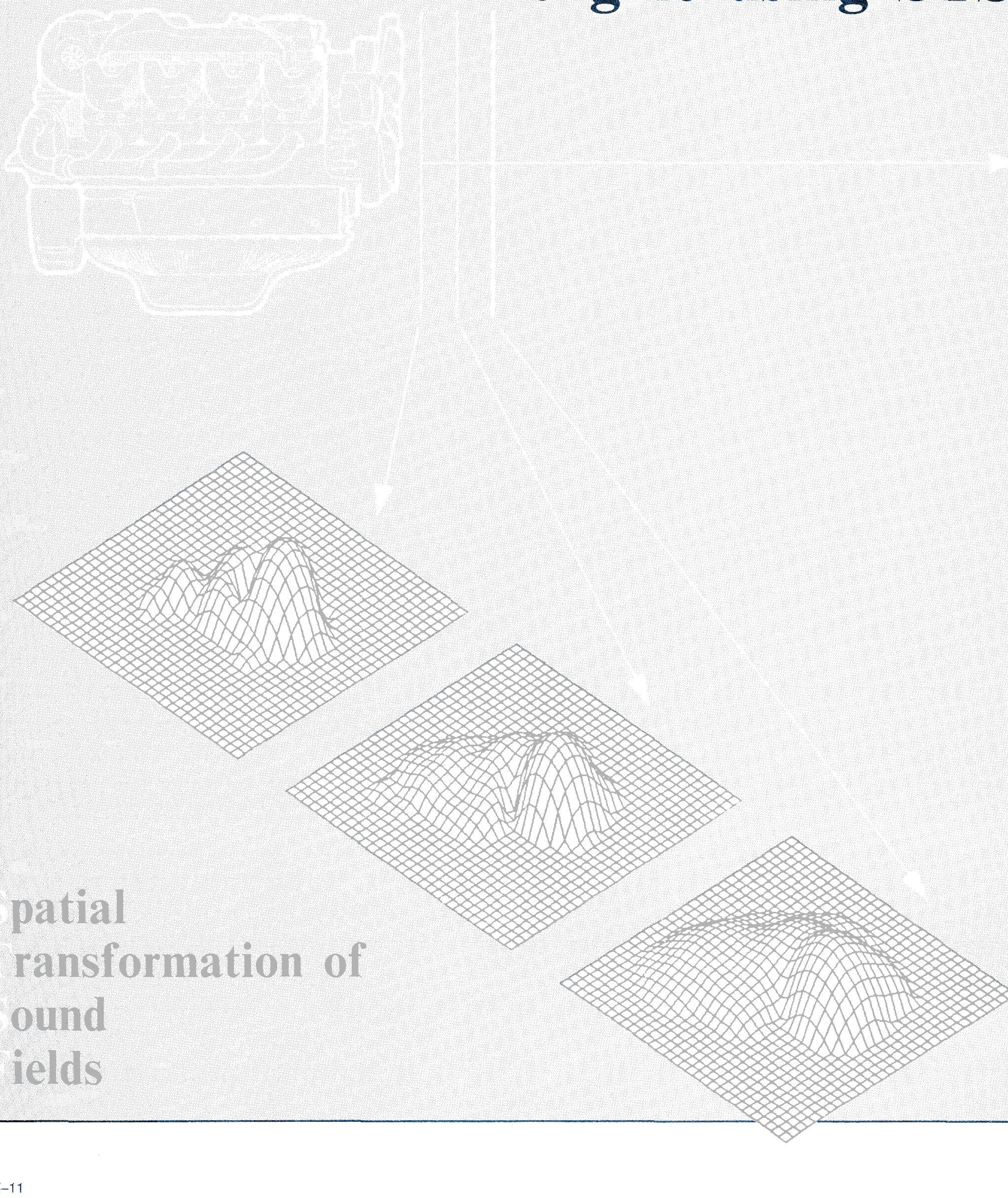
Brüel & Kjær application notes

Acoustical testing of a diesel engine using STSF



Spatial
Transformation of
Sound
Fields

BO 0185–11

Acoustical testing of a diesel engine using STSF

by
Urban Willows, SAAB-SCANIA
J. Hald & K.B. Ginn,
Brüel & Kjær, A/S

Introduction

Research and development engineers invest considerable time and effort in performing tests on vehicles and engines in outdoor proving grounds in order to determine acoustical radiation patterns. As such tests are subject to the vagaries of the weather, the engineers would ideally like to make measurements close to the test object indoors in a test cell and then calculate quantities such as the sound pressure level at some reference distance. Few test cells are big enough to permit a direct measurement at the usual reference distance of 7,5 m.

Engineers investigating means of noise reduction on engines would also like to know where the main sources of noise are and what the effect on the sound field would be if part of the engine were damped. Spatial Transformation of Sound Fields (STSF) has been developed in cooperation with motorcar manufacturers to deal with these very problems.

What is STSF?

Spatial Transformation of Sound Fields is a term introduced by B & K to denote a powerful measurement and calculation technique. In the most general sense STSF involves making acoustical measurements near to a noise source and then transforming this sound field data to any other position, both closer to and further away from the noise source under test.

For calculating the acoustic field further from the source than the measurement surface, the Helmholtz' Integral Equation is employed. For calculating the acoustic field closer to the source than the measurement surface, a technique known as Near-field Acoustical Holography (NAH) is used.

A practical STSF system

B & K can offer a complete STSF system based on a 1/3 octave intensity analyser Type 2134/WH 1493 which is capable of measuring cross spectra [1]. A dedicated Application Package BZ 7007 used with the Graphic Printer 2313 controls the measurement, performs calculations by means of Helmholtz Integral Equation and transfers the measured data to a computer where the Extensive STSF program enables Near-field Acoustical Holography and simulated source attenuation to be performed. The Extensive STSF program is available for VAX and for HP 1000 computers. A resumé of the main specifications of the STSF system is given in Table 1.

General	Frequency range	10 Hz to 5 kHz
	Array dimensions	Flexible
	For measurement on large sources	Simply extend scan area
	Microphones	High quality condenser microphones
	Phase mismatch in microphones	Little influence because finite difference approximations to the particle velocity is avoided and minimized by use of high quality microphones and by spatial filtering
BZ 7007	Data recording	Digital cassette recorder
	Radiation pattern	Near-field and far-field
	Active intensity	
	Reactive intensity	
	Sound power	
Extensive STSF Program	Near-field investigation	Near-field acoustical holography: intensity, particle velocity, pressure
	Resolution limitation	Distance between microphones
	Simulation of source attenuation	

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Table. 1. Resumé of main specifications of STSF system

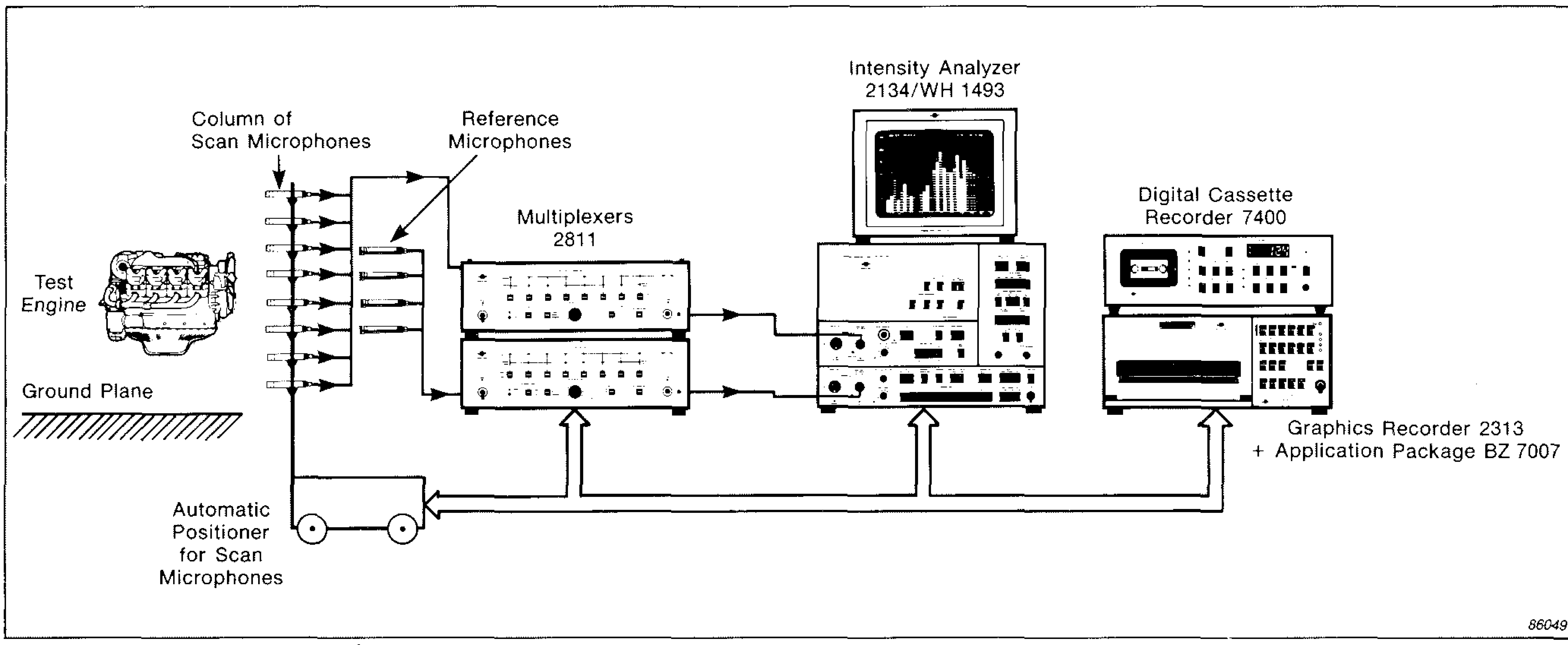

Fig. 1. Instrumentation for STSF

A typical STSF system is shown in Fig. 1. It consists basically of three parts: the microphones, the analyser and the controller/data storage/post-processing. A full description of the system is given in the Product Data Sheet for BZ 7007, together with a brief outline of the theory behind the technique [1].

