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A plane Wave Synthesis Facility for Sound Transmission Measurements on Panels

H.M.M. van der Wal and E.A.F.A. Demmenie

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ABSTRACT
Excitation of structures with low frequency, narrow banded noise is found in e.g. (propeller-driven) aircraft. The National Aerospace Laboratory NLR has a facility for narrowband, low frequency sound transmission research on panel-structures. The panels have free-free boundary conditions and are curved in one direction, can be stiffened or unstiffened, single or double and have maximum dimensions of 1.2 x 2.0 m^2.
The accoustic excitation of the panels can be a pure tone or periodic random noise; it is performed by an array with 3 x 4 ducts with an independently driven loudspeaker in each duct. The cross sectional dimensions of each duct ensure that only a plane wave can propagate in the 80 - 320 Hz frequency band. The amplitude and phase of the incident and reflected sound field in each duct are determined with a two microphone technique. In each duct the amplitude and phase of the incident wave are within a margin of $\pm$ 0.5 dB and $\pm$ 5 from a desired value, specified per frequency. The transmitted sound power is measured with a sound intensity probe mounted on a low noise scanning robot. This paper describes the facility and measurement method. Potential measurement errors - connected with the set-up - are discussed, like flanking transmission and reflections.

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Summary

Excitation of structures with low frequency, narrow banded noise is found in e.g. (propeller-driven) aircraft. The National Aerospace Laboratory NLR has a facility for narrowband, low frequency sound transmission research on panel-structures. The panels have free-free boundary conditions and are curved in one direction, can be stiffened or unstiffened, single or double and have maximum dimensions of 1.2 x 2.0 m^2.

The acoustic excitation of the panels can be a pure tone or periodic random noise; it is performed by an array with 3 x 4 ducts with an independently driven loudspeaker in each duct. The cross sectional dimensions of each duct ensure that only a plane wave can propagate in the 80 - 320 Hz frequency band. The amplitude and phase of the incident and reflected sound field in each duct are determined with a two microphone technique. In each duct the amplitude and phase of the incident wave are within a margin of ± 0.5 dB and ± 5^o from a desired value, specified per frequency. The transmitted sound power is measured with a sound intensity probe mounted on a low noise scanning robot.

This paper describes the facility and measurement method. Potential measurement errors - connected with the set-up -are discussed, like flanking transmission and reflections.

Samenvatting

Excitatie van constructies met laagfrequent, smalbandig geluid vindt men o.a. bij propellervliegtuigen. Het Nationaal Lucht- en Ruimtevaartlaboratorium NLR heeft een faciliteit voor smalbandig laagfrequent geluidstransmissie-onderzoek aan panelen. De panelen hangen vrij in de opstelling, zijn in één richting gekromd en kunnen onverstijfd of verstijfd, enkel- of dubbelwandig zijn. De maximum paneelafmetingen bedragen 1.2 x 2.0 m^2.

De panelen kunnen met sinusvormige signalen of met periodieke ruis worden geëxciteerd: De excitatie wordt verzorgd door een array van 3 x 4 kanalen met in elk kanaal een onafhankelijk aan te sturen luidspreker. De dwarsafmetingen van elk kanaal zijn zodanig dat zich daarin, in de frequentieband van 80 tot 320 Hz, alleen een vlakke golf kan voortplanten. De amplitude en fase van de invallende en gereflecteerde geluidsgolf wordt in elk kanaal gemeten met een twee-microfoontechniek. In elk kanaal liggen de amplitude en fase van de invallende golf binnen een marge van ± 0.5 dB en ± 5^o van een gewenste waarde, die per frequentie is gespecificeerd. Het afgestraalde geluidsvermogen wordt gemeten met een intensiteitsmeetsonde, die is bevestigd aan een geluidsarme zwaairobot.

In dit artikel worden de opstelling en meetmethode beschreven. De - met de opstelling samenhangende - potentiële meetfouten worden besproken, zoals flankerende geluidstransmissie en reflecties.

Zusammenfassung

Konstruktionen, die mit Schmalbandgeräuschen im niedrigem Frequenzbereich angeregt werden, findet man u.a. auch bei Propellerflugzeugen. Das Nationale Luft- und Raumfahrtlaboratorium NLR verfügt über eine Einrichtung zur Erforschung von schmalbandiger Schalltransmission an Paneelkonstruktionen im niedrigen Frequenzbereich. Die Paneele hängen frei in der Versuchsaufstellung, sind in einer Richtung gekrümmt und können sowohl versteift als auch unversteift, einzel- oder doppelwandig ausgeführt sein. Die maximalen Paneelabmessungen können bis zu 1.2 x 2.0 m^2 betragen.

Die Paneele werden mit Sinussignalen oder mit periodischem Geräusch angeregt. Für die Anregung sorgt eine Matrix bestehend aus 3 x 4 Kanälen, wobei jeder Kanal über einen unabhängig angesteuerten Lautsprecher verfügt. Die Querschnittabmessungen jedes Kanals sind so gewählt, daß in jedem Kanal im Frequenzbereich von 80 bis 320 Hz eine ebene Welle propagiert. Per Kanal wird die Amplitude und die Phase der einfallenden und der reflektierten Schallwelle mit Hilfe einer Zweimikrophontechnik gemessen.

Die Amplitude und die Phase der einfallenden Welle in jedem Kanal weichen dabei um nur maximal ± 0.5 dB beziehungsweise ± 5^o von dem gewünschten Wert ab, welcher per Frequenz spezifiziert werden kann. Die durch die Konstruktion abgestrahlte Schallleistung wird mit einer Intensitätsonde gemessen, die auf einem geräuscharmen Schwungroboterarm montiert ist.

In diesem Artikel werden die Versuchsaufstellung und die Meßmethode beschrieben. Außerdem werden die - mit der Versuchsaufstellung zusammenhängenden - Meßungenauigkeiten (flankierende Schalltransmission und Reflektionen) diskutiert.

1 Introduction

For party-walls, windows and other building elements standardized measurement methods are available for the determination of the sound insulation, see e.g. (Ref. 1). These methods make use of a diffuse sound field to excite the test items, and give broadband information, usually in third octave bands. For building acoustics these methods are useful, because in practice the excitation of building components has a random incidence character. For aircraft fuselages however, in particular for propeller excitation, there are well defined relations for the amplitude and phase of the sound field on the fuselage (see e.g. Ref. 2). It is therefore possible to excite a fuselage mock-up in a more realistic way, e.g. by a ring of loudspeakers (Refs. 3, 4). Locally a plane wave is a good approximation of the sound field of a propeller (Ref. 5). For panels a plane wave is thus a suitable type of excitation.

In this paper a set-up will be described for the experimental determination of the transmission loss of panels, which are excited with a plane wave. This plane wave is generated in an array of ducts. A typical feature of this set-up is that not only the total pressure at the panel surface, but also the complex amplitudes of the incident and reflected wave can be determined from the measured sound pressures.

