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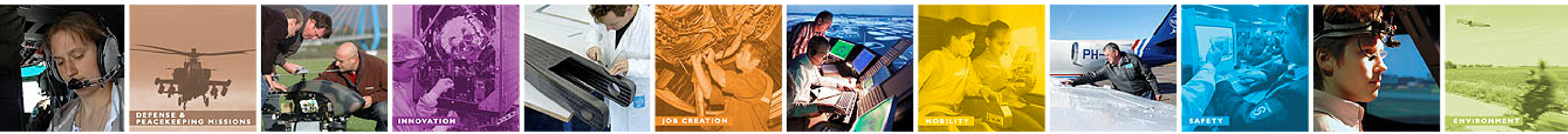

Using Phased Array Beamforming to Identify Broadband Noise Sources in a Turbofan Engine

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National Aerospace Laboratory NLR
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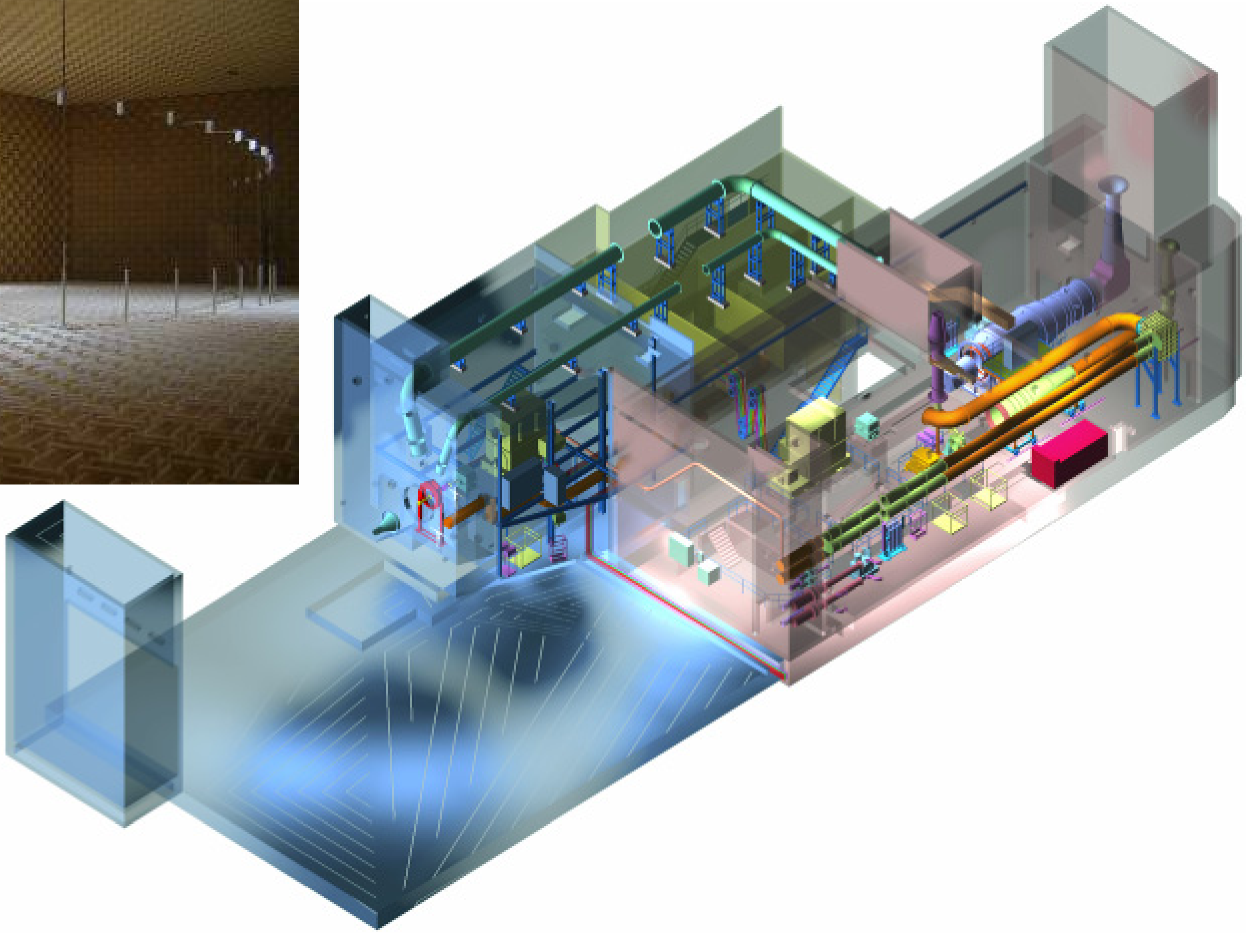
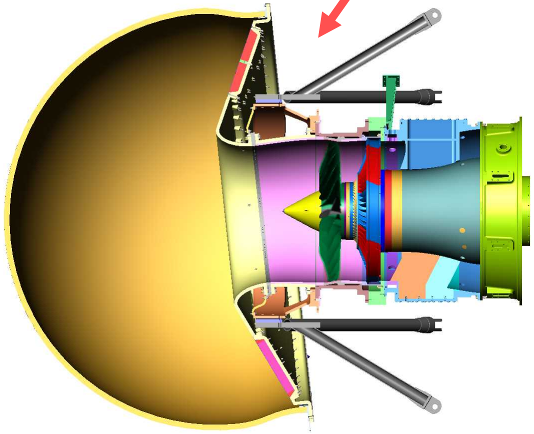
PROBAND rig testing at AneCom

anechoic hall

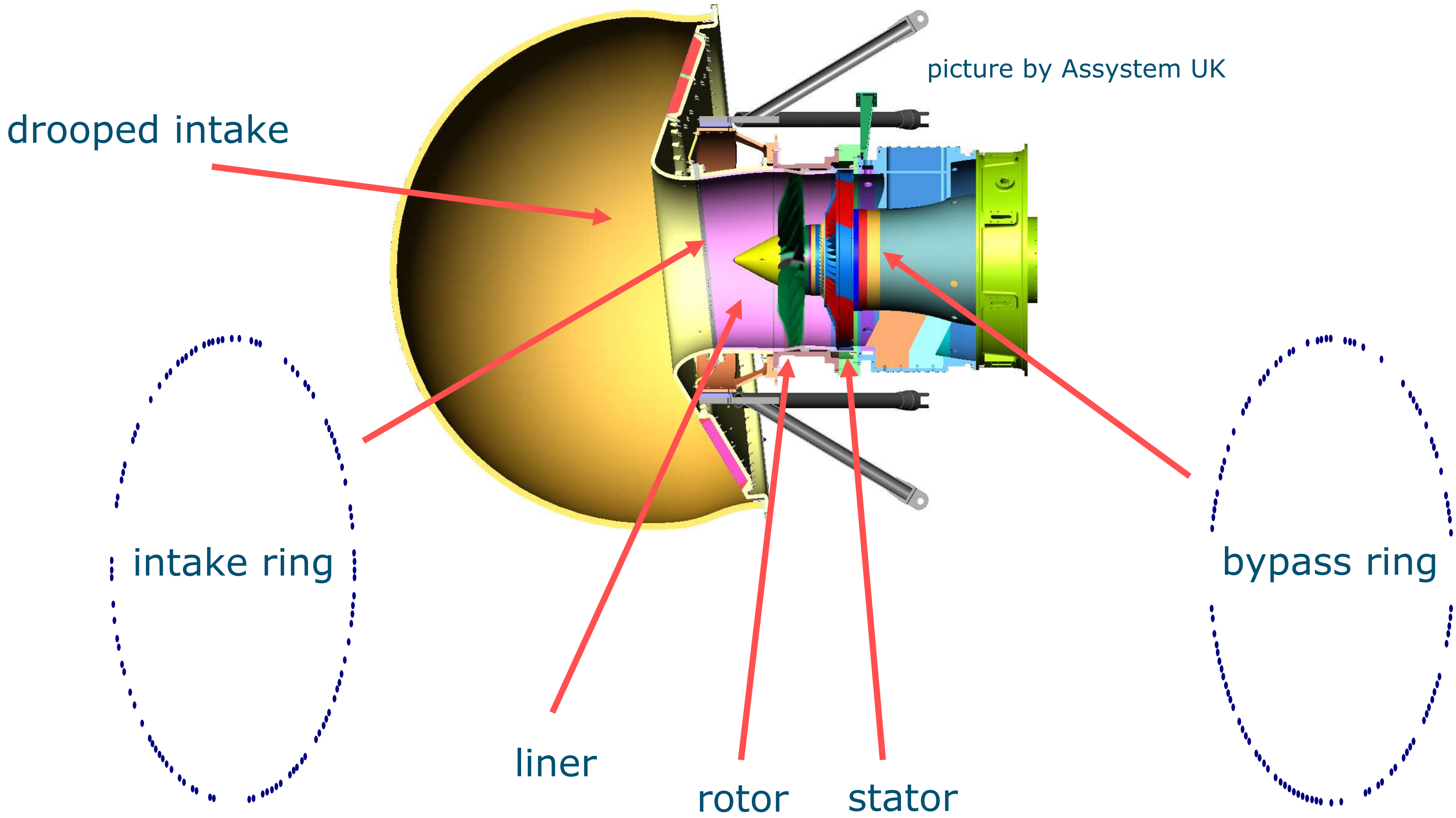
AneCom-AeroTest facility
(near Berlin)



RR fan rig

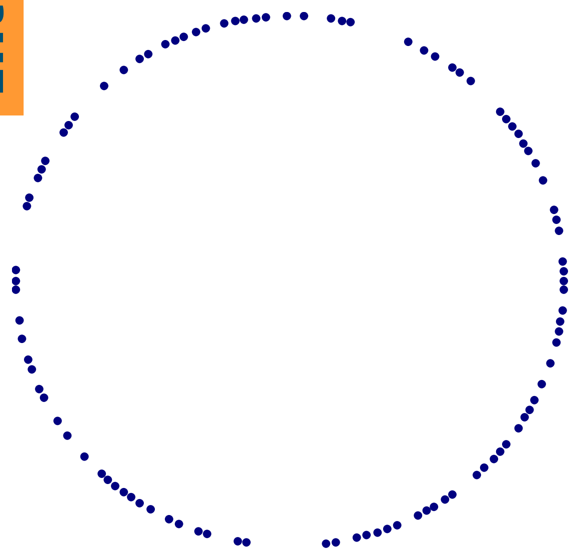


NLR contribution to rig tests

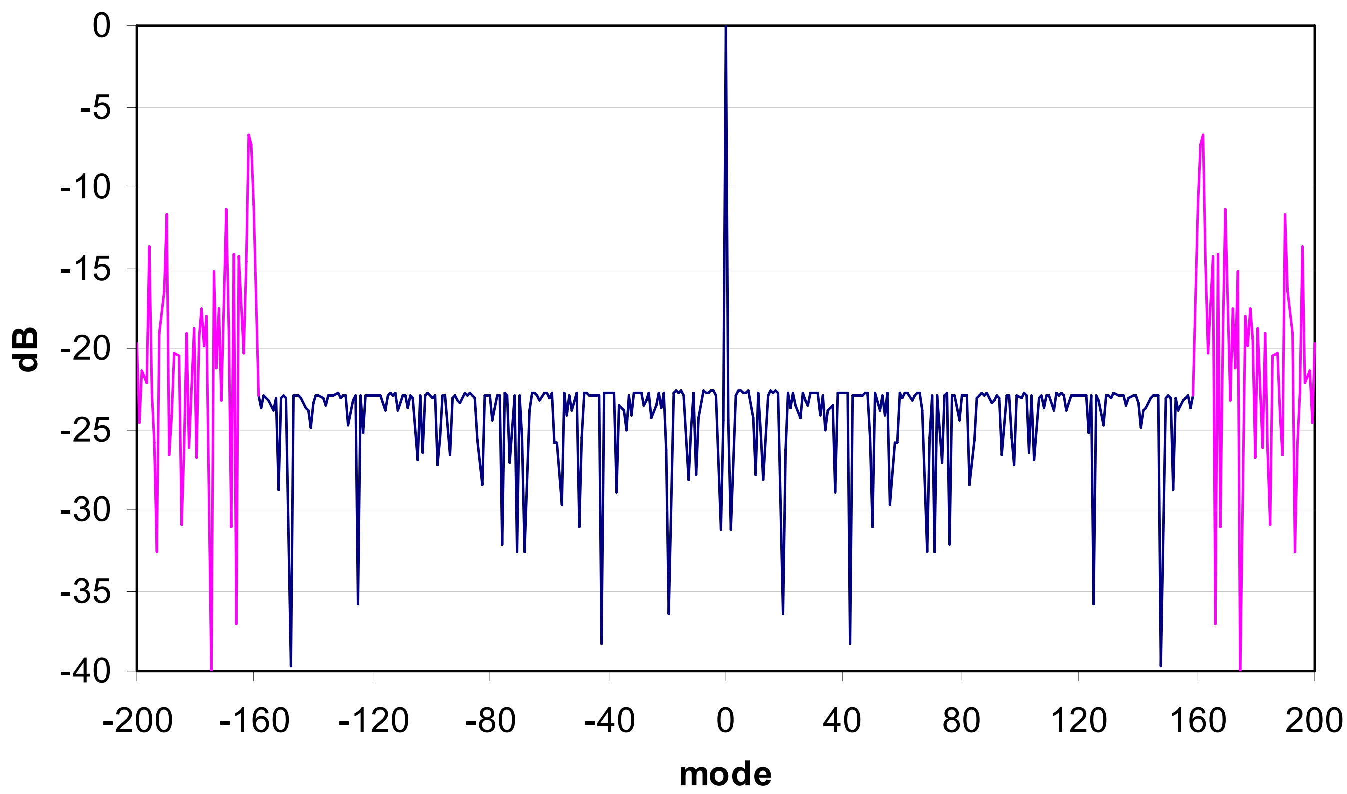


Introduction

Non-uniform arrays for azimuthal mode detection



array response of single azimuthal mode



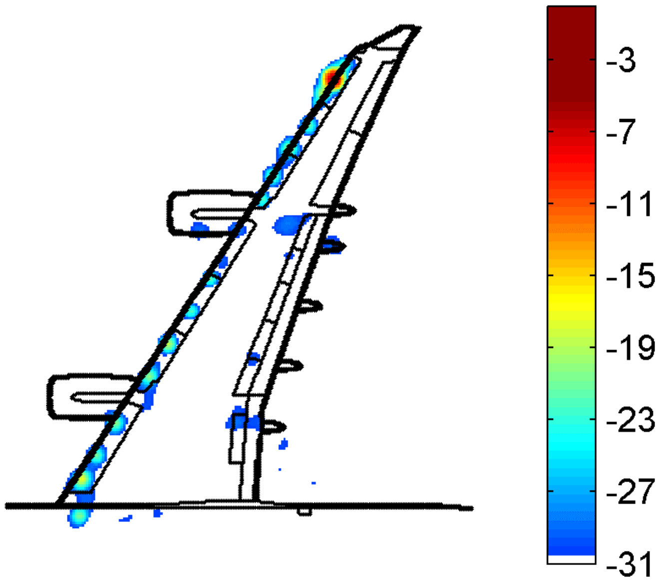
Merits of azimuthal mode detection

- **Valuable for tonal noise**
  - Gives information about noise generating mechanisms:
    - Rotor alone noise
    - Rotor/stator interaction noise
    - Interaction by steady distortion
  - Gives information about liner performance