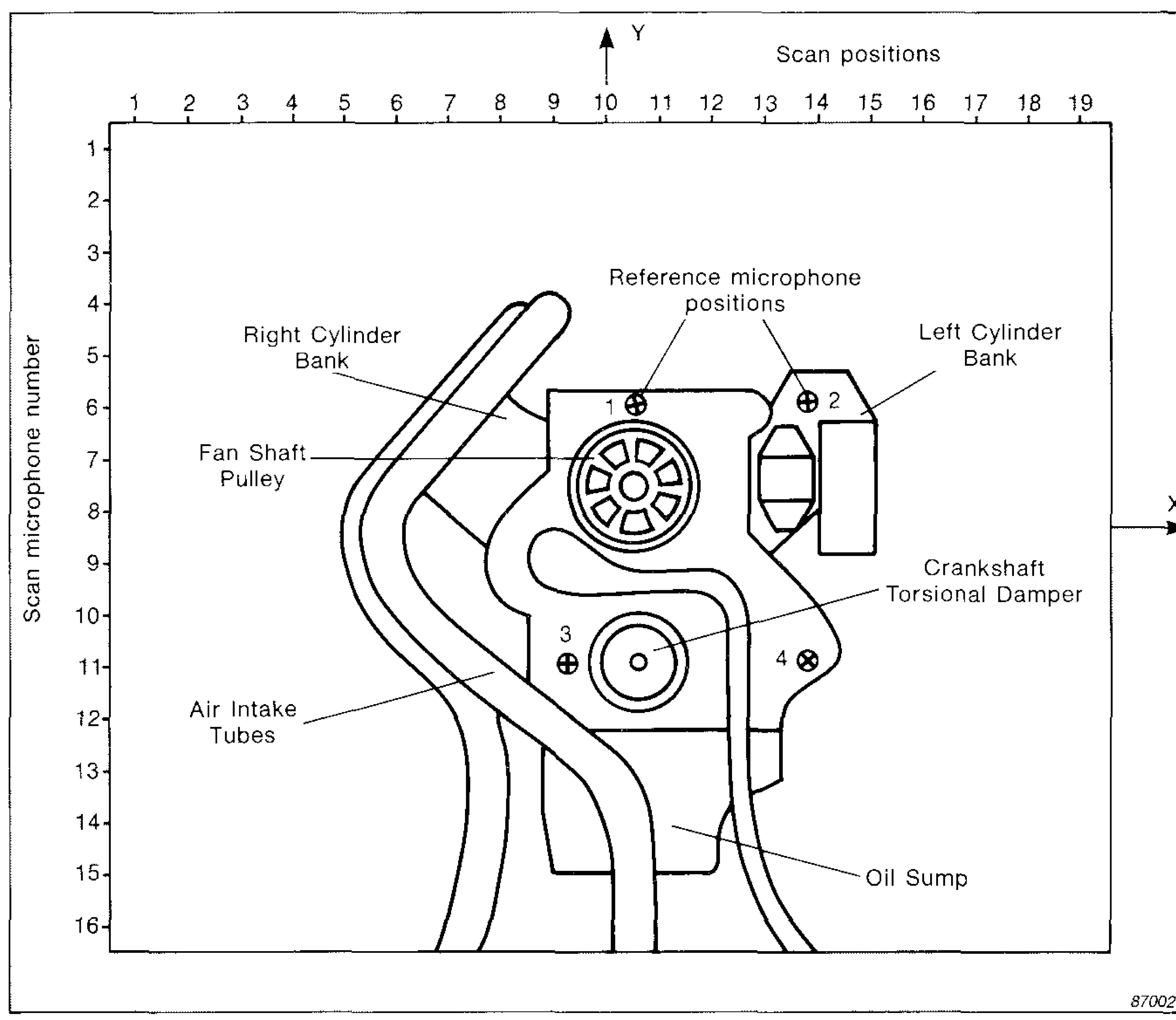

Fig. 2. Position of the 4 reference microphones the measurement positions and the outline of the 8 cylinder diesel supercharge 14 litre engine seen in the xy plane

Measurements in a diesel engine test cell

To demonstrate how the system performs in practice, B & K were invited to the SAAB-SCANIA engine laboratory in Södertälje, near Stockholm in Sweden. Measurements were performed in a semianechoic test cell on an 8 cylinder diesel supercharge 14 litre engine, with the engine running at 1000 rpm under a constant load. For the measurements 4 reference microphones, 16 scan microphones and 19 scan positions were used. This number of transducers required 3 multiplexers. The positions of the 4 reference microphones, and the measurement positions are shown in Fig. 2. Multiple traverses on the scan area are also allowed if fewer scan microphones are available.

The total measurement time including calibration of the microphones was 1½ hours. If an automatic positioner had been available then the scan could have been performed entirely under the control of the BZ 7007 which would have made the measurements somewhat faster. Several automatic postioners are commercially available.

Definition of the measurement

The measurement conditions are precisely described by a number of measurement parameters in one of the 3 set-ups available in the Application Package BZ 7007. This measurement set-up is then stored on the Digital Cassette Recorder as documentation for the measured data (Fig. 3) together with a measurement number and an identifying text.

A complete measurement consists of a reference measurement and a scan. The reference measurement is a measurement of cross spectra between each reference microphone and every other reference microphone, whereas the scan consists of measuring cross spectra from each scan microphone position to each of the references in turn and of measuring the autospectrum (i.e. pressure) in each scan microphone position. The source must be kept stationary during the measurement procedure in order to obtain a good model of the sound field.

Validity of data

Before performing any calculations, the validity of the data should be checked by comparing the measured sound pressure level to the represented sound pressure level at a suitably selected set of array microphone positions. The represented sound pressure level is calculated from the measured cross spectra. An example taken from the diesel engine measurement is given in Fig.4. There will always be some discrepancies between the measured and calculated spectra at the scan microphone positions. In general at low frequency this deviation will be mainly due to too short an averaging time, and the high frequency deviation will be mainly due to an insufficient number of references or to a poor positioning of the references. The deviation will be smallest in regions close to the references.

MEASUREMENT SET-UP FROM TAPE:

Measurement number	1
Date 1986-04-28 Time 16:25:03	
Personal text 0	
Personal text 1	
Pressure gradient probe	NO
Mic. spacing in probe	0.0200 m
Number of ref. mic.	4
Number of array probes	16
Number of traverses	1
Positions per traverse	19
Spacing in x-direction	0.1000 m
Spacing in y-direction	0.1000 m
Ave. time in ref. meas.	2.00 sec.
Ave. time in cross meas.	0.50 sec.
Ave. time in pres. meas.	1.00 sec.
Lowest frequency	100 Hz
Highest frequency	1.6k Hz
Ground plane distance	0.9500 m
Scan plane tilt	0.0 degrees
Dist. to source centre	0.9000 m
2811 summation	NO
Mirror ground	NO
Background noise	NO
Temperature	20.0 Celcius
Relative humidity	50.0 %
Static pressure	101150.0 Pascal
TAPE NUMBER	1
FIRST SCAN FILE	1
LAST SCAN FILE	38
FILES PER SCAN POSITION	2

870025

Fig. 3. Measurement set-up as stored on Digital Cassette Recorder

For the rather large diesel engine measurement discussed here, the validation procedure shows that 4 references are sufficient at frequencies up to about 500 Hz, see Fig.4. To obtain good data at higher frequencies, a larger number of references would be necessary.

In practice the validation procedure should be carried through before a complete scan is made. This can be accomplished by initially taking measurements only in the set of array positions where the measured and the represented pressure levels are to be compared. By doing so, one avoids spending time taking complete measurements only to obtain bad data.

Good measurements may be obtained in environments with severe uncorrelated background noise by positioning the references very close to the source. By doing so the cross spectra and thus all STSF calculations will be unaffected by the background noise. Since, however, the measured autospectra (pressure) will be affected, the above validation procedure does not apply.