2 Set-up

The plane wave synthesis facility is designed for acoustic testing of panels in the frequency region between 80 and 320 Hz. The excitation of the panel can be a pure tone or periodic random noise.
Figure 1 shows a photograph of the plane wave synthesis facility. The facility consists of an array of 3 x 4 ducts, a measurement enclosure, that is placed on top of the testpanel, and a scanning robot with an intensity probe. The facility is placed in a semi-anechoic room, with 0.5 m long sound absorbing wedges.

Each duct has a loudspeaker, which is fed by an independent signal generator, and two microphones, which are placed along the axis of the duct, at a distance of 0.05 and 0.35 m from the panel. The dimensions of each duct (0.50 x 0.40 m^2) are such, that only a plane wave can propagate in the frequency region of interest (80 - 320 Hz): higher modes are evanescent. In this case of the exclusive propagation of a plane wave, the incident and reflected sound power can be determined with a two microphone method (see next section).
The test panels are excited with an overall plane wave in the 80 - 320 Hz frequency region, with a total amplitude of about 120 dB. By means of a special feed back algorithm the phases and

amplitudes of the incident waves in all the ducts are adjusted within 0.5 dB and 5^o from a desired value. By choosing different desired values for phase and amplitude in each duct, it is also possible to simulate other sound fields.

The transmitted sound power is determined from the average sound intensity over a measurement surface. This surface should enclose the panel, so that all power radiated by the panel flows through the surface. Other acoustic sources (or sinks) should not be enclosed, e.g. the slit between the test panel and the array of ducts. To facilitate this, a measurement enclosure with a cross section of 1.2 * 2.0 m^2 is placed on top of the test panel, see figure 1. As measurement surface the cross section at about 30 cm distance from the test panel has been chosen. The intensity probe, which has a microphone spacing of 5 cm, is mounted on a scanning robot, see figure 1. The noise production of this scanning robot is negligible compared to the sound power radiated by the test panel.

The test panel has free-free boundary conditions: The panel hangs in springs and has no mechanical contact with the duct array or the measurement enclosure. The slit between panel and array (enclosure) is between 1 and 2 mm.

3 Measurement Method

In this section the measurement method for the acoustic transmission loss of a test panel is described by means of mathematical expressions for incident, reflected and transmitted sound power. In the following all pressures are assumed to be Fourier transformed.

The complex amplitude of the incident and reflected plane wave in each duct is measured with a two microphone method. Figure 2 shows the principle of the measurement method.
For frequencies below the cut-off frequency only a plane wave can propagate in a duct in axial direction (z). The sound pressure in each duct can be written as the sum of an incident and a reflected wave:

$$p(z,\omega) = P_{inc}(\omega) \cdot e^{-ikz} + P_{refl}(\omega) \cdot e^{+ikz} \qquad (1)$$

The angular frequency is denoted by ω and k is the wavenumber (= ω/c, with c the speed of sound). $P_{inc}(\omega)$ and $P_{refl}(\omega)$ are the complex amplitudes of the incident and the reflected wave respectively.
In each duct, the sound pressure is measured in two different cross sections z_1 and z_2. From the measured sound pressures $p(z_1,\omega)$ and $p(z_2,\omega)$ the complex amplitudes P_{inc} and P_{refl} can be

calculated as follows:

$$P_{inc}(\omega) = \frac{p(z_2,\omega)\cdot e^{+ikz_1} - p(z_1,\omega)\cdot e^{+ikz_2}}{2i\cdot \sin[k\Delta]} \quad (2)$$

$$P_{refl}(\omega) = -\frac{p(z_2,\omega)\cdot e^{-ikz_1} - p(z_1,\omega)\cdot e^{-ikz_2}}{2i\cdot \sin[k\Delta]} \quad (3)$$

with $\Delta=z_1-z_2$ the microphone spacing.

The incident sound power in a duct, $W_{inc}(\omega)$, is defined as:

$$W_{inc}(\omega) = \frac{P_{inc}(\omega)\cdot P^{*}_{inc}(\omega)}{2\rho c}\cdot S \quad (4)$$

with ρ the density of air and S the duct cross section. The * symbol denotes a complex conjugate. The total incident sound power is obtained by summation of the $W_{inc}(\omega)$ data of the 12 ducts.

The sound power, that is reflected by the panel, can be determined in a similar fashion.

The sound power, transmitted by the test panel, is the product of the average sound intensity across the measurement surface and its area. The sound intensity is determined with the cross power spectrum method, using the following expression (see e.g. Ref. 6):

$$I(\omega) = \frac{E\left\{Im\{G_{AB}(\omega)\}\right\}}{\omega\,\rho\,\Delta_{int}} \quad (5)$$

$E\{Im\{G_{AB}(\omega)\}\}$ is the imaginary part of the "spatially averaged" crosspower of the two pressures measured with the sound intensity probe. Δ_{int} is the distance between the two microphones of the sound intensity probe.

Finally, when the incident and transmitted sound power are known, the transmission loss of the test panel can be determined:

$$TL(\omega) = 10 \cdot \log \left(\frac{W_{inc,tot}(\omega)}{W_{tr}(\omega)} \right) \qquad [dB] \qquad (6)$$

4 Frequency Limitations

The measurement method, described in the previous section, can only be used in a limited frequency band, which depends on the duct dimensions.

The high frequency limitation is caused by the propagation of the lowest higher cross mode in the ducts. As mentioned before, the cross section of the ducts, used for the plane wave array, is 0.5m * 0.4m. The cut-off frequency for the lowest higher mode is thus equal to 340 Hz (i.e. the frequency where the longest side of the duct cross section is equal to half a wavelength). In practice reliable measurements can be performed for frequencies up to 320 Hz.

There is also a low frequency limitation, which is caused by inaccuracies in the calculation process of the complex amplitude P_{inc} of the incident wave. For very low frequencies the denominator in equation 2 and 3 becomes small. As the amplitudes P_{inc} and P_{refl} remain finite, the numerators in these equations become small as well. This implies that, for low frequencies, the errors in P_{inc} and P_{refl} will become larger than the errors in the measured pressures, p_1 and p_2. This is due to loss of significant digits, i.e. both terms in the numerator are much larger than their difference. Calculations and test measurements have shown that for a microphone spacing Δ of 0.30 m this effect becomes significant at frequencies below 80 Hz.

5 Potential Measurement Errors

In addition to the frequency limitations, there are some other potential sources of measurement errors - connected with the set-up - in the determination of incident and transmitted power, W_{inc} and W_{tr}.

