Experimental and Theoretical Instability Wave Noise Shielding Investigations

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Motivation

The first estimations of the shielding effect were done in the 1970's:

Von Glahn, U., Goodykoontz, J., and Wagner, J., "Nozzle Geometry and Forward Velocity Eeffects on Noise for CTOL Engine-Over-The-Wing Concept," NASA TM-X-71453, Oct. 1973
Von Glahn, U., Groesbeck, D., and Reshotko, M., "Geometry Considerations for Jet Noise Shielding with CTOL Engine-Over-The-Wing Concept," AIAA Paper 74-568, June 1974.
Von Glahn, U., Groesbeck, D., and Wagner, J., "Wing Shielding of High-Velocity Jet and Shock- Associated Noise with Cold and Hot Flow Jets," AIAA Paper 76-547, July 1976.

These calculations showed extremely high efficiency of the engine noise shielding. It gave a stimulus to a works which was dedicated to the search of the general arrangement for airplanes with airframe structures shielding noise of the aviation engine

Motivation

Numerous investigations were dedicated to the peculiarities of solving diffraction problem for the case of moving medium :

1. D.G. Crighton, F.G. Leppington. Scattering of aerodynamic noise by a semi-infinite compliant plate. J. Fluid Mechanics, vol. 43, part 4,1970, pp. 721-736
2. S.N. Heavens. J. Fluid Mechanics, Vol. 84, 1978, pp. 331-335.
3. S. W. Rienstra. Sound diffraction at a trailing edge. J. Fluid Mechanics, vol. 108, 1981, pp. 443-460
4. R. K. Amiet. Unified Aeroacoustics Analysis for High Speed Turboprop Aerodynamics and Noise. Volume II - Development of Theory for Wing Shielding. NASA Contractor Report 185192, May 1991.
5. S. Redonnet, G. Desquesnes, E. Manoha, C. Parzani. Numerical Study of Acoustic Installation Effects with a Computational Aeroacoustics Method, AIAA Journal, Vol.48, No. 5, May 2010.
6. R. Ewert, A. Neifeld, A. Fritzsch. Jet Mixing Noise from Single Stream Jets using Stochastic Source Modelling. AIAA Paper 2011 – 2887.
7. S. Mayoral, D. Papamoschou. Prediction of Jet Noise Shielding with Forward Flight Effect. AIAA Paper 2013-0010.
8. C. Burley, T. Brooks, F. Hutcheson, M. Doty, L. Lopes. Noise Scaling and Community Noise Metrics for the Hybrid Wing Body Aircraft. AIAA Paper 2014 – 2626, June 2014.
9. J. W. Delfs. Aeroacoustic tunnel effect in noise shielding problems. AIAA Paper 2014 – 3181, June 2014.
10. Mayoral S., Papamoschou D. Experiments on Shielding of Jet Noise by Airframe Surfaces // AIAA Paper 2009-3326
11. Mayoral S., Papamoschou D. Effects of Source Redistribution on Jet Noise Shielding // AIAA Paper 2010-652
12. Papamoschou D. Wavepacket Modeling of the Jet Noise Source // AIAA Paper 2011–2835
13. Huang C., Papamoschou D. Numerical Study of Noise Shielding by Airframe Structures // AIAA 2008-2999
14. Piantanida S., Cavalieri A. V. G., Wolf W., Donadon M., Jordan P. Scattering of Turbulent Jet Wavepackets by a Flexible Composite Plate // AIAA Paper 2016 – 2704
15. Suzuki T., Colonius T. Instability Waves in a Subsonic Round Jet Detected Using a Near-Field Phased Microphone Array // Journal of Fluid Mechanics, 2006, Vol. 565, Pp. 197–226.

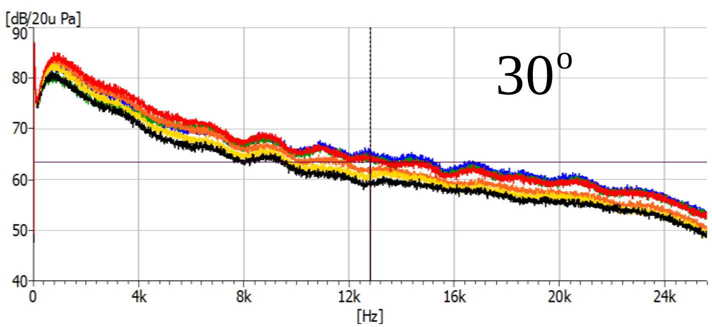
In the present work, we are interesting in the effect on shielding efficiency for *instability waves* noise reduction.