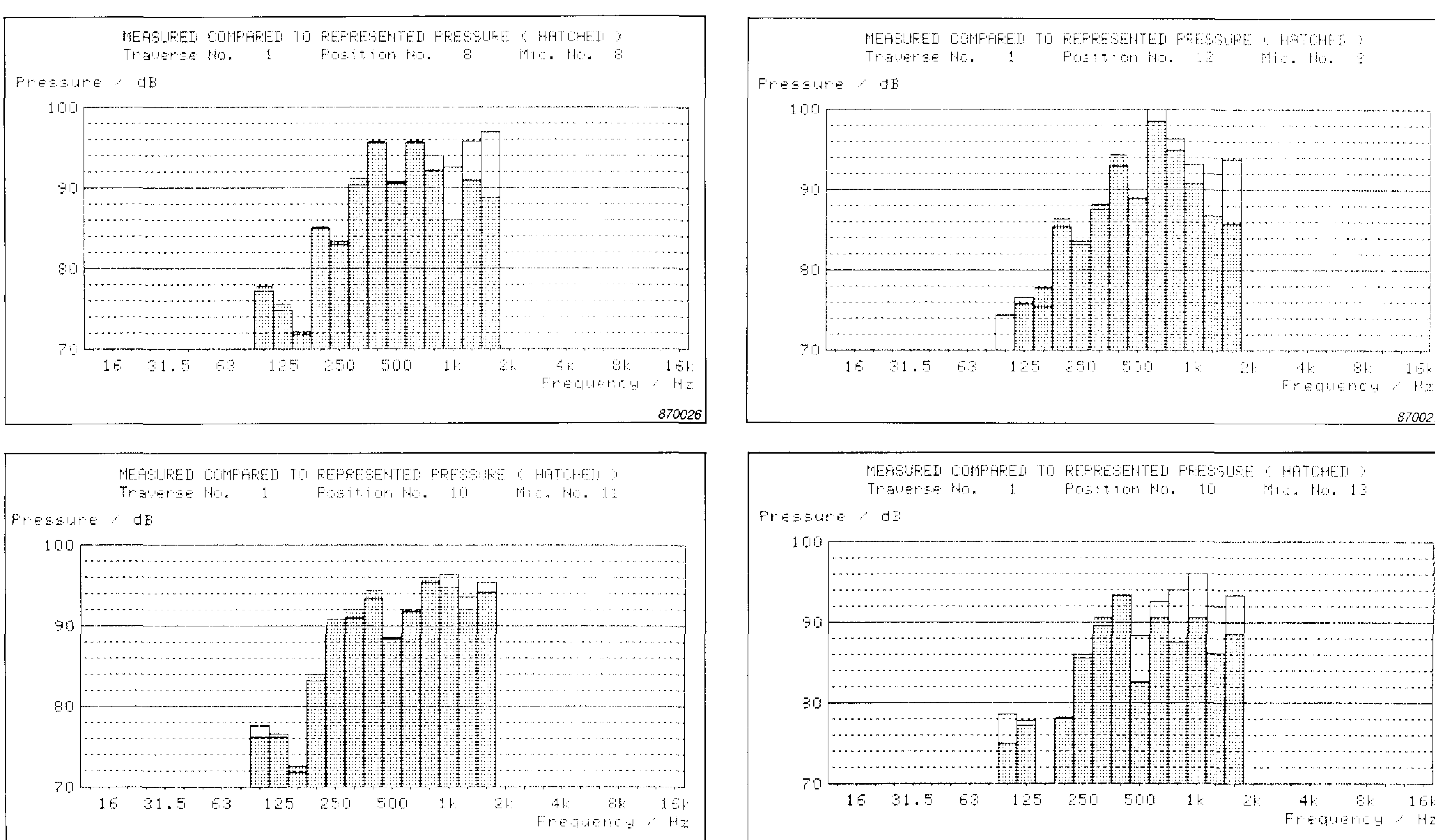

Fig. 4. Comparison of measured to represented sound pressure level at four different scan microphone positions. There is good agreement between measured and calculated values up to 500 Hz

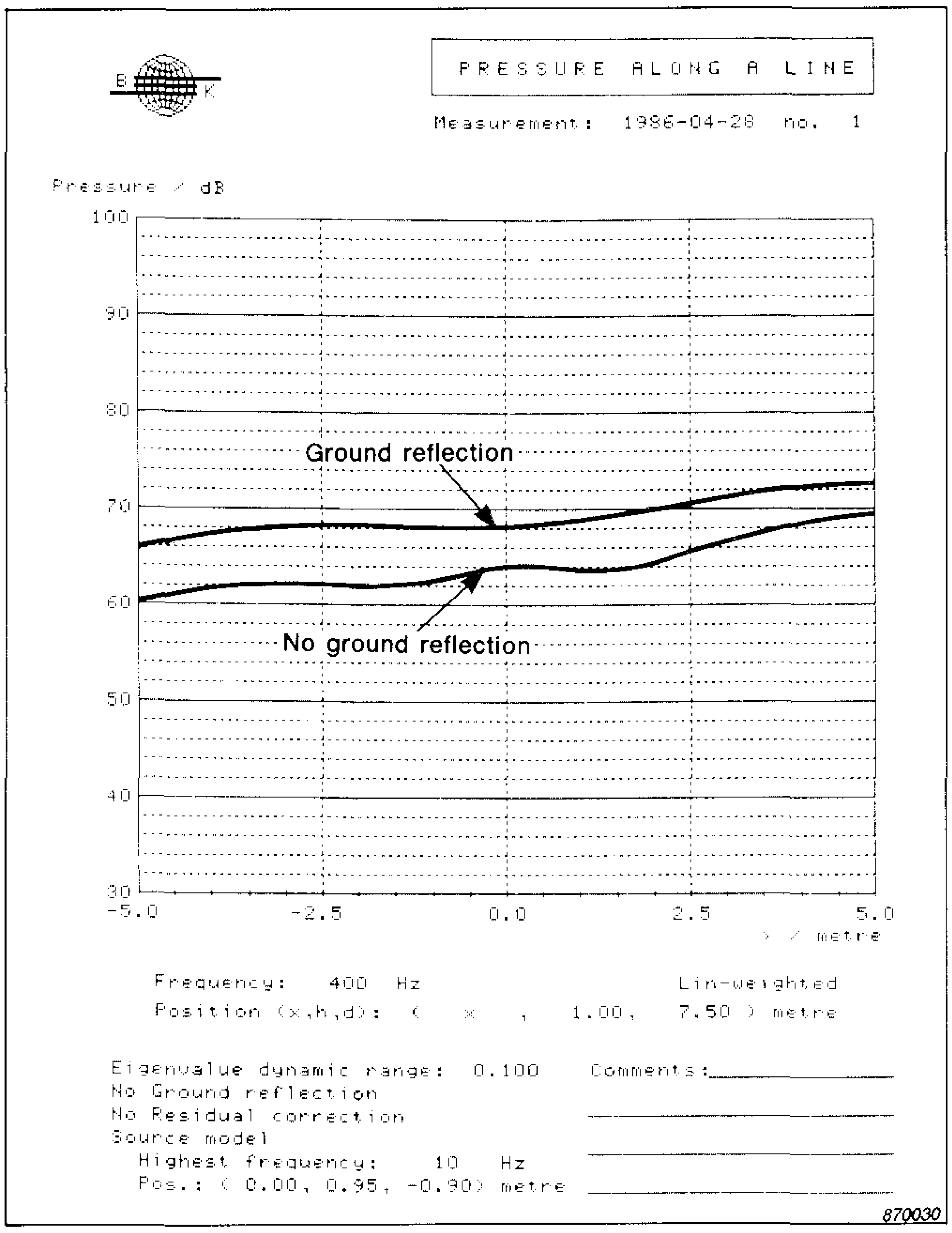

Fig. 5. Sound pressure level at 7,5 m distance with and without a reflecting ground plane for the 1/3-octave band at 400 Hz

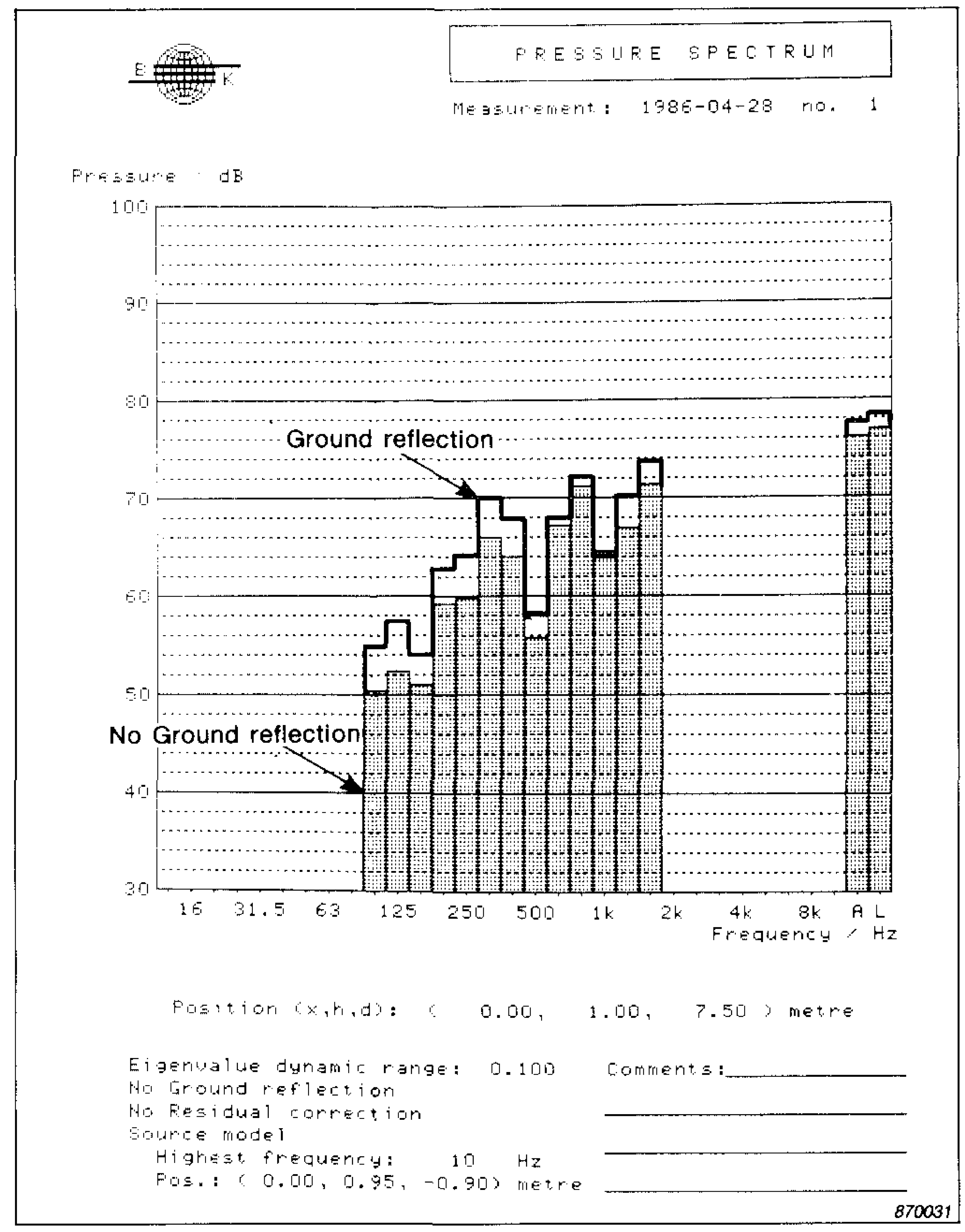

Fig. 6. Sound pressure level spectrum at 7,5 m distance, 1 m above ground, with and without reflective ground

