Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Feasibility of Noise Source Location by Phased Array Beamforming in Engine Ducts

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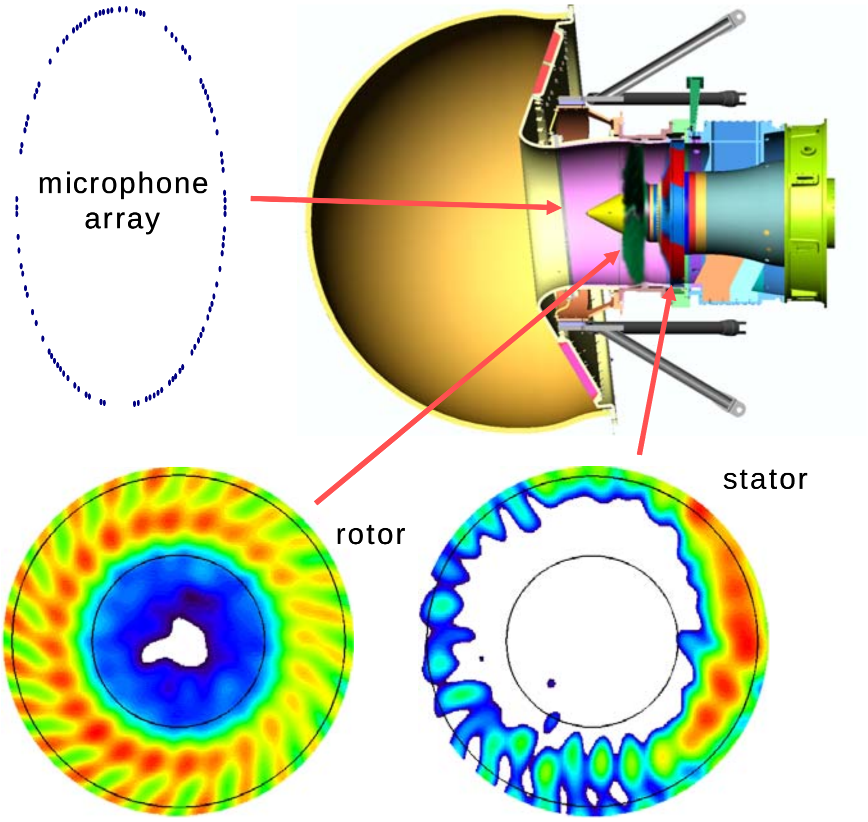

Problem area

Research is needed to develop innovative concepts and enabling technologies to reduce aircraft engine noise at source. Fan broadband noise is a major aircraft noise challenge now and in the future will be even more important. Novel low-noise engine architectures, such as ultra-high-bypass-ratio engines and lower-speed fans, can help address jet noise and fan tone noise, but previous EC-funded programmes have shown they are unlikely to reduce significantly fan broadband noise without improved understanding of the source mechanisms.

One of the aims of the EU-project PROBAND is to develop a better understanding of broadband noise generation mechanisms using

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This report is based on a presentation held on the 13th AIAA/CEAS Aeroacoustics Conference, Rome, 21-23 May, 2007.

advanced experimental and computational techniques.
Within PROBAND, NLR has done a feasibility study to investigate the applicability of advanced phased array (beamforming) techniques to locate broadband noise sources on rotors and stators, and to separate their contributions to the total noise in the forward arc.

Description of work
Existing phased array techniques were made suitable for fan rig measurements with a microphone array upstream of the fan. These techniques include the separation of broadband noise from tonal noise, beamforming on stationary sources, and beamforming on rotating sources. The free-field Green's function is used to model the sound transfer from sources to microphones.
The techniques were successfully applied to experimental data from the EU-project SILENCE(R). A circular array of 100 microphones mounted in the (drooped) intake was used for beamforming. Within SILENCE(R) this array has been used for azimuthal mode detection. Although beamforming with a circular array provides, theoretically, lower quality noise source maps than with a planar array, the results are very promising. The quality of the beamforming results agreed with simulations. Noise sources on rotor and stator are clearly visible.
A simulation study was carried out to investigate the effects of an intake liner. Use was made of synthesized microphone data obtained using a Green's function in a lined flow duct. It was shown that a liner is absolutely necessary for obtaining meaningful beamforming results, but the liner properties are not critical for this.
The simulations also showed that the inlet mode detection has practically no axial resolution, i.e., the beamforming results do not provide information about the axial position of the sound sources. With an alternative array, consisting of a number of parallel microphone rings in the intake, this disadvantage can partly be removed, especially at the higher frequencies. Moreover, such an array provides also higher spatial resolution in the other directions

Results and conclusions
The main conclusions of the present study are:
- Beamforming on rotor and stator with an intake mode detection array is feasible.
- The presence of a liner is absolutely necessary, but the liner properties are not critical.
- The beamforming results may be improved by using an in-duct wall array with axial extent.

Applicability
The in-duct beamforming technique will be applied to a selected set of measured data from the fan-OGV rig test, to be carried out within PROBAND. Thus, knowledge will be obtained about the most important broadband noise source mechanisms.

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Summary

This paper discusses the possibility of source location by phased array beamforming on fan and stator of turbofan engines using an intake wall-mounted microphone array. To demonstrate the feasibility, beamforming techniques were applied to existing measured data of a circular microphone array in the intake of a fan rig. This array is normally used for azimuthal mode detection. From the measured data set a test case was selected with low engine speed, and with an intake liner between the fan and the array. Beamforming methods with both stationary and rotating focus are applied, and the contributions of tonal noise and broadband noise were separated. Thus, tonal and broadband noise sources can be identified on both fan and stator. The free-field Green's function is used for the definition of the steering vectors, thereby ignoring duct wall reflections. By a simulation study it is shown that the presence of an intake liner is a necessary condition for obtaining meaningful beamforming results. Further simulations showed that significantly improved beamforming results can be obtained with an in-duct "cage" array consisting of a number of parallel microphone rings

Contents

Feasibility of In-Duct Beamforming

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This paper discusses the possibility of source location by phased array beamforming on fan and stator of turbofan engines using an intake wall-mounted microphone array. To demonstrate the feasibility, beamforming techniques were applied to existing measured data of a circular microphone array in the intake of a fan rig. This array is normally used for azimuthal mode detection. From the measured data set a test case was selected with low engine speed, and with an intake liner between the fan and the array. Beamforming methods with both stationary and rotating focus were applied, and the contributions of tonal noise and broadband noise were separated. Thus, tonal and broadband noise sources could be identified on both fan and stator. The free-field Green's function was used for the definition of the steering vectors, thereby ignoring duct wall reflections. By a simulation study it was shown that the presence of an intake liner is a necessary condition for obtaining meaningful beamforming results. Further simulations showed that significantly improved beamforming results can be obtained with an in-duct "cage" array consisting of a number of parallel microphone rings.

A Nomenclature

CB	=	Conventional Beamforming
CSM	=	Cross-Spectral Matrix
LE	=	Leading Edge
PSF	=	Point Spread Function
ROSI	=	ROtating Source Identifier
SNR	=	Signal to Noise Ratio
A	=	source power
$\mathbf{C}$	=	cross-spectral matrix
c	=	speed of sound
F	=	sound transfer function
f	=	frequency
G	=	Green's function
$\mathbf{g}$	=	steering vector
i	=	imaginary unit
m, n	=	microphone indices
N	=	number of microphones
p	=	acoustic pressure
R	=	fan radius
t	=	time
U	=	speed of uniform flow (in x-direction)
$\vec{x}_n$	=	microphone position
$\vec{\xi}$	=	point on scan plane
Δt	=	retarded time delay
δ	=	Dirac-delta function
σ	=	emitted signal

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I. Introduction

THROUGH better design and the use of higher bypass ratios, aircraft turbofan engine noise has been substantially reduced over the last decades. As a consequence, on modern aircraft (e.g., the Airbus A340) many other noise sources, like slats, flaps, and landing gears, have comparable strengths. Nevertheless, even in the landing phase, the engines are still the loudest noise sources[1]. Hence, there is a continuous need for further reducing engine noise.

Engine noise can be either tonal (buzz-saw noise, rotor alone noise, fan-stator interaction, blade row interaction in the turbine) or broadband (jet noise, fan broadband noise). Tonal noise and jet noise are extensively studied since many years, and this has led to significant noise reduction. As a consequence, the relative contribution of fan broadband noise is increasing, and is therefore becoming a more and more important research topic[2].

Especially at lower engine speeds, typically during approach, fan broadband noise is a major component of the total noise emitted by turbofan engines. This broadband noise can be caused by various possible mechanisms: interaction of the intake duct boundary layer with the fan blade tips, interaction of the turbulent fan wakes with the stator vanes, fan blade self noise (trailing edge noise), and stator vane self noise.

For investigations of broadband noise reduction devices it is important to know which of the above-mentioned source mechanisms prevail. Unfortunately, there is no straightforward recipe to locate these sources experimentally, and to estimate their strengths. A possible tool may be the phased array beamforming technique, which has become a standard tool for acoustic source location in wind tunnel and flight testing. In the present study the applicability of this tool inside a turbofan engine is examined.

For phased arrays inside a turbofan engine there is limited freedom in microphone positioning, as the microphones should not disturb the flow. Possible microphone positions are the duct wall, a turbulence control screen, struts, and stator vanes. The present study is focused on forward radiating noise, so the possibility of microphones in struts or stator vanes will not be considered. The possibility of a microphone array in the turbulence control screen will not be considered either, mainly because the distance to the source region is too large to obtain results with an acceptable spatial resolution. Therefore, this paper is focussed on microphone arrays in the intake.

Phased array beamforming techniques make use of a theoretical model for the sound transfer from source to receiver. In traditional applications, where the microphone array is at a certain distance from the model, the free-field Green's function (with possibly a uniform flow) is used for that purpose. Inside a duct this might not be the most appropriate choice, because reflections of the duct wall are not included. It may be better to use numerically calculated Green's functions which include the presence of the nacelle. Even measured Green's functions may be used. Nonetheless, inaccuracies will remain, because these Green's functions do no include the (often unknown) source directivities.

In this paper, no attempt is made to solve the issues associated with Green's functions that include wall reflections. In other words, we will hold on to the free-field Green's function. However, it is anticipated that an intake liner is helpful to reduce the negative effects of reflections. In an earlier study[3] it was demonstrated that lining on parallel wind tunnel side plates significantly improves the quality of beamforming results.

