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FFT INTENSITY METERS USED FOR SOUND SOURCES AND ACOUSTICAL ENVIRONMENT CHARACTERIZATION

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The major importance of phase errors between the two microphone channels appeared as early as the beginning of the use of the two microphone method to measure the acoustic intensity. Thereby, it is essential to proceed to a phase matching of measuring channels (electronic devices adjustment and transducer selection) or to correct the cross-spectrum with a transfer function when FFT processing is used. In spite of these precautions, the limited accuracy of calibration gives an incertitude $|\Delta\Phi|$ on the systematic phase error introduced in the measurement. It is shown [1] that the acoustic intensity error is approximatly proportional to $|\Delta\Phi|/\Phi_{21}$. Φ_{21} being the relative phase shift of the two microphone signals (cross-spectrum phase function when using dual-channel FFT).
For progressive plane waves, Φ_{21} is simply proportional to the propagation delay between the two microphones ($\Phi_{21} = \omega\tau = \omega\Delta r\cos\alpha/c = k\Delta r\cos\alpha$). The influence of residual error $|\Delta\Phi|$ is essentially sensitive in the low frequencies. This pattern is used to define a low frequency limit to the measuring range.
However, the situations encountered in the industrial practice has shown that in most cases Φ_{21} gave values well lower to those supplied by the plane wave model. The sensitivity to phase errors is much greater than estimated by users who usually test their instrument calibration only in free field conditions.
Moreover, Seybert [2] demonstrated the influence of random errors in acoustic intensity measurement. The great number of sound sources and their reflexion by obstacles decrease the measured pressure coherence function between the two microphones. In this case, the statistical error is all the more important as the phase Φ_{21} is lower.
The lack of quantitative information on these two types of error cannot allow to estimate the accuracy of measurements made in industrial conditions and leads to some surprising phenomena such as sign inversion. It is necessary to introduce quality indicators to remove any doubt.

CONFIDENCE INTERVAL DETERMINATION FOR INTENSITY MEASUREMENT

They depend on two types of errors : systematic errors and random errors. The 68% confidence interval associated to the measurement is defined from the total normalized standard error ε :

$$\hat{I}(1-\varepsilon) \leqslant I \leqslant \hat{I}(1+\varepsilon) \qquad \text{with} \quad \varepsilon = \sqrt{\varepsilon_b^2+\varepsilon_r^2} \qquad (1)$$

- the normalized error ε_b is the incertitude on the systematic error and depends on the estimate of the residual phase error $|\Delta\Phi|$ after calibration :

$$\varepsilon_b = |\Delta\Phi| \ \mathrm{cotg}\ \Phi_{21} \qquad (2)$$

- the normalized random error ε_r for stationary processes depends on the cross-spectrum phase and coherence functions and also on the BT product (BT=n: number of FFT samples averaged). From [1], the following expression is used

$$\varepsilon_r = \sqrt{1/2BT}\,\{(1/\gamma^2-1)+\mathrm{cotg}^2\Phi_{21}(1/\gamma^2+1)\}^{\frac{1}{2}} \qquad (3)$$

Figure 1 illustrates an acoustic intensity measurement with its confidence interval simultaneously obtained by FFT analyzers. The users has in situ complete information to estimate the accuracy and the quality of measurement, and optimize the test by changing the average time or by adjusting the microphone spacing (to act on Φ_{21} and γ^2).

QUALITY INDICATORS

The expression of incertitude on acoustic intensity measurement shows that the phase and the coherence of cross-spectrum may be considered as measurement quality indicators and used for sound field characterization . In experimental work, the difference between pressure and

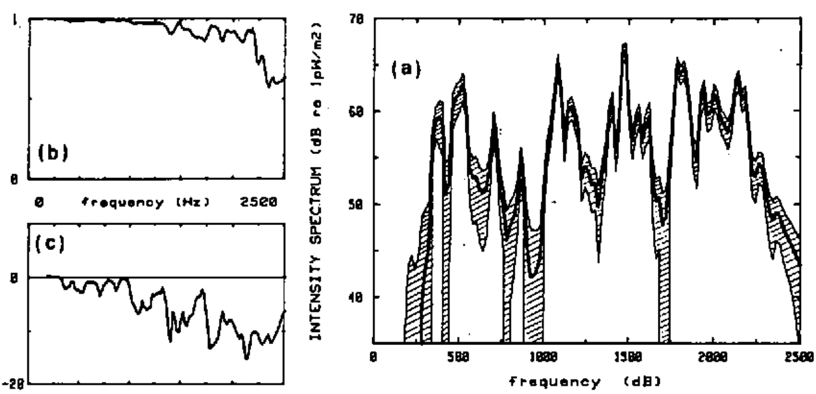

Fig.1- 68% confidence interval (a) of intensity spectrum.
Corresponding coherence (b) and phase (c) functions.