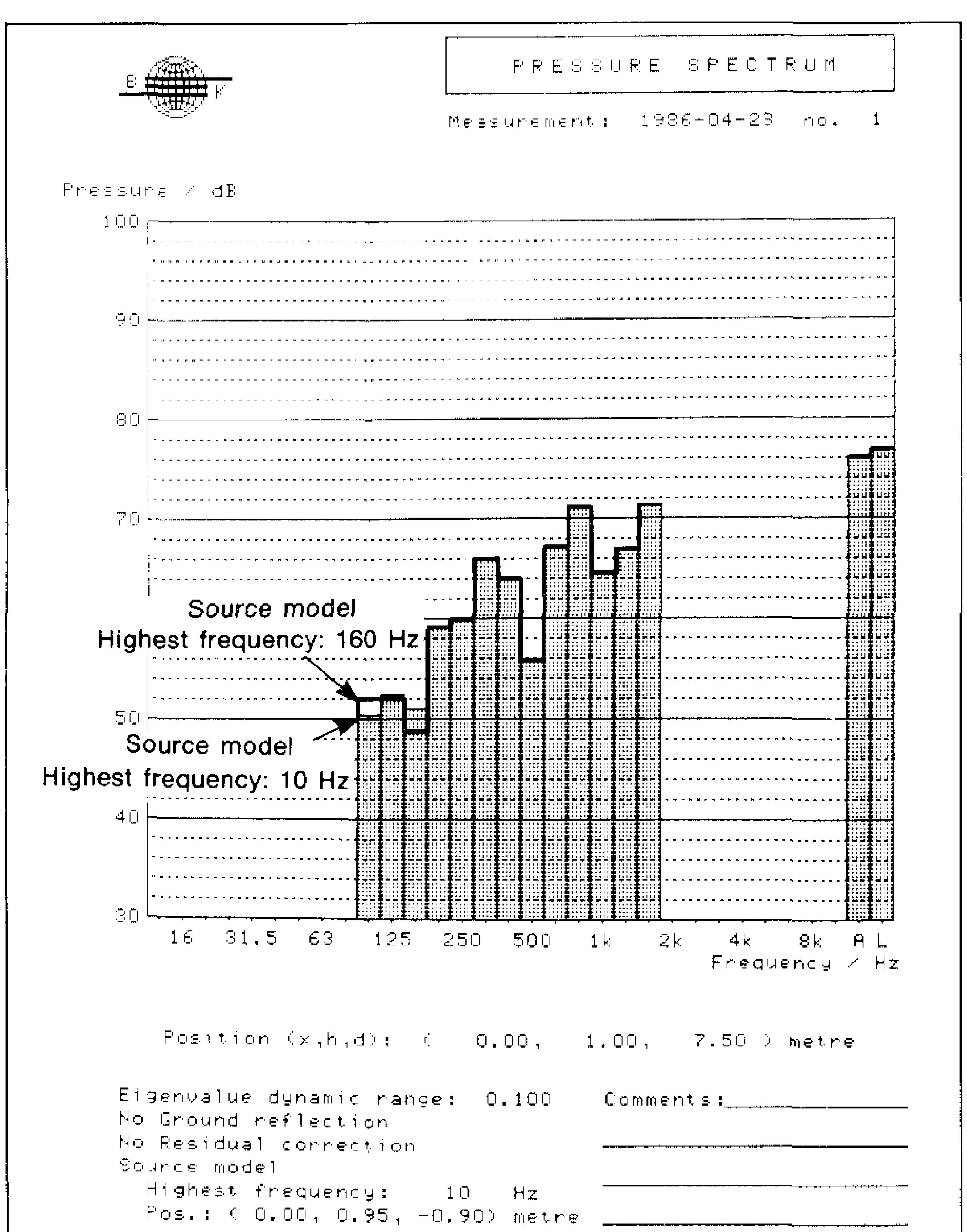

Fig. 7. Sound pressure level at 7,5 m distance, 1 m above ground, with and without source model for frequencies up to 160 Hz

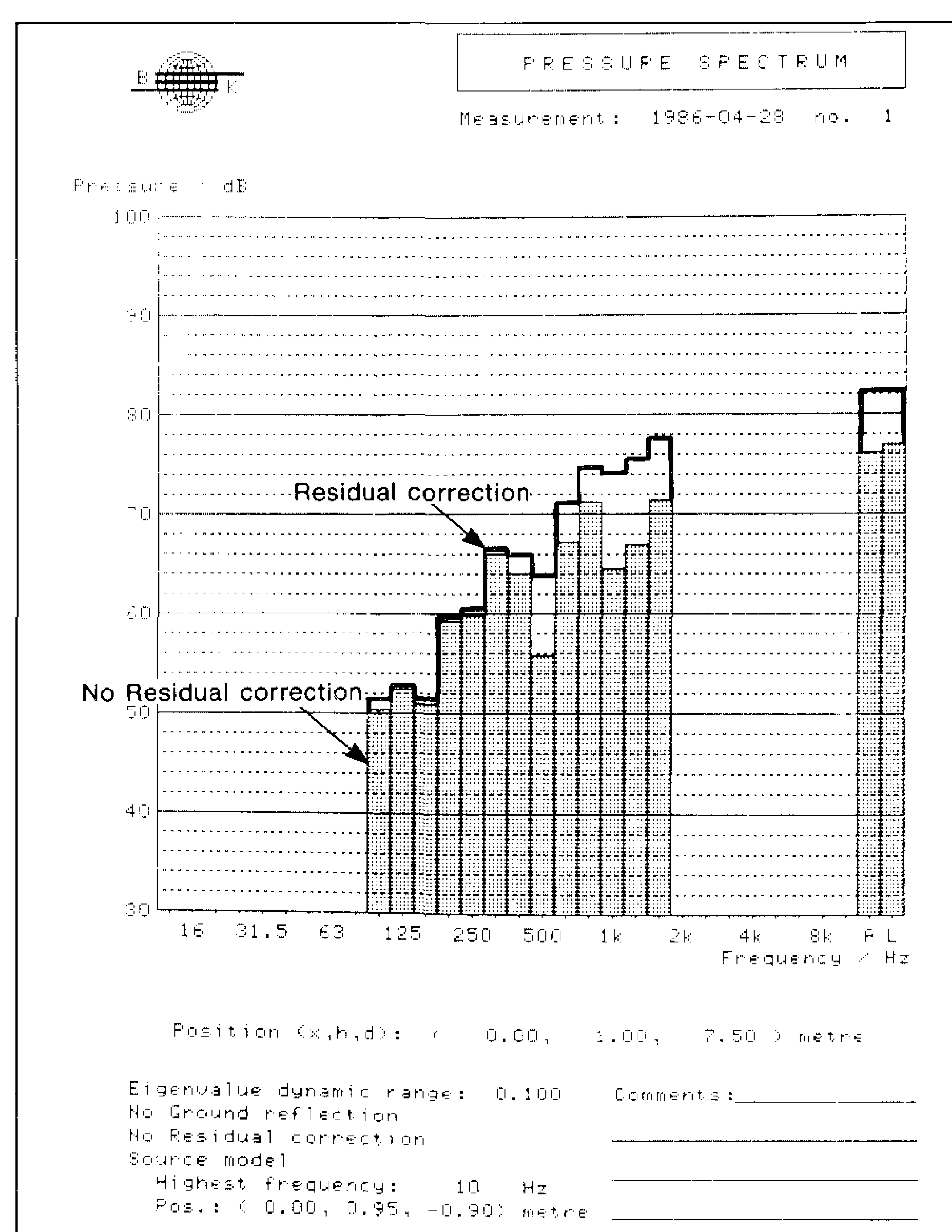

Fig. 8. Sound pressure level spectrum at 7,5 m distance, 1 m above ground, with and without residual correction

Results

All of the results to be presented are for the ⅓-octave band at 400 Hz, allowing the various plots to be compared.

Calculation of SPL along a line using BZ 7007

Fig. 5 shows the calculated Sound Pressure Level (SPL) along a line situated 7,5 m from the measurement plane, 1 m above the ground plane. The SPL is calculated both with and without a perfectly reflecting ground plane. Apparently the SPL has a pronounced maximum level in the region $x > 2{,}5$ m when reflections from the ground plane are not considered. The variation along the line is due to the constructive and destructive interference of the various sources. The greater radiation in the positive x-direction is also shown in Fig. 9 and Fig. 16.

Fig. 6 shows the calculated SPL spectrum at the centre position $x = 0$ on the line at 7,5 m distance for the cases of no ground reflection and of a perfectly reflecting ground plane. The values at 400 Hz in Fig. 6 can be found in Fig. 5 at the on-axis position. The ground reflection is seen to increase the SPL at that point for almost all of the ⅓-octave frequency bands considered.

Fig. 7 depicts the calculated SPL spectrum in the same point for the case of no ground reflection but without and with the use of a low-frequency source modelling technique up to 160 Hz. In the application package BZ 7007, the source model consists of a single monopole. In the present calculations, the monopole is positioned 0,9 m behind the scan area and 0,95 m above the floor. The application of the source model is based on the assumption that the effect of the finite measurement area on the calculated SPL is the same for the actual sound source as it is for the monopole source.

In the Extensive Program up to 9 monopoles may be employed for source modelling.

The use of a small number of references means an incomplete representation of the sound field at the higher frequencies, as explained in connection with Fig. 4. This means that the sound pressure level at higher frequencies tends to be under estimated. The effect of this incomplete representation can be investigated by application of the *residual correction* feature in the BZ 7007. Fig. 8 shows the calculated SPL spectrum for the position considered in Figs. 6 and 7 with and without the use of the residual correction. Clearly the use of only four references implies a rather large uncertainty above 500 Hz.