The incident sound power W_{inc} is assumed to be independent of the axial (z-) coordinate along the duct axis. In a duct, the dissipation of energy between the microphones and the sound transmission through the duct walls (5 mm steel) are certainly negligible compared to the incident power. A more important potential error source is the slit between panel and ducts in case of a panel with free free boundary conditions.
An upper bound for the relative error $\Delta W/W_{inc}$ in the incident power can be found by

considering the energy balance between incident, reflected and transmitted sound power:

$$\frac{\Delta W(\omega)}{W_{inc,tot}(\omega)} = 1 - \frac{W_{refl,tot}(\omega)}{W_{inc,tot}(\omega)} - \frac{W_{tr}(\omega)}{W_{inc,tot}(\omega)} \qquad (7)$$

In this equation the energy dissipated by the test panel is assumed to be negligible. In the next section some measured data will be presented.

A potential error in the sound power transmitted by the panel is caused by flanking sound transmission. The sound, transmitted through the slit and through the walls of the duct array, and reflected partially by the walls of the semi-anechoic room, enters the measurement enclosure at the top and interferes with the sound transmitted by the test panel.
For sound pressure measurements or intensity measurements on isolated grid points this error will be significant. The transmitted sound power W_{tr}, however, is determined from the average intensity over a (closed) measurement surface. The error in W_{tr} due to flanking transmission may therefore - in theory - be neglected, assuming that the flanking sound is reflected back into the room again by the test panel. In practice, the error may become important, because of limitations in the intensity measurement equipment (small) sound absorption by the test panel and sound transmission through the slit between panel and measurement enclosure. This will happen in particular, when the ratio between transmitted power and the sound power related to the flanking sound transmission becomes smaller, i.e. when structures with a high sound insulation are tested. To get an indication of the error caused by flanking transmission diagnostic measurements were carried out. The results of these measurements will be presented in the next section.
In order to minimize the acoustic power transmitted through the duct walls and thus the flanking transmission, the duct walls were constructed from 5 mm thick steel plates. Flanking transmission was further reduced by a sound insulating enclosure around the array of ducts and by increasing the slit depth between panel and ducts from 5 to 50 mm (see next section).

Sound, entering the measurement enclosure from the bottom, i.e. through the slit between measurement enclosure and test panel, is assumed to be negligible. This concerns in particular the sound, transmitted through the slit between ducts and test panel and radiated into the semi-anechoic room. From geometrical considerations it follows that only a small portion of this sound will be transmitted into the measurement enclosure through the slit between test panel and measurement enclosure.

A third potential cause for errors in determining transmitted power are the reflection of the sound waves - radiated by the panel - at the edge of the measurement enclosure and the reflection by the ceiling of the room. The same considerations apply here as for the error caused by flanking sound transmission, i.e. the error in the transmitted power W_{tr} will be small, if the reflections

are not too strong.
The reflection coefficient of an infinite unflanged duct is less than 0.5 for wavelengths less than about 2 duct diameters, see reference 7. Assuming that this also applies for the measurement enclosure (which has a cross sectional area of 2.4 m^2) a reflection coefficient of 0.5 corresponds with a frequency of about 100 Hz. The reflection coefficient of the ceiling, which is lined with 0.5 m foam wedges, is in the order of 0.5 at 100 Hz. This results in a joint reflection of approximately half the transmitted power. Based on earlier experience, see (Ref. 8), it is anticipated that in these conditions a reliable determination of transmitted sound power using sound intensity measurements is still possible.

6 Experimental Verifications

During test measurements several issues were investigated, such as the amplitude and phase accuracy of the incident wave, the energy balance, flanking transmission and maximum transmission loss. Some results of the test measurements are presented in the following sub sections.

6.1 Amplitude and phase accuracy

Figure 3 shows a typical amplitude and phase spectrum of the ratio between the measured and the desired value of the complex amplitude P_{inc} of the incident sound wave, for one of the ducts. This figure illustrates that the deviations from the plane wave can be kept well within ±0.5 dB and ±5°.

6.2 Energy Balance

The overall energy balance according to equation (7) between incident, reflected and transmitted sound power was studied, and also the incident and reflected sound power per duct.

Figure 4 shows the energy balance for a transmission loss measurement on a single, stiffened test panel: the reflected and transmitted fractions of the total incident acoustic power are plotted ($W_{refl}(\omega)/W_{inc}(\omega)$ and $W_{tr}(\omega)/W_{inc}(\omega)$ respectively, see figure 2). The sum of the reflected and transmitted fractions is between 80 % and 90 %. The remaining part of the incident power is transmitted through the slit between the test panel and the ducts, dissipated by the test panel (damping) and transmitted through the duct walls. When the remaining 10 to 20 % fraction is considered as an error in $W_{inc}(\omega)$ - a conservative estimate - this fraction corresponds with an error of 0.5 to 1 dB.

If the ducts are considered separately, it appears that in some ducts the reflected power is larger than the incident power at certain frequencies, which if illustrated by figure 5. These large

reflections are compensated for by smaller reflections in other ducts, so that the overall reflected fraction of the incident power always remains smaller than one. The cause of this behaviour is that, because there are panel modes, some parts of the panel vibrate more strongly than other parts and thus reflect more.
This behaviour of the panel can be seen as a sound power transfer, via the panel between the ducts. This power transfer makes it more difficult to generate an overall plane incident wave: changing the input signal of a loudspeaker in one duct leads to different values of the incident sound power in each duct. Therefore, a special feed back algorithm was developed for the source signals fed to the loudspeakers.

6.3 Flanking Transmission

In order to reduce the sound transmission through the slit between the ducts and the test panel, the depth of the slits (i.e. the slit dimension perpendicular to the duct walls) at the outer edge of the duct array has been increased from 5 to 50 mm. This has been done by attaching a metal strip with a width of 50 mm to the outer edges. Test measurements showed that the modal damping (and thus also the transmission loss) of the test panel was hardly affected by these strips. Replacing W_{tr} in equation (6) by W_{slit} (which is the measured sound power radiated by the slit into the measuring room) the transmission loss of the slit can be determined. In figure 6 the transmission loss of the slit is plotted as a function of frequency before and after the increase of the slit depth. From this figure it appears that the transmission loss of the slit increases by, typically, 5 to 10 dB as a consequence of the increased slit depth. Finite element calculations with SYSNOISE showed an increase of 15 dB, see figure 6. From this figure it appears further that the calculated and measured transmission loss agree well for the 5 mm slit. For the 50 mm slit however the measured transmission loss is generally 5 to 10 dB smaller than the calculated value. This is probably caused by a larger slit width in practice (locally) than the value of 1 mm, which has been assumed in the calculations.

6.4 Maximum Transmission Loss

The maximum measurable transmission loss was determined with measurements on configurations with a high sound insulation. This maximum is governed by the amount of flanking transmission and the limitations of the intensity measurement equipment, i.e. the phase mismatch between the microphones of the intensity probe.

In figure 7 the transmission loss and the phase difference measured with the intensity probe (determined from the averaged cross power over the measuring surface), of the following three configurations has been plotted:

1. A 6 mm thick "lead rubber" sheet, with a mass of 15 kg/m^2.
2. Two sheets of "lead rubber", with 5 cm sound absorbing foam in between.
3. Two "lead rubber" sheets with 10 cm foam in between.

