A Sound Intensity Probe for Measuring from 50 Hz To 10 kHz

by F. Jacobsen, V. Cutanda) and P. M. Juhl, Department of Acoustic Technology, Technical University of Denmark, Building 352, DK-2800 Lyngby, Denmark*

Abstract

The upper frequency limit of a p-p sound intensity probe with a certain microphone separation distance is generally considered to be the frequency at which an ideal probe would exhibit an acceptably small finite difference error in a plane wave of axial incidence. This article shows that the resonances of the cavities in front of the microphones in the usual 'face-to-face' configuration give rise to a pressure increase that to some extent compensates for the finite difference error. Thus the operational frequency range can be extended to an octave above the limit determined by the finite difference error, if the length of the spacer between the microphones equals the diameter.

Résumé

Pour une sonde d'intensité acoustique à deux microphones séparés par une distance donnée, la limite supérieure de fréquence est généralement considérée comme la fréquence à laquelle une sonde idéale présenterait, pour une onde plane et une incidence de 0°, une erreur de différence finie acceptable. Cet article montre que le phénomène de résonance dû aux cavités frontales des microphones configurés "face à face" entraîne un accroissement de pression tendant à compenser cette erreur. La gamme de fréquence opérationnelle peut donc être élargie d'un octave au-dessus de la limite ainsi imposée, si le bloc d'espacement présente une longueur égale au diamètre.

*) Present address: U.P.M., E.U.I.T. de Telecomunicación, Department of Audiovisual Engineering and Communications, Ctra de Valencia km 7, E-28031 Madrid, Spain

Zusammenfassung

Die obere Grenzfrequenz einer Zwei-Mikrofon-Schallintensitätssonde mit einem bestimmten Mikrofonabstand wird allgemein als diejenige Frequenz betrachtet, bei der die ideale Sonde einen noch akzeptablen Fehler, bedingt durch den endlichen Abstand der beiden Mikrofone, für eine axial einfallende ebene Welle zeigt. Dieser Artikel zeigt, daß die Resonanzen der Hohlräume vor den Mikrofonen bei der üblichen Anordnung (Mikrofone einander gegenüber) einen Druckanstieg verursachen, der den Abstandsfehler teilweise kompensiert. Der Arbeitsfrequenzbereich kann daher auf eine Oktave über der durch den Abstandsfehler definierten Grenze erweitert werden, wenn die Länge des Mikrofonabstandstücks gleich dem Mikrofondurchmesser ist.

Introduction

Sound power determination is a central point in noise control engineering, and the method of sound power determination based on measurement of sound intensity has the significant advantage over other methods that it makes it possible to determine the sound power of a source of noise in situ, even in the presence of other sources.

Existing sound intensity probes in commercial production are based on the "two-microphone" (p-p) measurement principle in which the intensity is determined from the signals from two closely spaced pressure microphones.

One of the obvious limitations of this measurement principle is the frequency range; the fact that the method relies on the finite difference approximation clearly implies an upper frequency limit that is inversely proportional to the distance between the microphones. Unfortunately, the influence of phase mismatch and several other measurement errors is also inversely proportional to the distance between the microphones; therefore, one cannot extend the frequency range simply by placing the microphones very close together.

One can extend the frequency range by combining measurements with two sets of microphones. The purpose of this paper is to examine whether it is possible to cover a significant part of the audible frequency range, from 50 Hz to 10 kHz, with one single probe configuration.

Numerical Results

In what follows it is assumed that the intensity probe is a p-p probe with the two microphones in the usual 'face-to-face' arrangement with a solid 'spacer' between them.