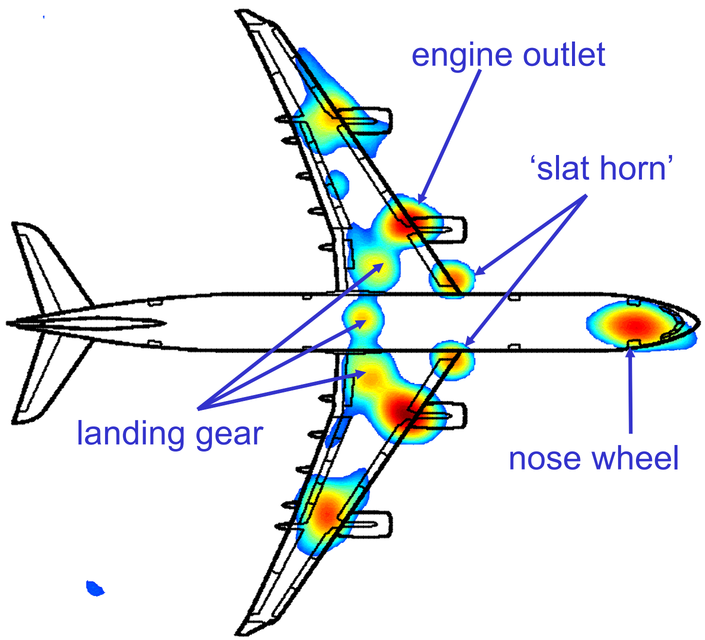
- **Less valuable for broadband noise**
  - Gives information about liner performance
  - Information about noise sources is limited
  - No detailed information about source location, e.g.:
    - rotor or stator
    - leading edge or trailing edge
    - spanwise or concentrated at the blade tips

Possible added value by phased array beamforming

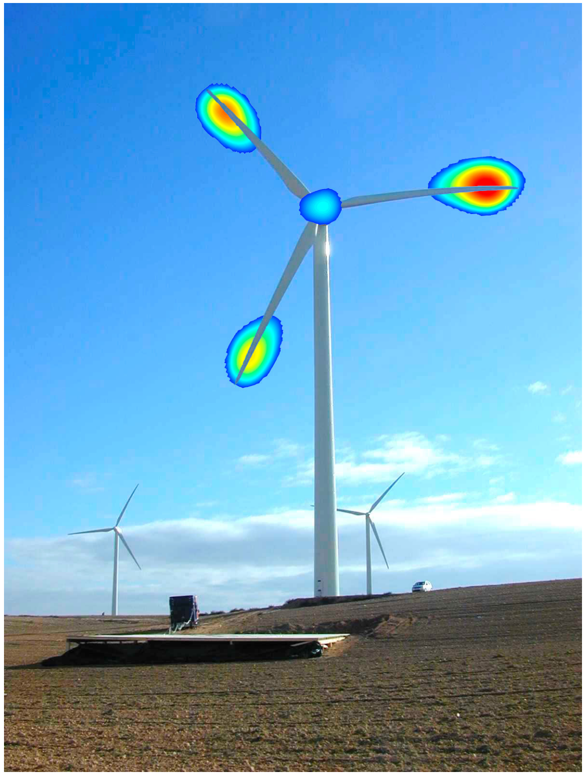
wind tunnel measurement



fly-over measurement

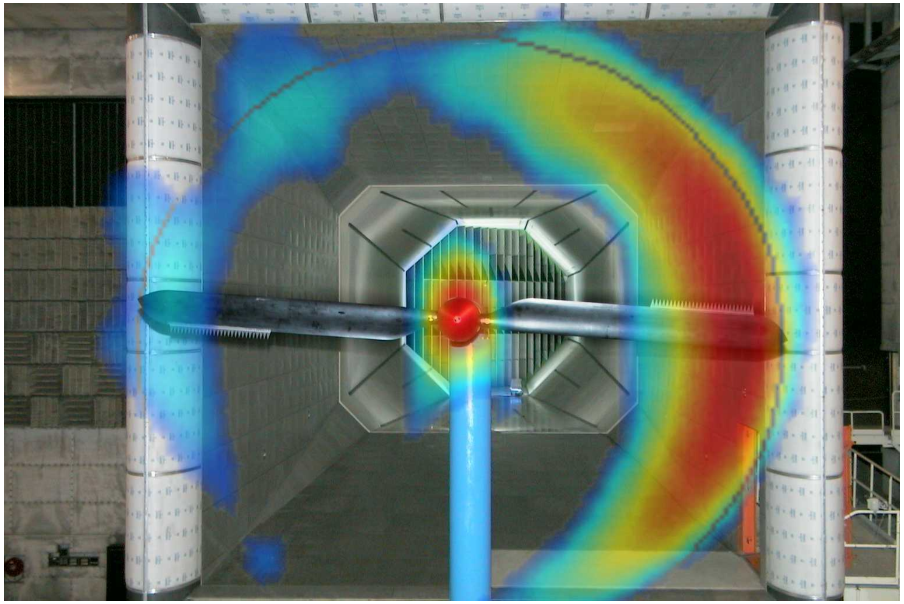


field measurement

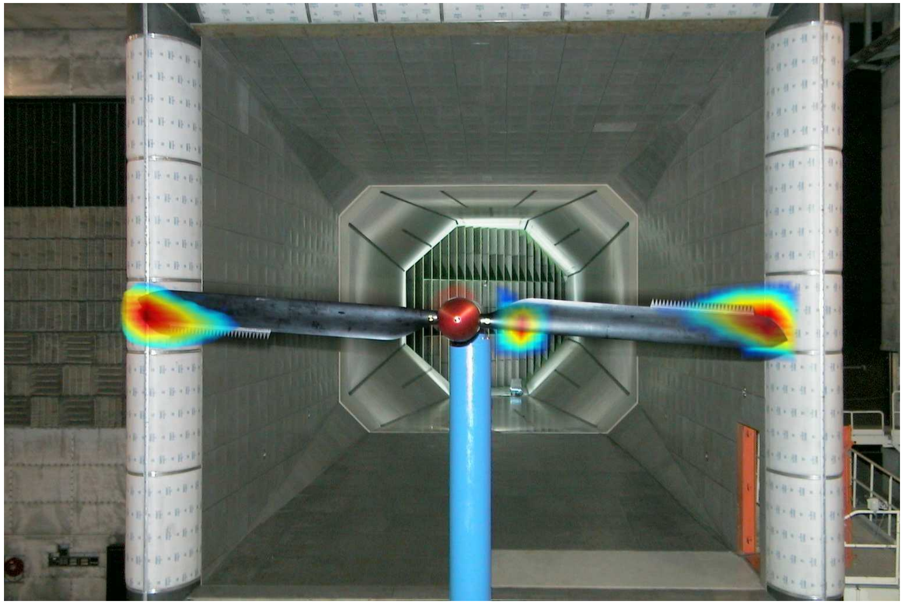


Beamforming: stationary and rotation focus (1)

Stationary focus



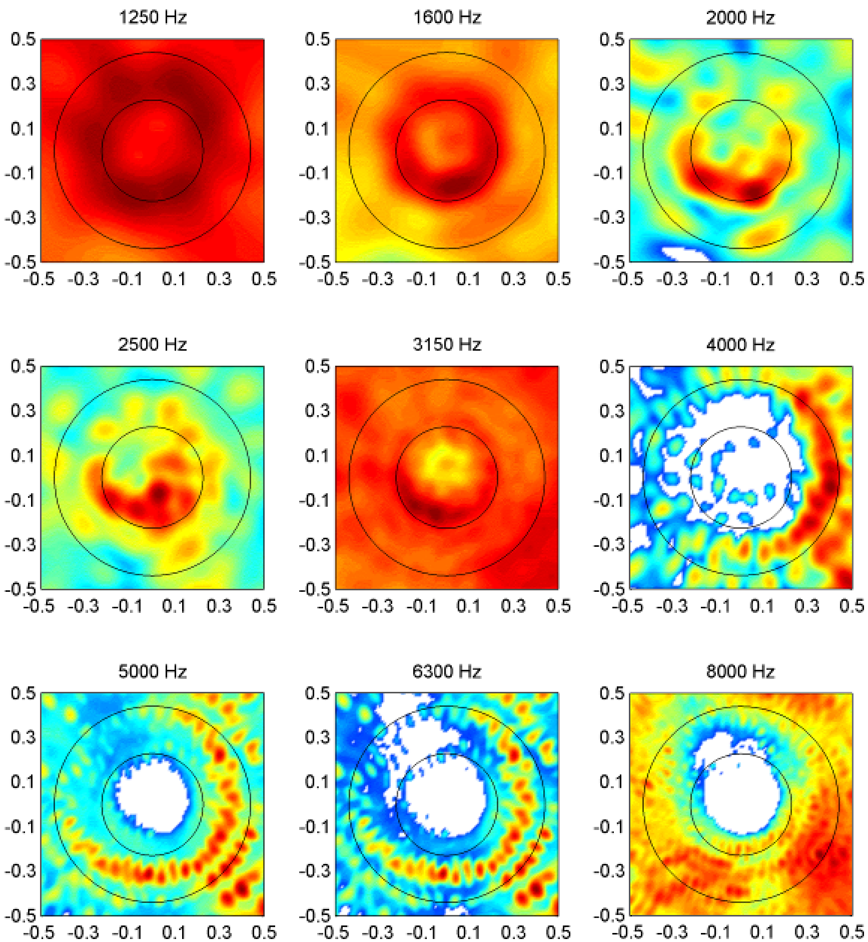
Rotating focus



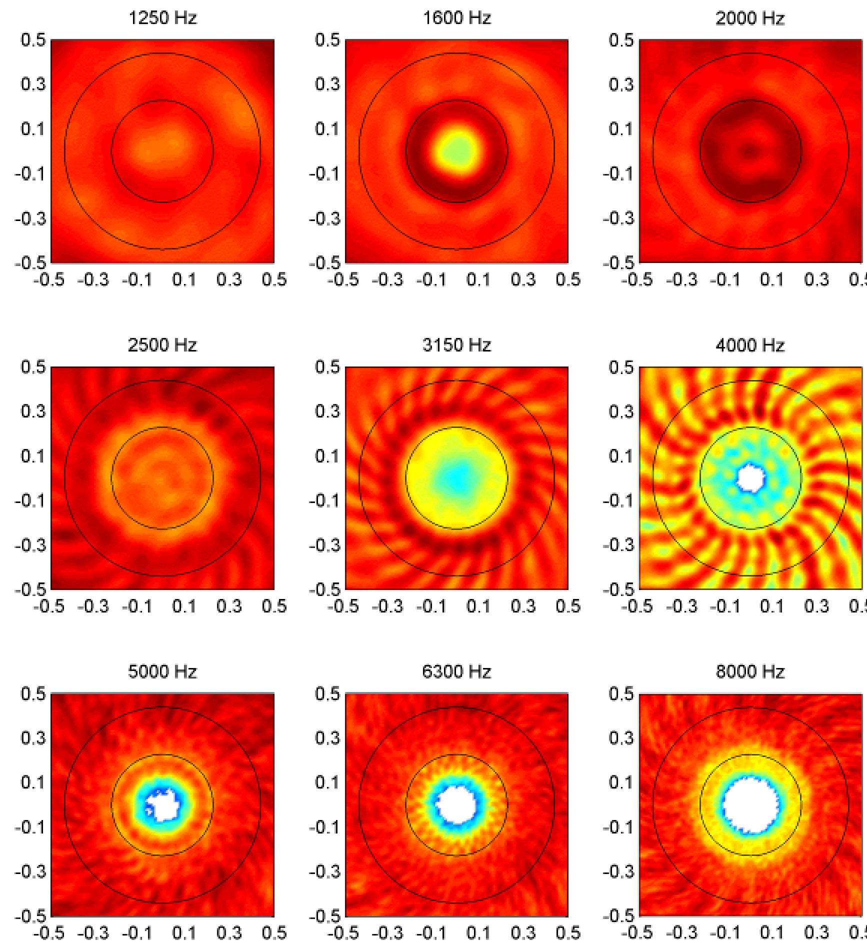
from [Sijtsma-2001]

Beamforming: stationary and rotation focus (2)

beamform results with intake array [sijtsma-2006]



stationary focus (stator LE)



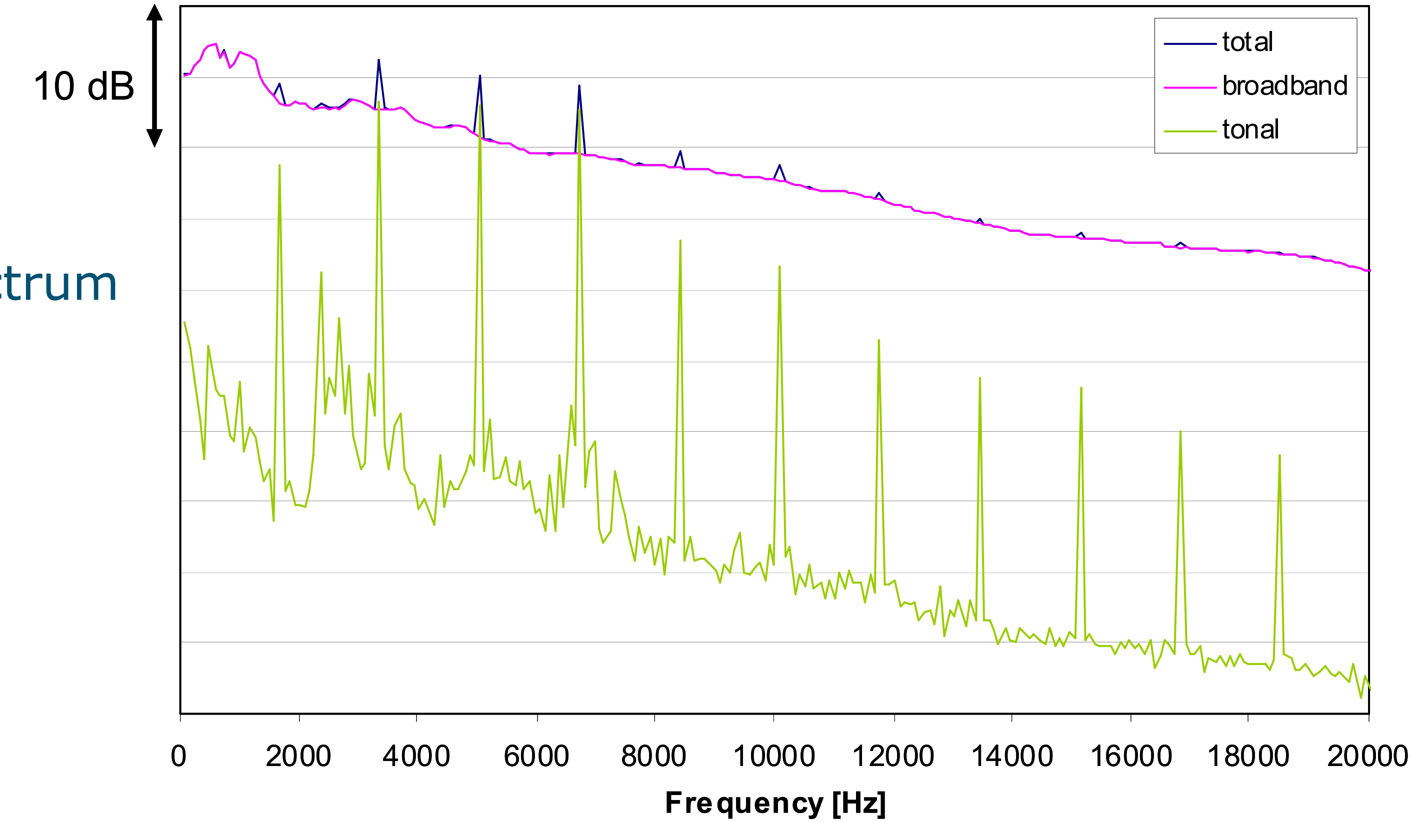
rotating focus (rotor LE)

Contents

Tonal and broadband noise (1)