The sheets of "lead rubber" were laid down on top of the ducts, so that there was no slit between the sheet and the ducts. In figure 7A the transmission loss of the three configurations is plotted. The curve for configuration 3 shows a number of oscillations, which are an indication of possible errors in the intensity measurement. From the phase difference as plotted in figure 7B, it appears indeed that the intensity measurement for configuration 3 is unreliable: for some frequencies negative phase differences have been measured, which are an indication for a reverse direction of the power flow, i.e. towards the test panel. Small phase differences can cause an error, when they are not large enough compared to the phase mismatch of the microphones: at frequencies below 250 Hz the phase mismatch is typically 0.05° and a measured phase difference of 0.5° will give an error of 0.5 dB (see e.g. Ref. 6).
From the measured phase difference for configuration 2 it appears that the intensity measurement for this configuration is still reliable for all frequencies between 80 and 320 Hz. For configurations with a relatively low transmission loss, such as configuration 1, the measured phase differences approximate the value for a plane wave, which is also plotted in figure 6B.

For test configurations *without* a slit the maximum measurable transmission loss has thus a value of at least the transmission loss of configuration 2 (see figure 7A). Measurements on configurations *with* a slit (depth 50 mm) showed a maximum measurable transmission loss which is about 5 dB smaller, in particular for frequencies larger than 200 Hz. In figure 8 the maximum measured transmission loss for both configurations has been plotted as a function of frequency. It is obvious that, for frequencies below 150 Hz, the maximum measurable transmission loss for configurations without slit is also determined by the the upper curve in figure 8.

7 Specifications

The most important characteristics of the NLR plane wave synthesis facility are summarized here:

- A 3x4 array of ducts with 12 independently driven loudspeakers, that create a plane wave or can simulate other sound fields.
- Two microphones in each duct to measure the complex amplitude of the incident and reflected wave (24 microphones in total).
- Amplitude and phase of incident sound wave in all ducts constant within ± 0.5 dB and $\pm 5^o$ respectively.
- Excitation: pure tone or random periodic noise in 80-320 Hz frequency band.
- Maximum SPL in the ducts over the 80-320 Hz frequency band: 120 dB.
- Sound intensity probe mounted on a low noise scanning robot for the measurement of the transmitted power.
- Test panels: ○ size: 2.00 x 1.20 m^2

  - curved in one direction
  - free-free boundary conditions (panels hang in springs)
  - single panels
  - double panels, with or without sound insulation material in the cavity
- maximum transmission loss:
  - no slit: ≥ 30 dB (100 Hz) to ≈55 dB (300 Hz)
  - with slit: ≥ 30 dB (100 Hz) to ≈45 dB (300 Hz)

8 Final Remarks

In this paper a description has been given of the NLR plane wave synthesis facility for experimental research on sound transmission through curved, single or double panels with free-free boundary conditions.
The present facility excites panels with a plane wave; other sound fields can easily be simulated.
The set-up has been succesfully used in experimental research and in the validation of theoretical (finite element) models.

9 Acknowledgement

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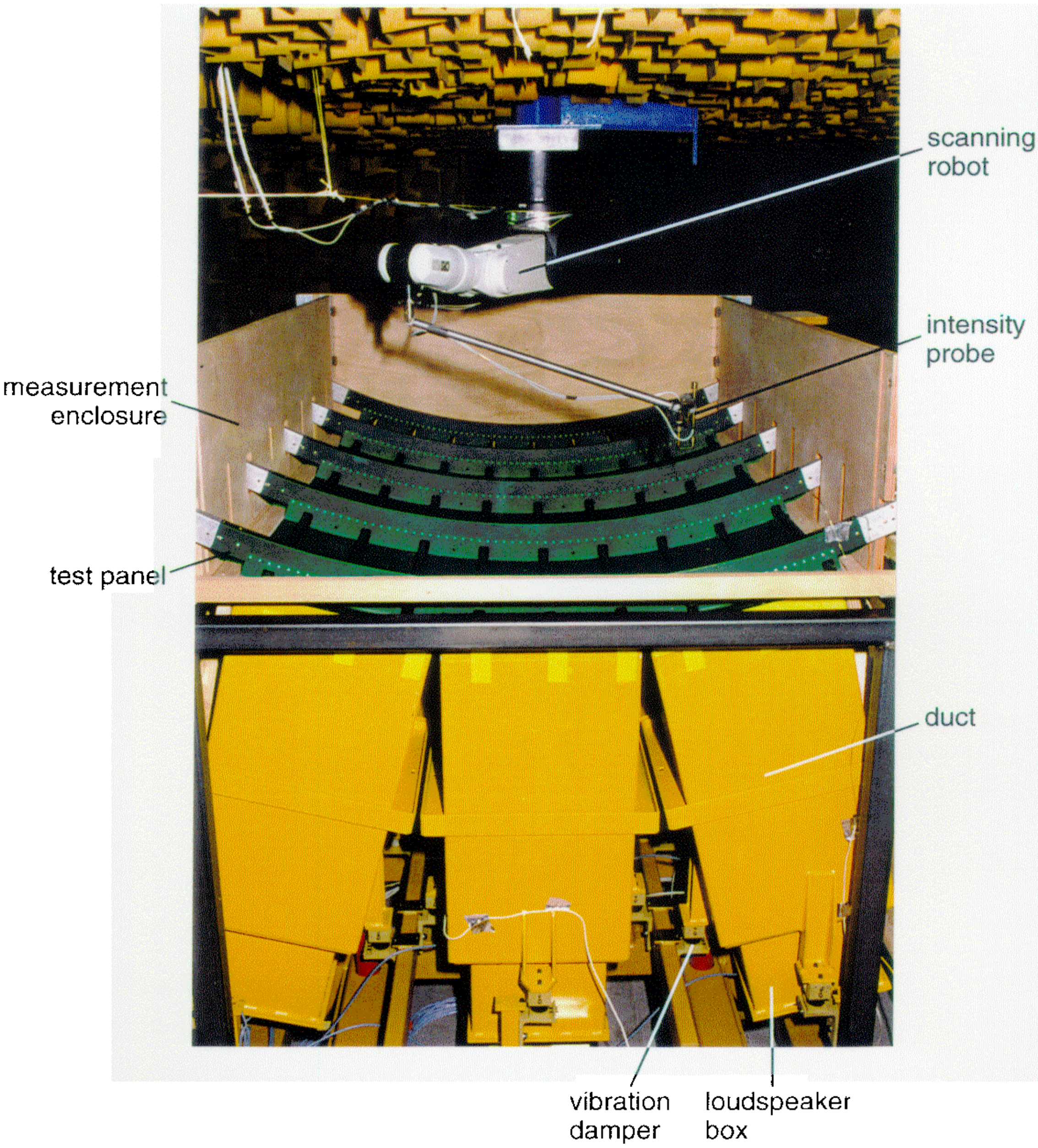