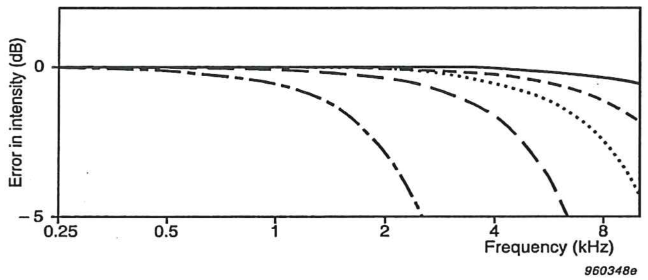

Fig. 1. Finite difference error of an ideal intensity probe which does not disturb the sound field in a plane wave of axial incidence for different values of the separation distance —, 5 mm; ---. 8.5 mm; ···, 12 mm; – – , 20 mm; – – – -, 50 mm

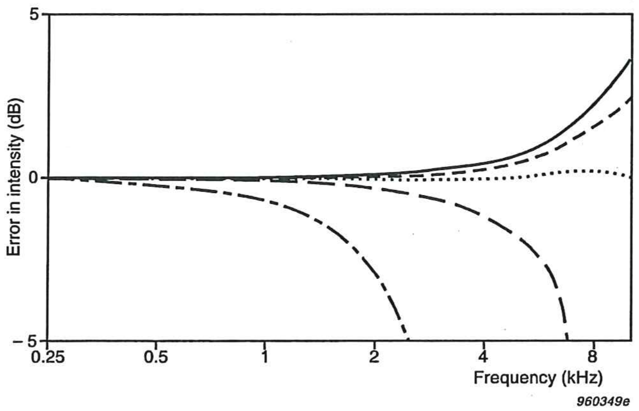

Fig. 2. Error of an intensity probe with 12 mm long half-inch microphones in a plane wave of axial incidence for different spacer lengths, —, 5 mm; ---, 8,5 mm; ···, 12 mm; – –, 20 mm; – – – -, 50 mm

The operational frequency range of an intensity probe depends on the particulars of the sound field conditions [1]. Nevertheless, the highest frequency at which an ideal p-p probe with a certain microphone separation distance would exhibit an acceptably small finite difference error in a plane wave of axial incidence has usually been regarded as the upper frequency limit [1]. This finite difference error is shown in Fig. 1. According to this reasoning a probe with half-inch microphones separated by a 12 mm spacer (which is a very common configuration) should not be used above, say, 5 kHz. However, more than ten years ago Watkinson and Fahy pointed out that the resonance of the cavities in front of the microphones in this configuration gives rise to a pressure increase that to some extent might compensate for the finite difference error [2] A recent investigation based on a boundary element model of an axisymmetric p-p probe has confirmed Watkinson and Fahy's observation [3]. Fig. 2, which corresponds to Fig. 1, shows the error calculated for a probe with two 12 mm long half-inch microphones. The error is essentially the result of the combined effect of the finite difference approximation and the pressure increase. It is

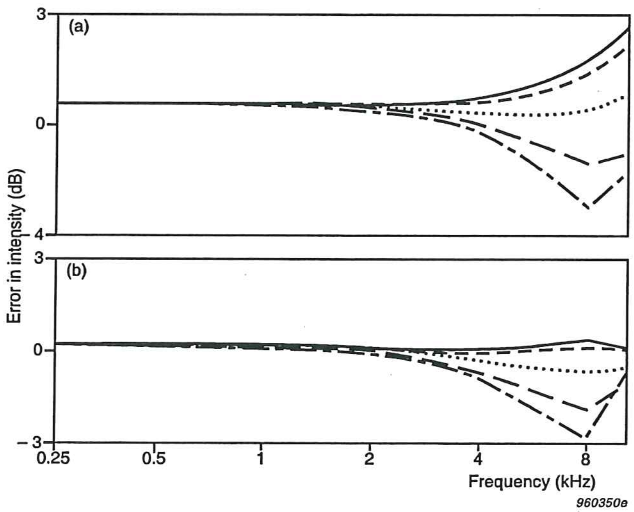

Fig. 3. Error of an intensity probe with 12 mm long half-inch microphones in a plane wave. (a) 8.5 mm spacer; (b) 12 mm spacer. Angle of incidence: —, 0°; ---, 20°; ···, 40°; – –, 60°; - - - -, 80°

apparent that the optimum length of the spacer is about 12 mm, and that a probe with this geometry performs very well in the case of a plane wave of axial incidence up to 10 kHz. It can also be deduced from the figure that such a probe is superior to a probe with quarter-inch microphones separated by a 12 mm spacer, owing to the fact that the compensating pressure increase is shifted an octave upwards for the latter configuration. In Fig. 3 is shown the corresponding error for non-axial incidence, calculated for two different spacer lengths.