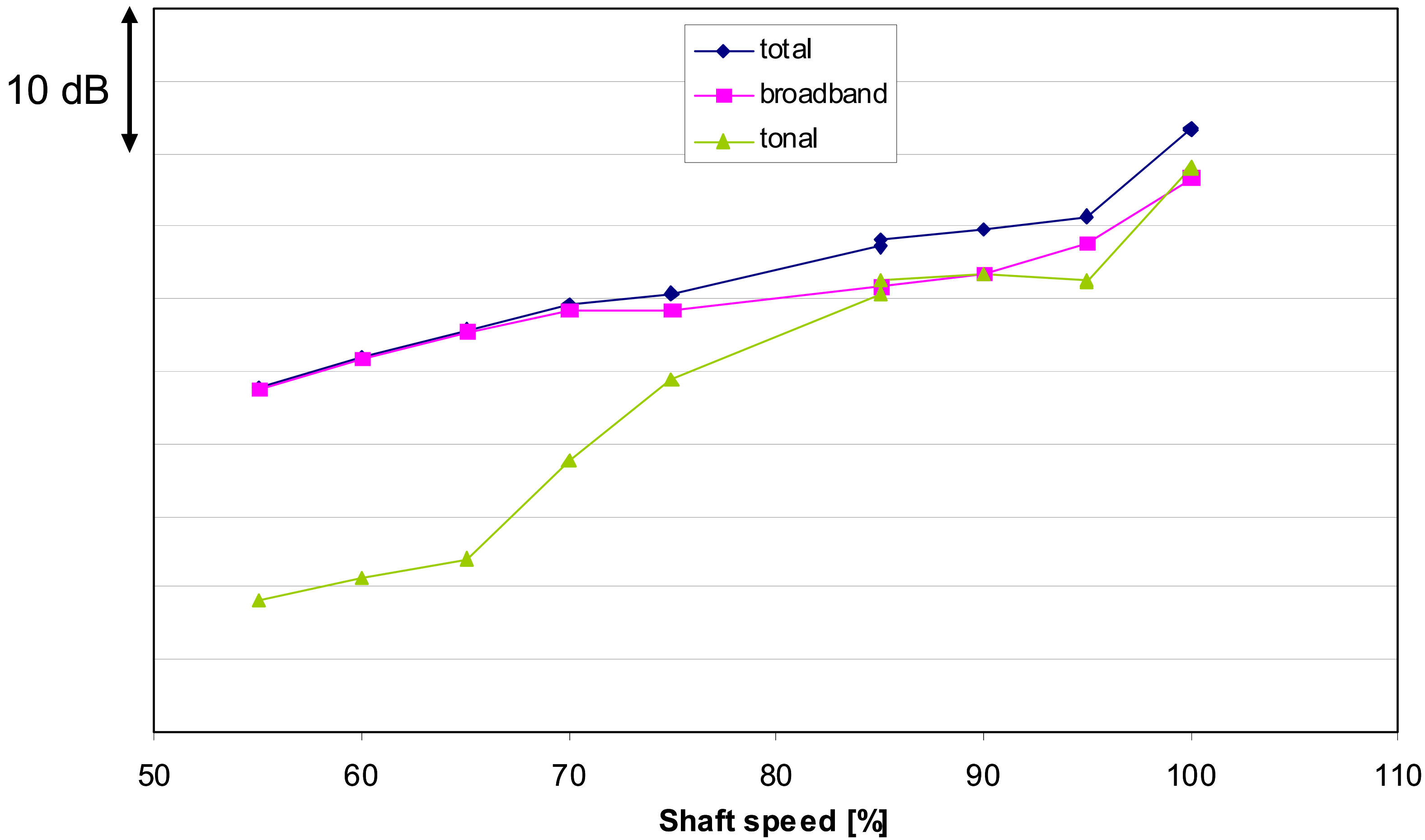
- **Tonal = rotor-bound (obtained with 1/rev pulse)**
- **"Broadband" = what remains**

typical average spectrum
of bypass array at
55% shaft speed

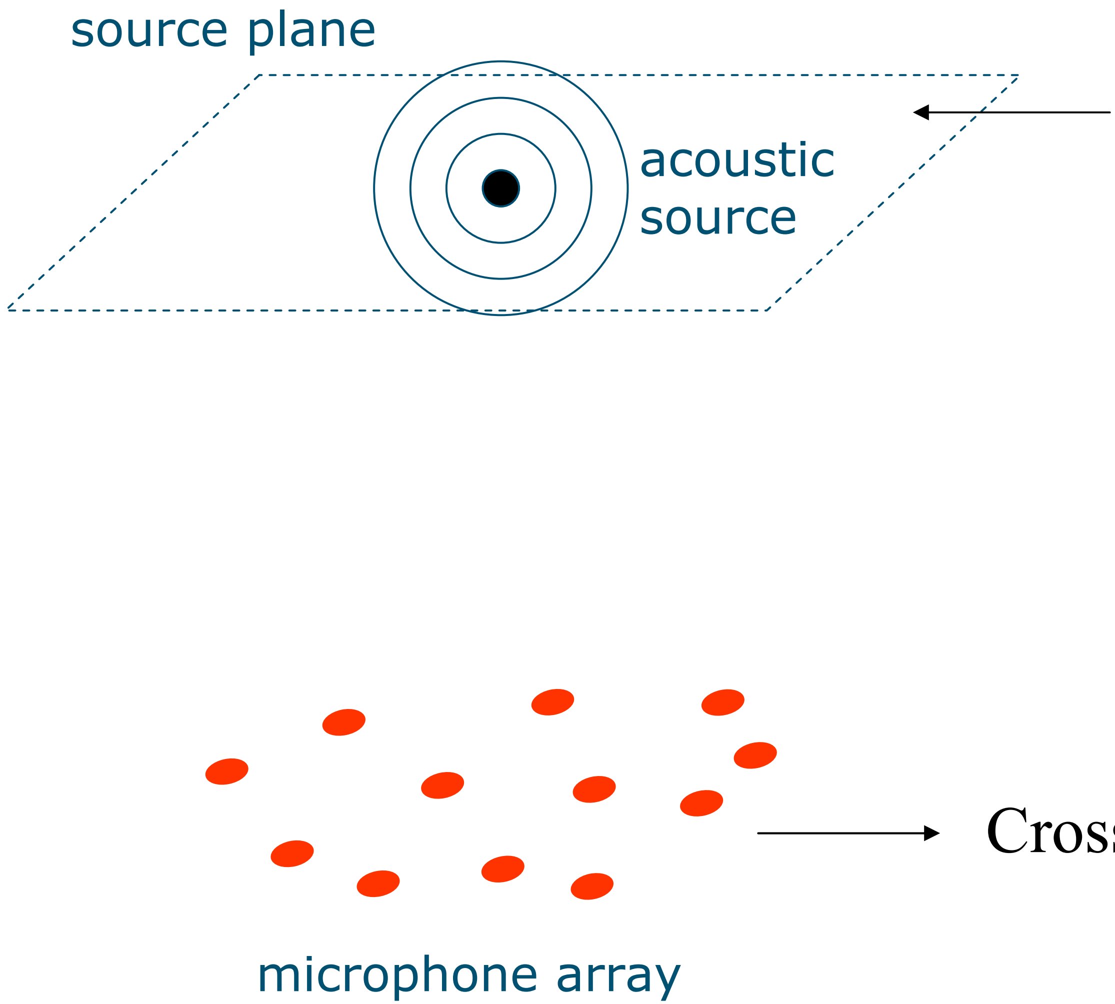


Tonal and broadband noise (2)

- **Broadband is significant at all shaft speeds**



Details of beamforming technique



scan points $\vec{\xi}_j$

Cross-Spectral Matrix: $\mathbf{C} = \left\langle \mathbf{pp}^* \right\rangle$

Beamforming summary

Conventional Beamforming:

Estimate source auto-power A_j in scan point $\vec{\xi}_j$ by

minimising $\left\| \mathbf{C} - A_j \mathbf{g}_j \mathbf{g}_j^* \right\|^2$, with $\mathbf{g}_j$ = steering vector

(microphone pressures due to theoretical point source in $\vec{\xi}_j$)

Solution: $A_j = \dfrac{\mathbf{g}_j^* \mathbf{C} \mathbf{g}_j}{\left(\mathbf{g}_j^* \mathbf{g}_j \right)^2}$.

Point source description

Steering vector: $\mathbf{g}_j = \begin{pmatrix} g_{1,j} \\ \vdots \\ g_{N,j} \end{pmatrix}, \; g_{n,j} = F(\vec{x}_n, \vec{\xi}_j)$

$\vec{x}_n$ are microphone locations, F is the transfer function

F can be a Green's function G (monopole source assumption)

(solution of partial differential equation $LG = -\delta\left(\vec{x} - \vec{\xi}\right)$

+ boundary conditions)

F can also be a derivative of G (dipole source assumption)

Options for Green’s function

- **Option 1: Free-field Green’s function in uniform flow**
- **Option 2: Green’s function in hard-walled duct and uniform flow [Lowis-2007]**
- **Option 3: Green’s function [Rienstra-2005] in soft-walled duct and uniform flow**
- **Option 4: Green’s function values calculated with CAA**
- **Option 5: Measured Green’s function values**

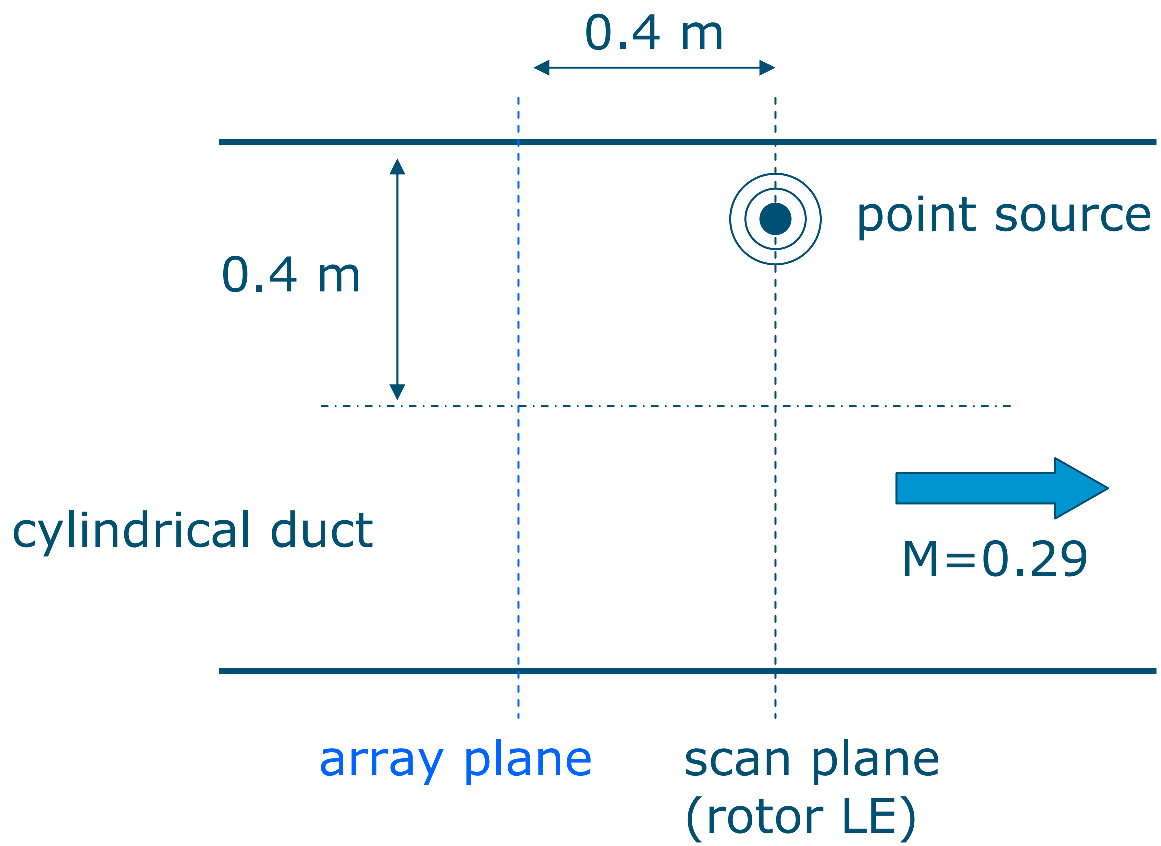
- ***Unknown source directivity is a critical issue for all options!***

Option chosen here

- **Free-field Green's function is chosen**
- **To minimize effects of reflections, a liner is required**
  - simulations shown in [Sijtsma-2007]
- **Non-circular geometry (drooped intake) is not a problem**
- **Beamforming with rotating focus (ROSI) is analogous to Conventional Beamforming(CB) [Sijtsma-2001]**

Lack of axial resolution (1)

- **Simulation study (lined duct)**

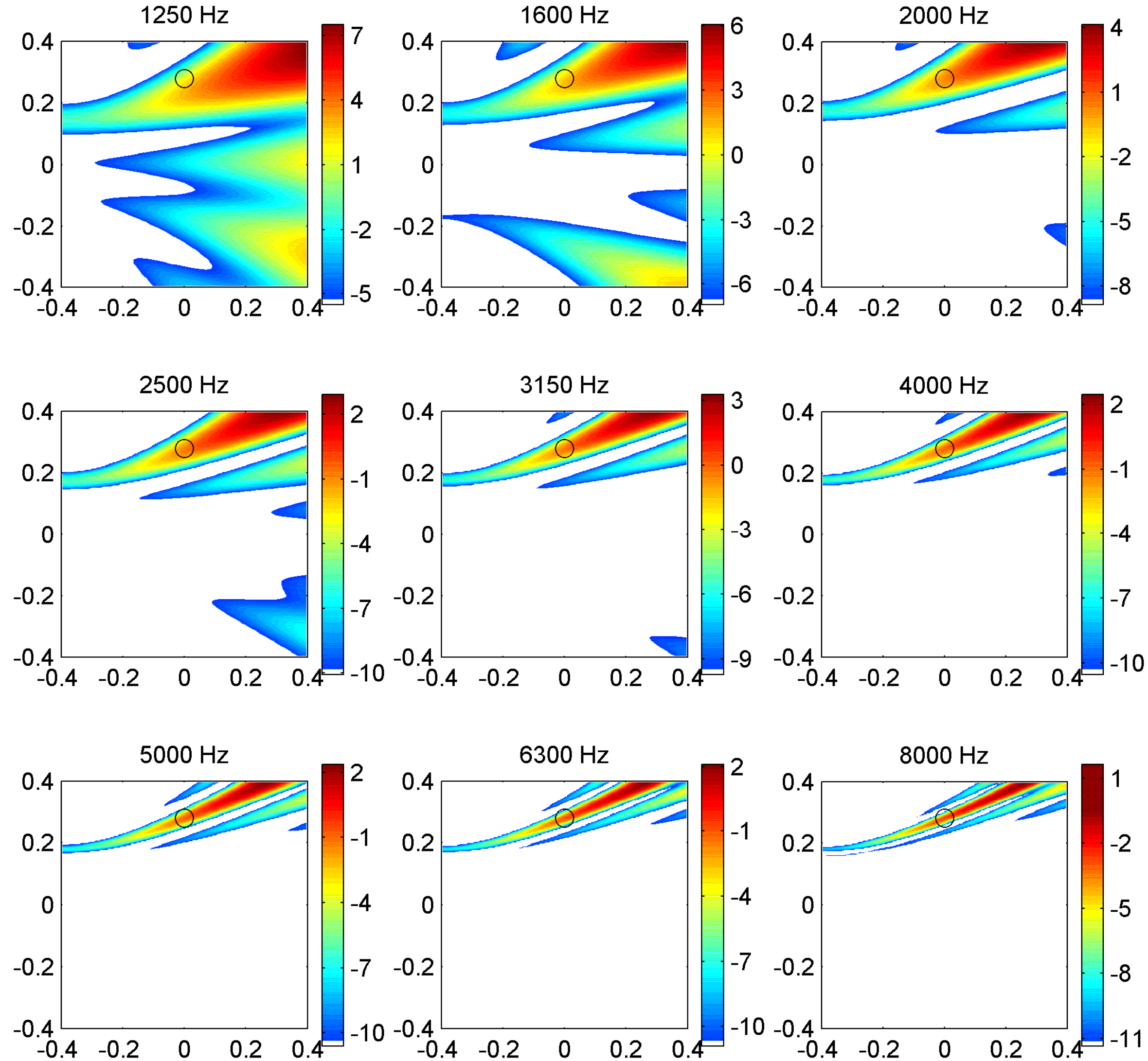


Lack of axial resolution (2)