Fig. 1 The experimental setup

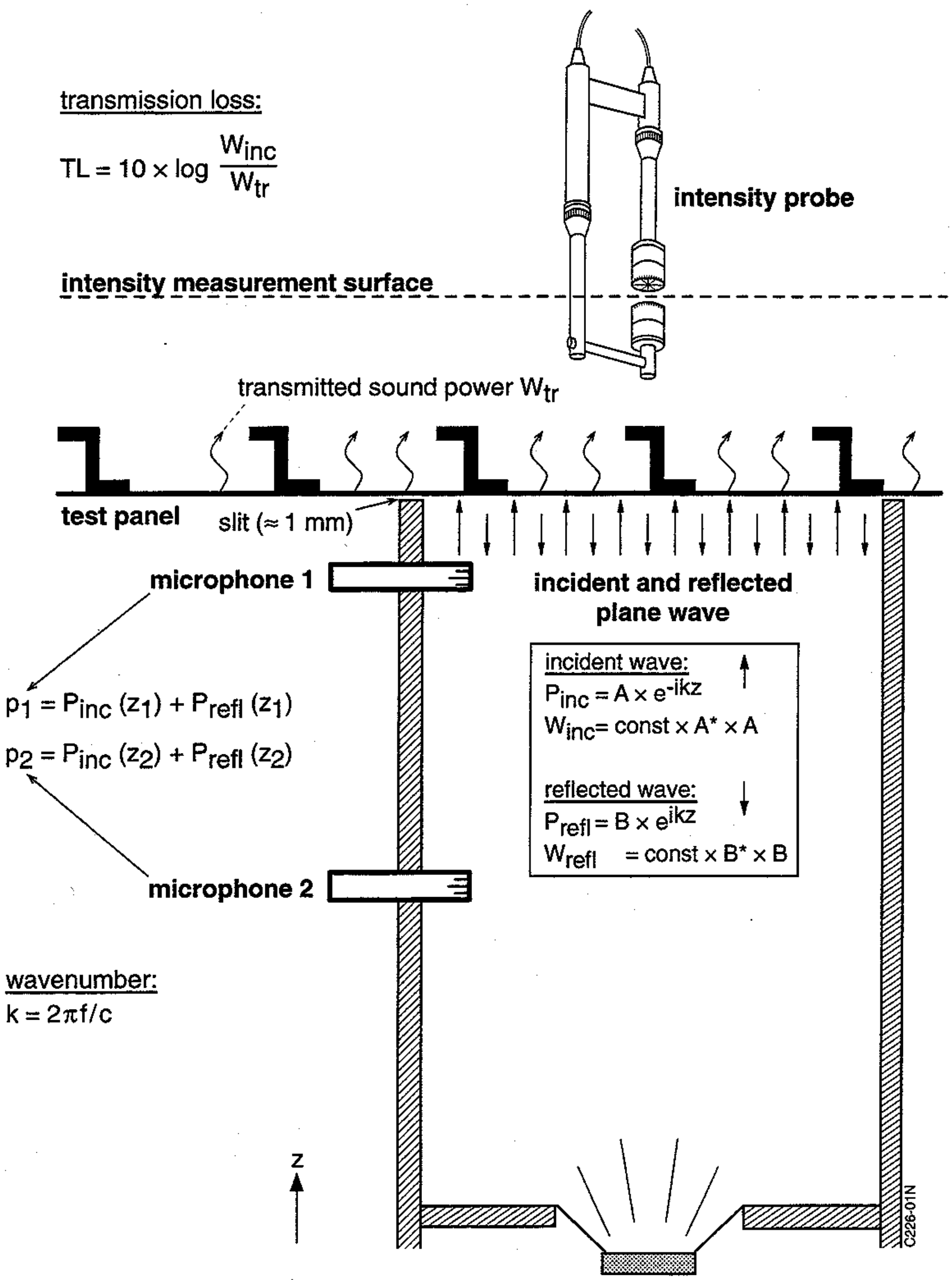

Fig. 2 Principle of the measuring method

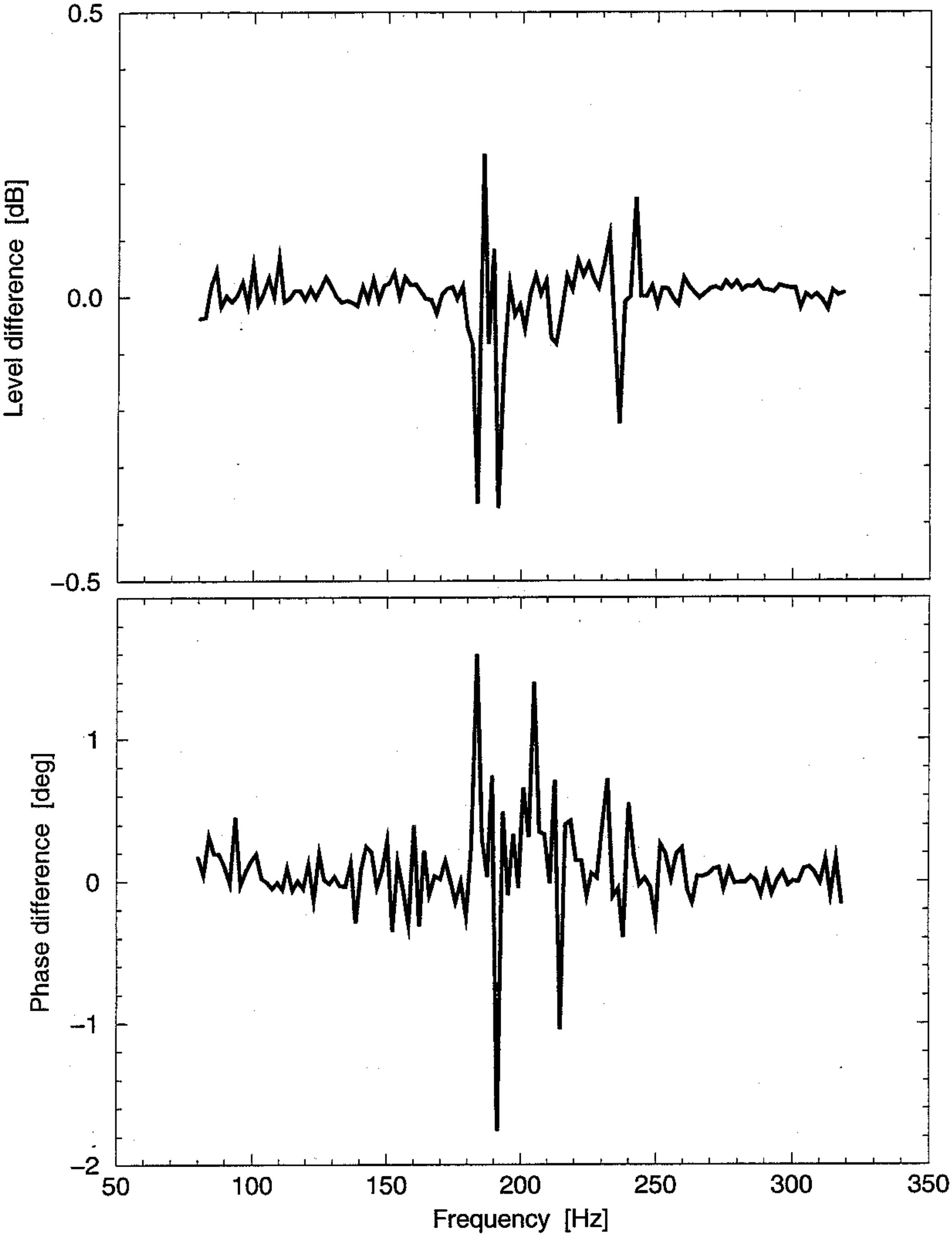

Fig. 3 Typical data for the ratio of the measured and the desired complex amplitude of the incident wave in one of the ducts

