Proceedings of The Institute of Acoustics

PRACTICAL APPLICATIONS OF REAL-TIME SOUND INTENSITY MEASUREMENTS

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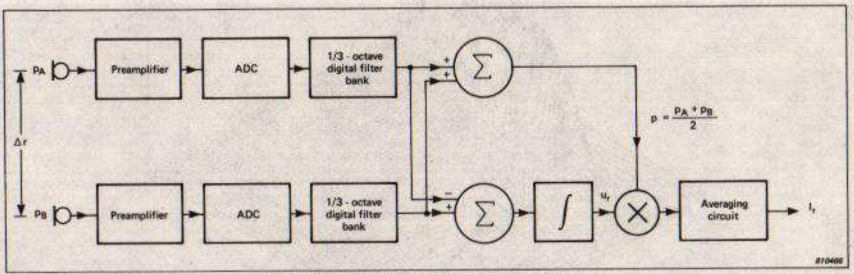

Fig.1.Real-time digital intensity analyser

The introduction of real time analysis using digital filtering techniques for the processing of signals from two closely spaced microphones has greatly improved the precision with which acoustic intensity measurements may be performed.

A third-octave digital system is shown in Fig.1. The signals from the two microphones are frequency analysed in parallel in real time and the sum and difference of the signals for each frequency band are calculated. The difference is integrated over time and divided by the distance between the microphones to yield the particle velocity u_r (see Fig.2). The sum and thus the pressure corresponding to the pressure midway between the microphones, is then multiplied by particle velocity to yield the sound intensity vector component I_r in a direction given by the orientation of the probe:

$$I_r = \overline{p\, u_r}$$

The use of the two microphone technique imposes limitations on the useful frequency range of the measuring system [1, 2, 3]. However by carefully phase-matching the two channels and using suitable spacers, sound intensity measurements can be performed over a wide frequency range with good accuracy (see Fig.3) [4, 5].

The main applications of a real-time sound intensity analysing system are:

1. Source location.
2. Determination of sound power of a machine or parts of a machine.
3. Measurement of absorption coefficients.
4. Measurement of sound transmission.

Absorption coefficients and sound transmission are dealt with by other papers in these proceedings.

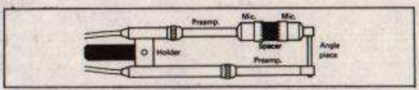

Fig.2.A sound intensity probe

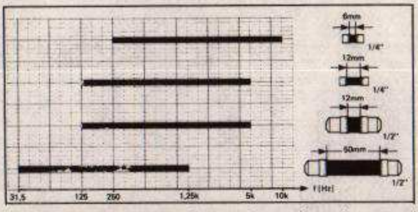

Fig.3.Frequency ranges for various microphone and spacer combinations for an accuracy in sound intensity level measurements of ± 1 dB

Source location

Real-time sound intensity measurements can be used to locate noise sources in a quick and direct manner in contrast to techniques such as 2-channel FFT or lead-wrapping. With the Sound Intensity Analysing System Type 3360, three approaches are available: direct comparison, continuous sweep and intensity mapping. From the directional characteristics of the probe (see Fig.4), it can be seen that the measured sound intensity is a maximum when incident on the front or the rear of the probe and a minimum when incident at right-angles to this axis. In preliminary surveys of machines, the sound sources might be located by pointing the probe directly over a suspected source and comparing, on the display unit, a measured spectrum with a stored spectrum. The spectrum containing the greater levels

PRACTICAL APPLICATIONS OF REAL-TIME SOUND INTENSITY MEASUREMENTS

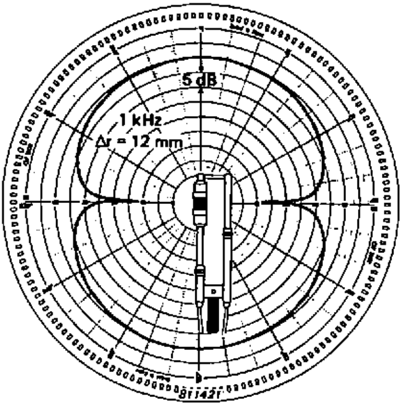

Fig.4.Directional characteristics of the probe

at the frequencies of interest is retained and compared with another measured spectrum. This comparison method only succeeds when the sources are widely separated as the maximum of the directional characteric is very broad (the measured intensity level decreases by only 3 dB from the maximum level at 60° off axis). For better definition the probe can be continuously swept over the surface of the machine with the axis of the probe parallel to the surface. When the minimum of the directional characteristics crosses a source/sink boundary for any frequency band, there is a rapid change in brightness on the display screen indicating that the direction of the intensity in that particular band has changed.