Application of the phased array technique inside a turbofan engine is a rather unexplored area. Recently first results were shown of beamforming applied to fan blades and stator vanes of a fan rig[4]. Also recently an analytical study was performed by Lowis and Joseph[5] on beamforming techniques applied to ducted rotors. Unlike the present study, they did include duct wall reflections in their sound transfer model.

In this paper it is demonstrated that beamforming on fan and stator is indeed feasible. This is done by using existing measured data from a circular array of microphones in the inlet of a fan rig. This array is normally used for the detection of azimuthal modes. Beamforming on the stator is done by Conventional Beamforming (CB), which assumes stationary sources. To locate rotating sources on the fan we use the ROSI (ROtating Source Identifier) method described in reference 6. This method was applied earlier to rotating blades of wind turbines[7], and to helicopters[8]. The sound field is split into tonal and broadband noise, and we will consider the beamforming results of these sound components separately. Through simulations it is demonstrated that the presence of an intake liner is indeed necessary to obtain meaningful results. Finally, the merits of a different array layout are investigated, which consists of 5 parallel rings of microphones in the intake. It is shown that significant improvements can be obtained with such an array.

II. Processing techniques

Beamforming on stationary sources

To locate stationary noise sources, e.g., sources on the stator, we use the CB technique. This is a frequency-domain method, which evaluates for each point $\vec{\xi}$ on the scan plane the expression

$$A = \mathbf{g}^* \mathbf{C} \mathbf{g} \Big/ \|\mathbf{g}\|^4 = \sum_{n=1}^{N} \sum_{m=1}^{N} g_n^* C_{nm} g_m \Bigg/ \left(\sum_{n=1}^{N} g_n^* g_n \right)^2 . \tag{1}$$

Herein, N is the number of microphones, A the source power, **C** the Cross-Spectral Matrix (CSM), and **g** the steering vector. Often, an expression similar to Eq. (1) is used, in which the main diagonal of **C** is removed. This is to obtain results at higher Signal to Noise Ratio (SNR).

The steering vector components g_n are the pressure amplitudes at the microphone positions $\vec{x}_n$ induced by a unit point source in the scan point $\vec{\xi}$. The values of g_n depend on the sound transfer model used. As mentioned in the introduction, we will use the free-field Green's function (G) in uniform flow:

$$g_n = G\left(\vec{x}_n, \vec{\xi}\right) . \tag{2}$$

The Green's function G is the solution of

$$\nabla^2 G - \frac{1}{c^2} \left(2\pi i f + U \frac{\partial}{\partial x} \right)^2 G = -\delta(\vec{x} - \vec{\xi}) , \tag{3}$$

where ∇ is the nabla operator, c the speed of sound, i the imaginary unit, f the frequency, U the uniform flow speed (in x-direction), and δ the Dirac-delta function.

Beamforming on rotating sources

To be able to locate rotating sources on the fan, we will apply the ROSI method[6], which is summarized below. ROSI is a time-domain beamforming technique. It starts from the following expression for a sound source moving at $\vec{\xi}(t)$ in a uniform flow:

$$\nabla^2 p - \frac{1}{c^2} \left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right)^2 p = -\sigma(t) \delta\left(\vec{x} - \vec{\xi}(t) \right), \tag{4}$$

where $\sigma(t)$ is the signal emitted by the sound source. The solution of Eq. (4) can be written as

$$p(\vec{x}, t) = \sigma(t - \Delta t) \Big/ F\left(\vec{x}, \vec{\xi}(t - \Delta t) \right), \tag{5}$$

where Δt is the retarded time delay, and F is the sound transfer function. Expressions for Δt and F can be found in reference 6. If $p_n(t)$ is the pressure fluctuation measured by microphone n, then $\sigma(t)$ can be reconstructed by the "delay-and-sum" method:

$$\sigma(t) = \frac{1}{N} \sum_{n=1}^{N} \sigma_n(t) , \tag{6}$$

with

$$\sigma_n(t) = p_n(t + \Delta t_n) F_n\left(\vec{x}_n, \vec{\xi}(t) \right) . \tag{7}$$

Source powers in the frequency domain can be obtained through Fourier transformation of $\sigma(t)$, and averaging:

$$A = \frac{1}{2}\left\langle |\hat{\sigma}|^2 \right\rangle = \frac{1}{N^2}\sum_{n=1}^{N}\sum_{m=1}^{N}\frac{1}{2}\left\langle \hat{\sigma}_n \hat{\sigma}_m^* \right\rangle . \tag{8}$$

By omitting the terms with $m = n$ in this summation, we obtain an expression similar to CB with CSM diagonal removal, which can be used to increase the SNR.

Splitting of tonal and broadband noise

Part of the noise signal, as measured by the microphones, is repeated every fan revolution. If the rotation speed is constant, then this "rotor-bound" noise consists of pure tones, the frequencies of which are multiples of the revolution frequency. By averaging, this rotor-bound noise is isolated from the total noise. Broadband noise is obtained by subtracting the rotor-bound noise from the total noise.

III. Application to experimental data

The above-mentioned beamforming methods were applied to experimental data from the SILENCE(R) project, measured on Rolls-Royce fan rig 644/6 in the AneCom-Aerotest facility near Berlin[9]. The diameter of the fan was approximately 80 cm. A circular array of microphones was mounted in the drooped intake (see Fig. 1). This array, which consisted of 100 Kulite sensors, was designed and used for azimuthal mode detection. It has a nonuniform lay-out in order to extend the range of modes to be detected[10].

From the SILENCE(R) data base a reference test case at low engine speed (50%; 4700 RPM; average intake Mach number 0.29) was selected with a liner installed in the intake, between the fan and the array. The number of fan blades and stator vanes was 24 and 52, respectively. A low engine speed was chosen because of the relatively high broadband noise levels that were expected. In Fig. 2 a breakdown of the average microphone spectrum into tonal (rotor-bound) and broadband noise is shown.

CB results (with CSM diagonal removal) are shown in Fig. 3, in 1/3 octave bands, at a range of 10 dB. The outer circles in the plots correspond to the fan tip locations, and the inner circles with the splitter (also close to the rotor hub). The lack of axial symmetry in the plots can be related to the droop of the intake. At 4000 Hz, 5000 Hz, and 6300 Hz the stator vanes are visible as noise sources, close to the tip region. At lower frequencies noise seems to be generated at or close to the splitter. Results after splitting into tonal and broadband noise are shown in Fig. 4 and Fig. 5, respectively. The levels are relative to the levels in Fig. 3. Tonal noise is dominating at 5000 Hz and 6300 Hz, whereas broadband noise is prevailing at other frequency bands. Only at 4000 Hz broadband noise sources on the stator vanes can be observed.

ROSI results (also with diagonal removal) are shown in Fig. 6. At the frequency bands 3150 Hz and 4000 Hz (and a little bit at 2500 Hz) the fan blades are visible. Results after splitting into tonal and broadband noise are shown in Figs. 7 and 8, where the levels are relative to Fig. 6. Broadband noise is now dominating, except at 4000 Hz. As in Fig. 6, the fan blades are visible as noise sources at 3150 Hz.

IV. Simulations with mode detection array

This section describes the results of simulations, which were made with an axisymmetric set-up, at similar dimensions as the reference test case of the previous section (see Fig. 9). These are the following:

- duct radius: $R = 0.4$ m ,
- position of mode detection array : $x = -0.4$ m ,
- position of fan leading edge (LE): $x = 0.0$ m ,
- uniform flow Mach number: 0.29.

Effects of intake liner

Simulations were made with a point source located at $(0.0, 0.28, 0.0)$, which is in the plane of the fan LE. The induced sound field was calculated in the free field, in a hard-walled duct, and in a lined duct. For the dimensionless wall impedance, we took the frequency-dependent value $3 - i/\tan\left(0.01 \times 2\pi f/c\right)$, which corresponds to a liner cell depth of 1 cm, and a dimensionless cover plate resistance of 3. For the calculation of the in-duct sound fields use was made of the Green's function expression by Rienstra and Tester[11], which is valid for cylindrical lined ducts with uniform flow. Results of CB are shown in Fig. 10 (free field), Fig. 11 (hard wall), and Fig. 12 (lined wall).

The results of Fig. 10 are known as Point Spread Functions (PSF). The dynamic range (peak level minus highest side-lobe level) of the array is about 7 dB. Commonly, arrays for beamforming have higher dynamic range (about 12 dB). Nevertheless, a dynamic range of 7 dB is still high enough for obtaining meaningful beamforming results.

The hard-wall results of Fig. 11 show poor beamforming performance. At a number of frequencies the source position is not recovered as the peak location in the plots. Instead, multiple sources are observed due to multiple (coherent) refections, which are not modelled by the sound transfer model (i.e., the free-field Green's function). Furthermore, large level errors are made (the peak levels should be 0 dB).

For the lined-wall results shown in Fig. 12 the source location and its level appear to be good, at frequency bands above 1500 Hz. For increasing frequencies the source maps are more and more similar to the PSF-maps of Fig. 10.

More simulations showed that source location with the mode detection array is feasible for axial flow Mach numbers up to 0.8, any radial and azimuthal location, a wide range of liner properties, and frequencies higher than 1500 Hz (dimensionless frequencies: $2\pi Rf/c > 11$). The accuracy of the source levels, as calculated by the beamforming algorithm, is about 2 dB. For sources close to the duct wall, and at high Mach numbers larger errors are possible.

Axial resolution

Using the same simulated sound field in the lined duct, hence with the source in $(0.0, 0.28, 0.0)$, a scan was made in the x, y-plane with $z = 0$. The results are shown in Fig. 13. At none of the frequency bands the peak location coincides with the actual source location. If cross-sections of the pictures are made at $x = 0$, then, at the higher frequency bands, $y = 0.28$ is found as the peak location. But if cross-sections are made at other axial positions, then the peak values are found at different values of y. This was confirmed by beamforming applications on the fan rig of Section III. When the scan plane was moved downstream, the source locations moved away from the axis. With the current mode detection array it is therefore not possible to determine the axial position of a sound source.

V. Simulations with in-duct cage array

The mode detection array that was used in the previous sections is located at a single axial position, which may be disadvantageous. In order to investigate the merits of an in-duct array with axial extent, simulations were made with a "cage" array consisting of 5 rings of 20 equidistant microphones (see Fig. 14). The 5 microphone rings have the following axial locations: $x = -0.40$, $x = -0.31$, $x = -0.22$, $x = -0.13$, and $x = -0.04$.