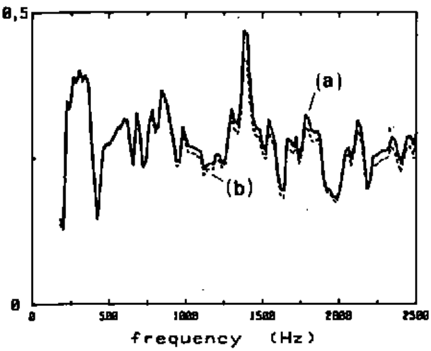

Fig.2- Comparison between the indicator $\Phi_{21}/k\Delta n$ (a) and the pressure - intensity ratio (b).

intensity levels is frequently used as a criterion and differences greater than 6 dB has been noticedto lead to difficult measurements. When using the complex expression of the pressure field $p = |p|^2 e^{j\varphi}$, the acoustic intensity may be expressed as :

$$\vec{I} = \frac{1}{2} \operatorname{Re}\{p \vec{v}^*\} = (1/2\rho c k) \operatorname{Im}\{p \, \overrightarrow{grad} \, p^*\} = \frac{|p|^2}{2\rho c} \frac{\overrightarrow{grad}\,\varphi}{-k} \quad (4)$$

The last expression putsout the intimate relation between the pressure intensity ratio and the phase gradient of the pressure field. In the r-direction : $I_r / (|p|^2 / 2\rho c) = -\partial\varphi / k\,\partial r$

An approximation of phase gradient is given from the measured phase between the two microphone signals (i.e : the cross-spectrum phase function) : $-\partial\varphi / k\,\partial r \simeq \Phi_{21} / k\Delta r$

It is therefore demonstrated that difference between pressure and intensity levels is a quality indicator equivalent to $\Phi_{21}/k\Delta r$. These two parameters are ploted on figure 2.

SOUND POWER DETERMINATION AND ENVIRONMENT CHARACTERIZATION

The acoustic power may be written from the mean value $\langle G_{21}\rangle = \frac{1}{N} \sum_i (G_{21})_i$ of the one-sided cross spectral density measured on a surface enclosing the source, with the probe in the normal direction

$$W = (S/\rho c k \Delta n) \operatorname{Im}\{\langle G_{21}\rangle\} \quad (5)$$

The accuracy of this determination is given by the standard deviation of these measurements which is the sum of two independent factors : one related to intensity measurement errors which depend on the nature of sound field, the other related to the surface sampling by N measurement points [3]

Equations (2) and (3) are used to express the first error, considering the phase and the coherence of the mean cross-spectrum $\langle G_{21}\rangle$ .However, if the measurements are not made simultaneously (parallel acquisitions for all N points), the measurements at each point will be independent and the standard deviation of the random error ε_r have to be divided by $\sqrt{N}$.

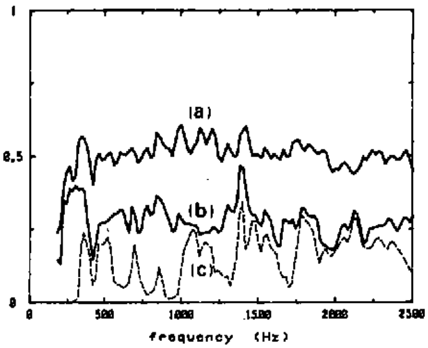

Fig.3- Values of $\dot{\Phi}_{21}/k\,\Delta n$ for various configurations:

(a) $S_1 = 3.05\ m^2$

(b) $S_2 = 1.55\ m^2$

(c) idem with perturbating source.

The phase $\dot{\Phi}_{21}$ and the coherence $\dot{\gamma}^2$ of $<G_{21}>$ has a global signification concerning the source radiation, the shape of the measurements surface and the sound environment of the test site.
Figure 3 describes the application of the indicator $\dot{\Phi}_{21}/k\,\Delta n$ in the case of a 4 mm thick steel parallelepipedic structure (.7x.5x.35 m) laid on a reflecting ground. For the first surface ($S_1 = 3.05\ m^2$, distance of the measuring point to the surface : 0.16 m) the value ranges around 0.5 ; this low value is chiefly due to the near field effect (the pressure intensity ratio increases with the proximity of vibrating surface). This effect is emphasized when reducing the distance (mid-point of probe situated at 0.04 m of the structure, $S_2 = 1.55\ m^2$).
Complementary experiments show that a perturbating source located out of the measurement surface reduces again the phase of $<G_{21}>$: only the real part is increased, the imaginary part remaining constant as the consequence of Gauss Law.
These indicators joined to the standard deviation of measured values can be used in the choice of the right measurement surface and the number of points for given test conditions.

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