A third possibility is to use the sound intensity analysing system in conjunction with a graphics plotter to measure the sound intensity a number of specified positions close to the vibrating surface and to plot the results in the form of an intensity map. Such an intensity map clearly shows where energy flows out of the surface (i.e. a sound source) and where energy flows into the surface (i.e. a sound sink). Sources and sinks can very well appear beside each other on the same machine. The reason might be that for very close measurements, only a fraction of a wavelength from the surface of a vibrator, there would not only be propagating waves but also evanescent waves whose amplitudes decrease exponentially with distance from the source. In highly reactive sound fields e.g. close to a vibrator, circulating energy would be found, that is energy which may leave a part of the vibrating surface only to turn round quickly, within a wavelength and flow back into another part of the surface. The energy is then returned through the vibrator back to the source area. Thus intensity maps should be interpreted with caution.

Sound power

By summation of the sound intensity over a surface the sound power radiated by the surface can be determined and the the various surfaces can be ranked in order of importance. The advantages of the intensity method over the pressure method for sound power determinations are:

1. No restrictions upon the room where the measurements are performed, provided that the sound field is stationary.
2. Measurements may be performed in the near field. Near-field measurements improve signal to noise ratio and require less "free space" about the source under test.
3. In common with the sound pressure, free-field method, intensity measurements have to be performed on an hypothetical surface enclosing the source of interest, however, the intensity method places no restrictions on the shape and size of this measurement surface.
4. Measurements are not influenced by continuous background noise.

Representation of sound intensity data

The representation of sound intensity data depends to a large extent on personal preference. The program developed by B & K for treatment of data measured with the Sound Intensity Analysing System Type 3360 includes:

1. Intensity maps (iso-intensity contours by interpolation).
2. Intensity maps (numerical values).
3. Three dimensional intensity maps.
4. Summation of intensity spectra and calculation of sound power.
5. Calculation of the intensity vector from three orthogonal measurements.

When measurements are performed *in situ* (e.g. in an aircraft or a motor vehicle) the system may be powered via an inverter and spectra can be stored on the Digital Cassette Recorder Type 7400 (up to 1200 third-octave or 2400 octave spectra per cassette) (Fig.5).

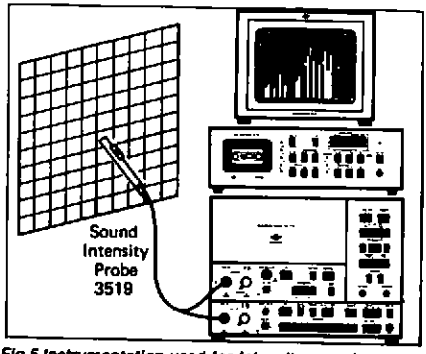

Fig.5.Instrumentation used for intensity mapping measurements showing grid of measurement points

PRACTICAL APPLICATIONS OF REAL-TIME SOUND INTENSITY MEASUREMENTS

Grid size and position

In general one can say that the grid should be as coarse as possible to limit the number of measurements but should be fine enough to pick out detail. If necessary the grid can be subdivided in regions of special interest. The spatial resolution must be smaller than the wavelength of sound, but to avoid the influence of the evanescent waves, below the critical frequency, the spatial resolution must be larger than the wavelength of the vibrator. Moreover a space-time-averaging must be performed, by sweeping the probe back and forth over the surface element during the measurement time, instead of performing point measurements.

The sound intensity field within a few centimetres of a vibrating surface (the hydrodynamic or evanescent near-field) can be extremely complex [6]. If one is only interested in the total sound power radiated by a surface then one should measure at least ten centimetres from the surface (the "far-field") where the intensity field is usually much more uniform. In highly diffuse fields as found, for example, inside aircraft, a far-field measurement is off little value as the measured sound intensity cannot be attributed to a single surface.

Intensity measurements on a motor & pump assembly

The aims of these measurements were to:

1. Measure the amount of noise radiated from the motor and the pump respectively in the assembly.
2. Reduce the noise if possible.
3. Verify whether intensity measurements can be used in a highly reactive environment.
4. Determine the number of measurement points required to give reliable results under these conditions.

The motor, a 20kW type operating at 1470 rpm, was placed on top of an oil reservoir (Fig.6)[7]. The pump was a Danfoss VPA 20, with an operating pressure of 180 bar with 7 pistons and with a capacity of 20 cm^3 per revolution. Thus the number of pulsations was

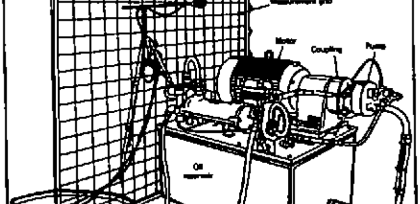

Fig.6.Reverberation chamber showing the motor, pump and oil reservoir assembly, the measurement grid and the intensity probe mounted on a tripod

7 × 1470 / 60 = 171,5 per second. The use of sound pressure measurements to determine the sound power radiated from various parts of the machinery were of no avail since the noise from the pump could not be dissociated from the noise of the motor. However sound pressure measurements did reveal that the radiated sound power from the unloaded motor was approximately 85 dB(A) re 1 pW and that from the motor when coupled to the pump was approximately 88 dB(A) re 1 pW, which indicated that the pump was the cause of the noise problem.

A rectangular box-shape was chosen as the enclosing surface for both the motor and the pump. On each of the eleven sides (5 around the motor and 6 around the pump) 25 measurement points were defined yielding 270 points in all. Each point represented 0,09 m^2 around the motor and 0,01 m^2 around the pump.