As in the previous section, beamforming simulations were made with a source at $(0.0, 0.28, 0.0)$ in a lined duct. The results, shown in Fig. 15, are definitely better than the simulations with the mode detection array (Fig. 12). The resolution is higher and the side-lobe levels are lower. In Fig. 16 it is shown that it is even possible to produce meaningful source maps in a hard-walled duct.

In Fig. 17 a source map is shown in an x, y-plane with $z = 0$. Compared to Fig. 13, the axial resolution is much better now. At the highest frequencies it may even be possible to distinguish between leading edge and trailing edge noise sources.

VI. Conclusion

Using existing data from a mode detection array in the intake of a fan rig, it was demonstrated that in-duct beamforming on a fan and a stator is feasible. By Conventional Beamforming, sources were made visible on the stator. Moreover, using beamforming with rotating focus, sources were visualized on the fan. Distinction could be made between tonal and broadband noise.

It was shown that the mode detection array has a dynamic range (peak vs. side-lobe level) of about 7 dB, when it is used for beamforming. This is less than for traditional phased arrays, but sufficient to locate sources. Simulations using a Green's function in a lined flow duct showed that a liner is absolutely necessary for obtaining meaningful beamforming results, but the liner properties are not critical. With an intake mode detection array there is, however, practically no axial resolution. Radial locations of peak sources depend on the axial positions of the scan plane.

With an in-duct "cage" array, consisting of 5 parallel microphone arrays in the intake, significant improvements are predicted in dynamic range and resolution. Also reasonably high resolution in axial direction is predicted, such that distinction between leading and trailing edge comes within reach. With such an array, it looks even possible to locate sources in the absence of a liner.

B Acknowledgments

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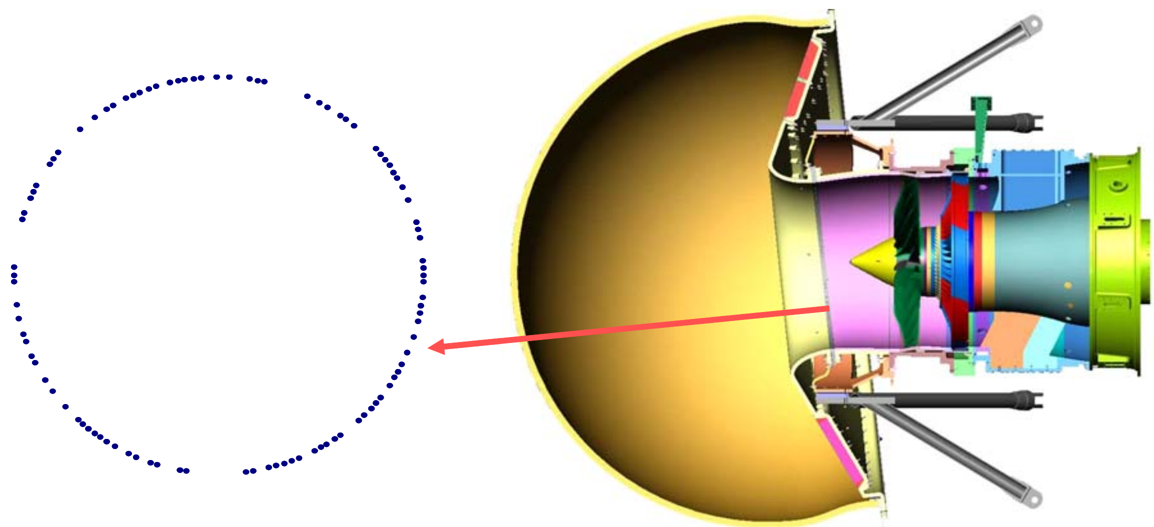

Figure 1. Drawing of fan rig; the mode detection array is located on the grey strip in the intake (fan and array diameter ±80 cm, array ±40 cm ahead of the fan).

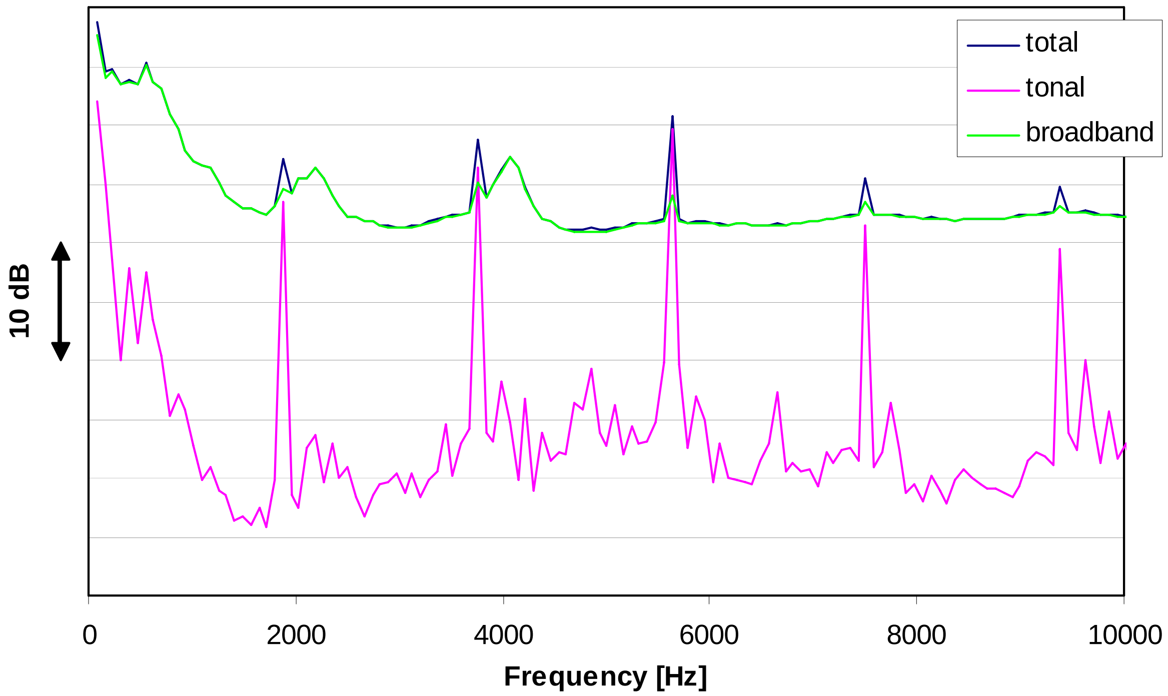

Figure 2. Average auto-spectrum at microphone array; breakdown into tonal and broadband noise.

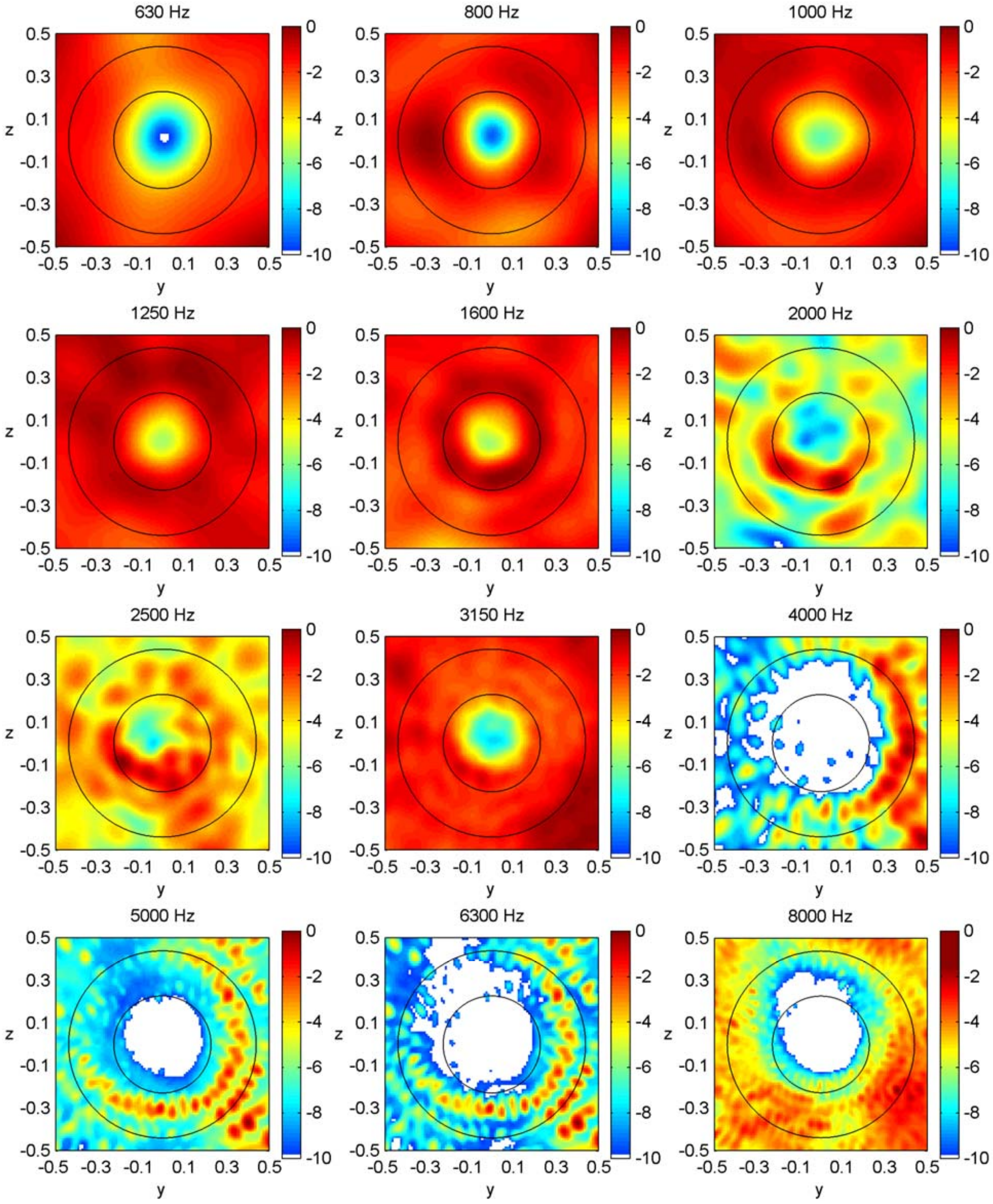

Figure 3. CB results on stator LE plane; fan rig measurements.