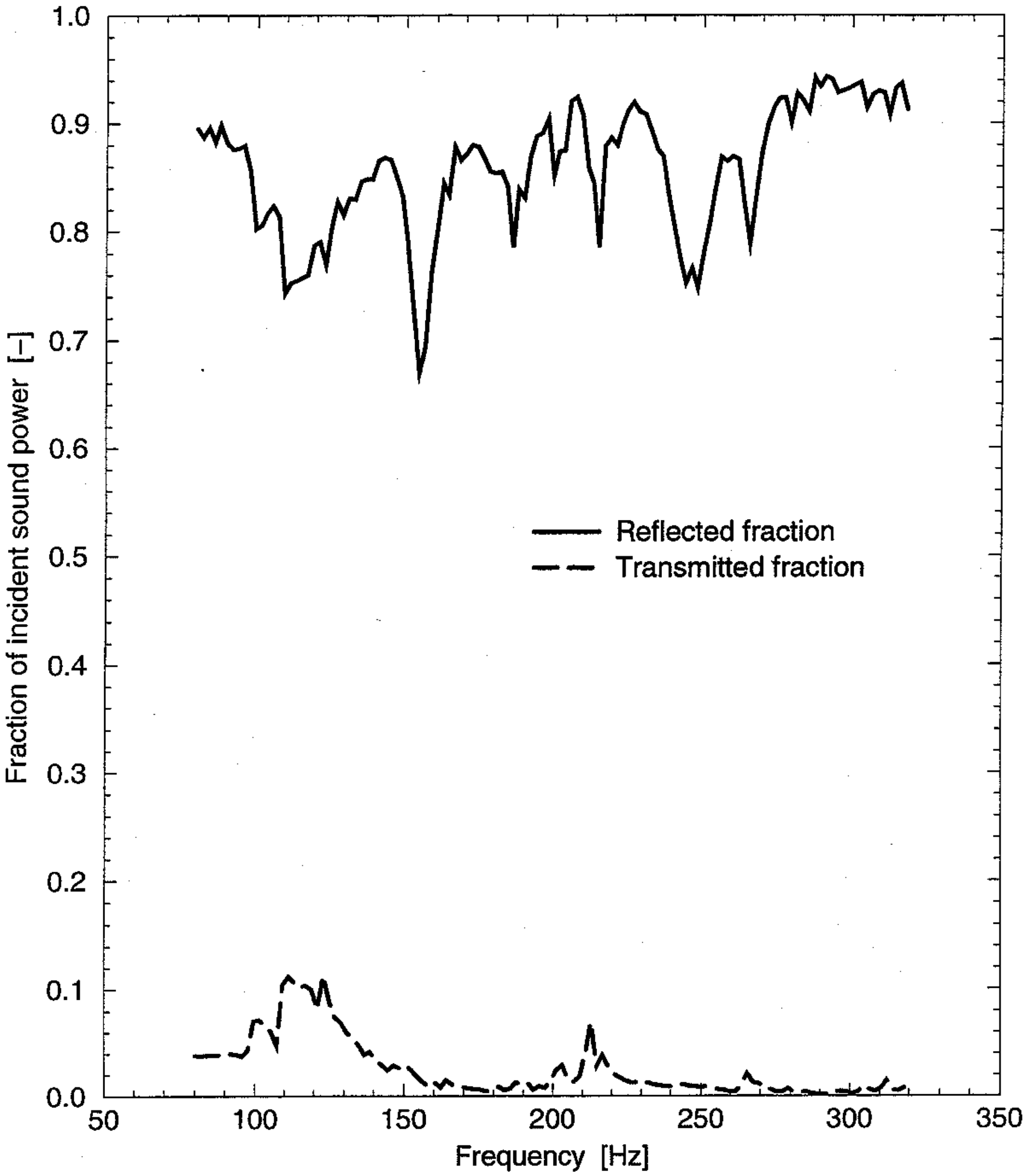

Fig. 4 Energy balance for a transmission loss measurement

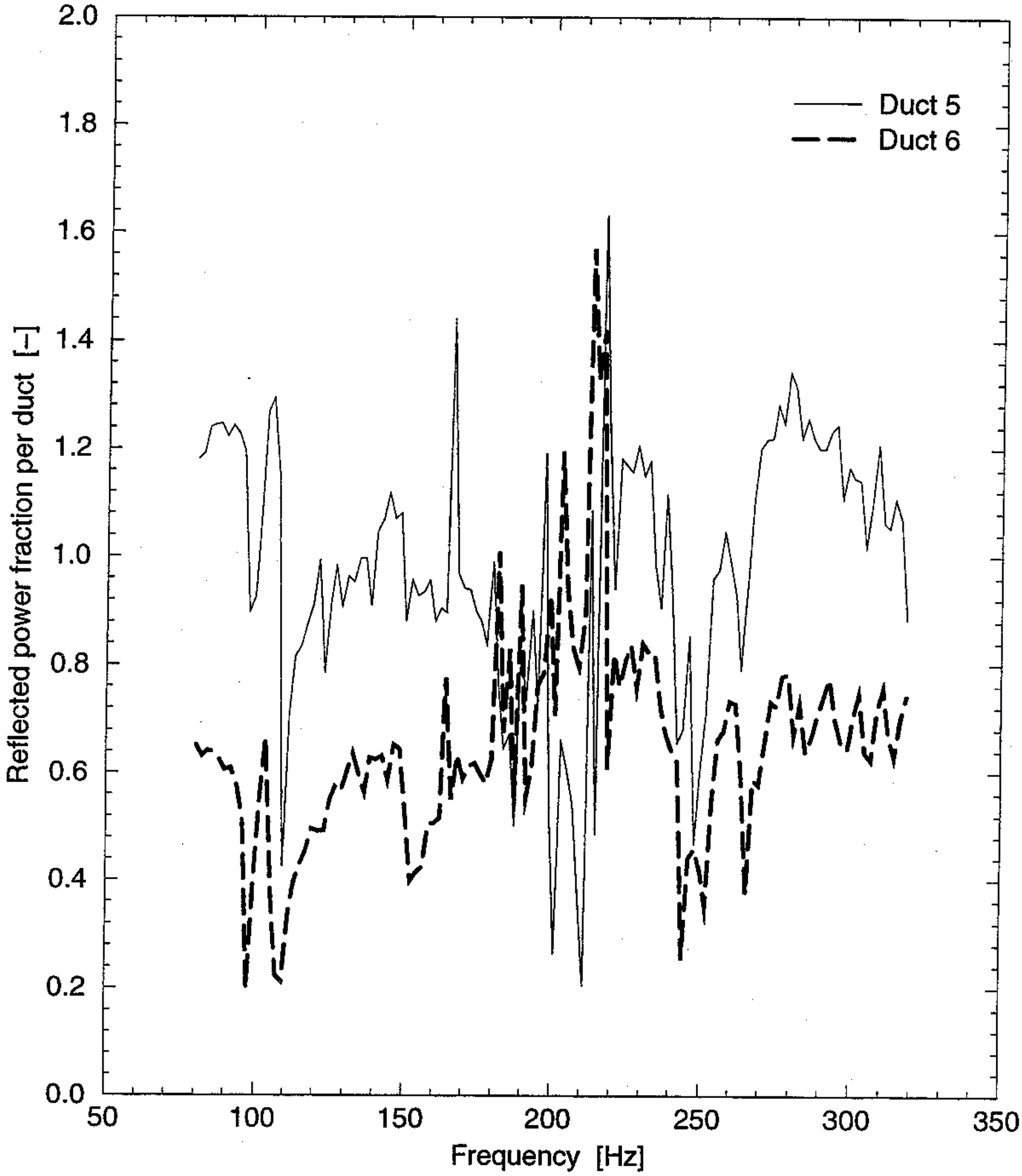

Fig. 5 Reflected fraction of the incident