Experimental Results

The numerical results briefly summarised in the foregoing imply that the frequency range of a probe with the conventional combination of half-inch microphones and a 12 mm spacer is wider than hitherto believed. To test this conclusion a series of experiments have been carried out: the sound power of a loudspeaker driven with pink noise, Brüel & Kjær Type 4205, was determined in a large (240 m^3) reverberant room with a reverberation time of about 4 s. The source was placed on the floor about 1.5 m from the nearest wall, and the ratiated sound power was estimated by scanning manually with an intensity probe over the five faces of a cubic surface of $1 \times 1 \times 1$ m.

A frequency analyser of Brüel & Kjær Type 3550 was used in combination with an intensity probe of Brüel & Kjær Type 3548, either with half-inch microphones of Brüel & Kjær Type 4181 or with quarter-inch microphones of Brüel & Kjær Type 4178. Since these microphones are so-called free-field microphones it is necessary to compensate for the drop of the pressure sensitivity at high frequencies. Fig. 4 shows the pressure response of the two sets of microphones, determined with an electrostatic actuator. All the results presented in the following have been corrected with the corresponding actuator response.

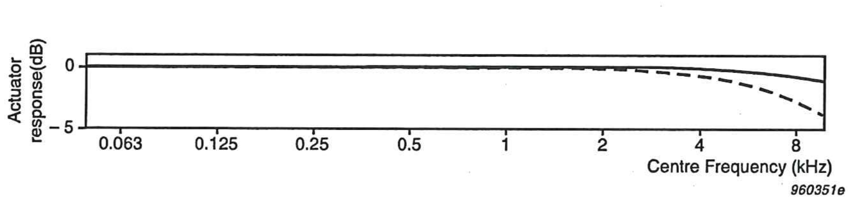

Fig. 4. Electrostatic actuator response of microphones. —, Brüel & Kjær Type 4178; ---, Brüel & Kjær Type 4181

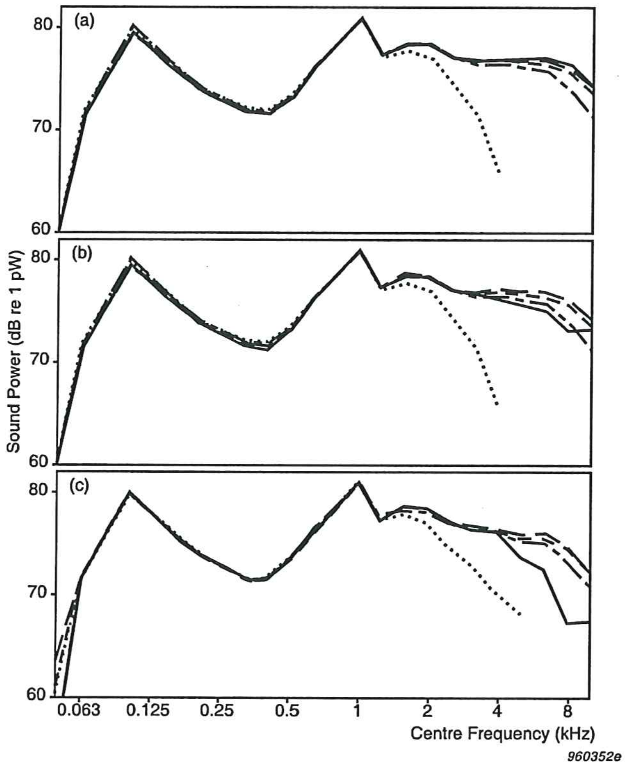

Fig. 5. Sound power of source, estimated with different combinations of microphones and spacers. (a) No extraneous noise, (b) strong diffuse background noise from an extraneous source, (c) strong diffuse and non-diffuse noise from an extraneous source. --, Half-inch microphones, 8.5 mm spacer; ---, half-inch microphones, 12 mm spacer; ···, half-inch microphones, 50 mm spacer; – –, quarter-inch microphones, 6 mm spacer; - - - -, quarter-inch microphones, 12 mm spacer

The measurements were carried out under three conditions: i) without extraneous noise, ii) with strong diffuse background noise from a distant source (Airap A14 from Électricité de France), and iii) with strong non-diffuse and diffuse background noise from the same source placed about 2.5 m from the surface. In the last mentioned case the partial sound power of the nearest 1 m^2 segment was negative in the entire frequency range.

