difference** (degrees)
40	0.05
63	0.05
125	0.05
250	0.00
500	-0.05
1K	-0.10
2K	-0.20
4K	-0.10
5K	0.15

C. The sound intensity measurement system:

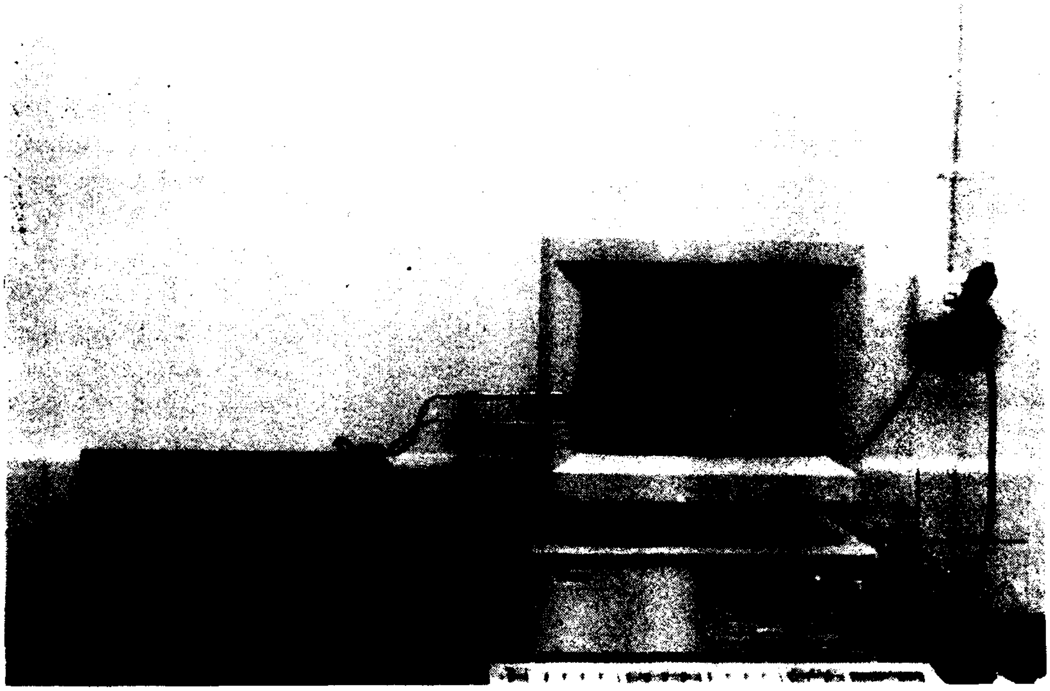


Figure 13: The sound intensity measurement system. Showing from left to right: the CF-350 FFT analyser, the intensity probe type 3520 and the microcomputer.

Appendix 2

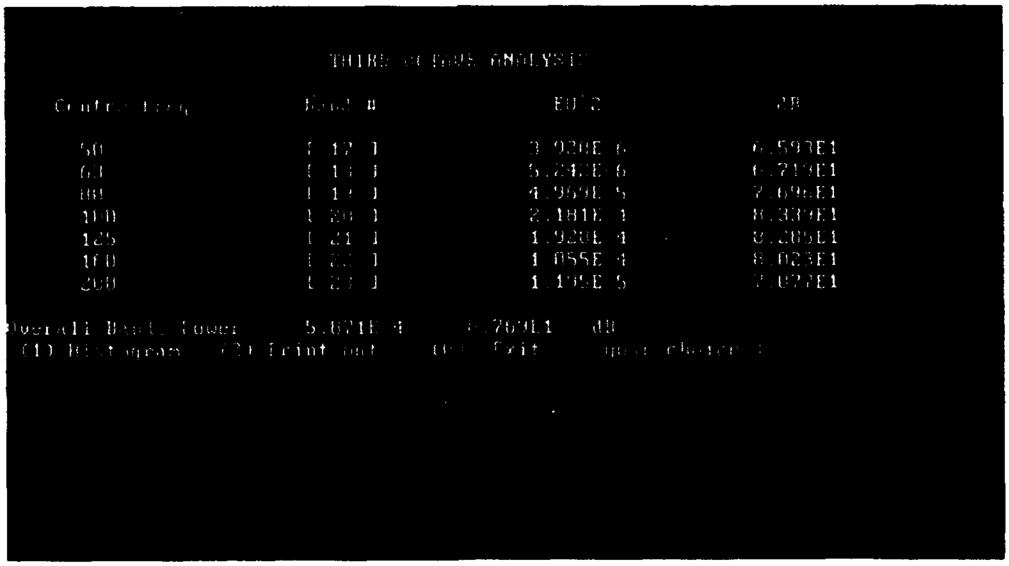
2A. *Sound source type 4205, 85 dB nominated output - 125 Hz band*:

2A.1 Full octave band analysis of the measured output power, pressure-intensity index and pressure-residual intensity index:

Microphone spacer Δr = 12 mm
Spectrum frequency range: 0 - 200 Hz

Octave Band	Measured Power		δ_{pI}	δ_{pI0}
Freq	*Mag*	*dB*	*dB*	*dB*
63	5.52E-05	78.32	2.007	13.436
125	5.16E-04	87.13	2.359	10.897
250	1.20E-05	70.77	3.583	18.493

2A.2 Third octave band analysis of the measured output power:
Below are the results as displayed by the sound intensity program.



```
                      THIRD OCTAVE ANALYSIS

 Centre Freq          Band #            EU^2              dB

    50               [ 17 ]          3.920E-6          6.593E1
    63               [ 18 ]          5.240E-6          6.719E1
    80               [ 19 ]          4.959E-5          7.696E1
   100               [ 20 ]          2.181E-4          8.339E1
   125               [ 21 ]          1.920E-4          8.285E1
   160               [ 22 ]          1.055E-4          8.023E1
   200               [ 23 ]          1.195E-5          7.077E1

Overall Band Power      5.871E-4      8.769E1   dB
 (1) Histogram    (2) Print out     (0) Exit     Your choice ?
```

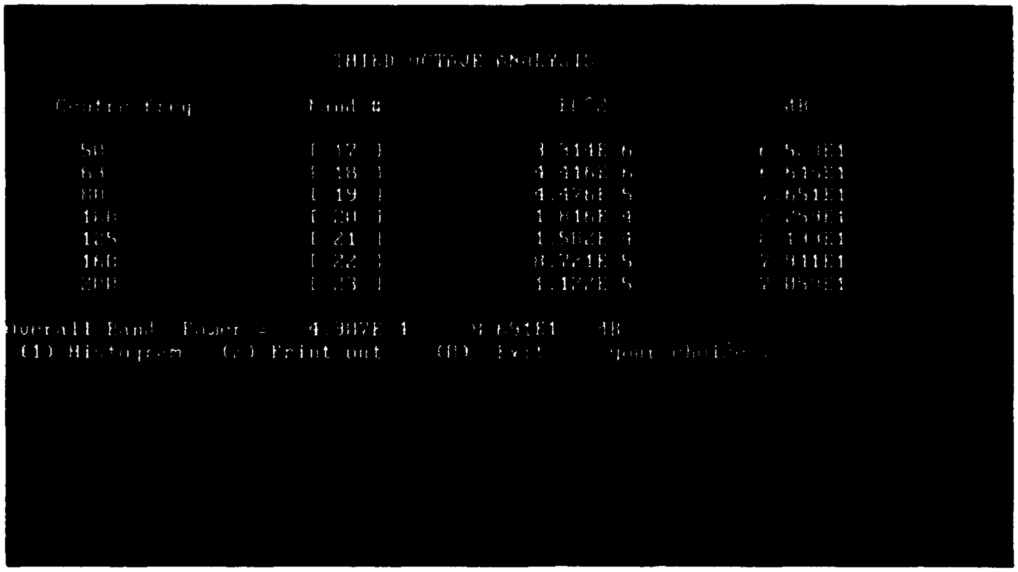
2B. ***Sound source type 4205, 85 dB nominated output - 125 Hz band***:

2B.1 Full octave band analysis of the measured output power, pressure-intensity index and pressure-residual intensity index:

Microphone spacer Δ r = 50 mm
Spectrum frequency range: 0 - 200 Hz

Octave Band	Measured Power		δ_{pI}	δ_{pI0}
Freq	*Mag*	*dB*	*dB*	*dB*
63	5.25E-05	77.2	2.61	19.634
125	4.27E-04	86.304	3.254	17.095
250	1.12E-05	70.5	3.872	24.691