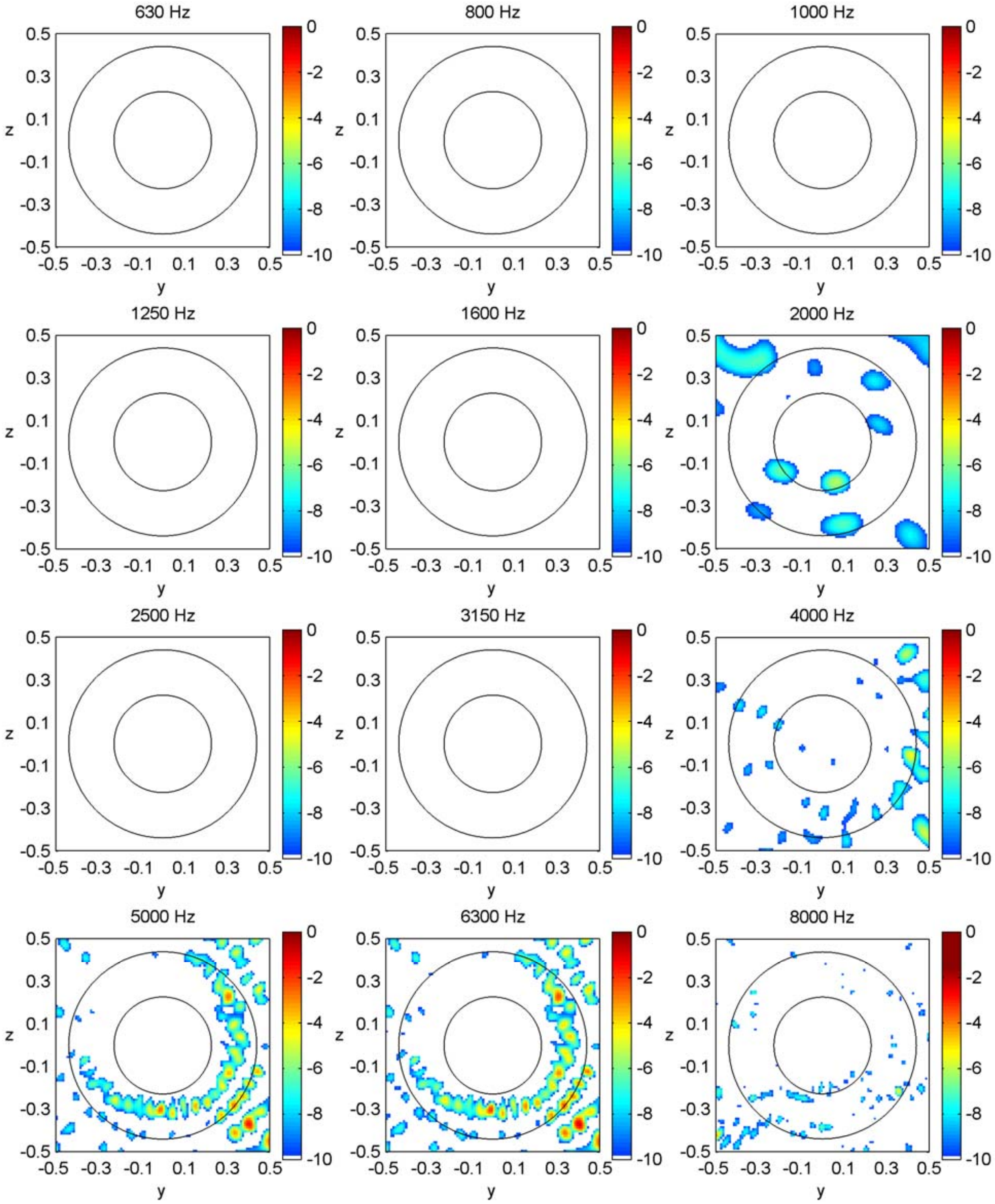

Figure 4. CB results on stator LE plane – tonal noise; fan rig measurements.

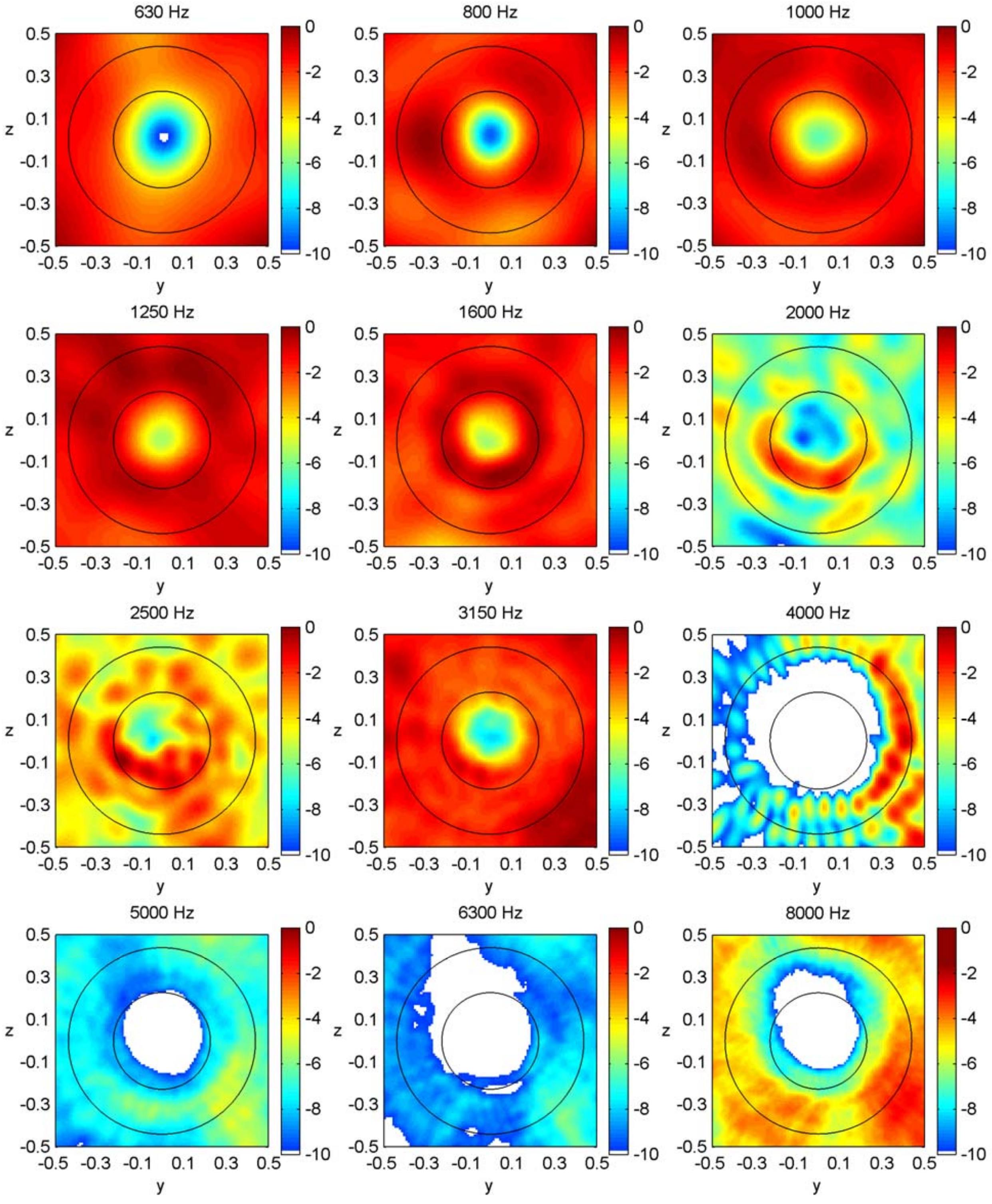

Figure 5. CB results on stator LE plane – broadband noise; fan rig measurements.

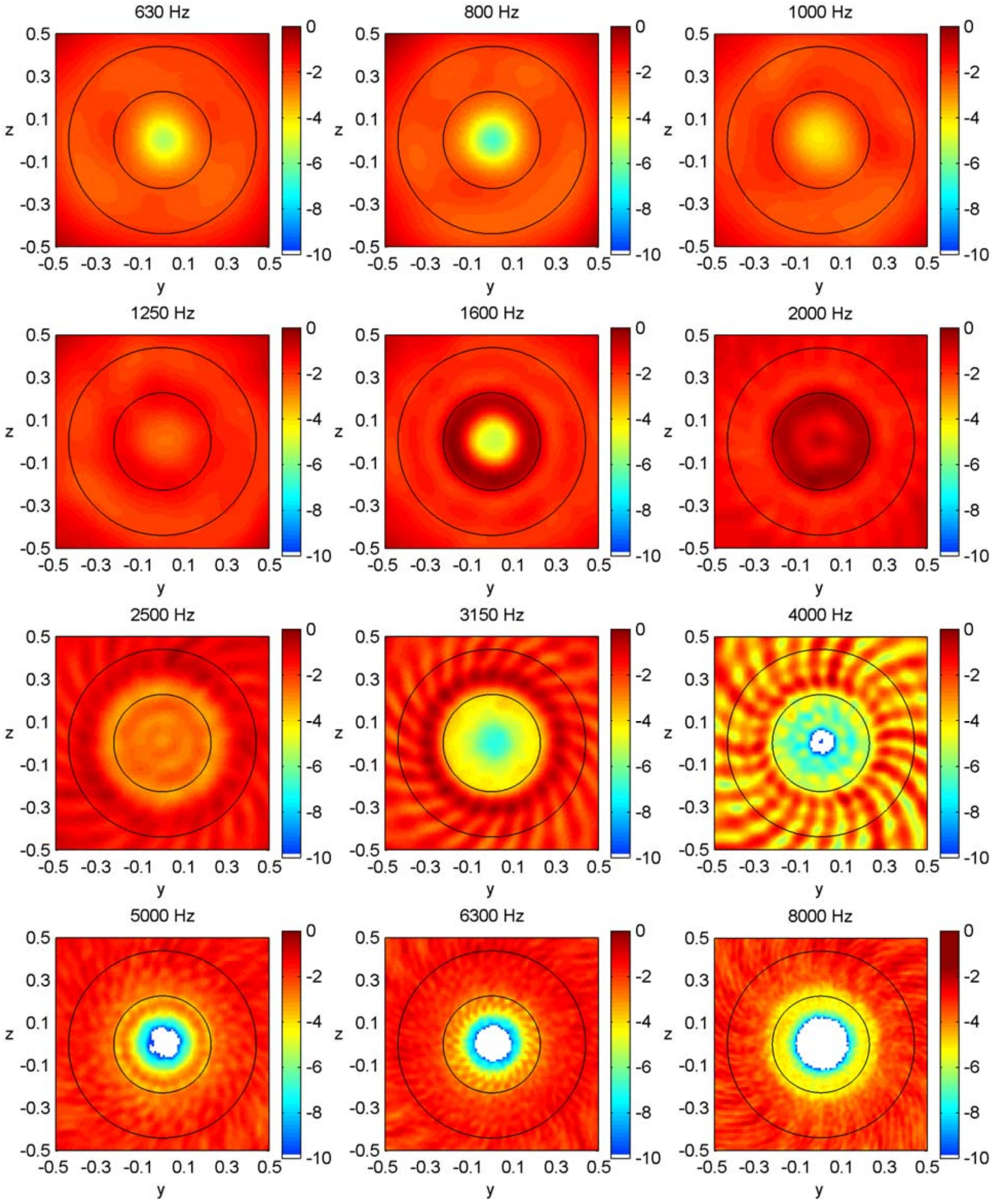

Figure 6. ROSI results on fan LE plane; fan rig measurements.