Practical experience shows that provided more than 8 references are applied in a measurement of the kind considered here, then the use of the

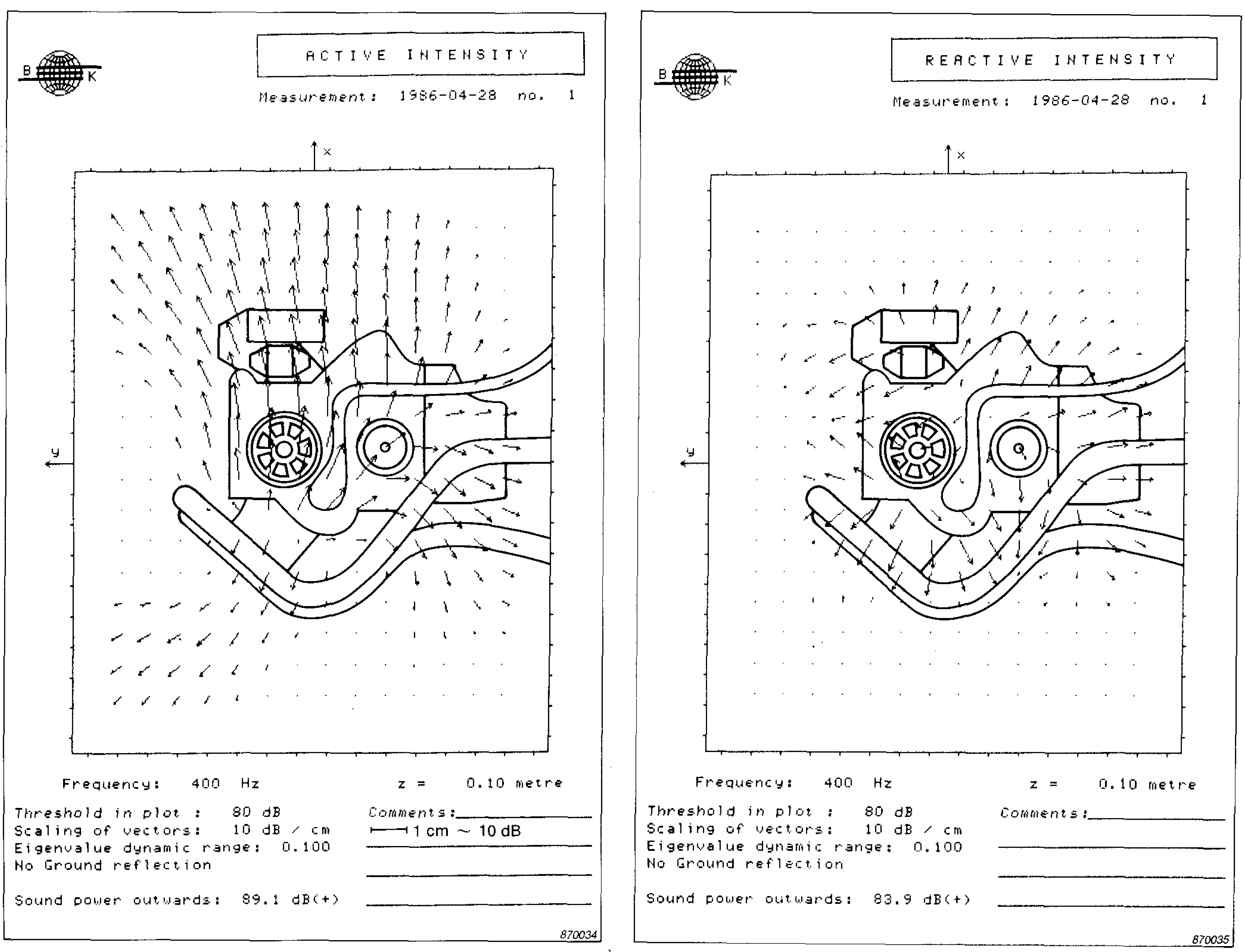

Fig. 9. Plots of intensity vectors in the plane z = 0,1 m for the 400 Hz ⅓-octave band produced by 2313/BZ 7007
a) Active intensity. Strong radiation from the right cylinder bank
b) Reactive intensity. Reveals regions of high pressure above both cylinder banks and around the crankshaft torsional damper
A threshold level equal to 80 dB has been applied. The scaling is indicated on the plot

residual correction leads to a better estimate of the far-field SPL at the higher frequencies. It should be noted that, the residual correction applies only in far-field estimation, and it does not apply with the presence of severe background noise.

Plots of Vector Intensity using BZ 7007

As an STSF measurement results in a complete description of the sound field in a certain solid angle, one can arguably call the measured data an acoustical hologram. From this data one can then calculate other acoustical parameters within the given solid angle.

The application package BZ 7007 enables the active and reactive intensity vectors to be plotted in sections of a box shaped volume in front of the scan area. These sections must be orthogonal to either the y-, the x- or the z-axis.

Fig. 9 shows projections of the active and reactive intensity vectors onto the plane z = 0,1 m which is 10 cm in front of the scan plane. The scan microphone positions with 10 cm in between are indicated by ticks on the frames around the plots. The intensity vectors have a length proportional to the level in dB for levels exceeding 80 dB.

To help in the interpretation of the plots, a brief explanation of the meaning of active and reactive intensity is given below. The active intensity vector represents the time average energy flow at the particular point. For the case of a monochromatic sound field the active intensity vector component denoted by the symbol I_r is related mathematically to the phase gradient by:

$$I_r = \frac{-p^2_{rms}}{\rho ck} \frac{\partial \phi}{\partial r} \tag{1}$$

where $\frac{\partial \phi}{\partial r}$ is the phase gradient of the sound field in direction r, p^2_{rms} is the mean square pressure, ρc is the impedance of the medium which is the product of the density of the medium ρ and the speed of sound in the medium c and k is the wave number.

Another useful quantity of the sound field closely associated with the active intensity is the reactive intensity denoted by the symbol Q. The reactive intensity is related to the amplitude gradient in the sound field and can be expressed mathematically as:

$$Q_r = \frac{-1}{\rho ck} \frac{\partial p^2_{rms}}{\partial r} \tag{2}$$

where Q_r is the reactive intensity vector component in direction r. An obvious question to ask is how will this extra information help an engineer to deal with a noise control problem. It should be borne in mind that all the acoustical quantities that could be measured are complementary. Sound pressure measurements can be used to establish the size of the noise problem, active intensity can be used to deter-

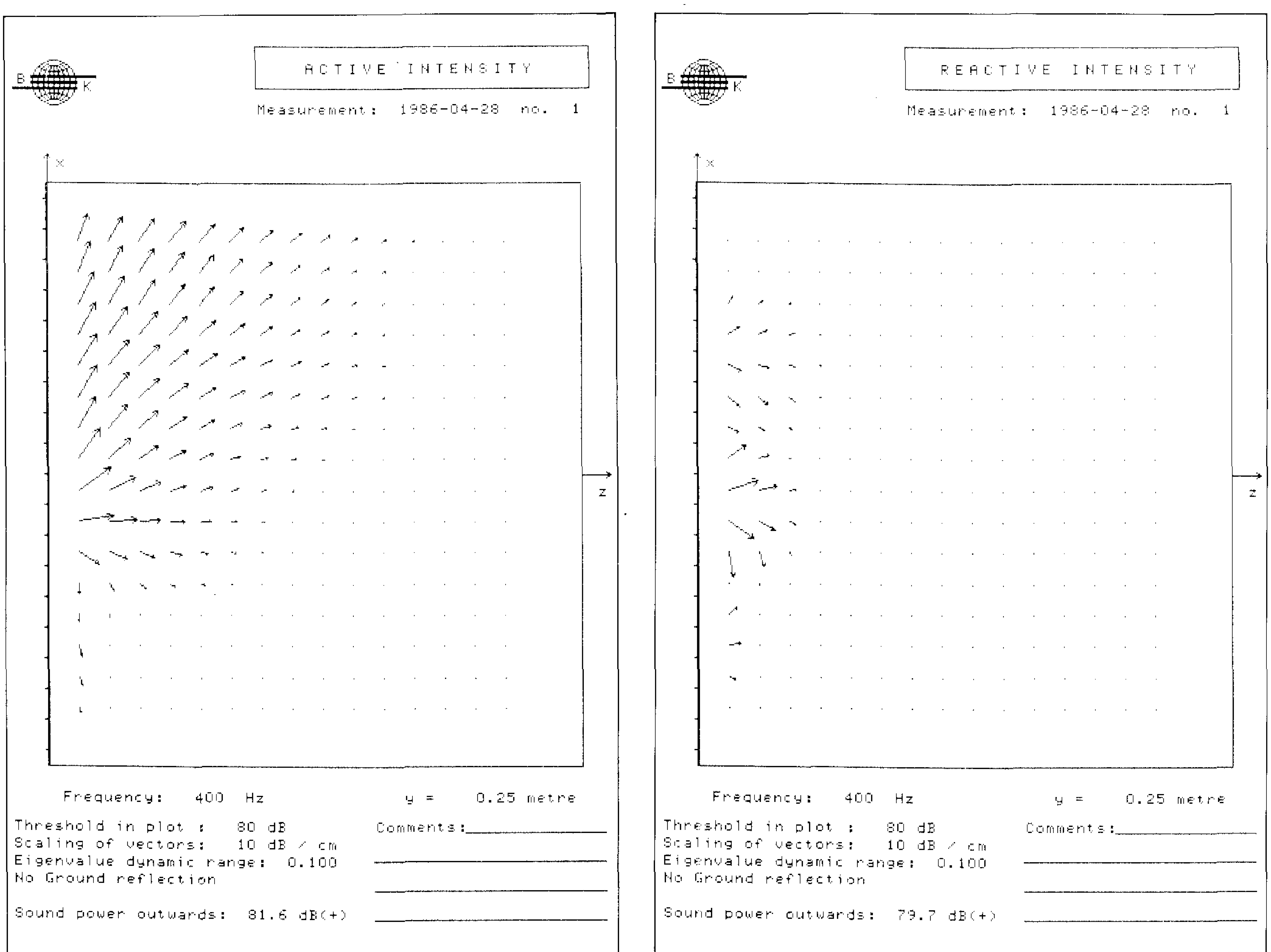

Fig. 10. Plots of intensity vectors in the plane y = 0,25 m for the 400 Hz 1/3-octave band.
a) Active intensity
b) Reactive intensity

mine the sound power of the noise source in situ while reactive intensity can yield information about the structure of the sound field close to the source. Reactive intensity is related to the gradient of potential energy in a sound field by:

$$Q_r = -\frac{c^2}{\omega}\frac{\partial V}{\partial r} \qquad (3)$$

where V is the potential energy at a point in the field and ω is the angular frequency $\omega = kc$. At pressure maxima and minima the gradient of potential energy is zero thus Q_r also becomes zero in these regions. The reactive intensity vector shows the directions from areas of high pressure to areas of lower pressure. Plots of reactive intensity therefore may be used for localization of regions with high acoustic potential energy and for investigating standing wave patterns.

The active intensity plots in Fig. 9(a) shows a high radiation from the right cylinder bank. Either the two large tubes to the left reflects the radiated sound or various sources on the engine combine in a way effectively producing a rather high directivity, in the positive x-direction. The strong radiation from the right cylinder bank dominates the plot. When one looks at the reactive intensity plot of Fig. 9(b) however, three large regions of high pressure are identifiable, the two cylinder banks and the crankshaft torsional damper.