2B.2 Third octave band analysis of the measured output power:
Below are the results as displayed by the sound intensity program.



```
                    THIRD OCTAVE ANALYSIS

  Centre Freq        Band #          W^2            dB

     50              [ 17 ]       3.314E-6      [illegible]
     63              [ 18 ]       4.416E-6      [illegible]
     80              [ 19 ]       4.426E-5      7.651E1
    100              [ 20 ]       1.816E-4      [illegible]
    125              [ 21 ]       1.582E-4      [illegible]
    160              [ 22 ]       8.721E-5      7.911E1
    200              [ 23 ]       1.127E-5      7.05[illegible]E1

Overall Band Power =   4.387E-4      8.6[illegible]1E1    dB
 (1) Histogram    (2) Print out     (0) Exit      Your choice ?
```

2C. *Sound source type 4205, 85 dB nominated output - 250 Hz band*:

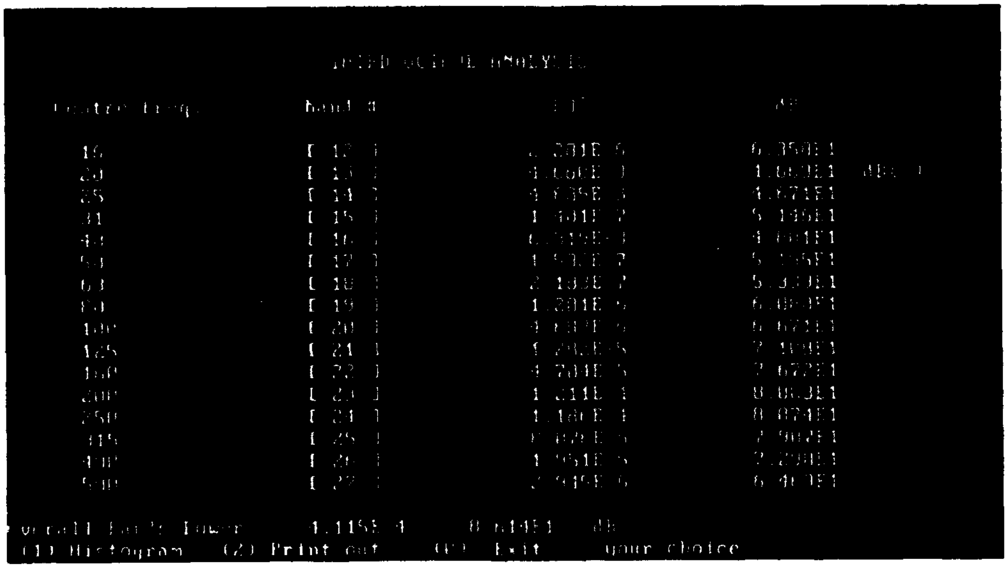
2C.1 Full octave band analysis of the measured output power, pressure-intensity index and pressure-residual intensity index:

Microphone spacer Δr = 12 mm
Spectrum frequency range: 0 - 500 Hz

Octave Band	Measured Power		δ_{pI}	δ_{pI0}
Freq	*Mag*	*dB*	*dB*	*dB*
31.5	2.50E-07	53.981	7.147	7.253
63	1.57E-06	61.966	6.081	9.516
125	6.45E-05	78.098	2.899	13.426
250	3.20E-04	85.0577	2.939	17.526
500	2.25E-05	73.513	2.926	16.932

2C.2 Third octave band analysis of the measured output power:

Below are the results as displayed by the sound intensity program.



2D. *Sound source type 4205, 85 dB nominated output - 500 Hz band*:

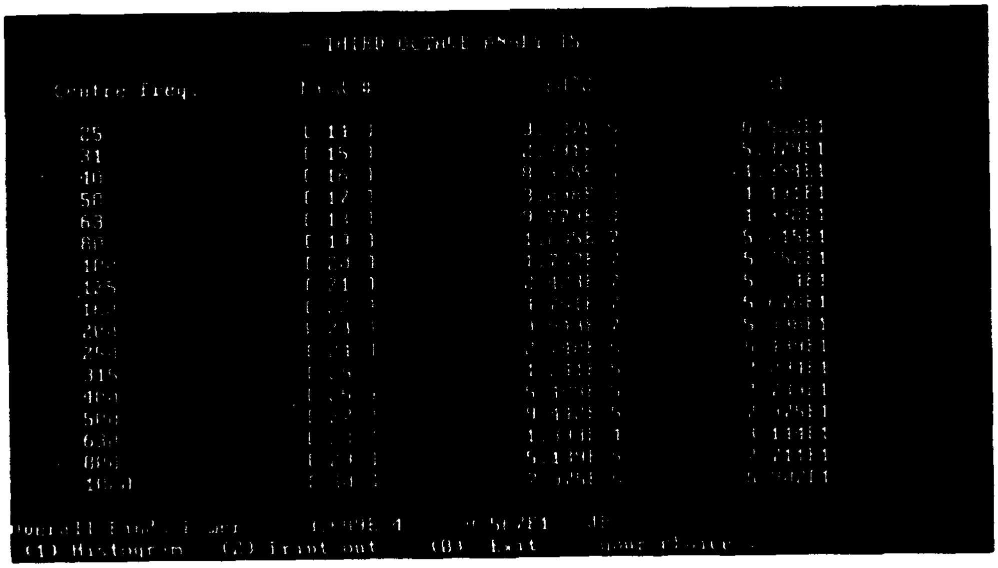
2D.1 Full octave band analysis of the measured output power, pressure-intensity index and pressure-residual intensity index:

Microphone spacer Δr = 12 mm
Spectrum frequency range: 0 - 1 kHz

Octave Band	Measured Power		δ_{pI}	δ_{pI0}
Freq	*Mag*	*dB*	*dB*	
31.5	6.51E-07	65.63	5.857	6.9
63	2.32E-07	53.659	7.391	9.765
125	8.97E-07	59.528	5.264	12.558
250	1.62E-05	72.082	2.882	16.954
500	2.89E-04	84.615	3.248	18.171
1.00E+03	5.94E-05	77.735	3.542	22.03

2D.2 Third octave band analysis of the measured output power:

Below are the results as displayed by the sound intensity program.



2E. *Sound source type 4205, 85 dB nominated output - 1 kHz band*:

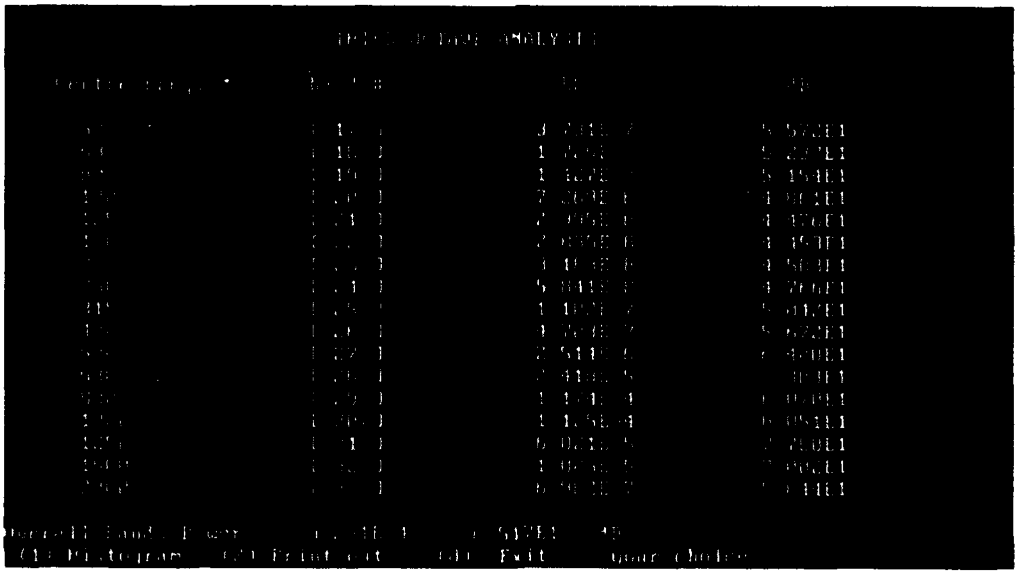
2E.1 Full octave band analysis of the measured output power, pressure-intensity index and pressure-residual intensity index:

Microphone spacer Δr = 12 mm
Spectrum frequency range: 0 - 2 kHz

Octave Band	Measured Power		δ_{pI}	δ_{pI0}
Freq	*Mag*	*dB*	*dB*	*dB*
63	2.09E-06	58.378	8.159	8.839
125	1.31E-07	51.17	9.424	11.978
250	2.00E-07	53.02	6.955	16.027
500	2.72E-05	74.339	3.115	19.121
1.00E+03	2.90E-04	84.62	3.152	20.084
2.00E+03	1.07E-05	70.313	2.471	20.888

2E.2 Third octave band analysis of the measured output power:

Below are the results as displayed by the sound intensity program.