- **Simulation study**

Conventional Beamforming

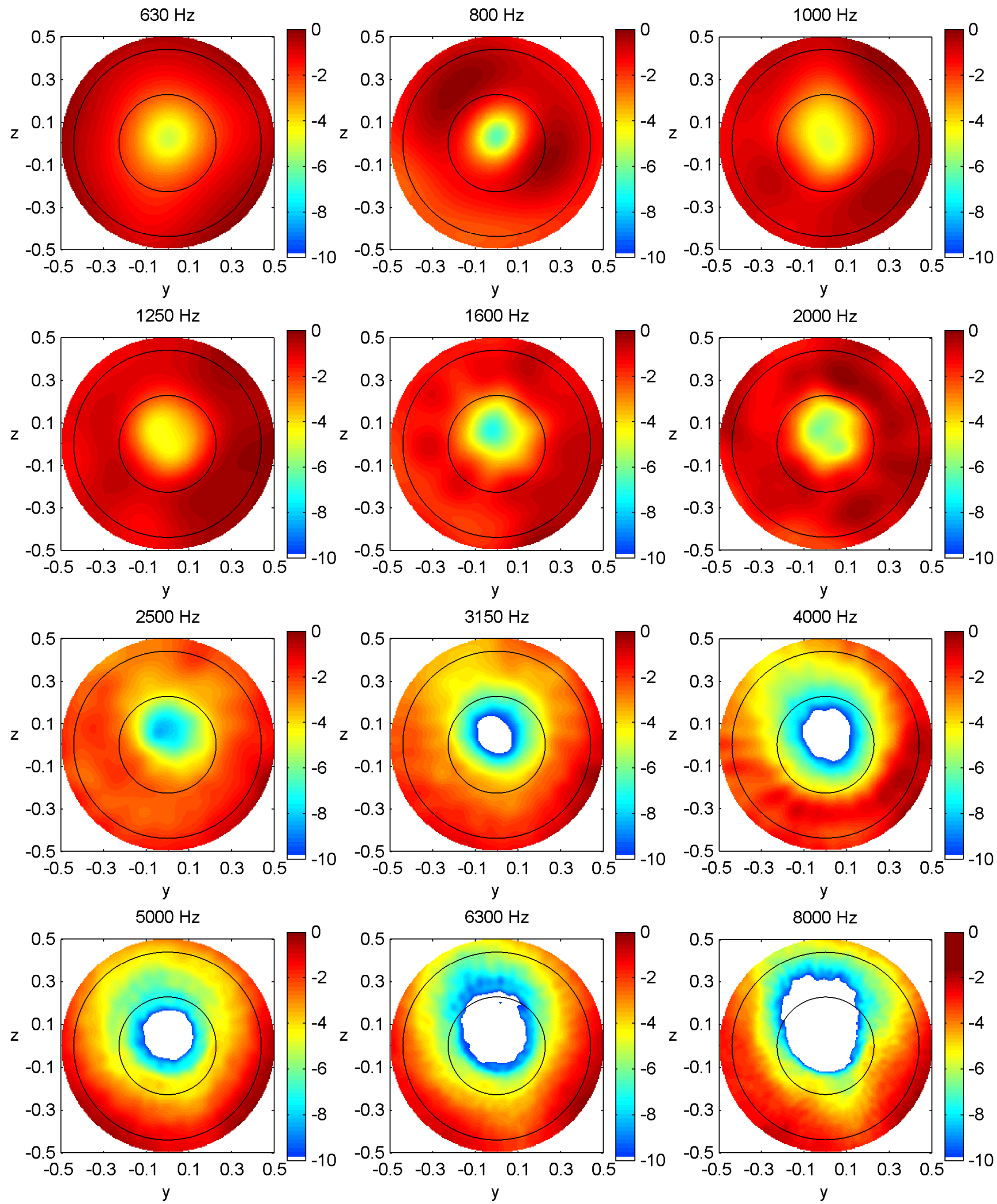
x,y-scan



Intake array (1)

CB results with intake array
scan grid on stator LE
55% shaft speed

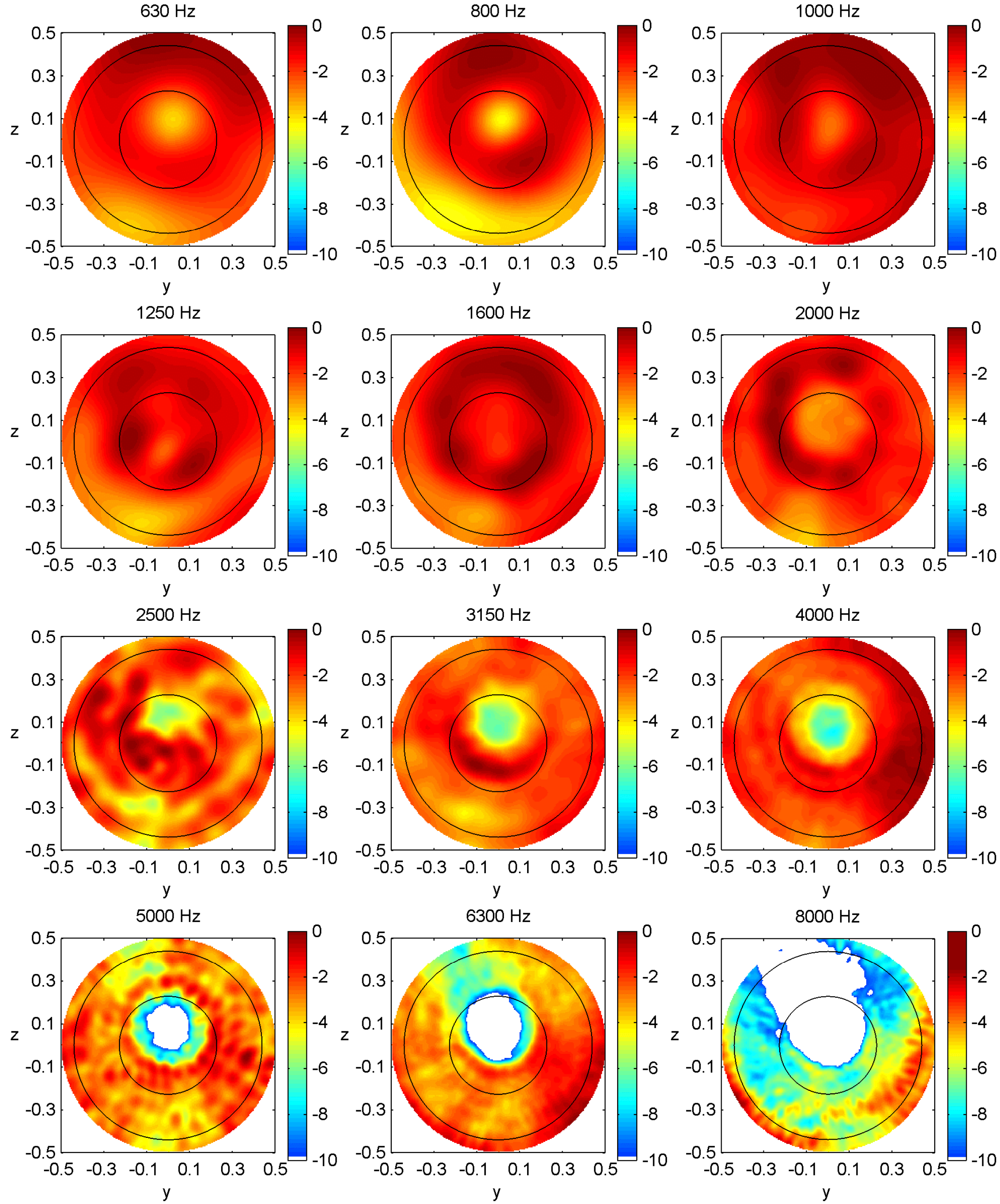
- No source details visible



Intake array (2)

CB results with intake array
scan grid on stator LE
75% shaft speed

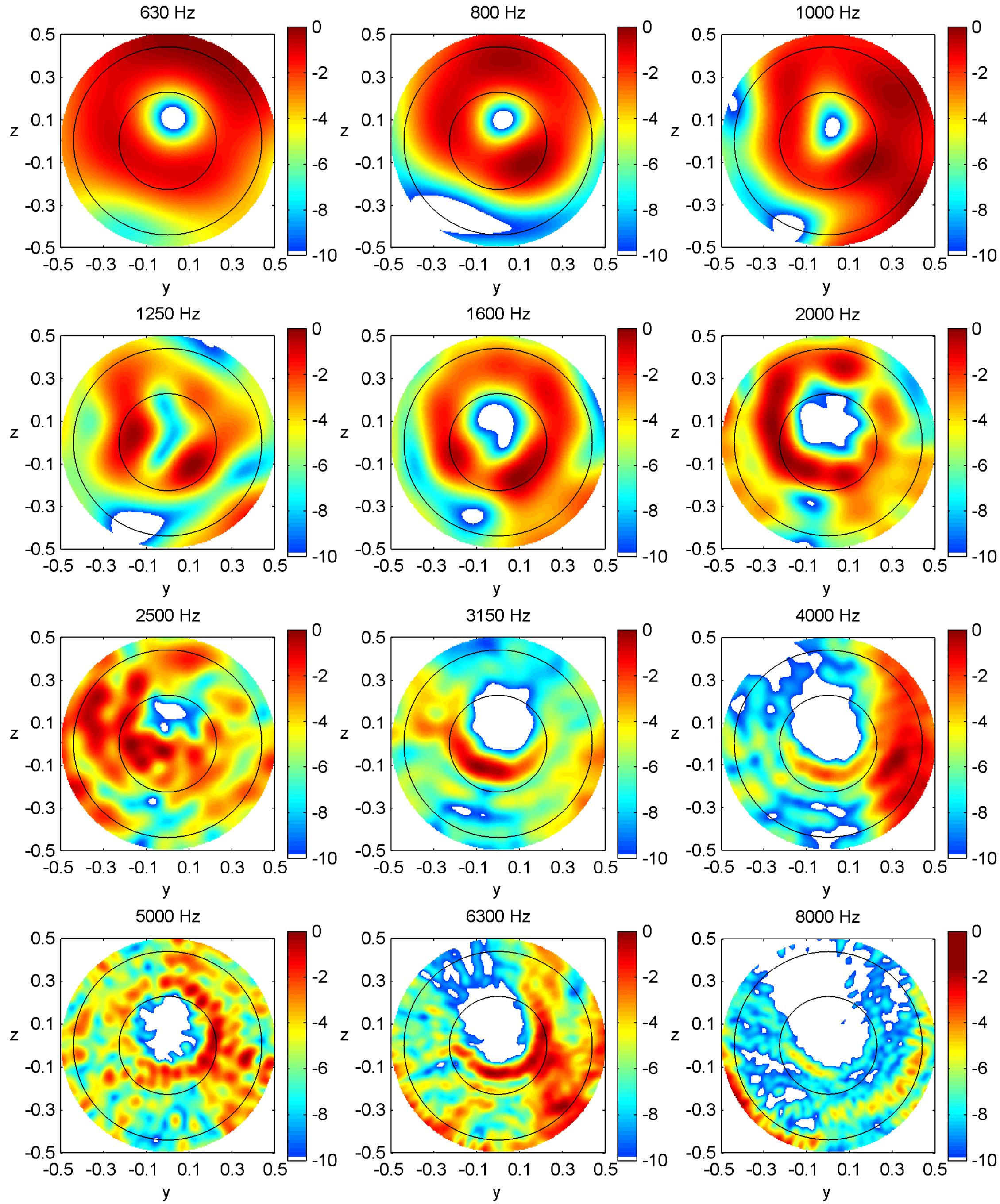
- Details visible at higher frequencies
- Best results with broadband noise



Intake array (3)

CB results with intake array
(using 2 principal components of the CSM)
scan grid on stator LE
75% shaft speed

- Coherent structure visible
- Sound sources due to vibrations rather than to aero-acoustic mechanisms?

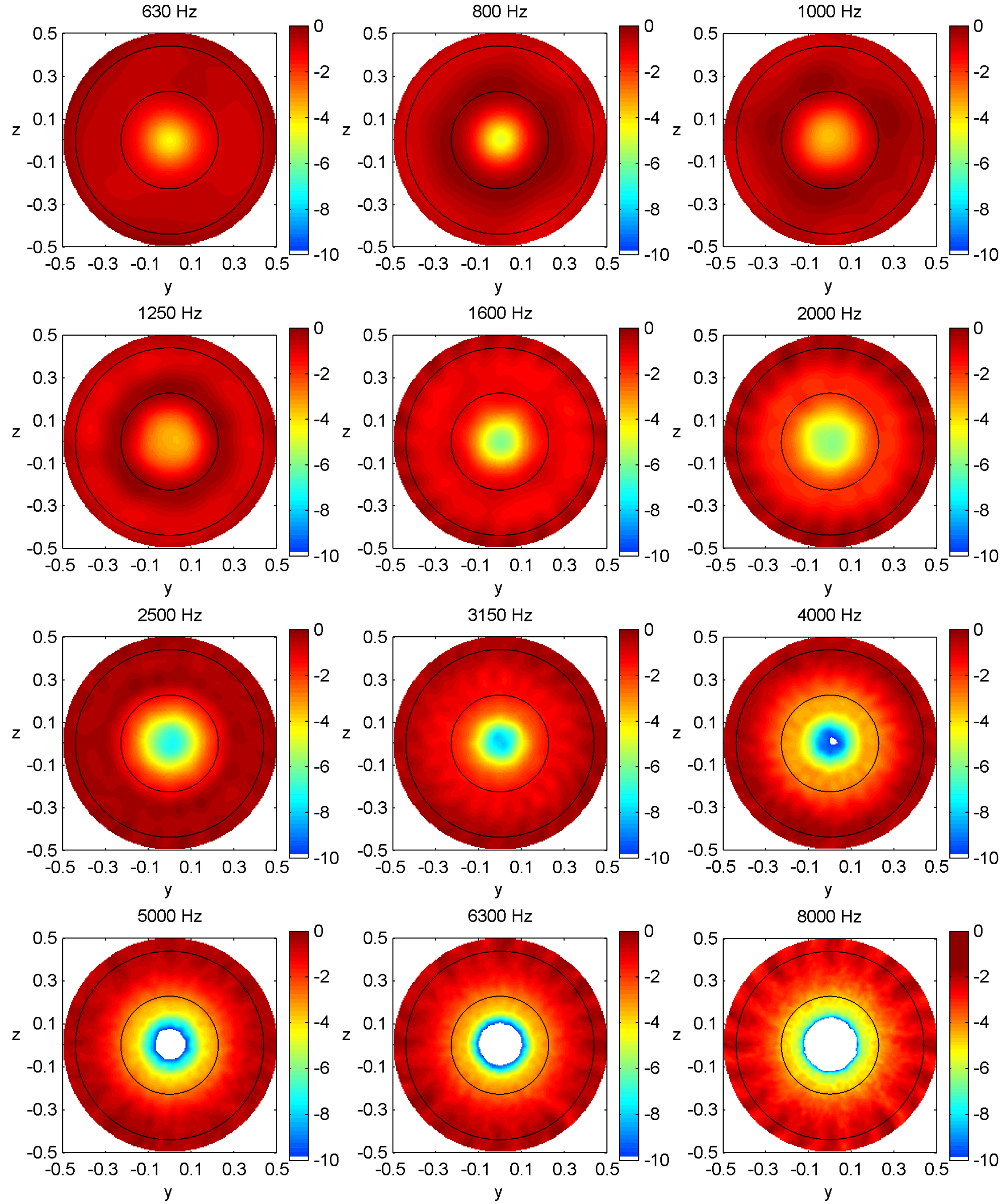


Intake array

Intake array (4)