To measure the sound intensity level at the measurement points, the probe was fitted with two 1/2" phased matched microphones and a 12 mm spacer, enabling sound intensity measurements to be performed in the frequency range 125 Hz to 5 kHz with an accuracy of ± 1 dB and up to 10 kHz with an accuracy of + 1 to - 4 dB. The probe was mounted on a tripod and fitted with a wind screen to reduce the effect of airflow used to cool the motor. A linear averaging time of 8 s was used which yielded a measuring time of 38 minutes.

It was discovered that the presence of a person moving about in the reverberation chamber affected the measurements. The relatively large amount of absorption provided by the person in the otherwise hard, reverberation chamber apparently had considerable effect on the highly reactive sound field. Entering and leaving the chamber to move the probe from position to position was therefore necessary. Such great alterations to the sound field during measurements are not usually encountered in practice.

Results from motor & pump assembly

The sound power from the motor and the oil reservoir was found to be 2,5 dB(A) higher than that from the pump, which means that most noise is radiated from the motor and not the pump. The conclusion is that the structure borne vibrations and the pulsations from the pump contribute far more to the sound power level than the direct airborne radiated noise.

In addition, the sound power was calculated from reduced numbers of measurement points. Despite the fact that measurements were performed in a highly reactive field, a drastic reduction in the amount of data remarkably yielded results within 1 dB of the calculation based on the full 270 points.

Noise reduction

As a result of these measurements, the oil reservoir (which possessed a considerable surface area) was removed from the assembly. A reduction in the overall noise level of 2,5 dB(A) was obtained and subtantiated the use of the intensity measurements. A further reduction can be expected by an improved design of the coupling between the motor and the pump.

Intensity measurements on a labelling machine
The aims of these measurements were to:
1. Measure the amount of noise generated by a labelling machine operating at full speed *in situ* in the tapping hall of a brewery where a high level of background noise was present.
2. Verify whether at the operator's position, the sound pressure level due to the labelling machine was below the 85 dB(A) specified by the manufacturer of the machine.

The dimensions of the machine were 2,25 × 2,6 × 1,9 m. At full speed the machine labelled 34500 bottles per hour. The noise due to the transportation of the bottles to and from the machine could not of course be "switched off" [8].

The enclosing surface was chosen to be a rectangular box with 24 measurement points defined on each of the vertical sides and 9 defined on the top of the enclosing surface yielding 105 points in all. With a linear averaging time of 8 s the measuring time was 14 minutes for gathering the sound intensity spectra. Broken bottles along the conveyor and in the machine were common which led to machine stoppages and increased the time for performing the measurements to 2 hours.

Results from labelling machine
The sound power determined from sound pressure level measurements, without any room corrections was 103,7 dB(A) and from sound intensity level measurements was 97,5 dB(A). The difference between these two values i.e. 6,2 dB(A) was taken as the increase in sound power level due to the presence of the reverberant field. The corrected value for the sound pressure level at the operator's position was then the measured sound pressure level minus 6,2 dB(A) which yielded

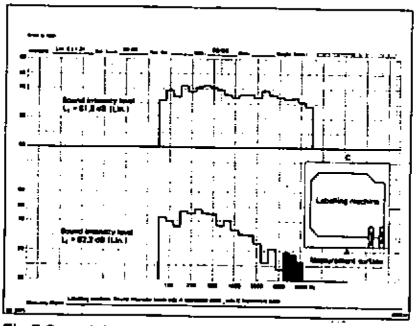

Fig.7.Sound intensity levels averaged over 24 measurement points on the conveyor side and the operator's side. Hatching indicates that intensity is incident from behind the probe at these frequencies

81,0 dB(A) which verified the manufacturer's specifications for the sound pressure level at the operator's position.

From the averaged spectra for each side of the machine, it was seen that the net flow of energy between 5 kHz and 10 kHz was towards the side where the bottles entered and left the machine. This was due to the rattling of bottles on the conveyor which produced a lot of high frequency noise(Fig.7).

An iso-intensity map of the overall intensity level was plotted for the operator's side of the machine (Fig.8). The numbers around the map are the intensity levels at the perimeter points to the nearest dB. The map shows that the highest intensity level is between 84 dB and 85 dB.

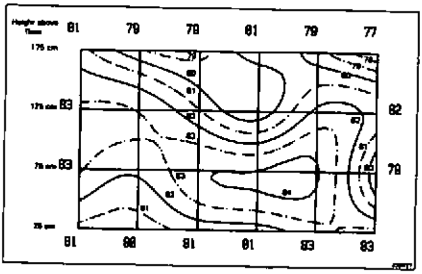

Fig.8.Sound intensity map of the total sound intensity levels over 24 measurement points on the operator's side

Conclusions
Sound intensity measurements provide a powerful and exciting tool for the acoustical or mechanical engineer. The rapidity of both measurement and the treatment of the data means that less time need be spent "data crunching" and more time is available for solving the problem in hand.

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