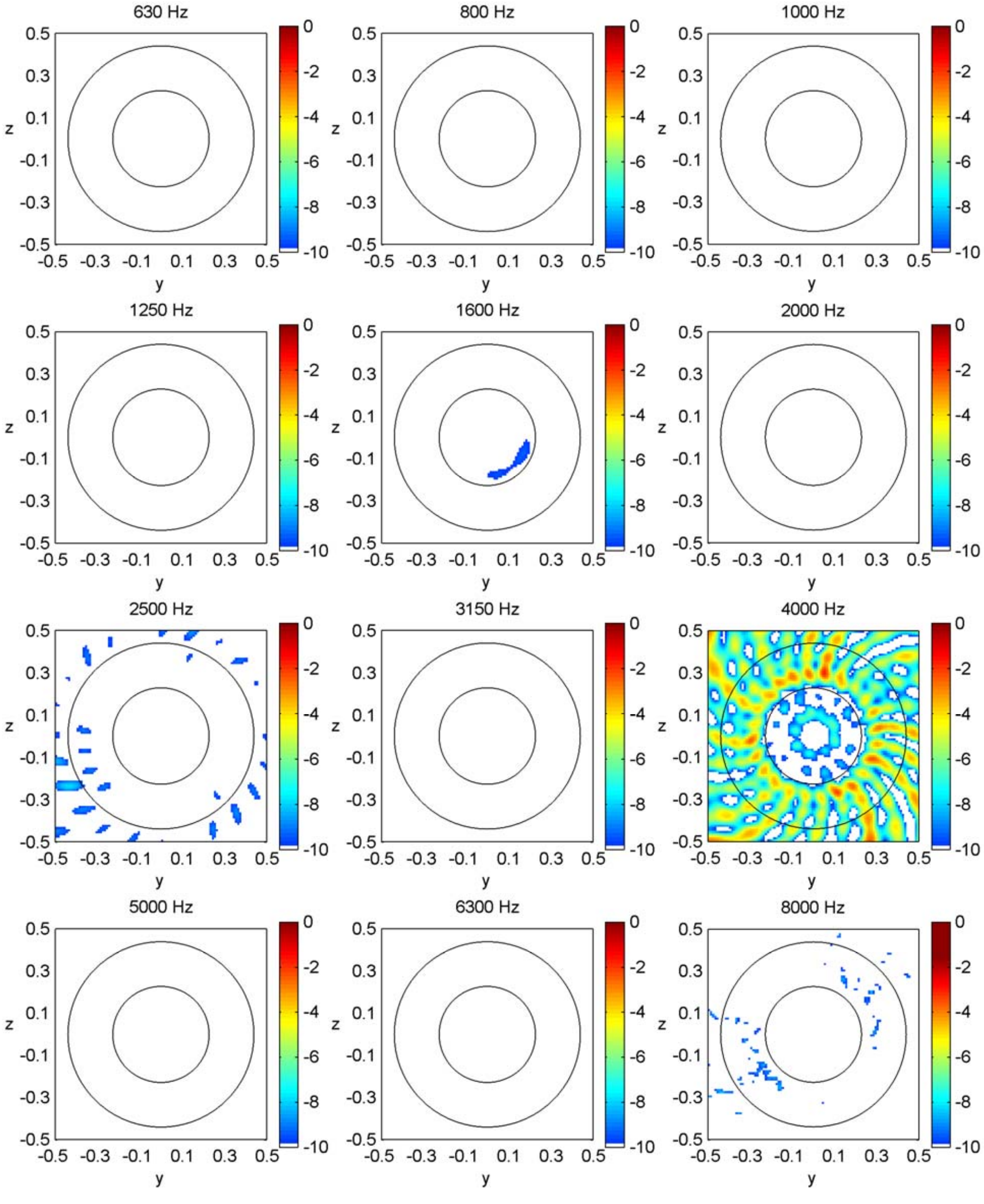

Figure 7. ROSI results on fan LE plane – tonal noise; fan rig measurements.

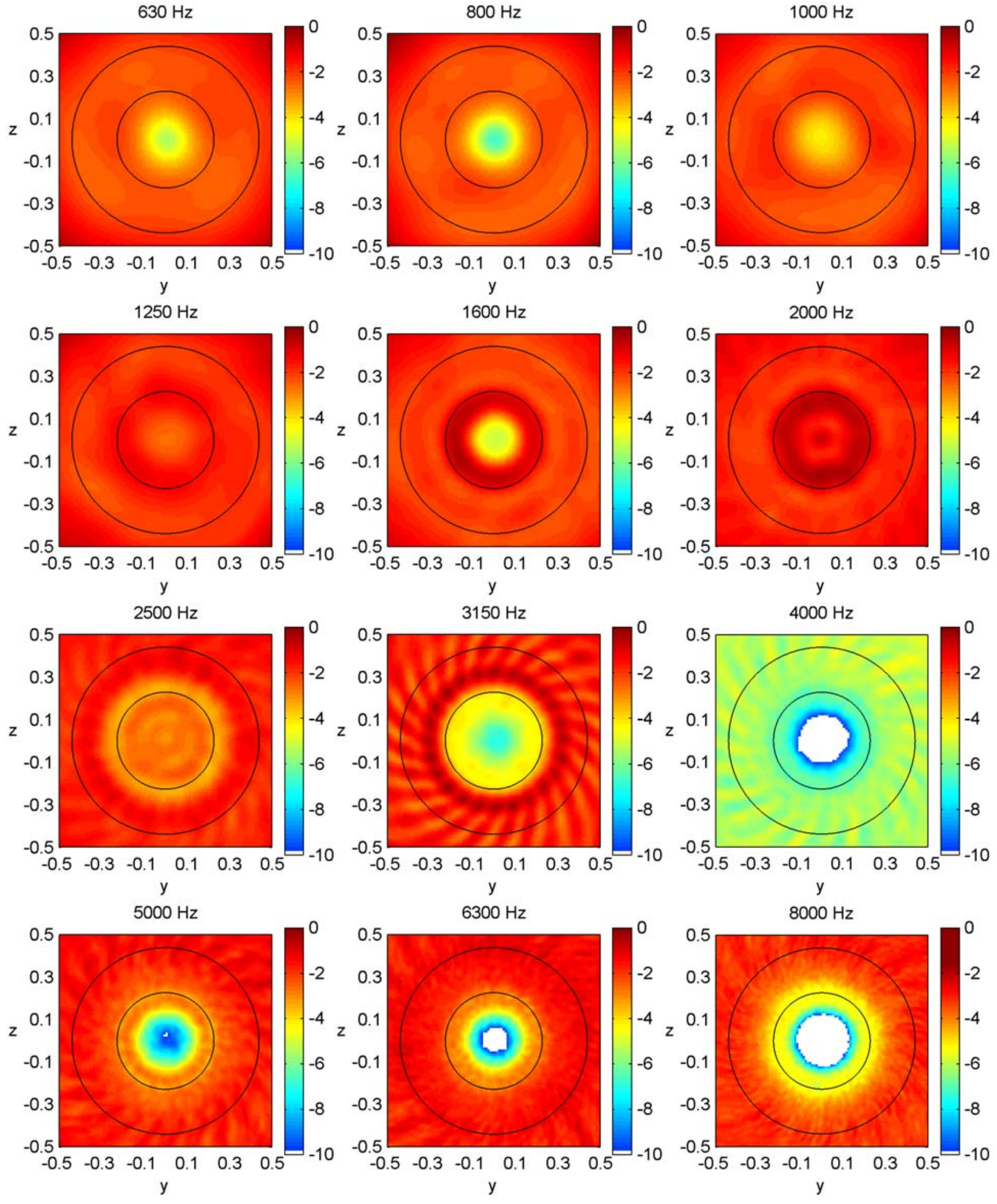

Figure 8. ROSI results on fan LE plane – broadband noise; fan rig measurements.