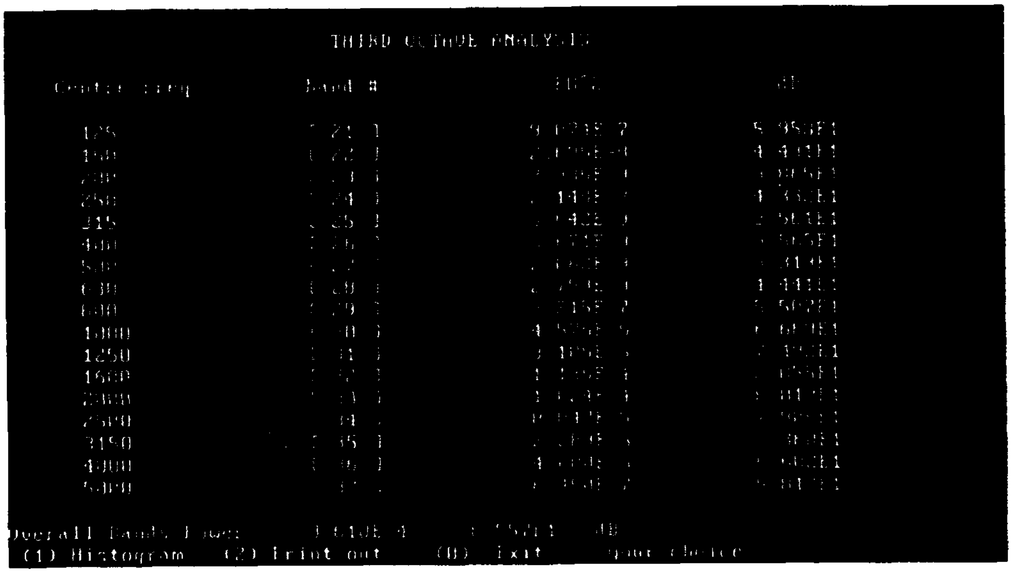
2F. *Sound source type 4205, 85 dB nominated output - 2K Hz band*:

2F.1 Full octave band analysis of the measured output power, pressure-intensity index and pressure-residual intensity index:

Microphone spacer Δ r = 12 mm
Spectrum frequency range: 0 - 5K Hz

Octave Band	Measured Power		δ_{pI}	δ_{pI0}
Freq	*Mag*	*dB*	*dB*	*dB*
250	3.25E-08	45.113	11.518	14.869
500	3.33E-08	45.23	9.324	18.342
1.00E+03	3.56E-05	75.511	3.084	20.65
2.00E+03	2.96E-04	84.72	2.988	22.733
4.00E+03	2.75E-05	74.399	3.472	21.445

2F.2 Third octave band analysis of the measured output power:
Below are the results as displayed by the sound intensity program.



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                    THIRD OCTAVE ANALYSIS

Center Freq            Band #            MAG               dB

   125                 ( 21 )        [illegible]       [illegible]
   160                 ( 22 )        [illegible]       [illegible]
   200                 ( 23 )        [illegible]       [illegible]
   250                 ( 24 )        [illegible]       [illegible]
   315                 ( 25 )        [illegible]       [illegible]
   400                 ( 26 )        [illegible]       [illegible]
   500                 ( 27 )        [illegible]       [illegible]
   630                 ( 28 )        [illegible]       [illegible]
   800                 ( 29 )        [illegible]       [illegible]
  1000                 ( 30 )        [illegible]       [illegible]
  1250                 ( 31 )        [illegible]       [illegible]
  1600                 ( 32 )        [illegible]       [illegible]
  2000                 ( 33 )        [illegible]       [illegible]
  2500                 ( 34 )        [illegible]       [illegible]
  3150                 ( 35 )        [illegible]       [illegible]
  4000                 ( 36 )        [illegible]       [illegible]
  5000                 ( 37 )        [illegible]       [illegible]