The measurements with quarter-inch microphones were carried out with a 6 mm spacer and with a 12 mm spacer. The former measurement, which can be expected to be reliable at high frequencies, served as the reference in the frequency range from 4 to 10 kHz. The measurements with half-inch microphones were carried out with an 8.5 mm spacer, a 12 mm spacer and a 50 mm spacer. In order to reduce the effect of transducer phase mismatch as far as possible, all measurements were repeated with the two microphones interchanged [4].

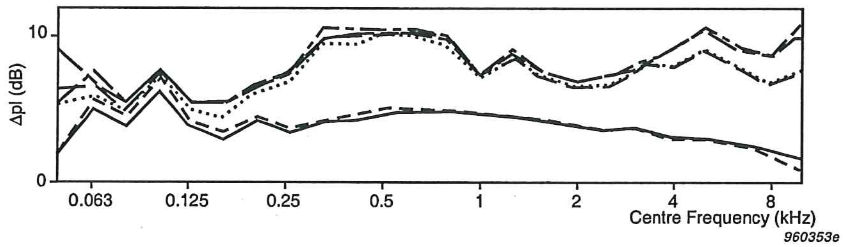

Fig. 6. Pressure-intensity index. —, Quarter-inch microphones, 6 mm spacer, no extraneous noise; ---, half-inch microphones, 12 mm spacer, no extraneous noise, ···, quarter-inch microphones, 6 mm spacer, diffuse noise; – –, half-inch microphones, 12 spacer, diffuse noise; – · –. quarter-inch microphones 6 mm spacer, non-diffuse and diffuse noise: – - - -, half-inch microphones, 12 mm spacer, non diffuse and diffuse noise

The results of the sound power measurements are presented in Fig. 5; and Fig. 6, which shows the pressure-intensity index, gives an impression of the acoustic conditions. It can be seen from Fig. 5 that practically all measurements are in agreement from 50 Hz to 1.25 kHz. An exception is the measurements with quarter-inch microphones at 50 Hz under the most difficult sound field condition. (This is probably the result of random errors due to electrical noise [5]; however, without compensation for phase mismatch significant errors occurred with the quarter-inch microphones in most of the frequency range.) From 1.6 kHz and upwards the combination of half-inch microphones and the 50 mm spacer underestimates, but it is worth noting that the error is less than predicted by the idealised expression for an axial plane wave (Fig. 1), and that the size of the error depends on the sound field conditions, which leads to the conclusion that one cannot compensate for the finite difference error. The combination of quarter-inch microphones and a 12 mm spacer leads to underestimation from 5 kHz and upwards, more or less as expected. The measurements with half-inch microphones and the 12 mm spacer are in fair agreement with the reference measurements, confirming the predicted advantage of this combination. In fact, only the combination of half-inch microphones and the 8.5 mm spacer behaves unexpectedly.

As can be seen, it overestimates slightly under mild measurement conditions, but underestimates under more difficult conditions. It seems as if the ability of suppressing extraneous noise at high frequencies deteriorates if the spacer is significantly shorter than the diameter of the microphones. A possible explanation is that the error depends more on the angle of incidence for this configuration, cf. Fig. 3.

Conclusions

One cannot compensate for the finite difference error of p-p intensity probes by using the theoretical plane wave expression, and one cannot extend the frequency range by using a spacer appreciately shorter than the diameter of the microphones. Moreover, existing quarter-inch microphones are not suitable for measurement of sound intensity at low frequencies. However, a numerical and experimental study of diffraction effects has demonstrated that the operational frequency range can be extended to an octave above the limit determined by the finite difference error if the length of the spacer between the microphones equals the diameter. This means that a probe with half-inch microphones can cover the frequency range from 50 Hz to 10 kHz.

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