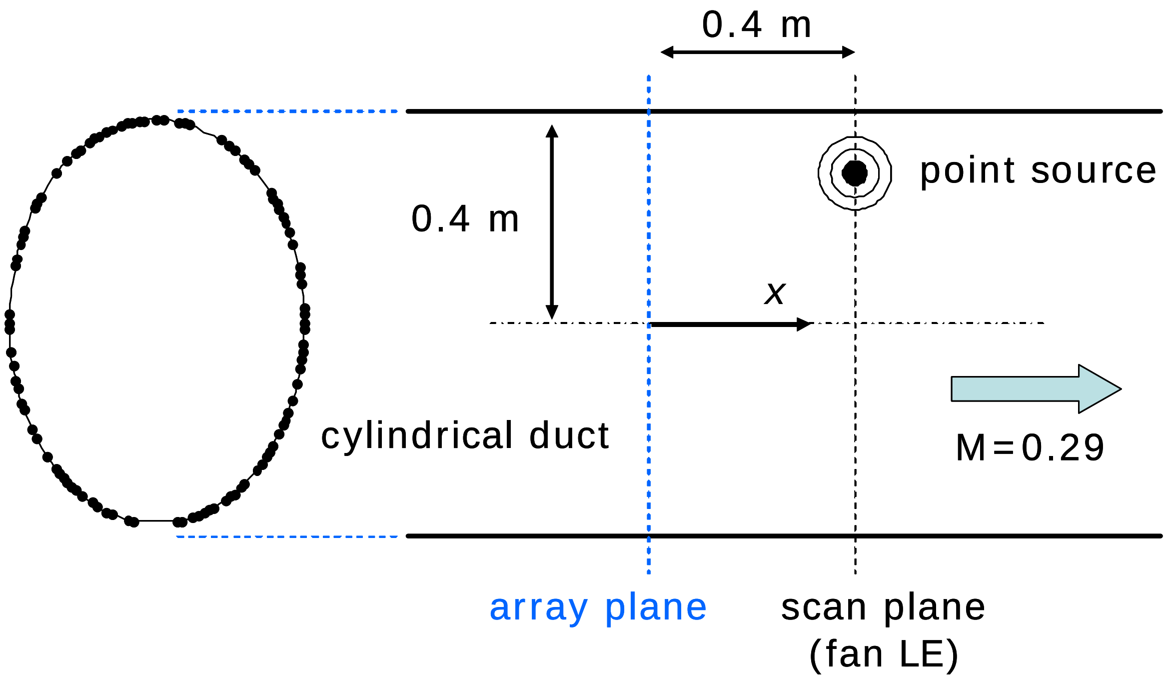

Figure 9. Sketch of geometry for simulations with mode detection array

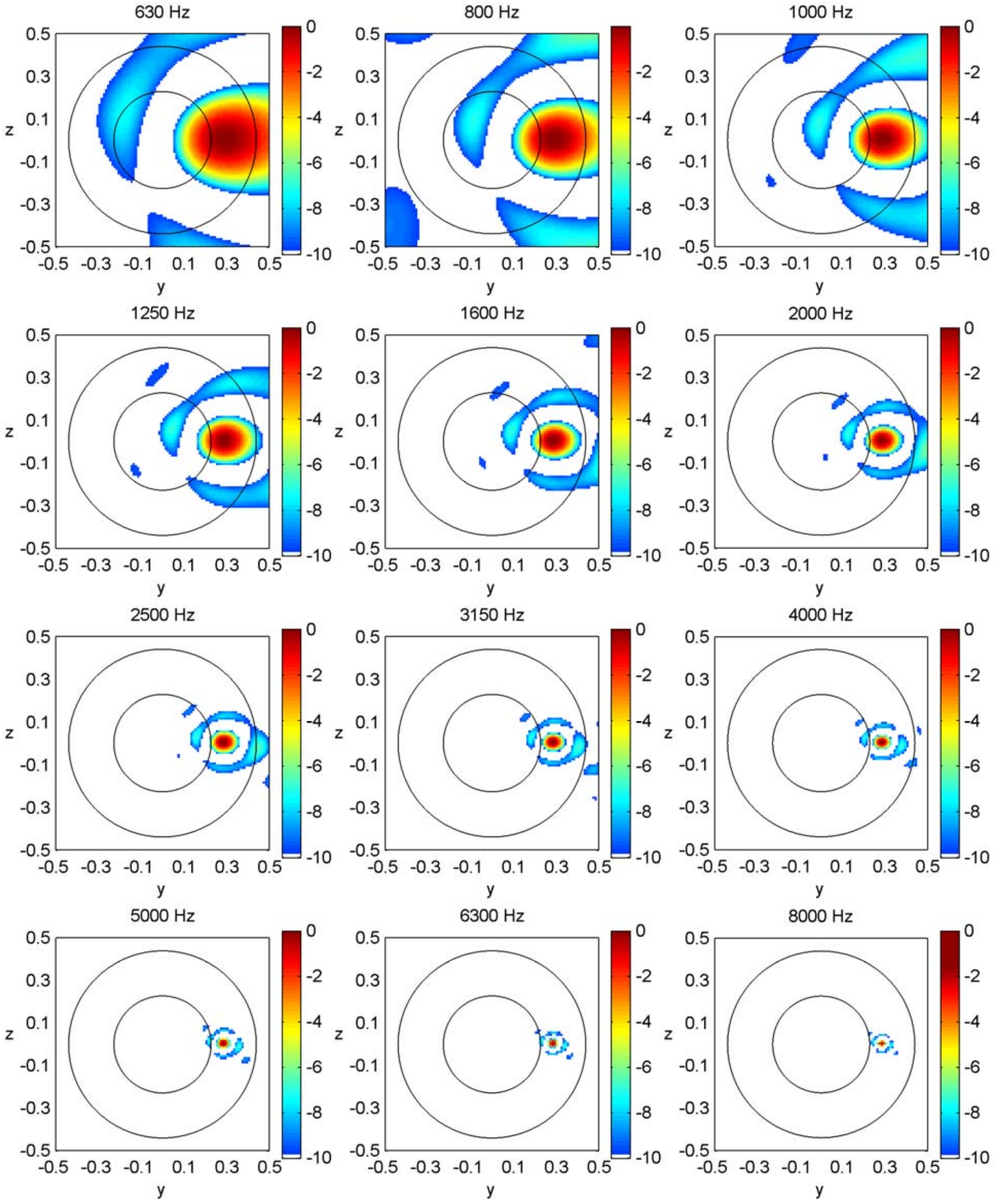

Figure 10. CB results of point source in free-field (PSF's) ; simulations with mode detection array.

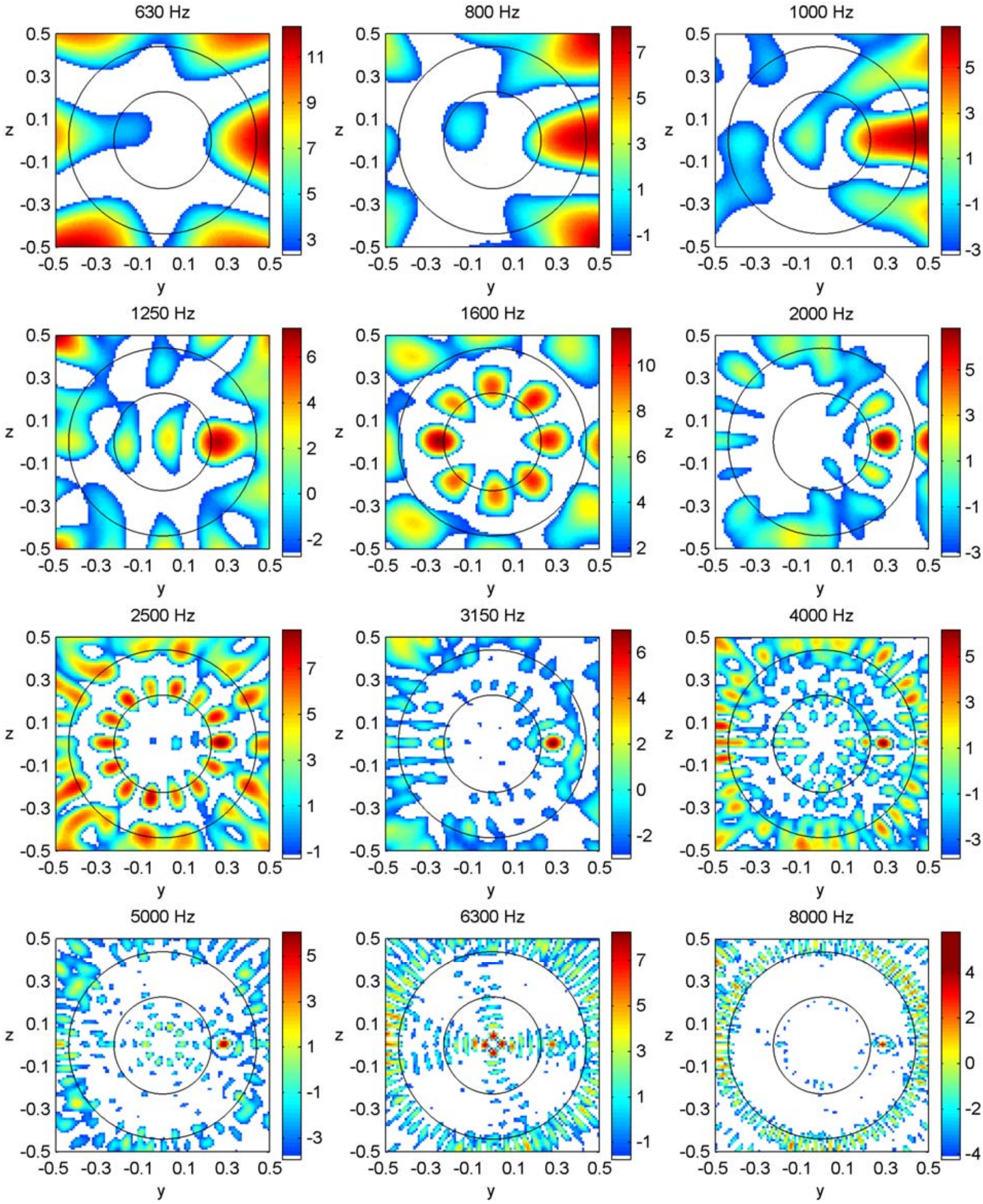

Figure 11. CB results of point source in hard-walled duct; simulations with mode detection array.