ROSI results with intake array
scan grid on rotor LE
55% shaft speed

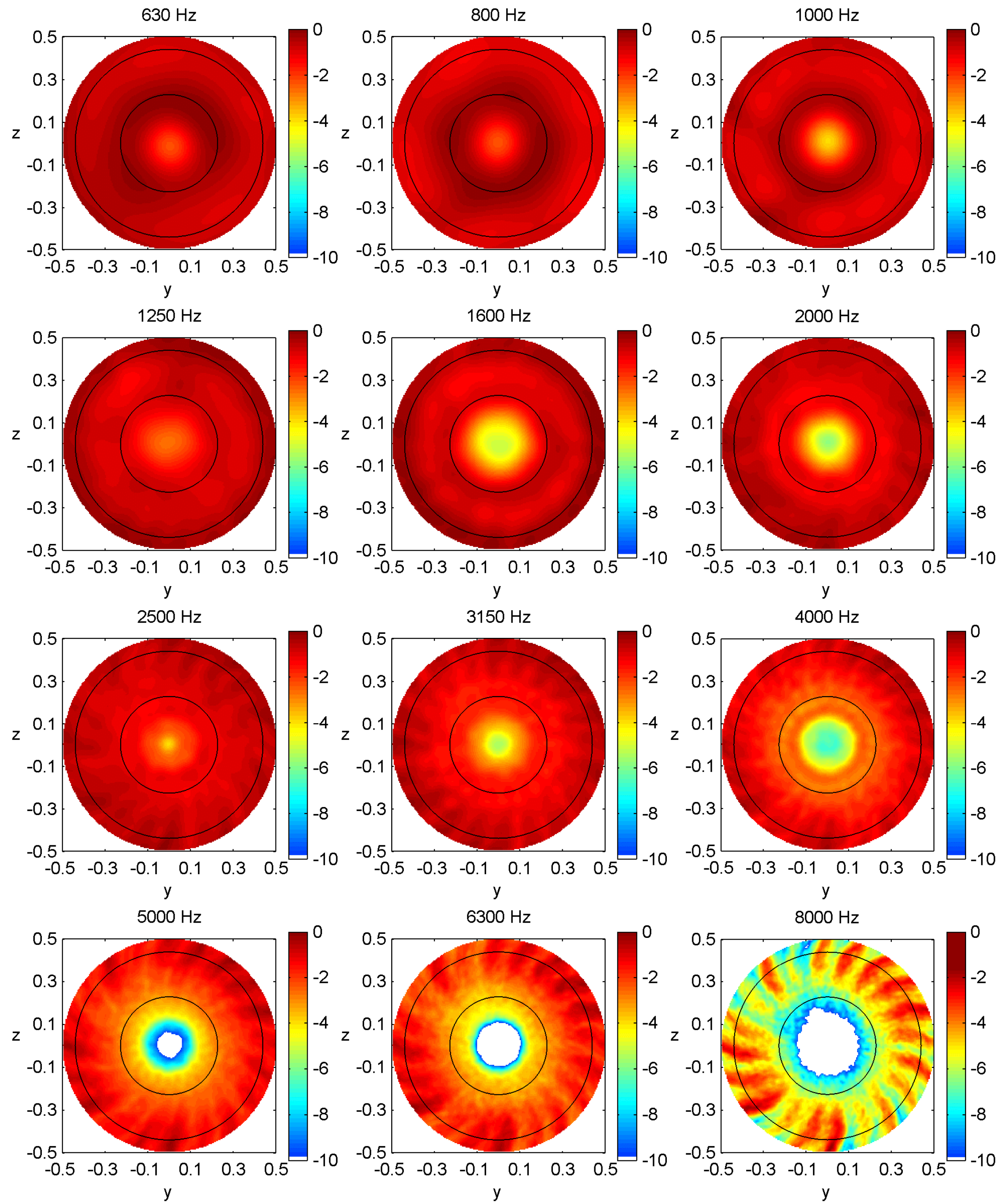
- Blades vaguely visible



Intake array (4)

ROSI results with intake array
scan grid on rotor LE
70% shaft speed

- Blades visible
- Best result with broadband noise



Intake array: rotor vs stator sources

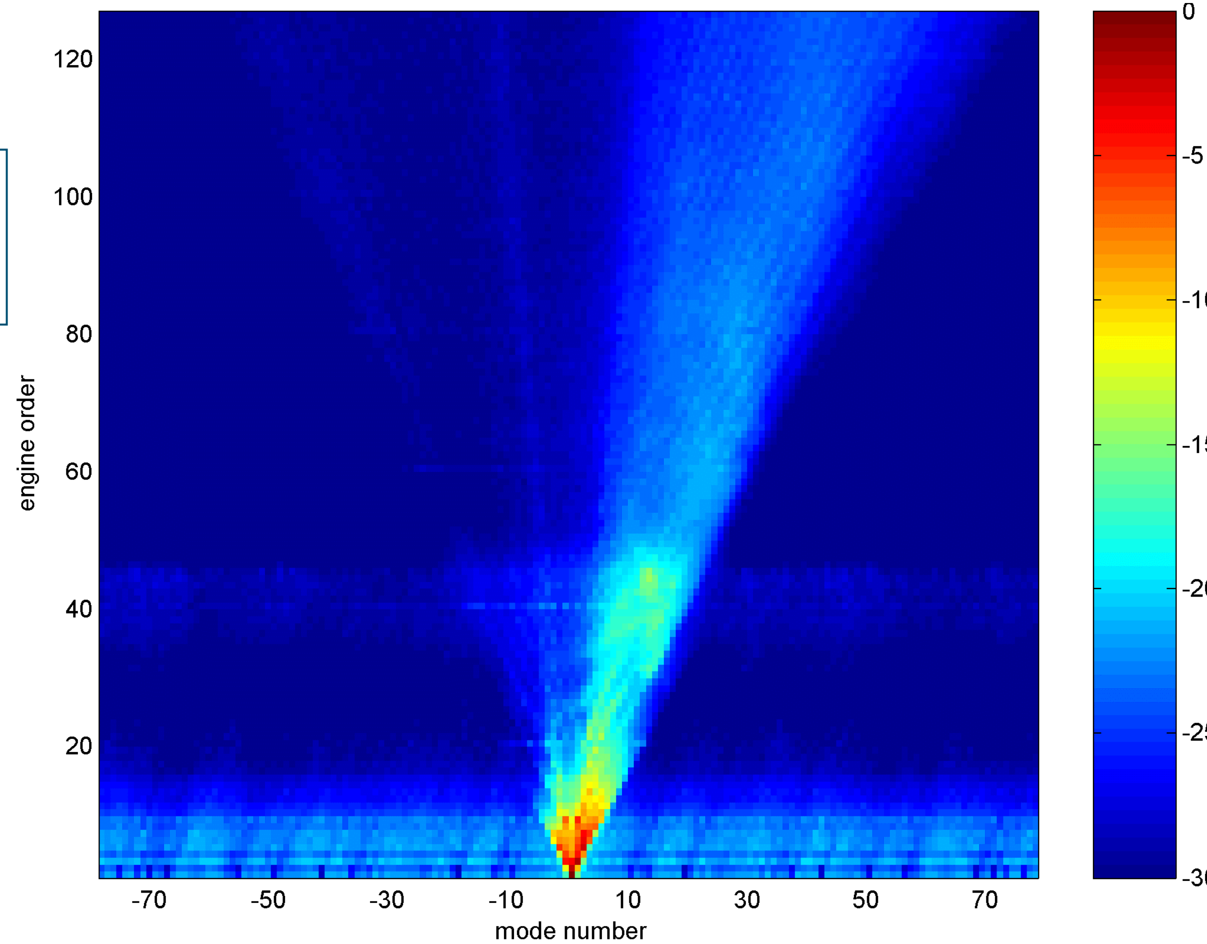
- **Difficult to unravel rotor and stator sources:**
  - lack of axial resolution
  - application of source integration technique not useful
  - rotor sources are "spread out" in stator plane, and vice versa

- **Looking at mode spectra might be helpful**

Intake array: azimuthal modes

Azimuthal modes of intake array
broadband noise
55% shaft speed

- Positive modes prevail



Why do positive modes prevail?

- **Possible explanations for dominance of positive modes:**
  1. Sources are rotor bound, and prevalence is due to source rotation
  2. Sources are stator bound, and prevalence is due to source directivity
  3. Sources are stator bound, and prevalence is due to rotor shielding

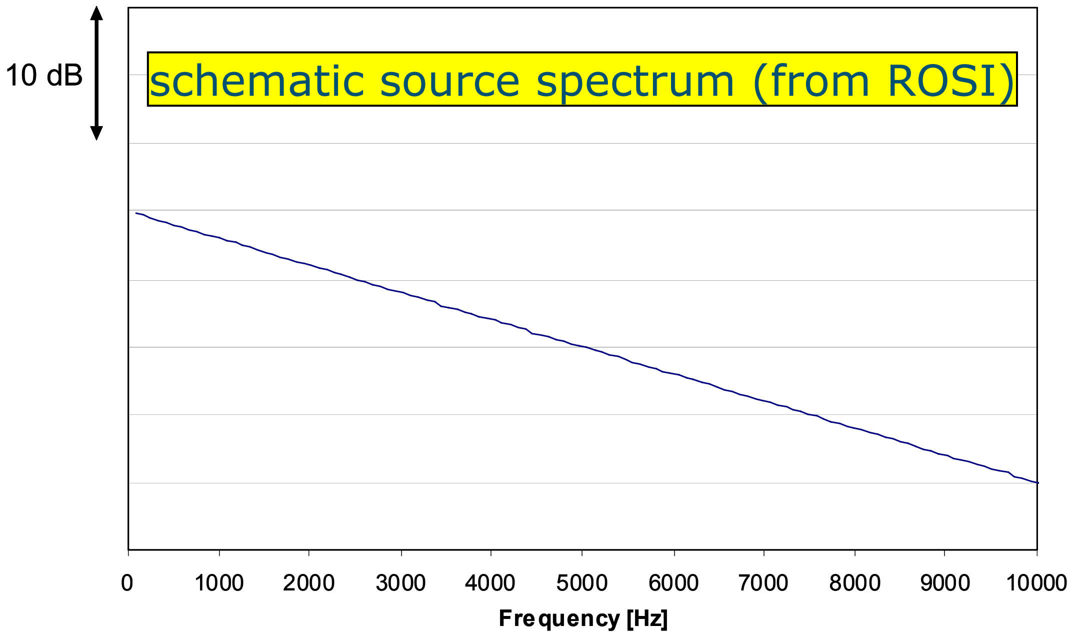
Option 1: Rotor source rotation (1)

Expression for rotating monopole:

$$p(\omega) = \frac{1}{2\pi} \sum_{m=-\infty}^{\infty} \sigma(\omega - m\Omega) e^{-im(\theta-\phi)} \sum_{\mu=1}^{\infty} e^{i\alpha_{m\mu}(x-\xi)} \frac{D_m(\varepsilon_{m\mu} r) D_m(\varepsilon_{m\mu}\rho)}{iQ_{m\mu} D_m(\varepsilon_{m\mu})^2}$$

source spectrum

fan rotation speed

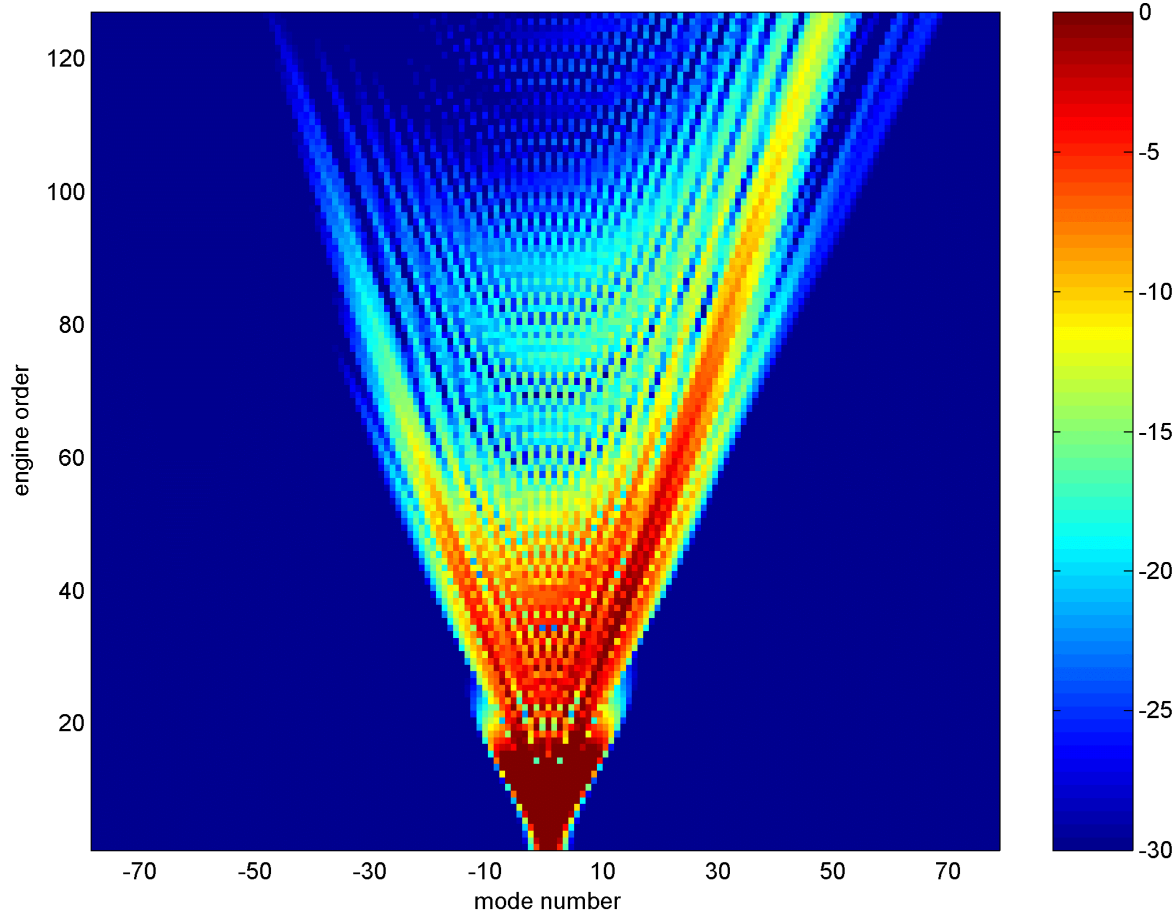


increasing m →
decreasing ω-mΩ →
increasing levels

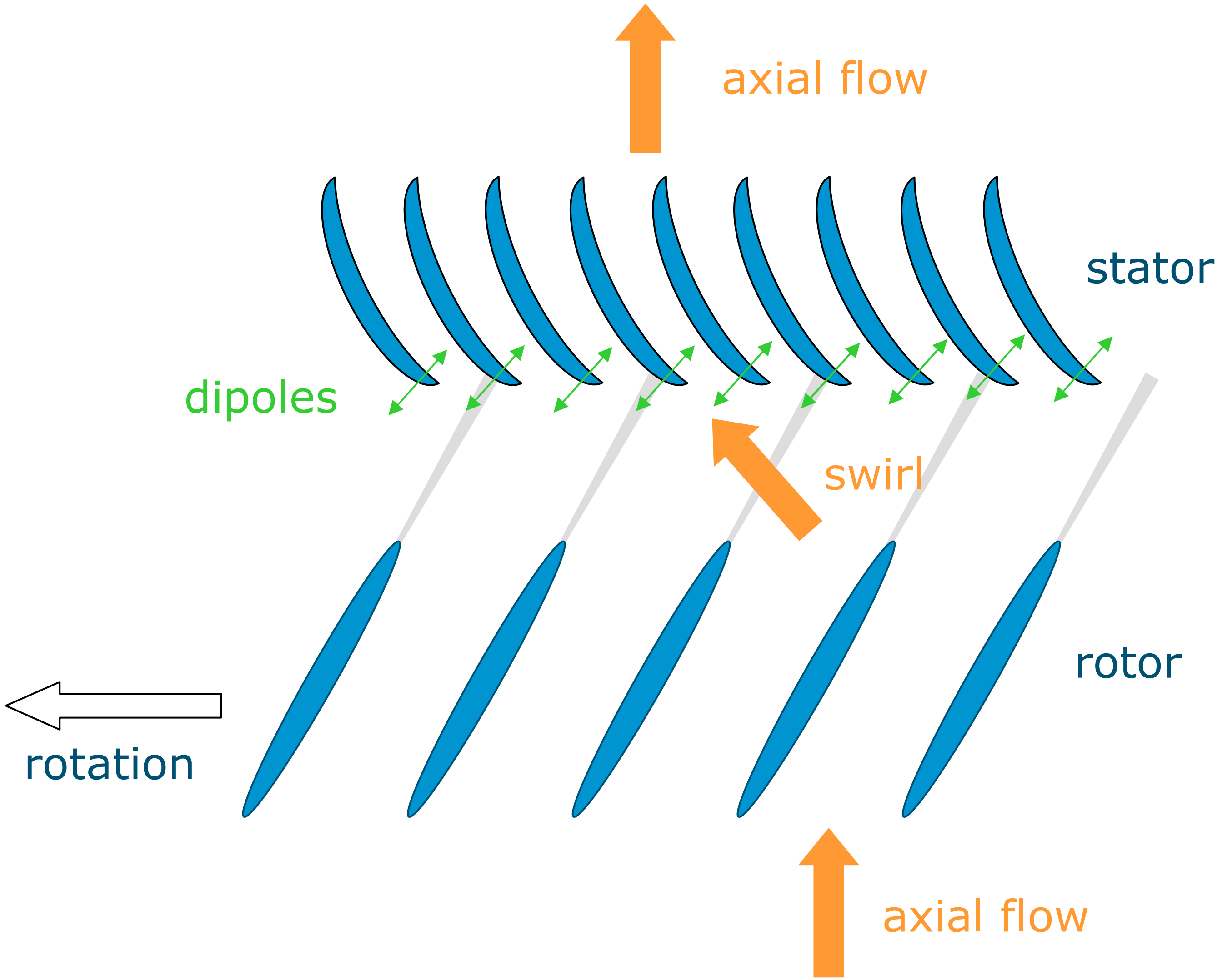
Option 1: Rotor source rotation (2)