Fig. 10 shows the active and reactive intensity vectors in the horizontal plane y = 0,25 m i.e. 25 cm or 2,5 microphone spacings above the centre of the scan area. The plot of active intensity shows the high directivity in the positive x-direction while the reactive intensity plot reveals three areas of high pressure or high potential energy. Each of the two cylinder banks produces a region of high pressure, the radiation from the right bank being split by the two air intake tubes.

The component of the intensity vectors orthogonal to the plot plane cannot be depicted. Instead this component is integrated (summed) over the plot area, and the resulting sound power (active or reactive) is printed. The active sound power through the plot area at z = 0,1 m is 89,1 dB. The reactive power is 83,9 dB.

Contour plots of intensity produced using Acoustical Holography

After transfer of the measured data from the 2313/BZ 7007 to a VAX computer, a series of contour plots were made using the Extensive Program which employs the Near-field Acoustical Holography technique.

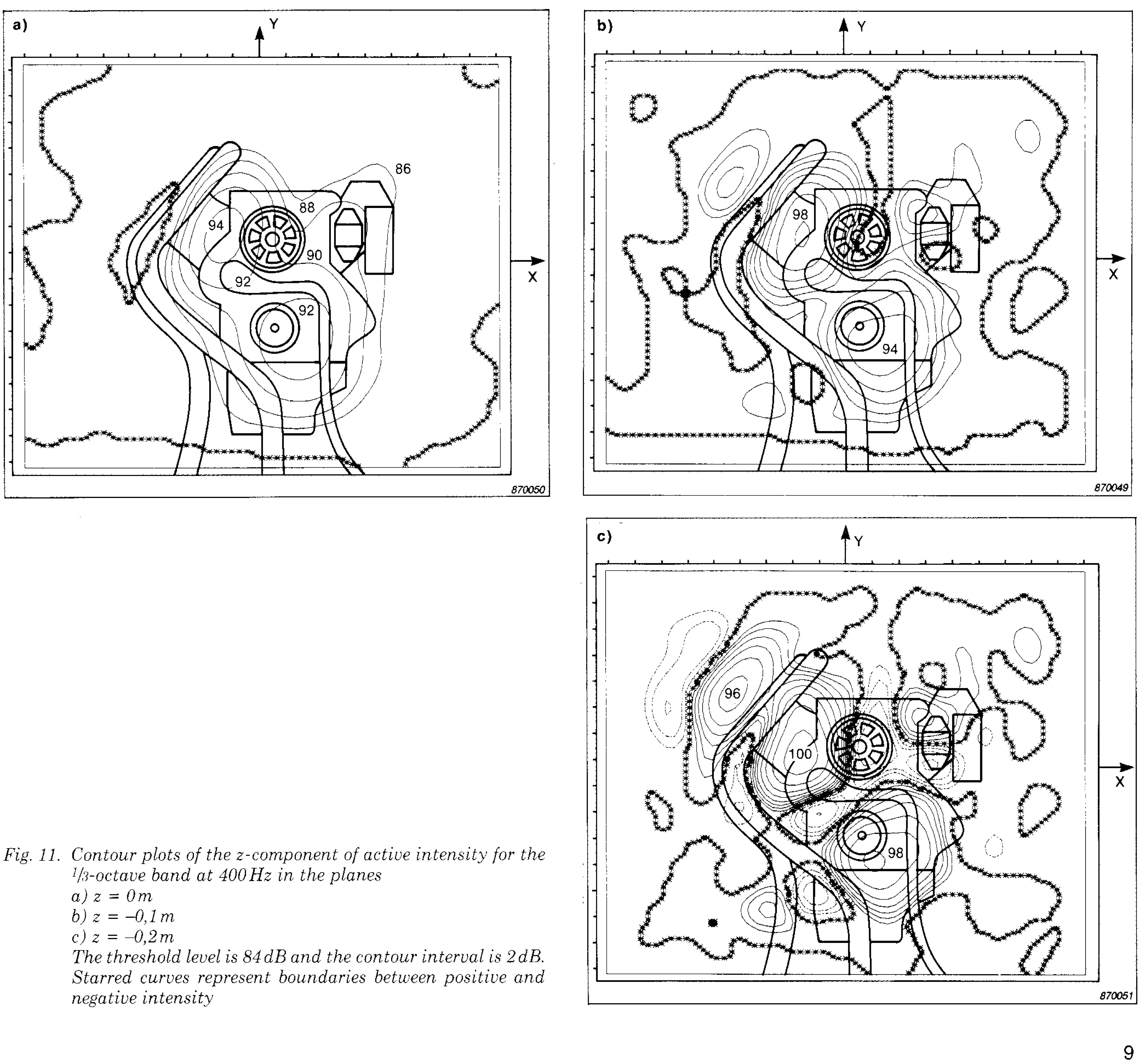

Fig. 11. Contour plots of the z-component of active intensity for the 1/3-octave band at 400 Hz in the planes
a) z = 0 m
b) z = –0,1 m
c) z = –0,2 m
The threshold level is 84 dB and the contour interval is 2 dB. Starred curves represent boundaries between positive and negative intensity

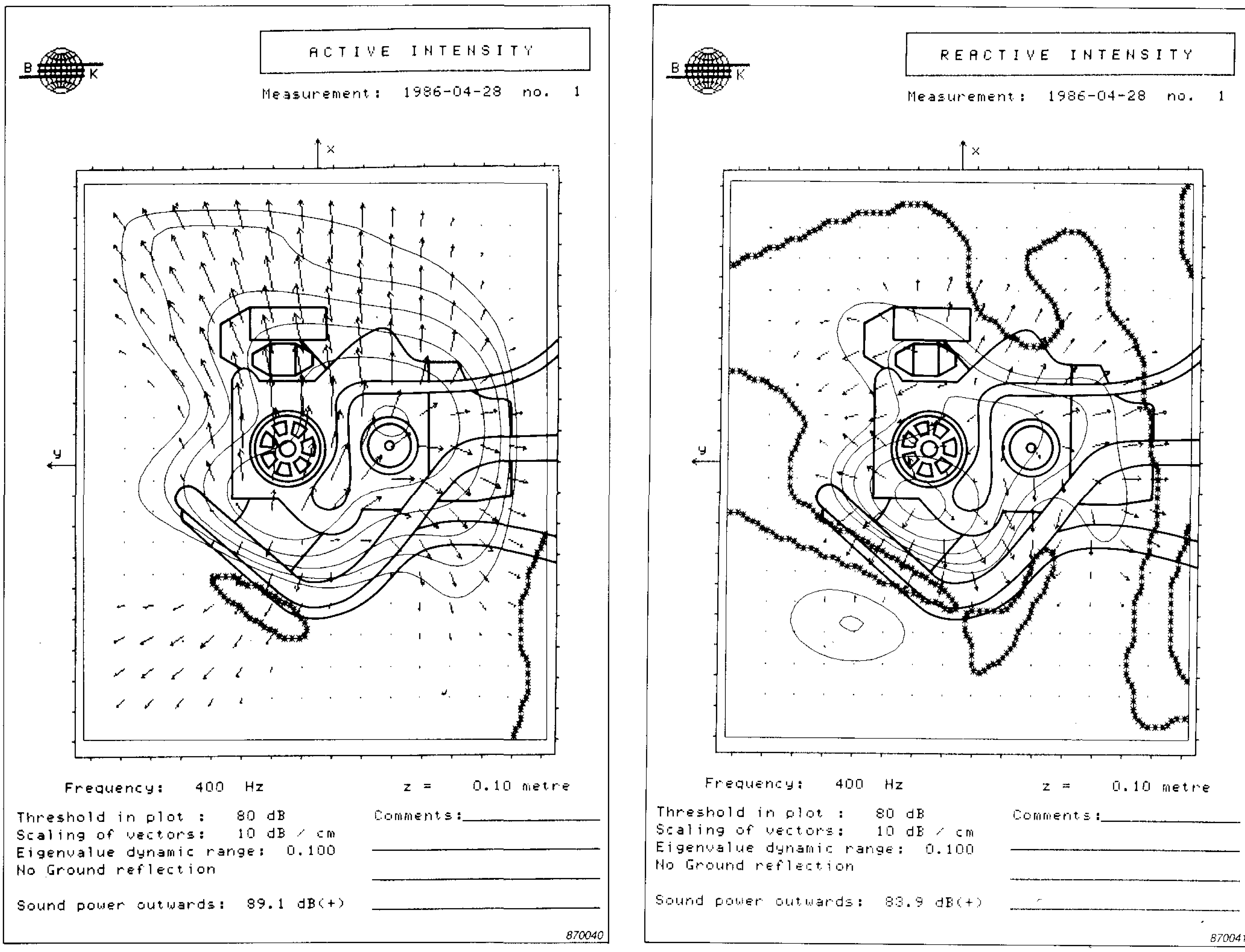

Fig. 12. Combined contour/vector plots of intensity in the plane z = 0,1 m for the 400 Hz 1/3-octave band
a) Active intensity
b) Reactive intensity.
The threshold level is 80 dB and the contour interval is 2 dB

Fig. 11 contains contour plots of the z-component of the active intensity in the planes z = 0, –0,1, –0,2 metre. Boundaries between positive and negative intensity regions are represented by starred curves, positive intensity meaning flow of power in the positive z-direction. A threshold level equal to 84 dB has been applied, which causes contours corresponding to levels equal to or less than 84 dB not to be plotted. The contour interval is 2 dB. Thus, the lowest level contours represent 86 dB positive or negative intensity. Positive intensity contours are solid curves, whereas negative intensity contours are dashed curves.

The main sources appear to be the right cylinder bank and the region around the crankshaft torsional damper, the radiation from the cylinder bank being split by the tubes. The left cylinder bank is seen to be only a minor noise source.

The distances from the scan plane to various points on the engine were

Engine block	30 cm
Crankshaft torsional damper	25 cm
Fan shaft pulley	15 cm
Air intake tubes	~ 12 cm

Combined contour and vector plots of intensity

By combining a contour plot of the intensity z-components with a vector plot convering the same area, a representation of the full three-dimensional intensity vectors in that plane is obtained.