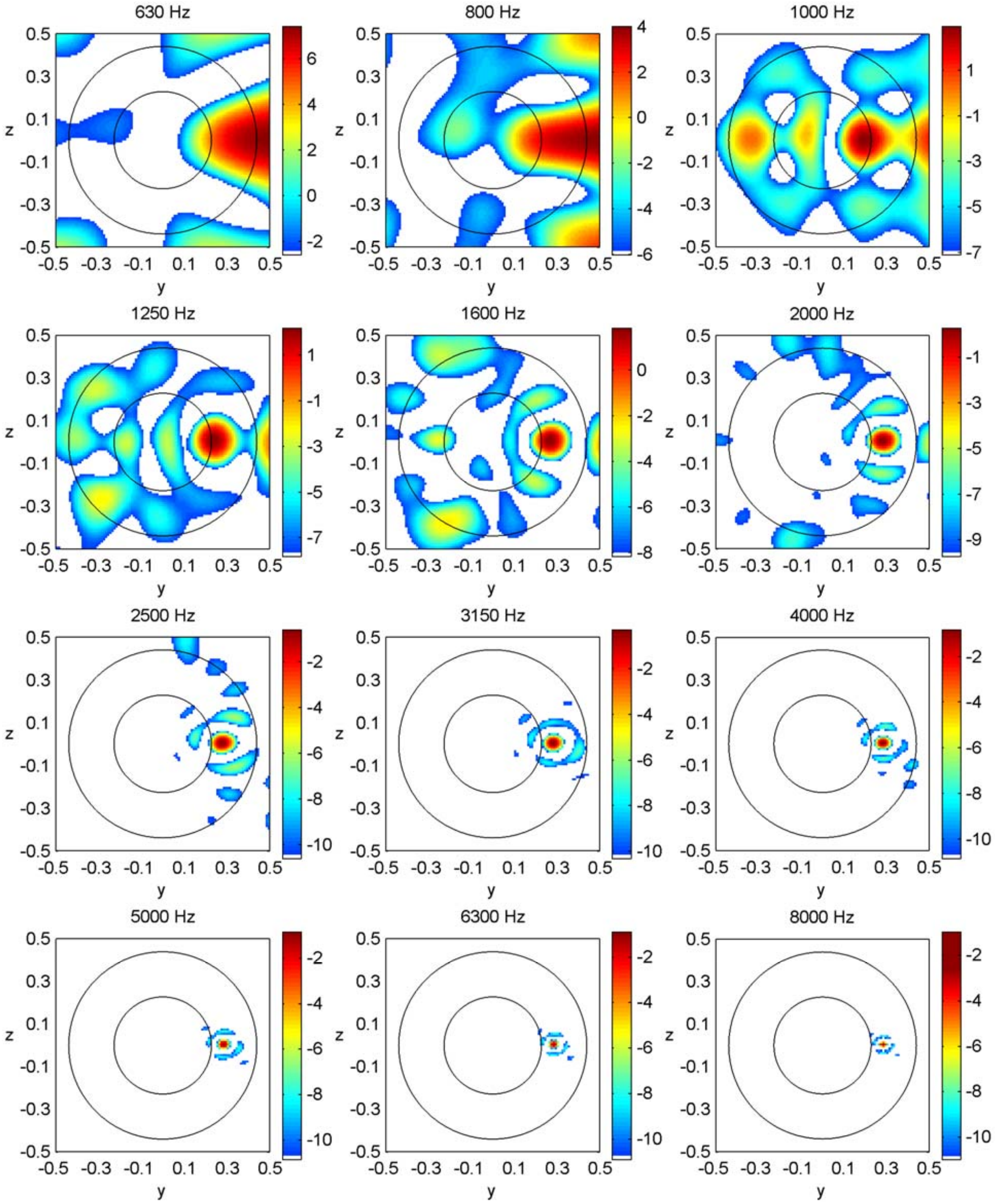

Figure 12. CB results of point source in lined duct; simulations with mode detection array.

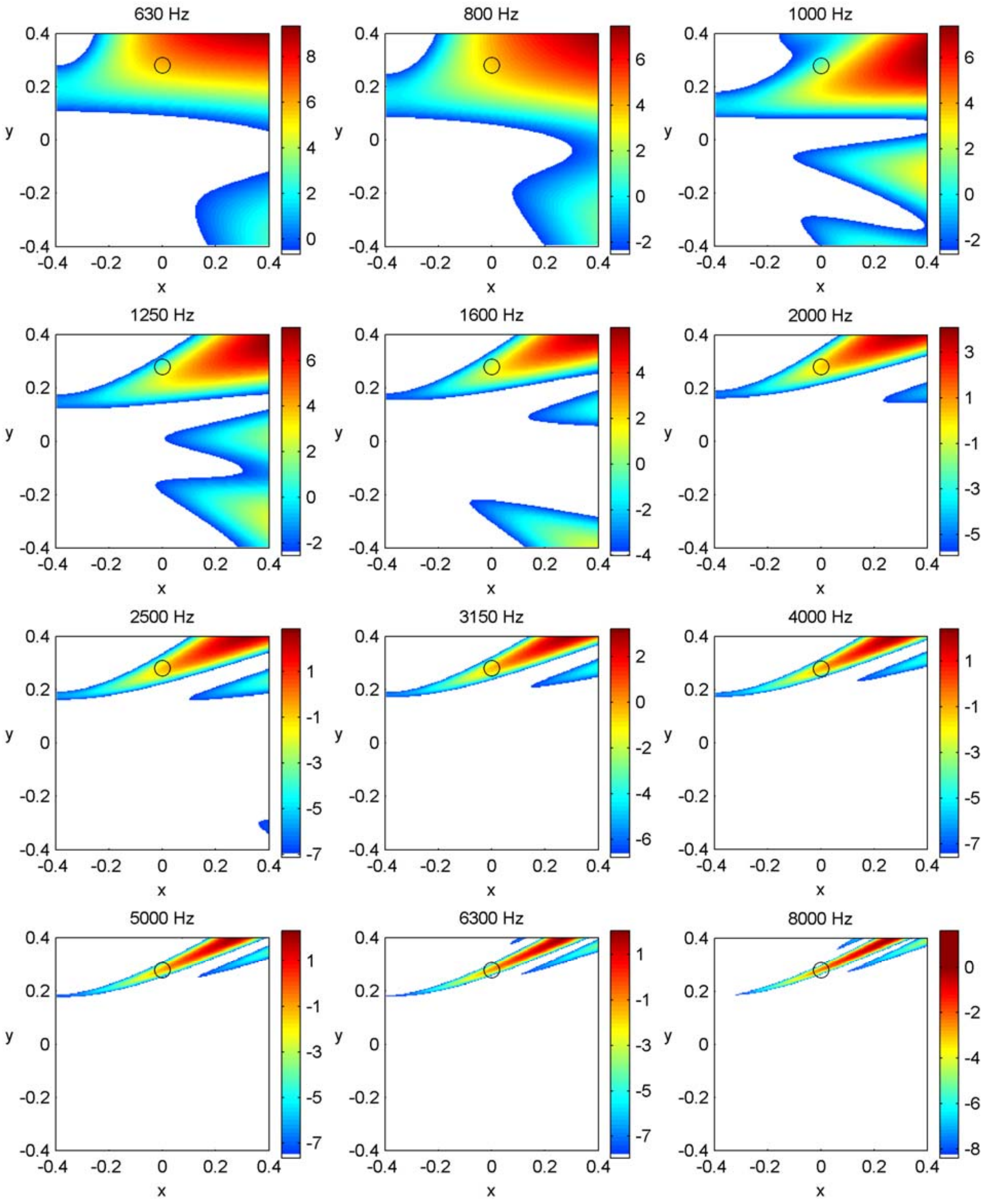

Figure 13. CB results of point source in lined duct; scan grid on x,y-plane (z = 0); simulations with mode detection array.