acoustic power for two ducts

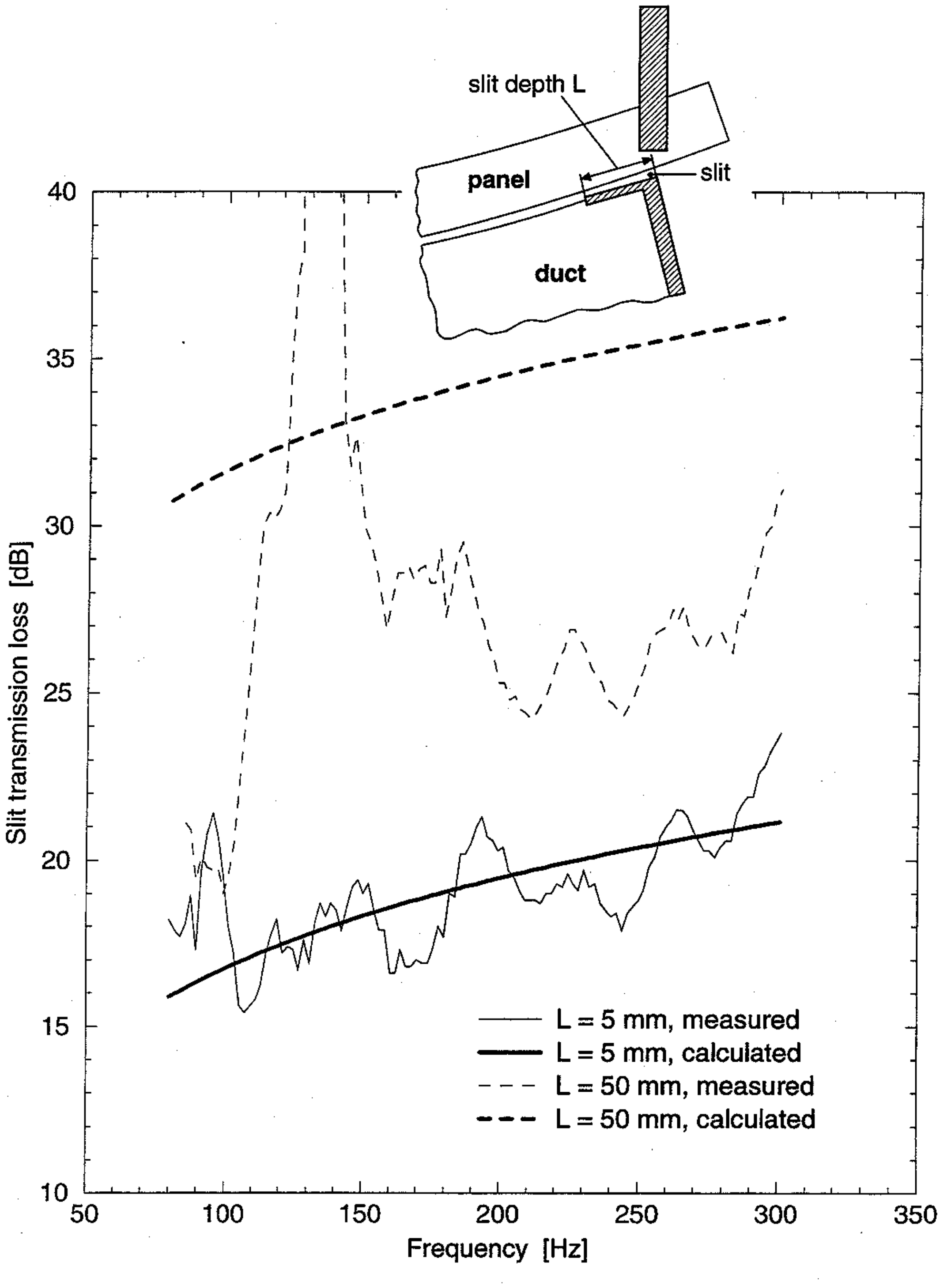

Fig. 6 Experimental and calculated slit transmission loss data for two different values of the slit depth L