Simulation
(including intake liner)

- Not like actual results



Option 2: Stator source directivity (1)

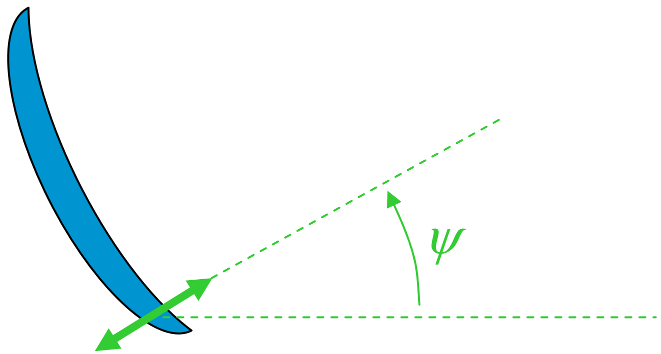


Option 2: Stator source directivity (2)

Expression for dipole:

$$p(\omega)=\frac{1}{2\pi}\sum_{m=-\infty}^{\infty}\sigma(\omega)e^{-im(\theta-\phi)}\sum_{\mu=1}^{\infty}\left(\alpha_{m\mu}\sin(\psi)-\frac{m}{r}\cos(\psi)\right)e^{i\alpha_{m\mu}(x-\xi)}\frac{D_m(\varepsilon_{m\mu}r)D_m(\varepsilon_{m\mu}\rho)}{Q_{m\mu}D_m(\varepsilon_{m\mu})^2}$$

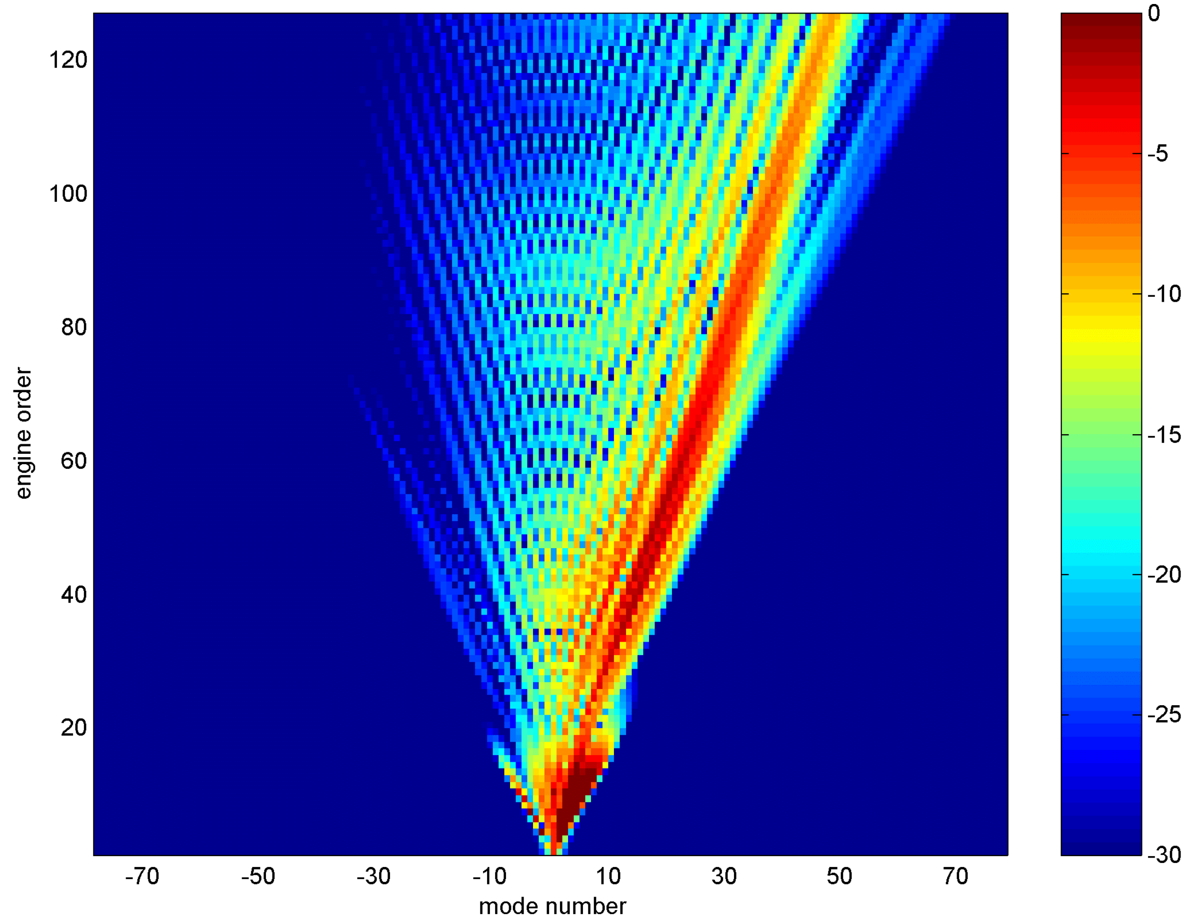
asymmetric with *m*



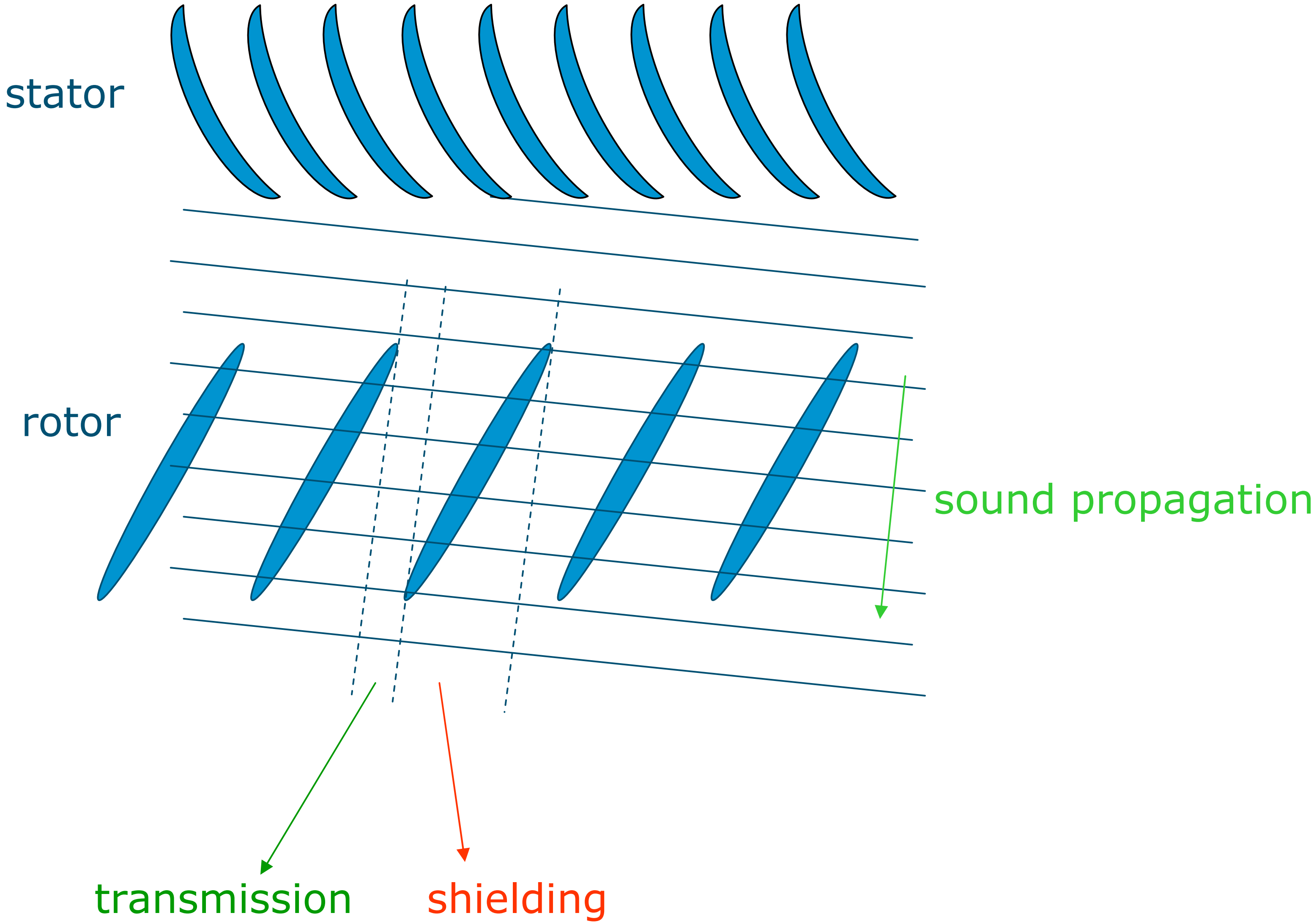
Option 2: Stator source directivity (3)

Simulation, ψ=30°
(including intake liner)

- More like actual results



Option 3: Rotor shielding (1)



Option 3: Rotor shielding (2)

Expression for “shielded fraction” [Schulten-1992]:

$$S_{m\mu}(\rho) = \min\left\{1, \frac{B}{2\pi}\left(x_{\mathrm{TE}} - x_{\mathrm{LE}}\right)\left|\frac{\Omega}{M} + \frac{m}{\mathrm{Re}(\alpha_{m\mu})\rho^2}\right|\right\}$$

monopole:

$$p(\omega) = \frac{1}{2\pi}\sum_{m=-\infty}^{\infty}\sigma(\omega)e^{-im(\theta-\phi)}\sum_{\mu=1}^{\infty}\left(1 - S_{m\mu}(\rho)\right)e^{i\alpha_{m\mu}(x-\xi)}\frac{D_m(\varepsilon_{m\mu}r)D_m(\varepsilon_{m\mu}\rho)}{iQ_{m\mu}D_m(\varepsilon_{m\mu})^2}$$

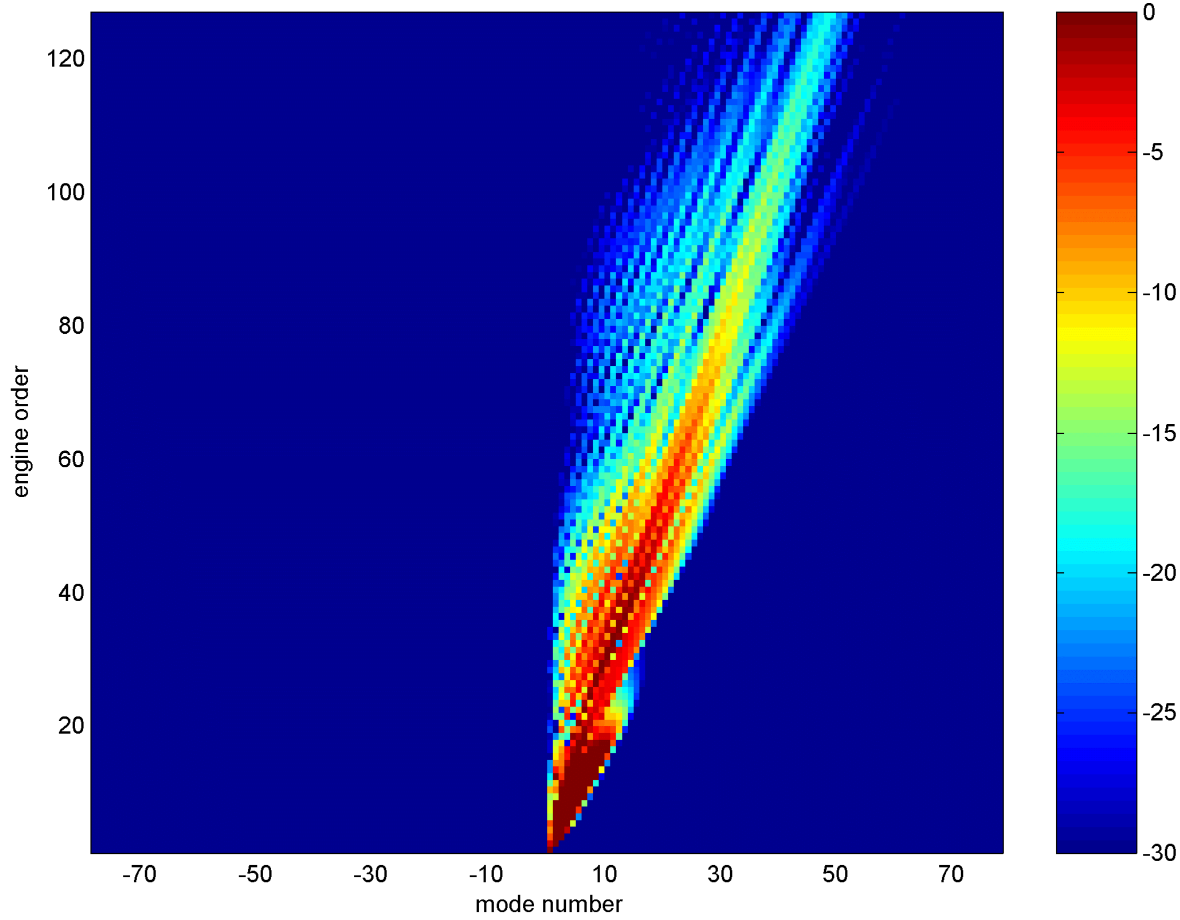
dipole

$$p(\omega) = \frac{1}{2\pi}\sum_{m=-\infty}^{\infty}\sigma(\omega)e^{-im(\theta-\phi)}\sum_{\mu=1}^{\infty}\left(1 - S_{m\mu}(\rho)\right)\left(\alpha_{m\mu}\sin(\psi) - \frac{m}{r}\cos(\psi)\right)e^{i\alpha_{m\mu}(x-\xi)}\frac{D_m(\varepsilon_{m\mu}r)D_m(\varepsilon_{m\mu}\rho)}{Q_{m\mu}D_m(\varepsilon_{m\mu})^2}$$

Option 3: Rotor shielding (3)

Simulation
monopole
(including intake liner)