Fig. 12 contains combined contour/vector plots of the active and of the reactive intensity in the plane z= 0,1 metre which is 10 cm in front of the scan plane. Both the contour plot and the vector plot is made with an 80 dB threshold level. The contour interval is 2 dB and the scaling of the vectors is as in Fig. 9.

Combined pressure contour/reactive vector intensity

It has already been mentioned that the reactive intensity vector is proportional with the negative of the gradient of the sound pressure level. This is illustrated by the plots in Fig. 13. Here, a contour plot of the sound pressure level in the plane z = 0,1 metre is superimposed by a plot of reactive intensity vectors in the same plane. Both plots have a threshold level equal to 80 dB. The contour interval is 2 dB and the vector plot is identical to the plot in Fig. 9 b. Clearly the reactive intensity vectors point in the "downhill" direction (the negative gradient) of the pressure.

Simulation of partial source attenuation

Fig. 11 revealed the right cylinder bank as being a major source of radiation and Figs. 5, 9 and 10 showed a high directivity of the radiation in the positive x-direction. Some information about, how the radiation from the right cylinder bank influences radiation from the remaining parts of the engine can be obtained by simulating an attenuation of the radiation from this cylinder bank, and by calculating the radiation from the modified source thus obtained.

This simulation is performed by calculating the z-component of the particle velocity in a plane close to the surface of the source (in this case z = –0,2 m), attenuating the particle velocity distribution over the relevant areas, and then from the modified velocity map calculating the sound field after the attenuation.

A simulation of source attenuation is described in three stages; firstly, the form of the attenuation function, secondly, the modified active intensity contour plot, thirdly, the modified radiation pattern expressed as a sound pressure level along a line.

The attenuation function applied to the particle velocity map in the plane z = –0,2 m is shown as a contour plot in Fig. 14. The radiation from the right cylinder bank was attenuated by 20 dB.

Fig. 15 shows the z-component of active intensity in the attenuation plane z = –0,2 m after the attenuation. As in Fig. 11 the threshold level is 84 dB and the contour interval is 2 dB. Obviously the intensity map has been changed significantly also over regions outside the attenuation area. The radiated sound power has been decreased from 90,9 dB to 87,2 dB. From Fig. 9 one sees that the sound power through the scan area at 10 cm further away from the scan plane is 89,1 dB. The difference of 1,8 dB is due to several factors. Firstly in BZ 7007 the outer measurement points have not been included in the calculations to avoid edge effects. When using the Extensive Program these points are included as windowing and extrapolation can be employed. Furthermore, the closer the calculation plane the more sound power is included as less escapes around the edge.

The sound pressure level at 7,5 m distance and 1 m above ground, before and after the attenuation, is depicted in Fig. 16. It is evident that the strong directivity in the positive x-direction has disappeared. At x = 5 m the sound pressure level has been decreased by 6,3 dB, whereas at x = –5 m the decrease is only 0,8 dB. This type of change shows that either the radiation from the different parts of the engine is highly correlated, or the dominant radiation from the cylinder bank is directed in the positive x-direction. A simulation of an attenuation of the entire map except over the right cylinder bank reveals a high directivity of the radiation from the cylinder bank.

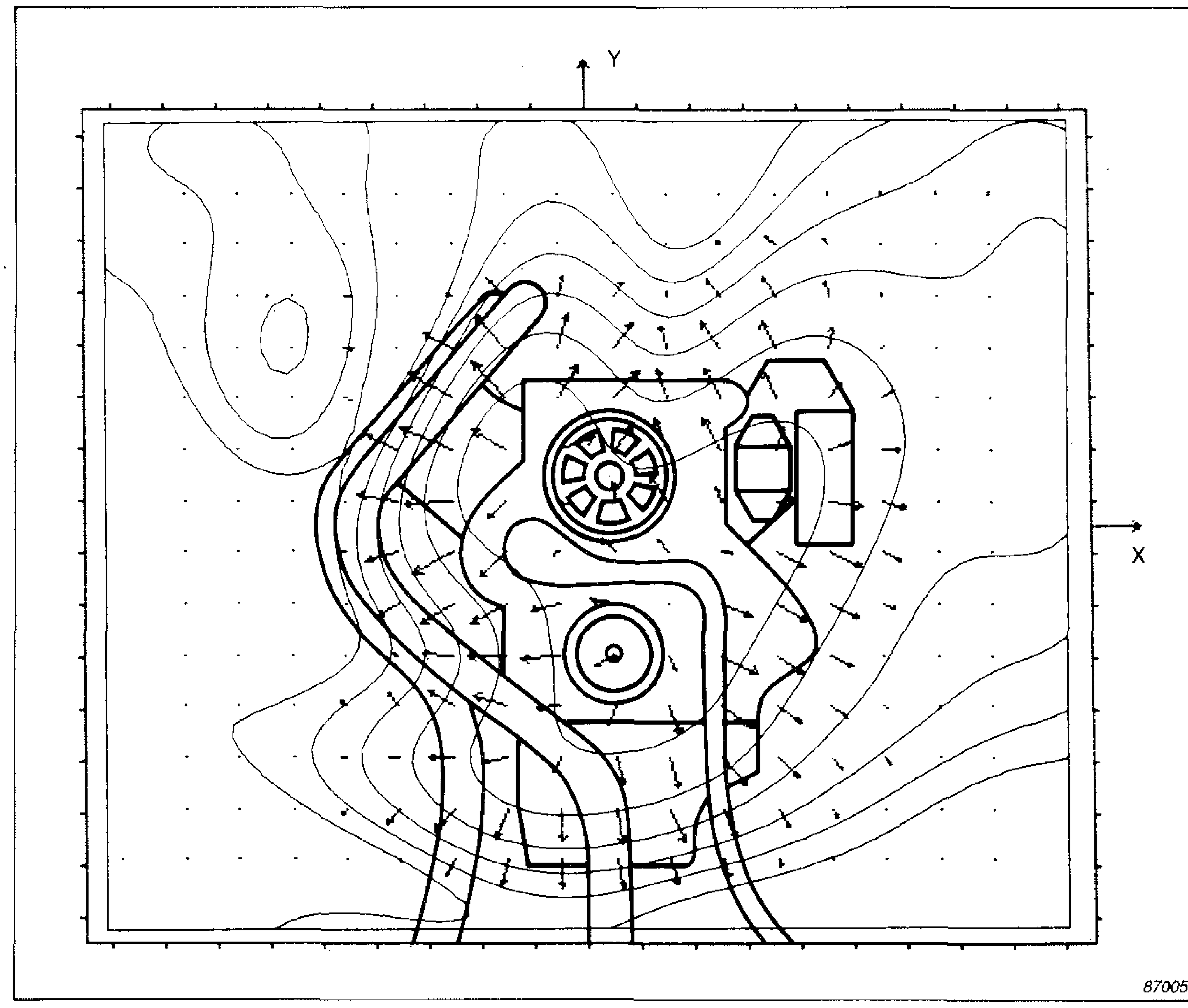

Fig. 13. Combined pressure contour/reactive vector intensity plot in the plane z = 0,1 m for the 400 Hz 1/3-octave band. The threshold level is 80 dB and the contour interval is 2 dB

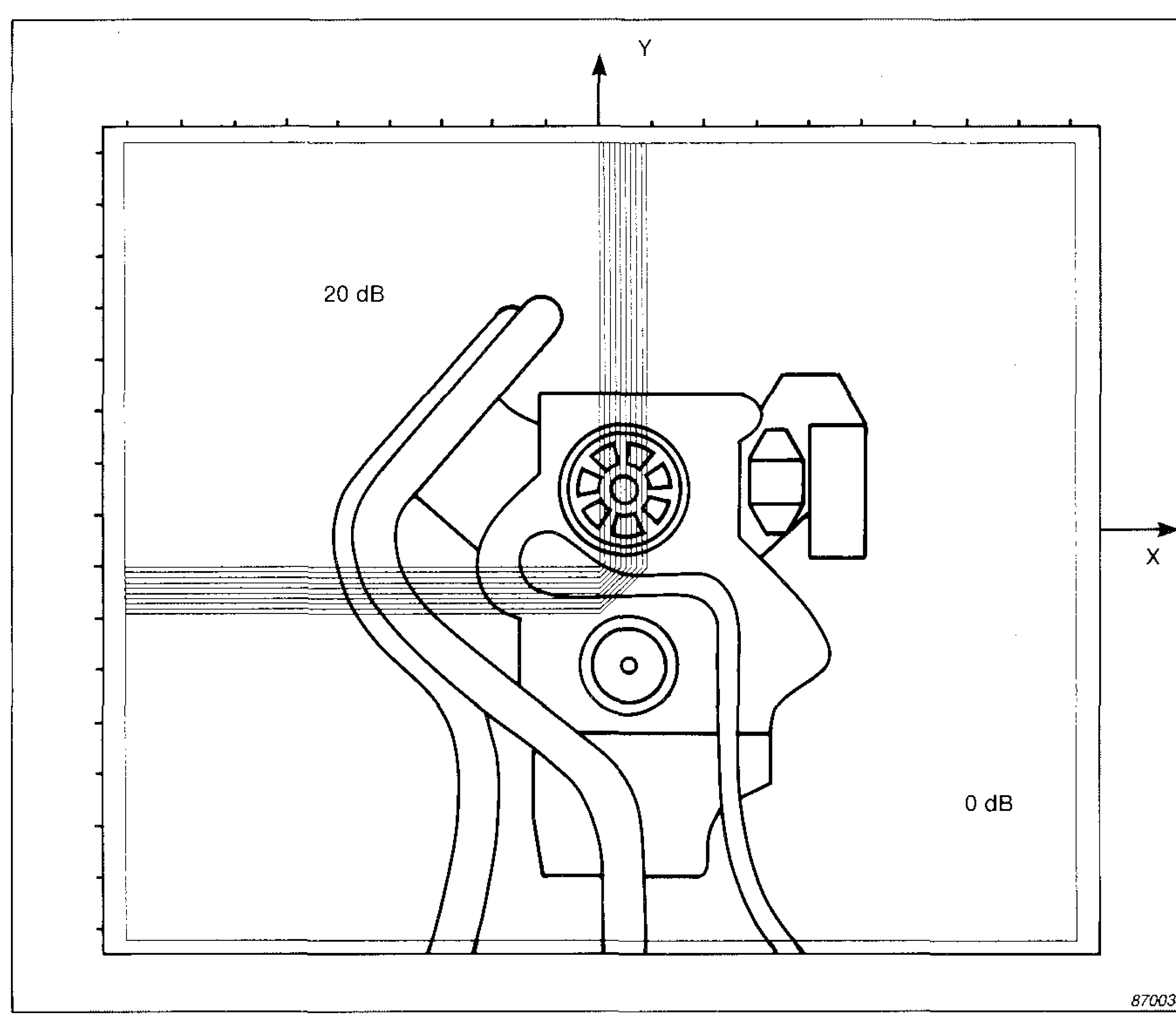

Fig. 14. Contour plot of attenuation function used in simulation of source attenuation. The attenuation is 20 dB over the right cylinder bank and elsewhere 0 dB

The difference between the calculated SPL in Fig. 16 (upper curve) and in Fig. 5 (lower curve) is due to a better accuracy in Fig. 16, which is obtained from the VAX program. The VAX program allows a spatial filtering and windowing of the measured data which is not possible using the 2313/BZ 7007. Measurement of pressure gradient instead of pressure data over the scan area would provide better results using the 2313/BZ 7007.