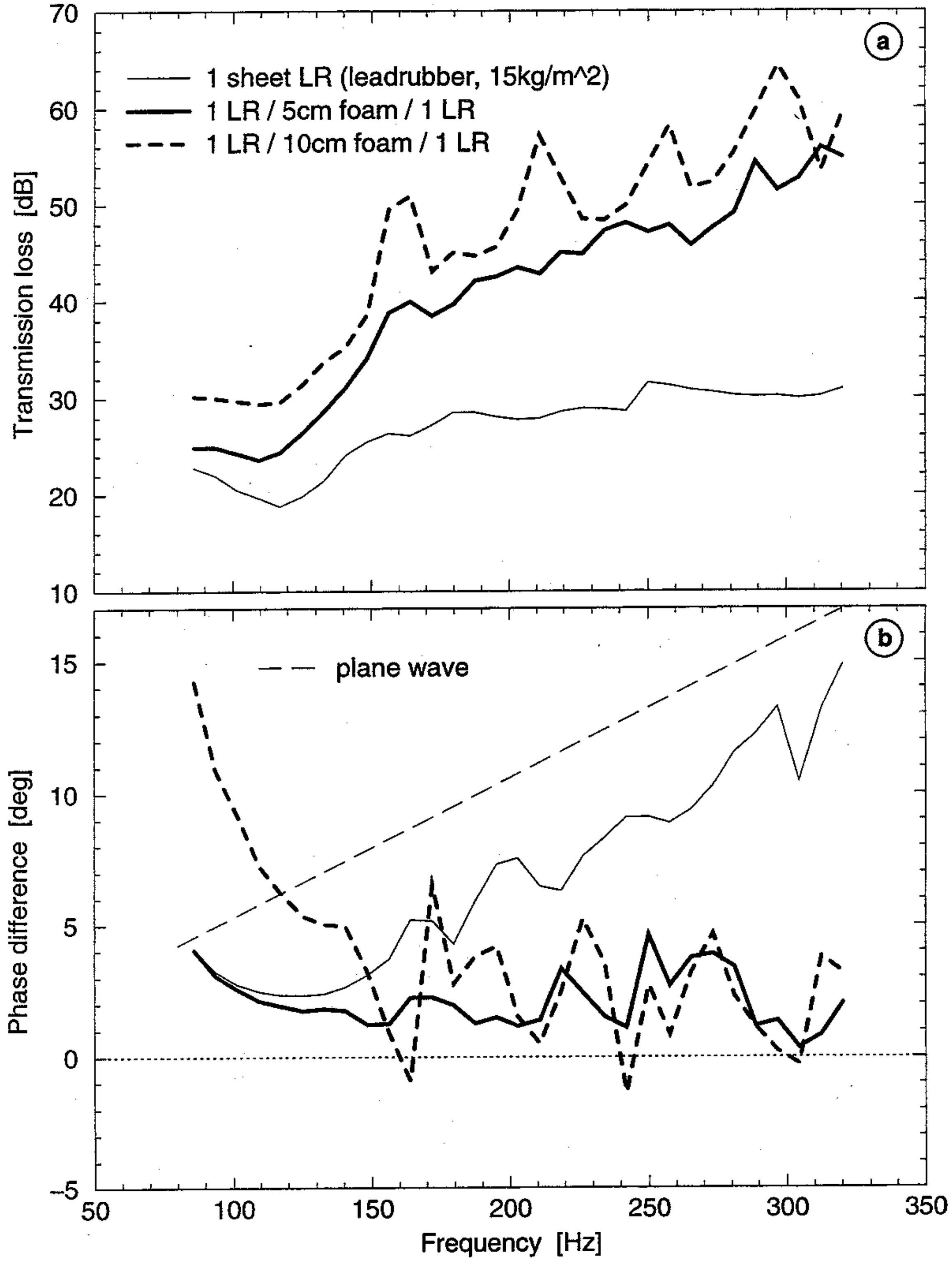

Fig. 7 Transmission loss and phase difference between the intensity probe microphones for some test measurements

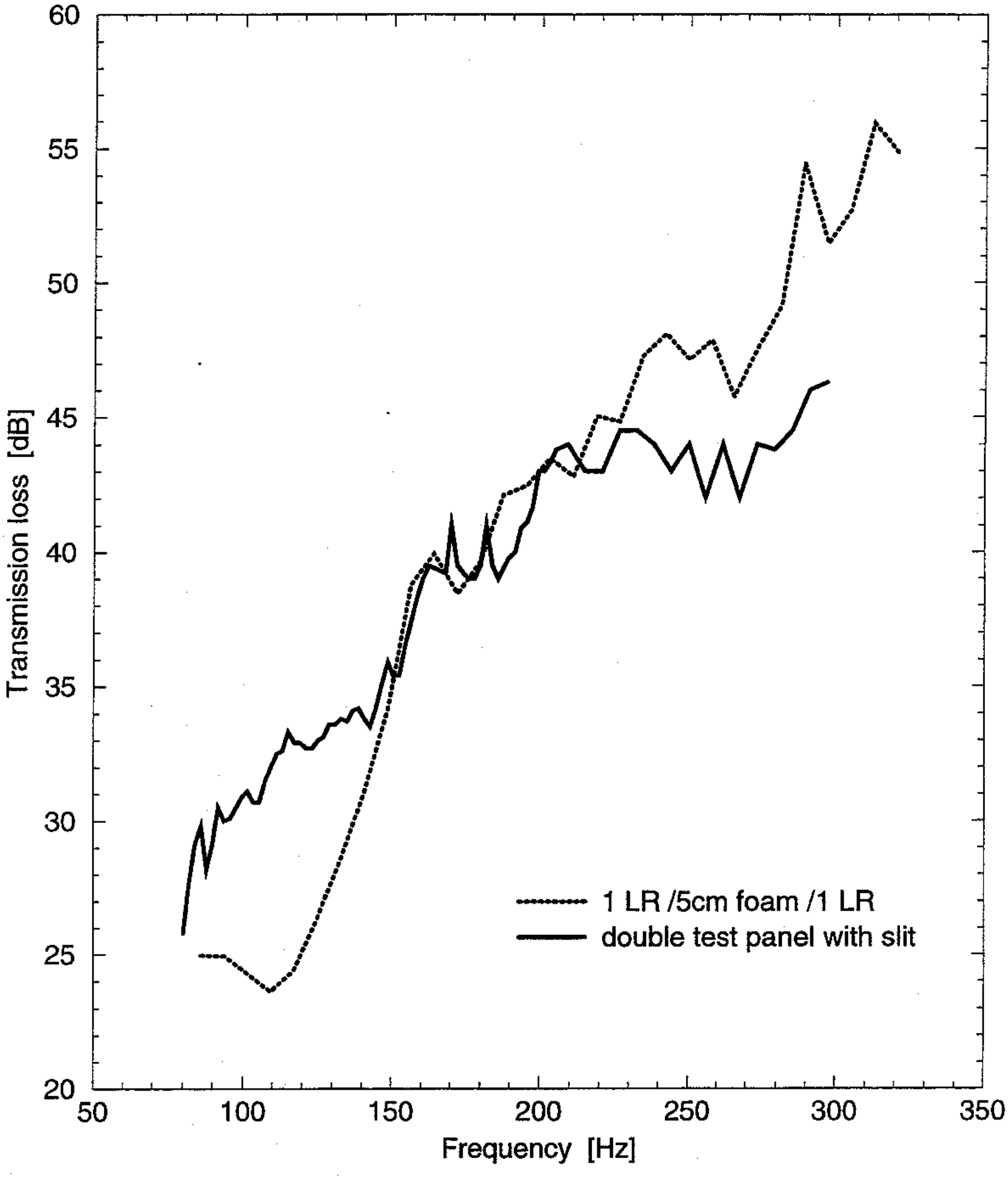

Fig. 8 Transmission loss data of test structures with a high sound insulation, with and without a slit