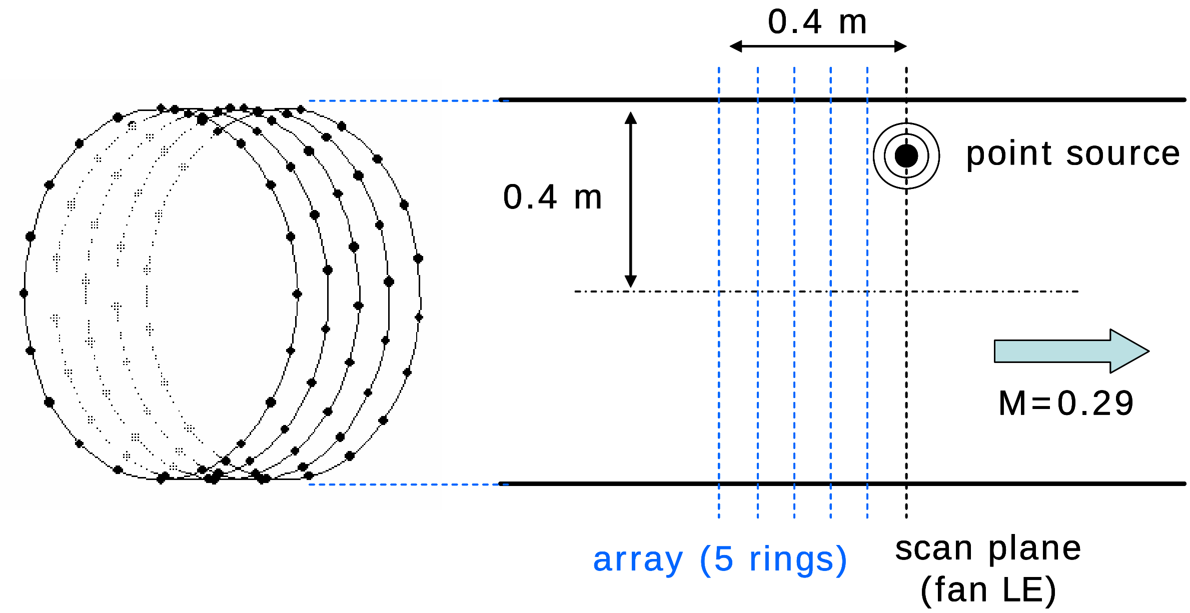

Figure 14. Sketch of geometry for simulations with cage array

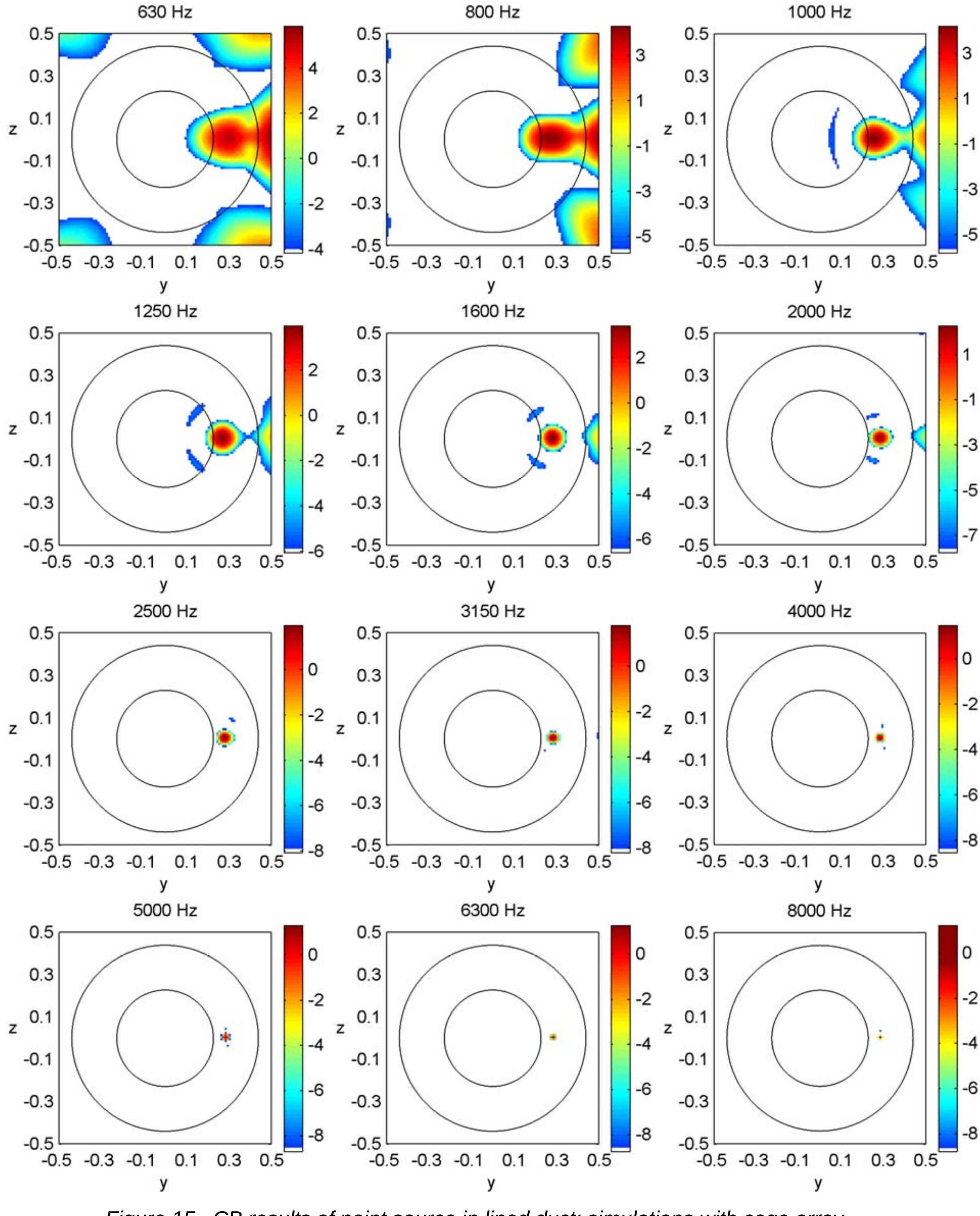

Figure 15. CB results of point source in lined duct; simulations with cage array.

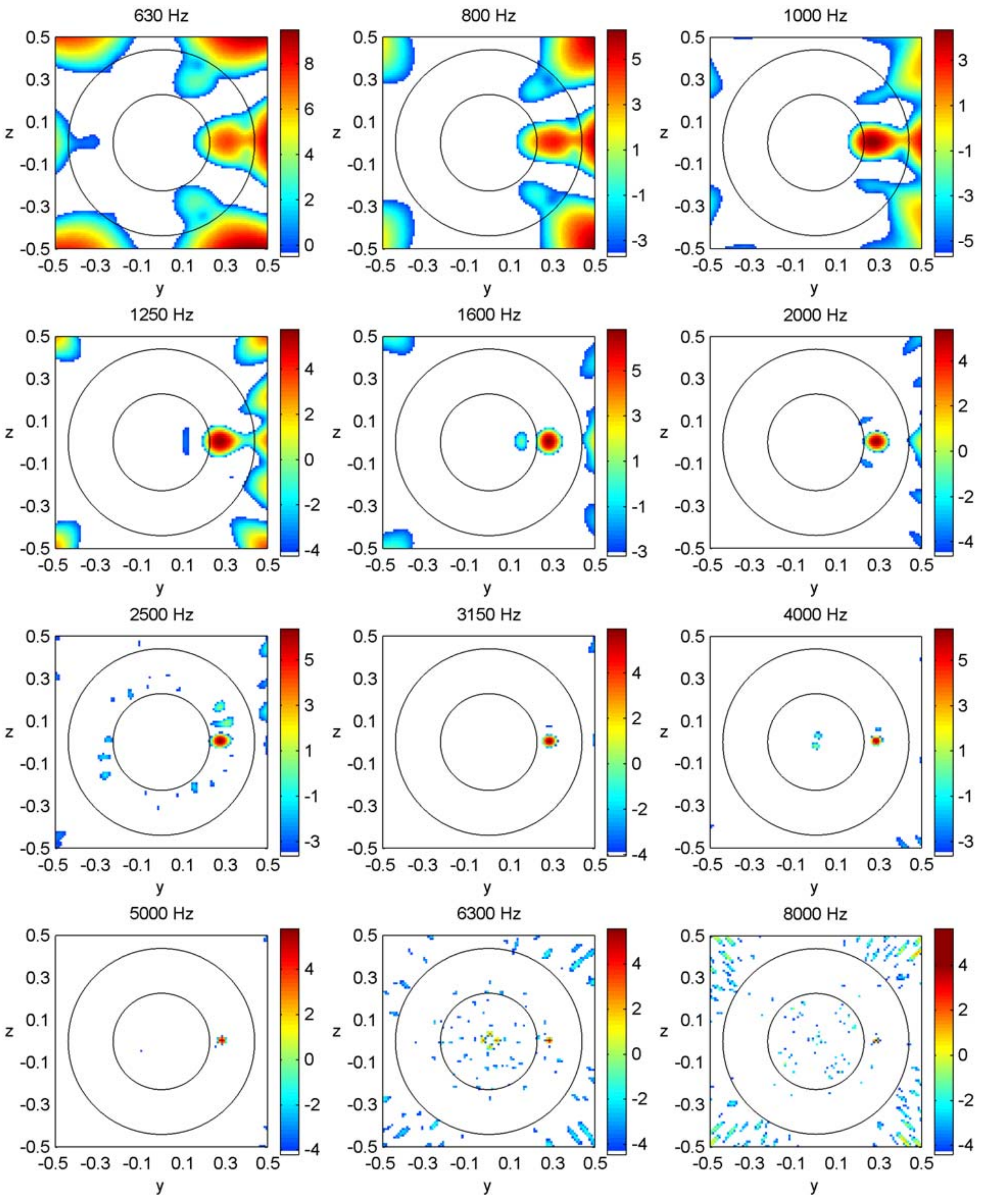

Figure 16. CB results of point source in hard-walled duct; simulations with cage array.

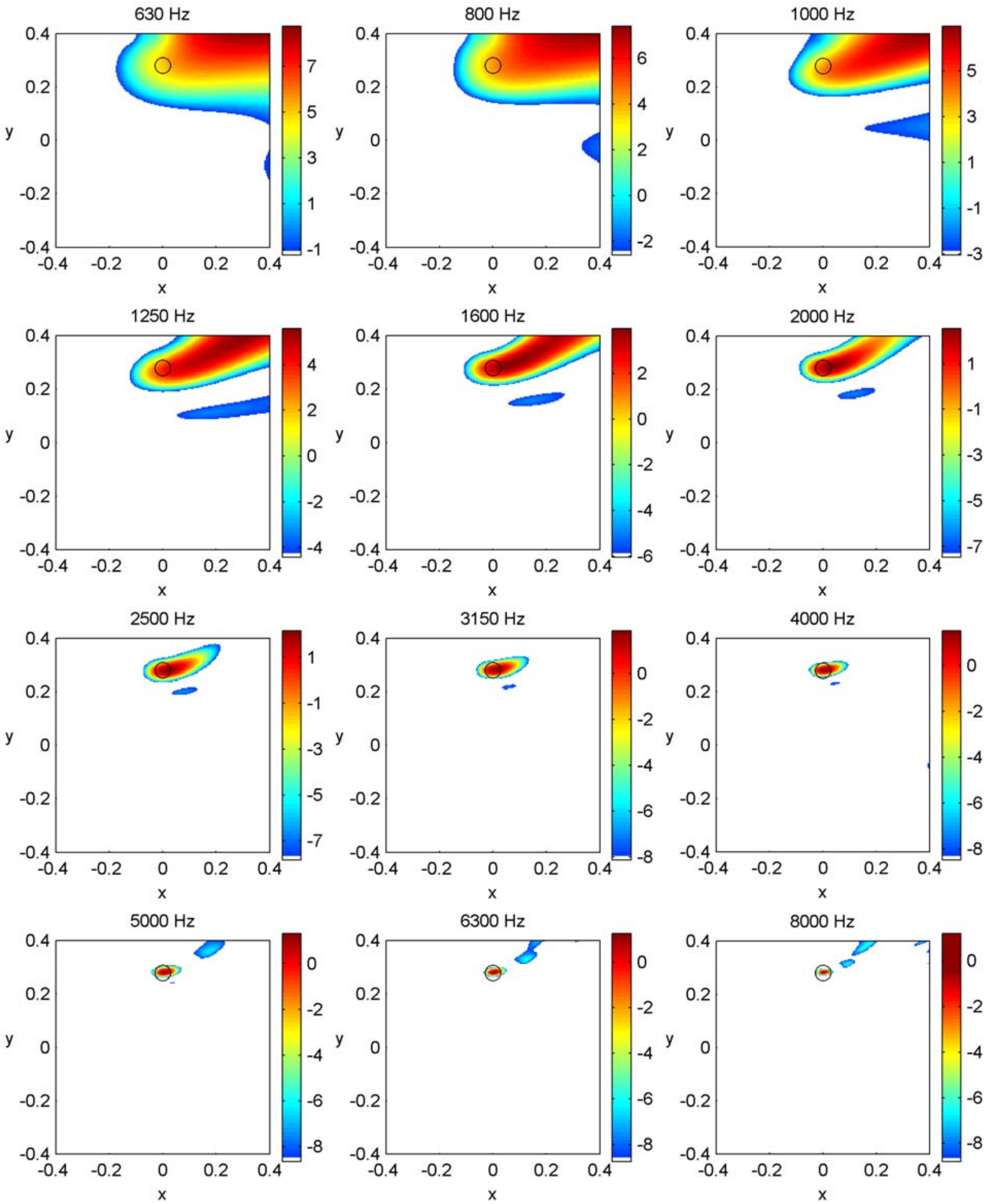

Figure 17. CB results of point source in lined duct; scan grid on x,y-plane (z = 0); simulations with cage array.