Conclusion

The results presented in this note show how from just one measurement, an engineer can obtain a wealth of information about his test engine. The STSF technique is a further step towards an understanding of the complicated sound fields met in practical situations. STSF offers research and development engineers a means of measurement and calculation which yields a complete description of the sound field within a given solid angle subtended at the noise source.

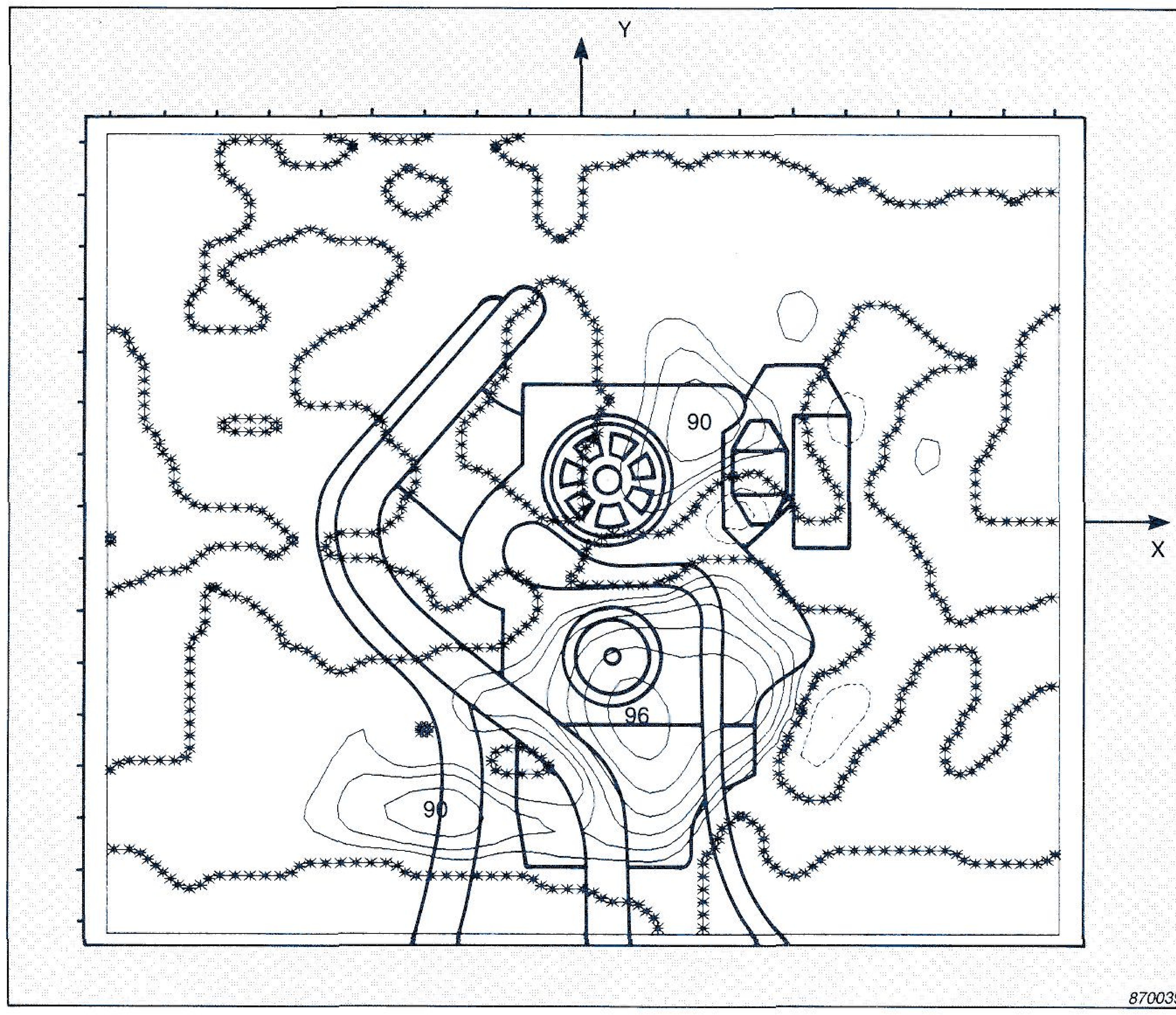

Fig. 15. Contour plot of active intensity in the plane z = –0,2 m for the 400 Hz 1/3-octave band after attenuation of the right cylinder bank. The threshold level is 84 dB and the contour interval is 2 dB

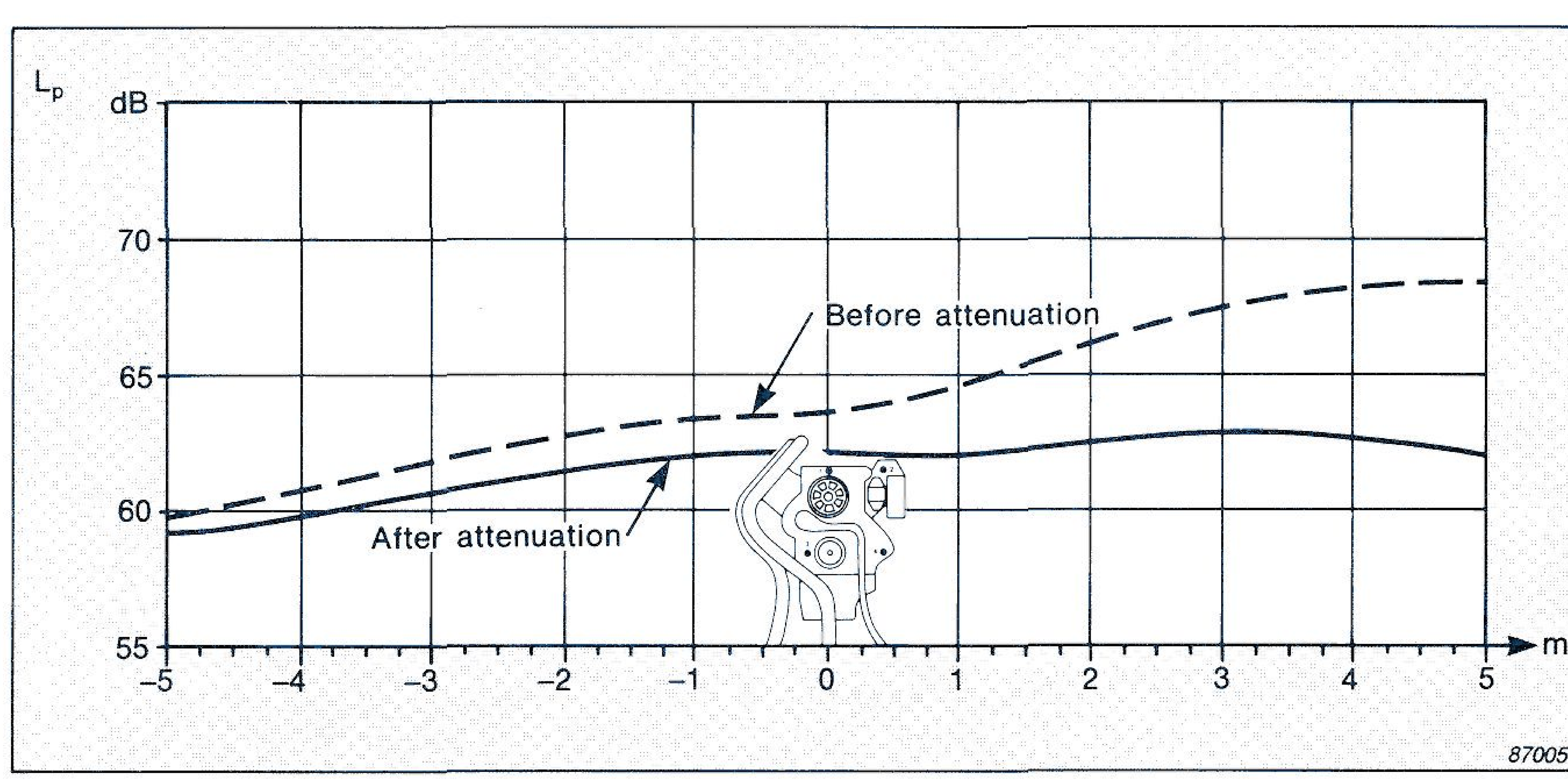

Fig. 16. Sound Pressure Level along a line at 7,5 m distance, 1 m above a non-reflective ground, before and after attenuation of the right cylinder bank. The results are for the 400 Hz 1/3-octave band

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Brüel & Kjær

WORLD HEADQUARTERS: DK-2850 Nærum · Denmark · Telephone: +45 2 80 05 00 · Telex: 37316 bruka dk

Australia (02) 450-2066 · Austria 02235/563*0 · Belgium 02 · 242-97 45 · Brazil 246 8149 · Canada (514) 695-8225 · Finland (90) 80 17 044 · France (1) 64 57 20 10
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