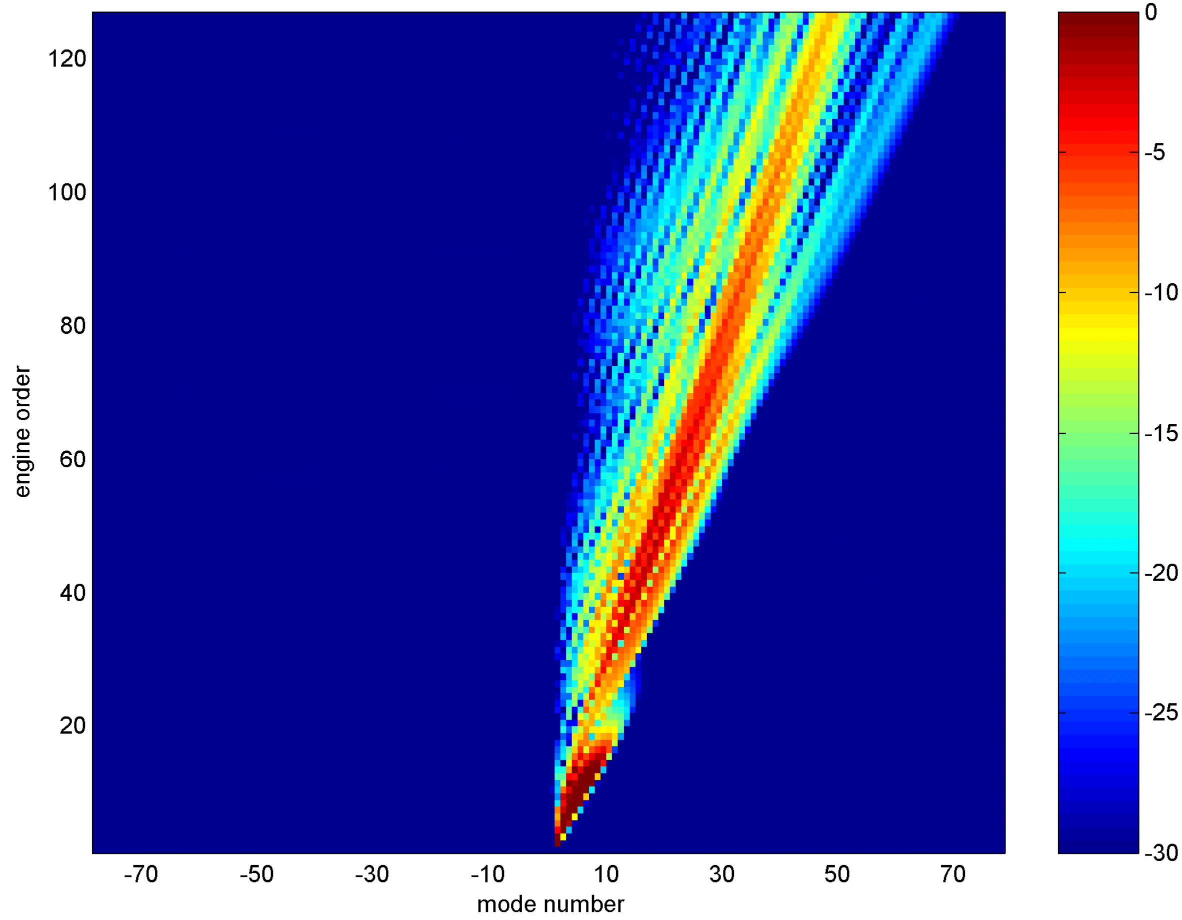
- Quite like actual results



Option 3: Rotor shielding (4)

Simulation
dipole, ψ=30°
(including intake liner)

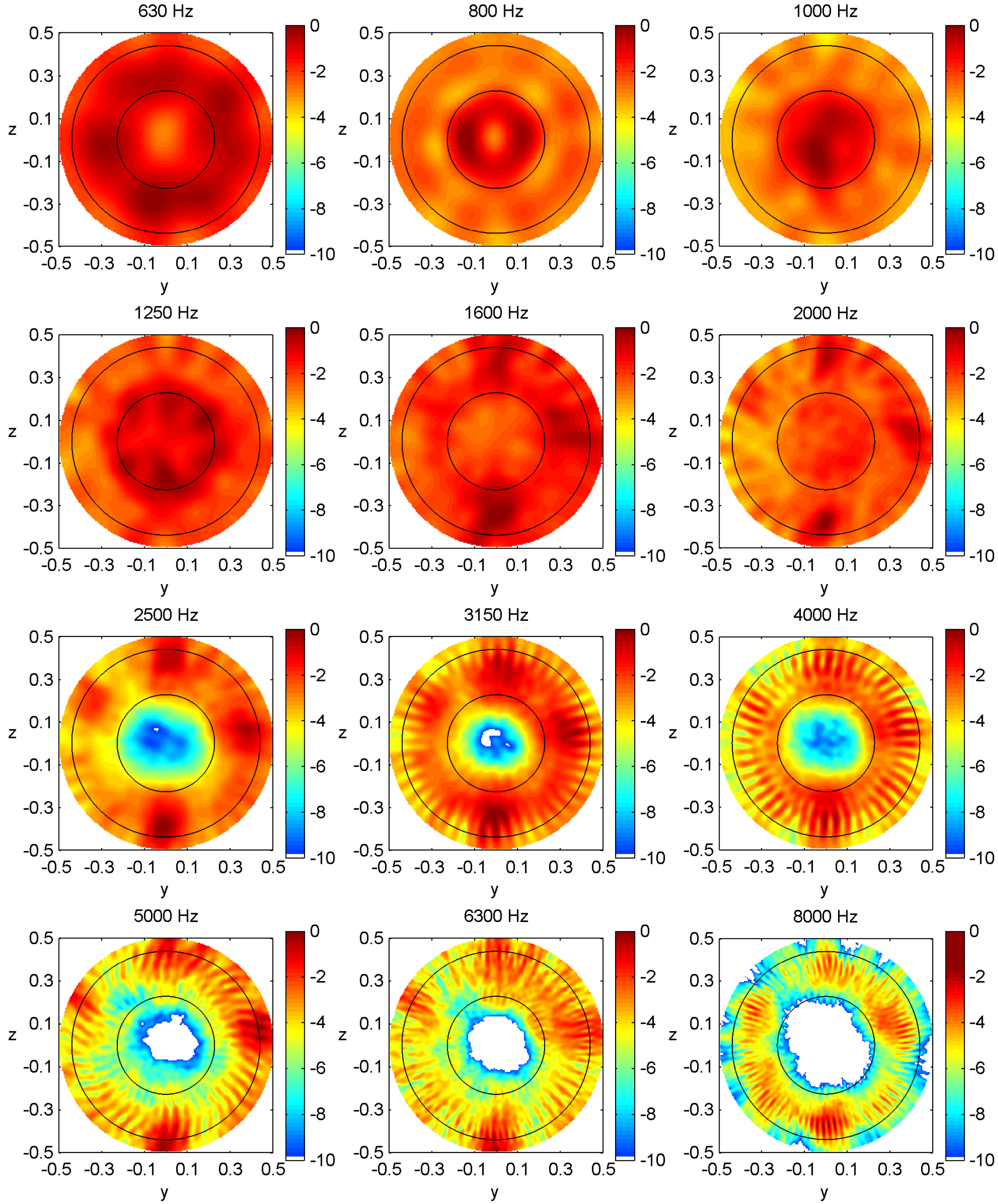
- Quite like actual results
  (maybe even better)



Bypass array (1)

CB results with bypass array
scan grid on stator TE
55% shaft speed

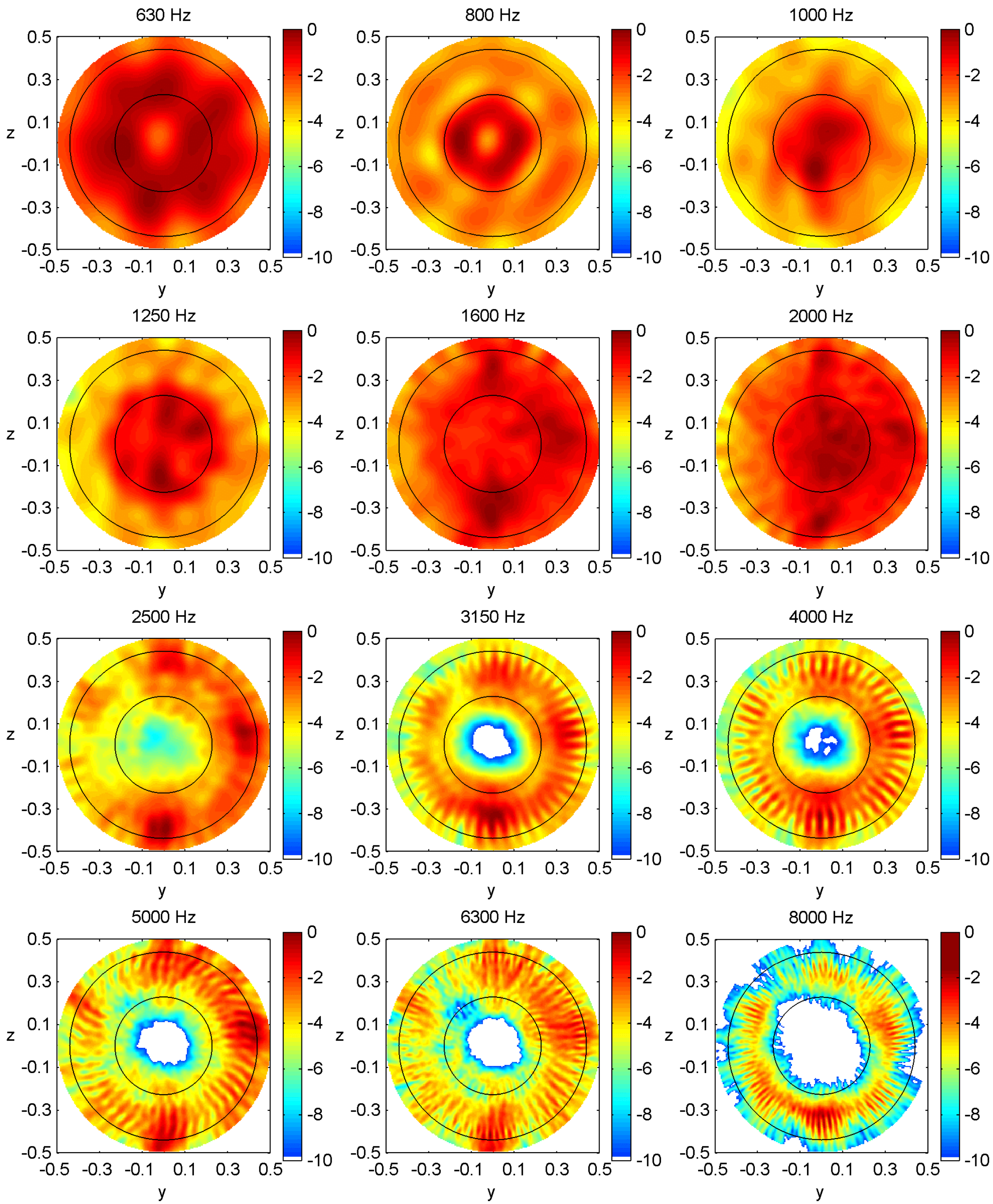
- Stator vanes clearly visible



Bypass array (2)

CB results with bypass array
scan grid on stator TE
70% shaft speed

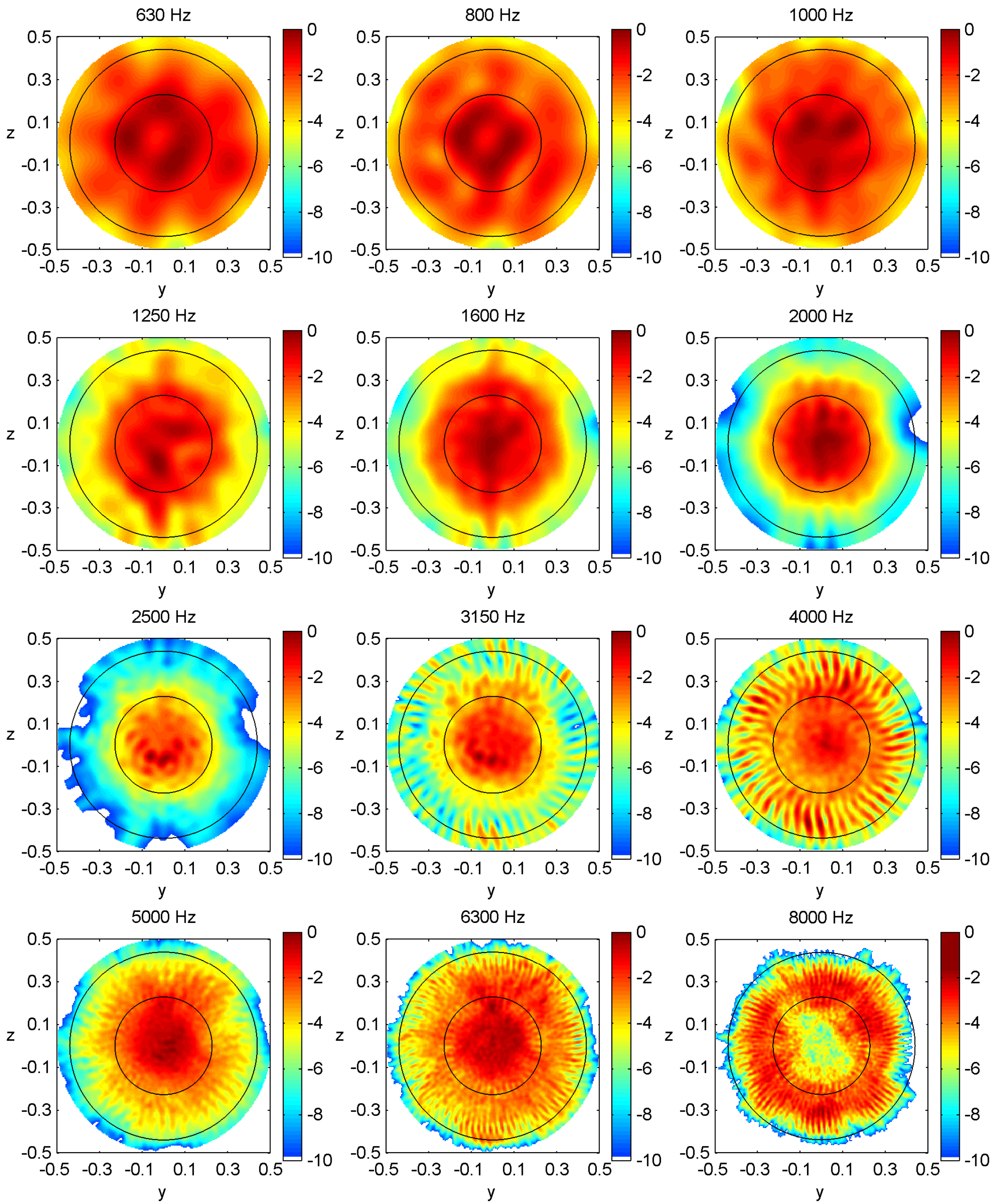
- Stator vanes clearly visible



Bypass array (3)