Overall Band Power:      [illegible]      [illegible]  dB
 (1) Histogram    (2) Print out     (0)  Exit       Your choice
```

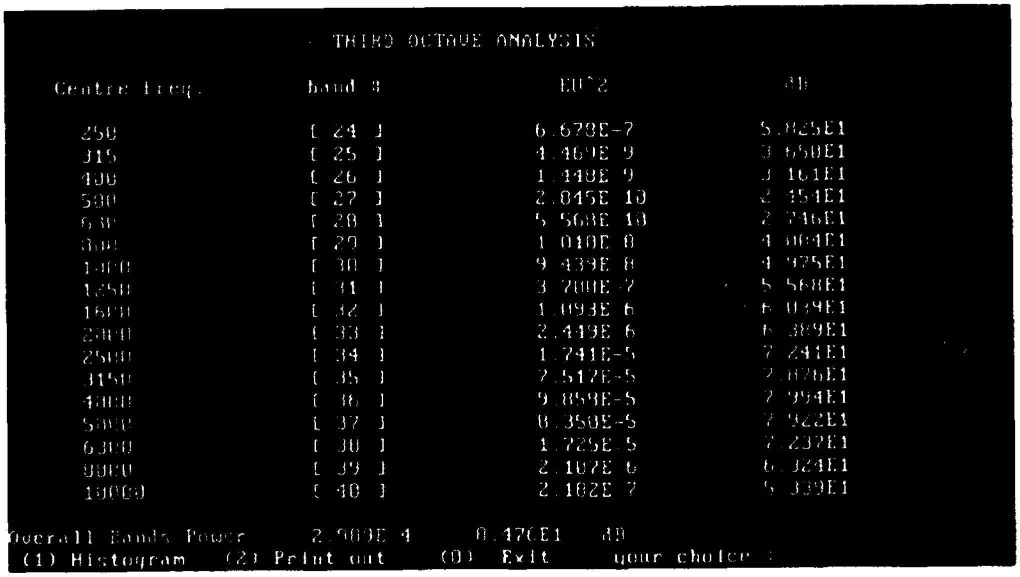
2G. *Sound source type 4205, 85 dB nominated output - 4K Hz band*:

2G.1 Full octave band analysis of the measured output power, pressure-intensity index and pressure-residual intensity index:

Microphone spacer Δ r = 12 mm
Spectrum frequency range: 0 - 10K Hz

Octave Band	**Measured Power**		**δ_{pI}**	**δ_{pI0}**
Freq	*Mag*	*dB*	*dB*	*dB*
500	2.29E-09	33.597	10.654	18.657
1.00E+03	5.75E-07	57.6	3.774	21.219
2.00E+03	2.10E-05	73.36	3.031	22.375
4.00E+03	2.57E-04	84.14	3.145	20.019
8.00E+03	1.96E-05	72.9	4.022	17.827

2G.2 Third octave band analysis of the measured output power:
Below are the results as displayed by the sound intensity program.



```
                    THIRD OCTAVE ANALYSIS

  Centre freq.          band #           EU^2              dB

     250                [ 24 ]        6.678E-7          5.825E1
     315                [ 25 ]        4.469E-9          3.650E1
     400                [ 26 ]        1.448E-9          3.161E1
     500                [ 27 ]        2.845E-10         2.454E1
     630                [ 28 ]        5.568E-10         2.746E1
     800                [ 29 ]        1.010E-8          4.004E1
     1000               [ 30 ]        9.439E-8          4.975E1
     1250               [ 31 ]        3.700E-7          5.568E1
     1600               [ 32 ]        1.093E-6          6.039E1
     2000               [ 33 ]        2.449E-6          6.389E1
     2500               [ 34 ]        1.741E-5          7.241E1
     3150               [ 35 ]        7.517E-5          7.876E1
     4000               [ 36 ]        9.858E-5          7.994E1
     5000               [ 37 ]        8.350E-5          7.922E1
     6300               [ 38 ]        1.725E-5          7.237E1
     8000               [ 39 ]        2.107E-6          6.324E1
     10000              [ 40 ]        2.182E-7          5.339E1

Overall Bands Power      2.989E-4      8.470E1    dB
 (1) Histogram   (2) Print out     (0)  Exit      your choice :
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TITLE

Measurement of sound intensity and sound power

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ABSTRACT

In this report the concept of a measurement technique for calculating sound intensity in the frequency domain is discussed and also how such a measurement system can be implemented in practice by using a frequency domain analyser.

The technique described employs a dual-channel FFT analyser to obtain a cross power spectrum from the two microphones from which sound intensity is calculated. This approach enables a general-purpose FFT analyser together with a micro-computer to perform the function of a dedicated sound intensity analyser.

The application of sound intensity measurement technique in sound power determination of a reference source is presented.

Measurement of Sound Intensity and Sound Power

Vinh Trinh

(MRL-TR-93-32)

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