CB results with bypass array
scan grid on stator TE
85% shaft speed

- Stator vanes clearly visible

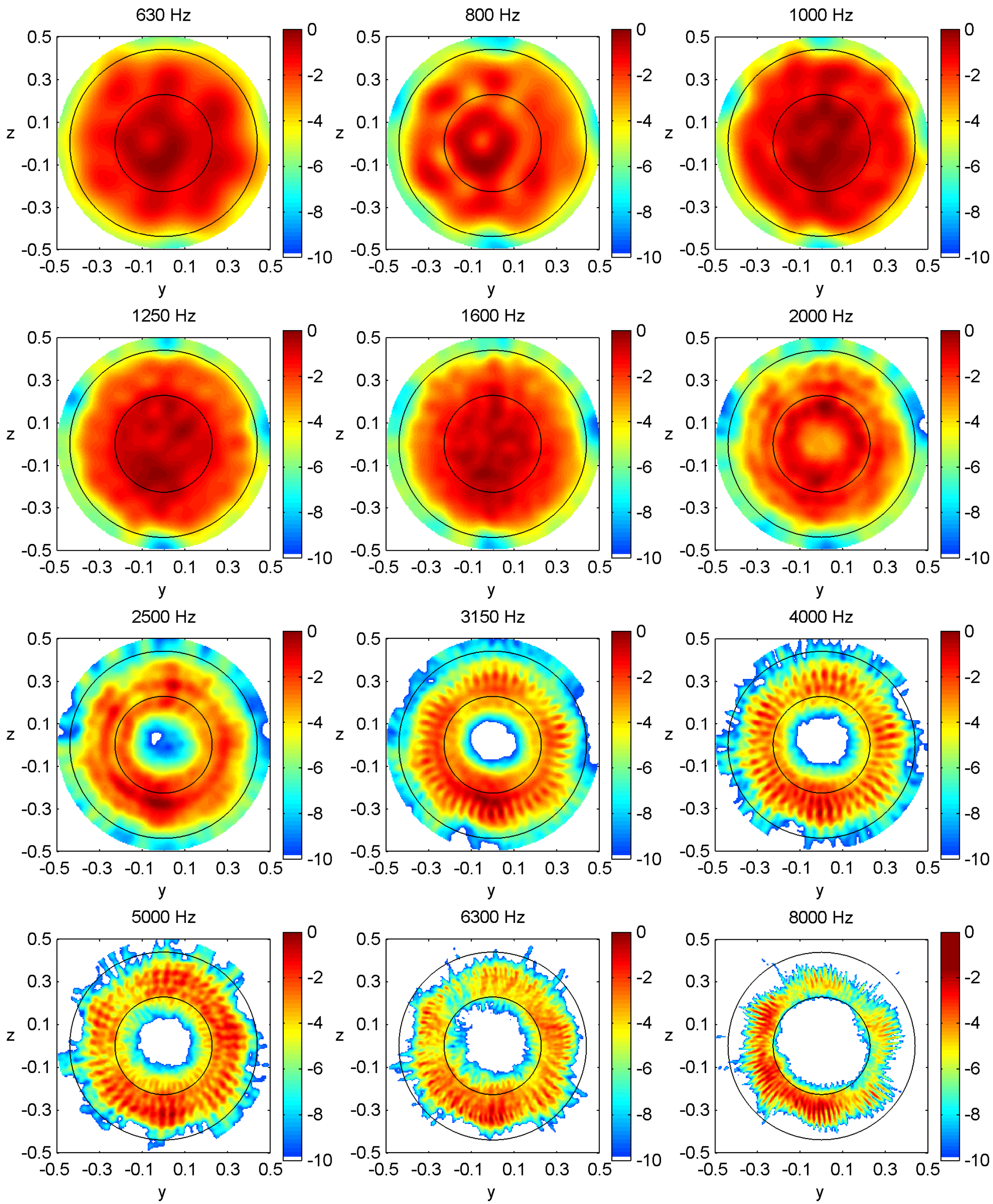


Bypass array

Bypass array (4)

CB results with bypass array
scan grid on stator TE
100% shaft speed

- Stator vanes clearly visible



Bypass array beamforming summary

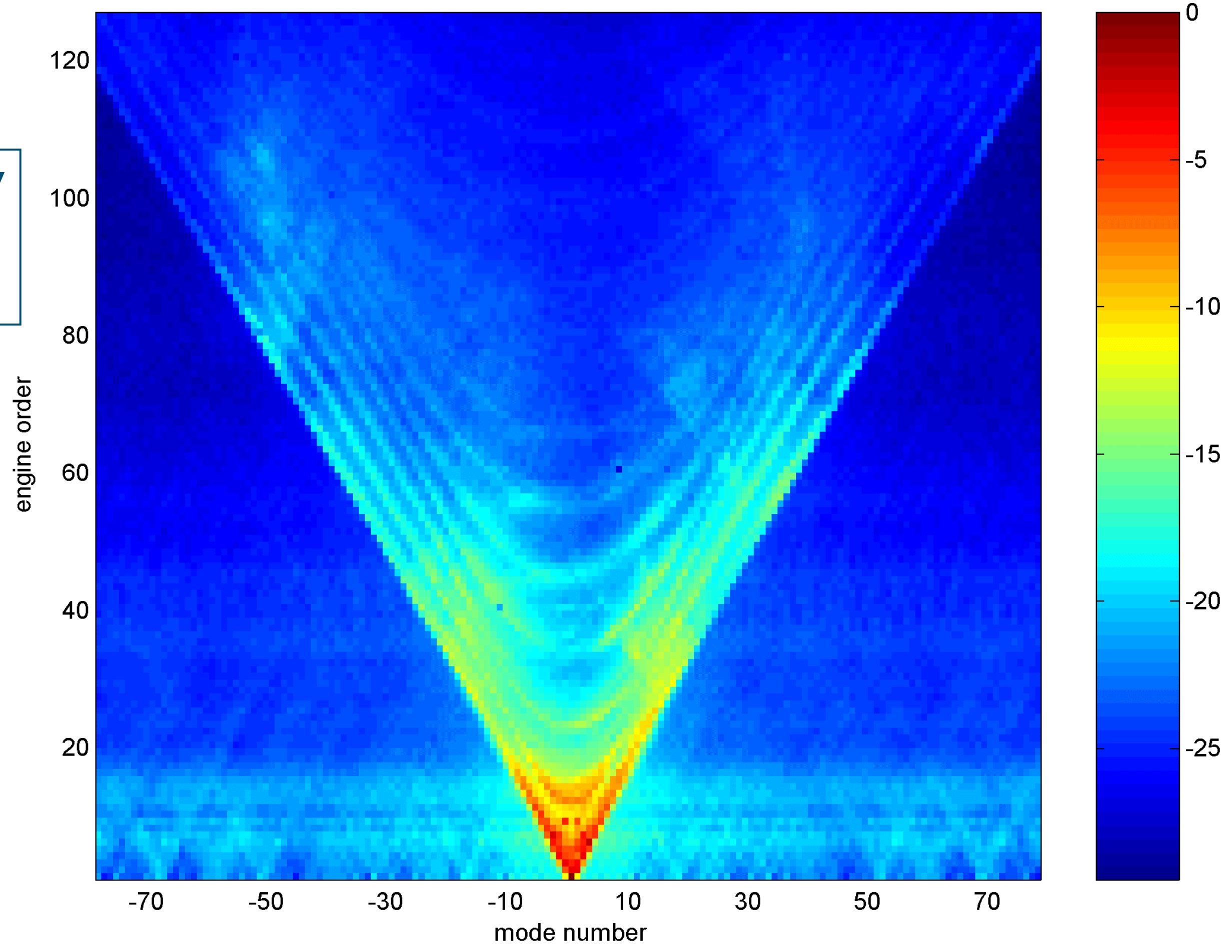
- **Results are remarkably good**
  - Duct is annular
  - No liner between stator and array
    - Uniform flow assumption in simulations maybe not adequate

- **Spanwise sources rather than tip sources**

Bypass array: azimuthal modes (1)

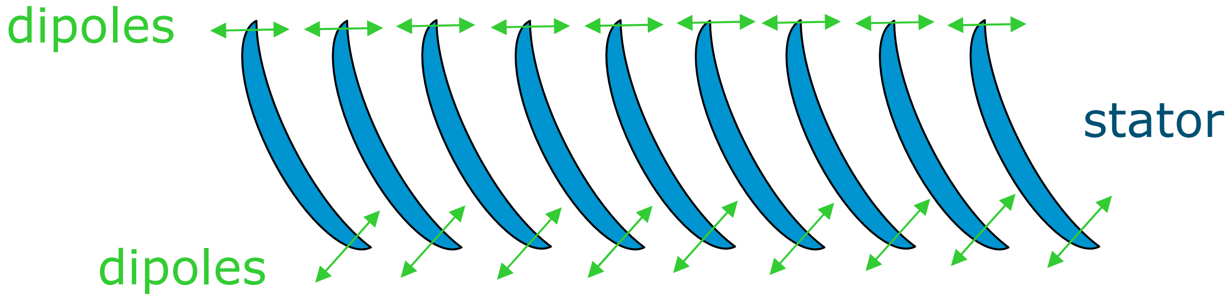
Azimuthal modes of bypass array
broadband noise
55% shaft speed

- Symmetry in modes

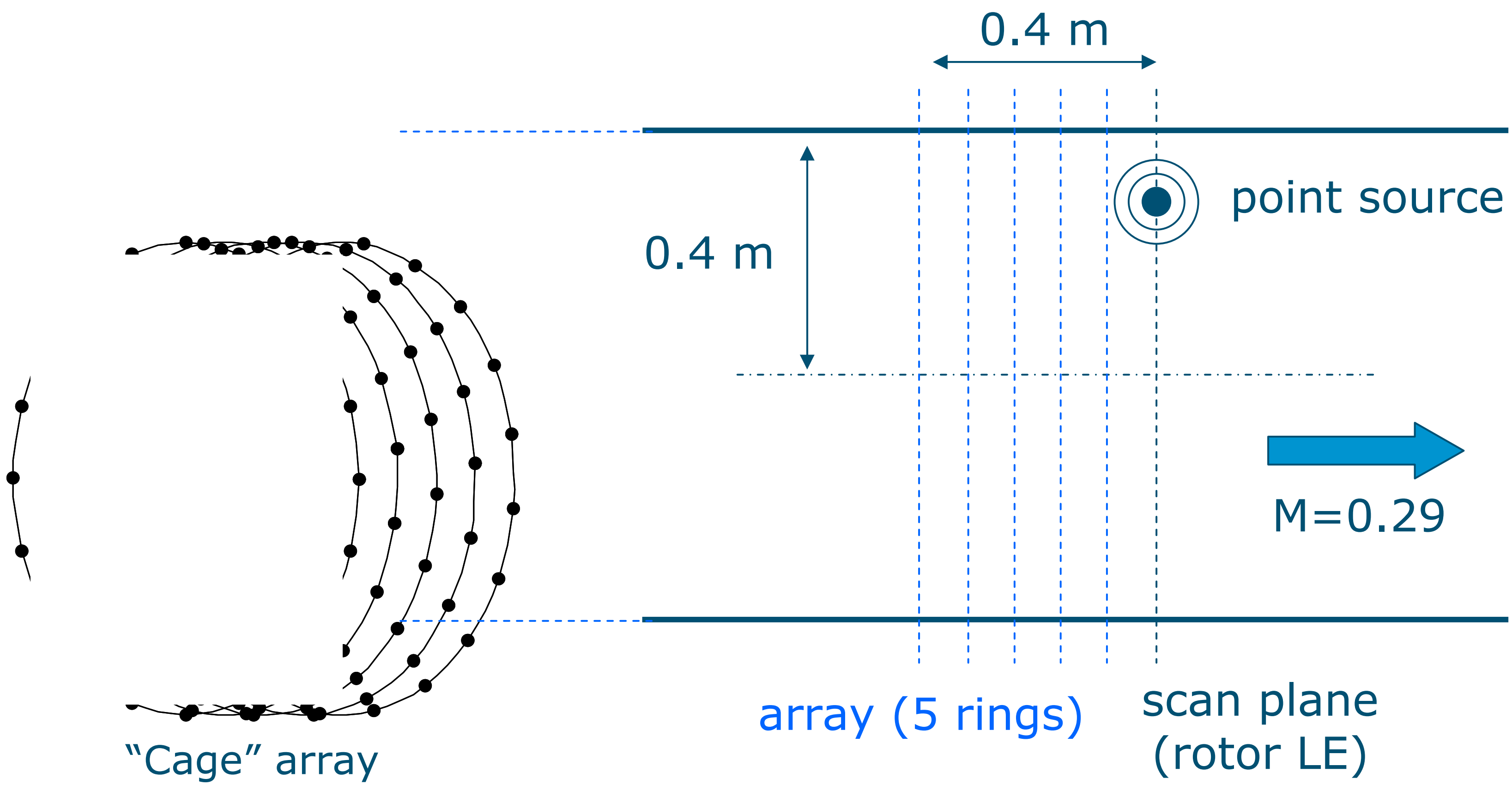


Bypass array: azimuthal modes (2)

- **Azimuthal modes are symmetric**
- **Sound probably generated at trailing edges**

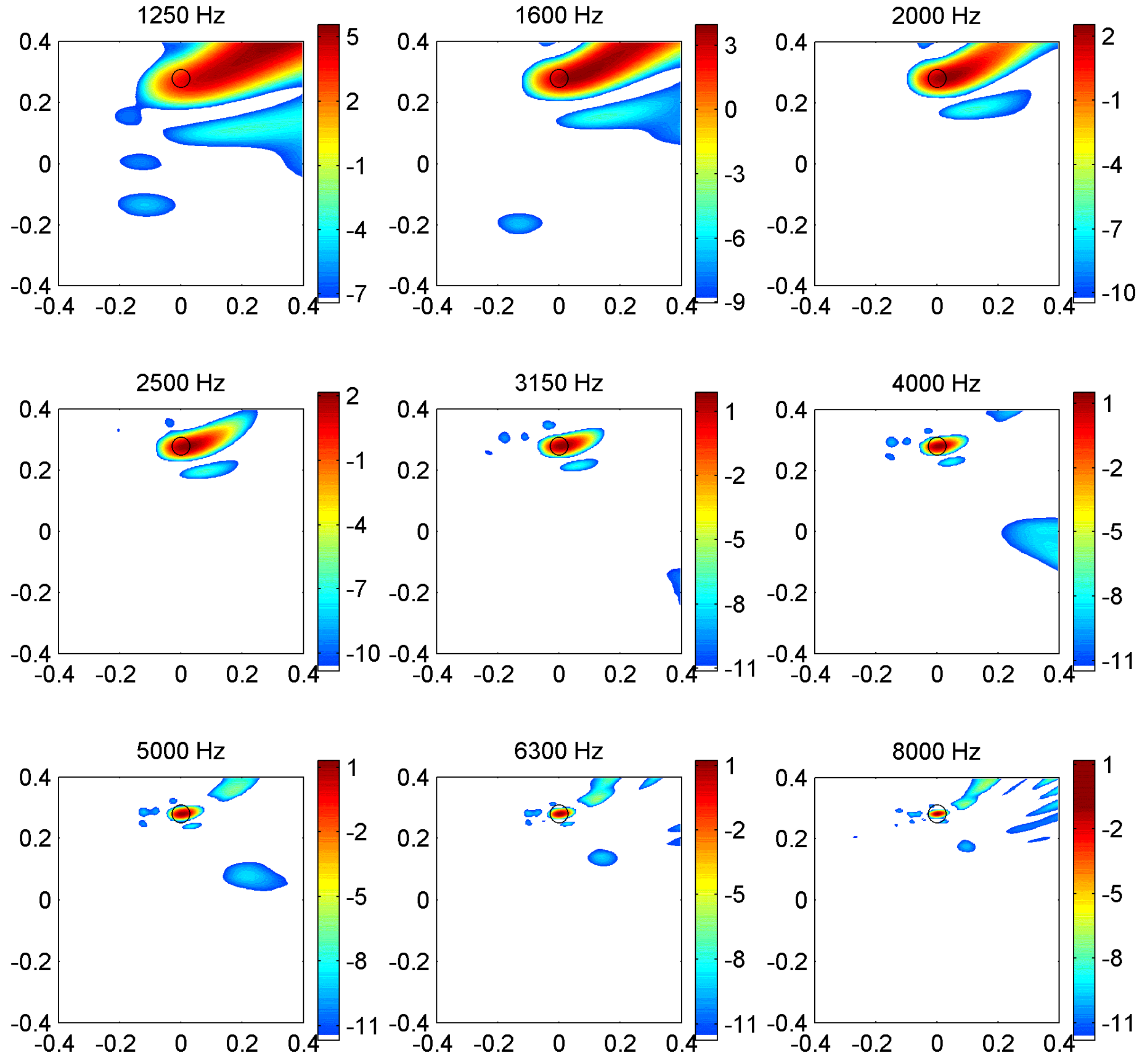


Possible improvement: cage array (1)



from [Sijtsma-2007]

Possible improvement: cage array (2)



- Much better axial resolution

Conclusions

- **Beamforming was done using the free-field Green's function**
  - tonal sound was filtered out
- **Beamforming with the intake array on the stator did not show much detail of broadband noise source locations.**
  - Only at 70% and 75% shaft speed, the OGV stator vanes seemed to be visible.
  - In those cases, there appeared to be large coherent source structures, probably due to an instability.
- **By beamforming with the intake array on the rotor, the blades were vaguely recognized as sound sources.**
- **The mode detection results seem to indicate that most noise in the intake is generated at the stator.**
- **By beamforming with the bypass array, sources on the stator vanes could be made clearly visible.**
- **The noise sources on the stator vanes seem to be distributed along the span.**
  - Hence, tip noise sources seem to be of lower importance.
- **The bypass mode detection results seem to indicate that the noise sources are located at the trailing edges of the stator vanes.**
- **Improvements in beamforming are possible with other array configurations**

References

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