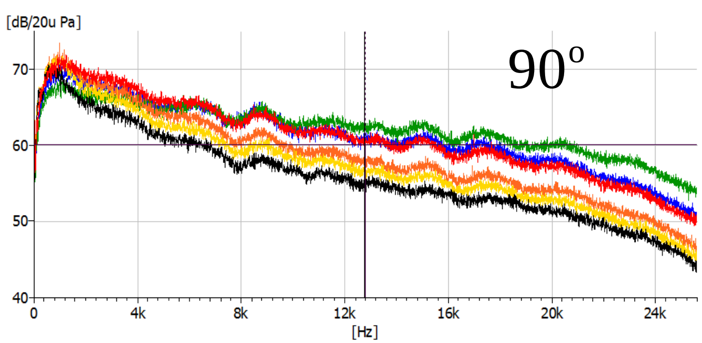
This work based on previous works dedicated to the experimental and theoretical investigations of instability waves:

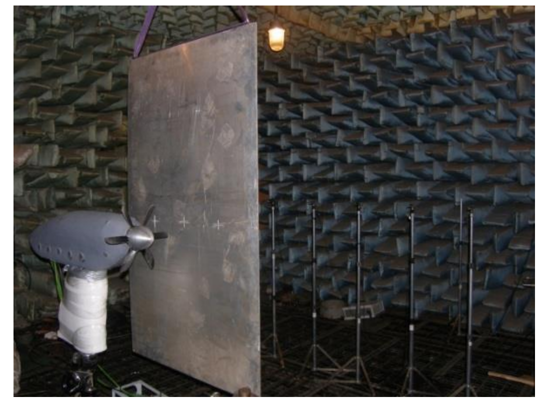
1. Kopiev V.F, Ostrikov N.N., Chernyshev S.A., Elliott J.W., "On the Possibility of Noise Control in Corrugated Supersonic Jets", AIAA Paper №2004-2828, pp. 1-24
2. Kopiev V.F, Ostrikov N.N., Chernyshev S.A., Elliott J.W., "Aeroacoustics of supersonic jet issued from corrugated nozzle: new approach and prospects", International Journal of Aeroacoustics, 2004, 3 (3), pp. 199-228
3. Kopiev V.F, Ostrikov N.N., Chernyshev S.A., Elliott J.W., "Aeroacoustics of supersonic jet issued from corrugated nozzle: new approach and prospects", In "Jet Aeroacoustics" edited by G. Raman, Multi-Science Publishing CO. LTD., 2008, pp 33-66
4. V.F. Kopiev, N.N. Ostrikov "Axisymmetrical Instability Wave Control due to Resonance Coupling of Azimuthal Modes in High-Speed Jet Issuing from Corrugated Nozzle", AIAA 2012-2144

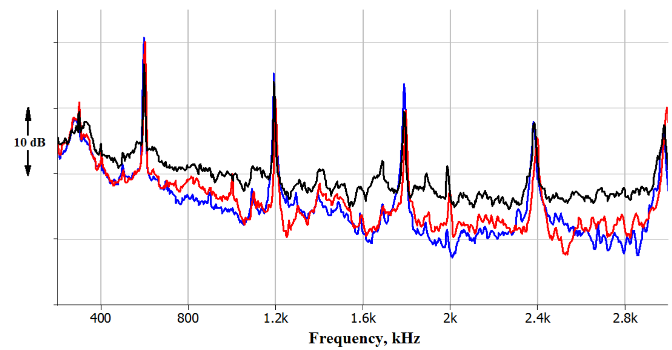
Motivation and Background - I

Our previous investigations were dedicated to the effect of source noncompactness on shielding effect for *the case of mean flow absence* (AIAA Paper 2015 – 2691)





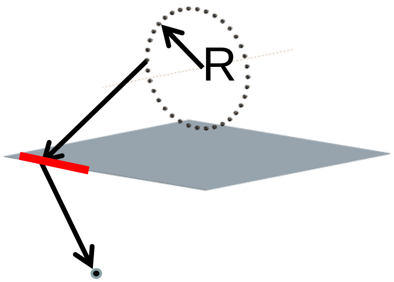


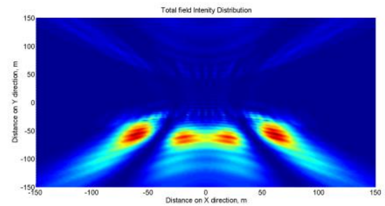


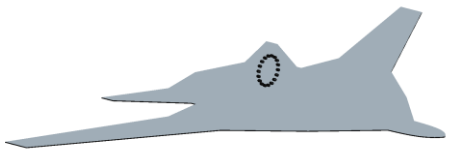
Tone and broadband rotor noises have different type of shielding

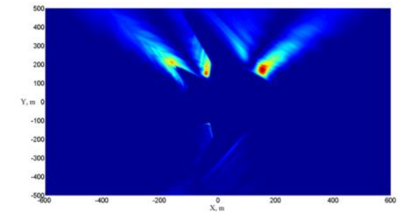
Calculation Background

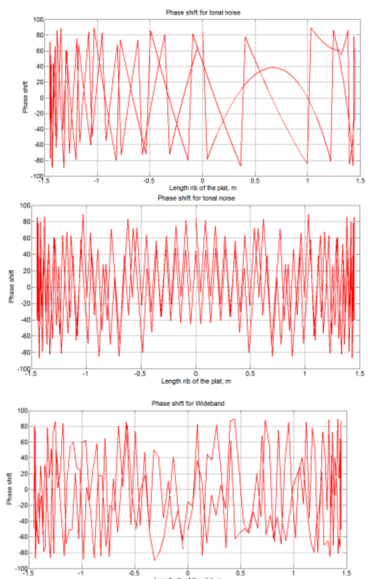
The peculiarities of shielding effect for tone and broadband noise extracted from GTD/UTD (Uniform Theory of Diffraction) approach to diffraction problem (AIAA Paper 2015 – 2691)

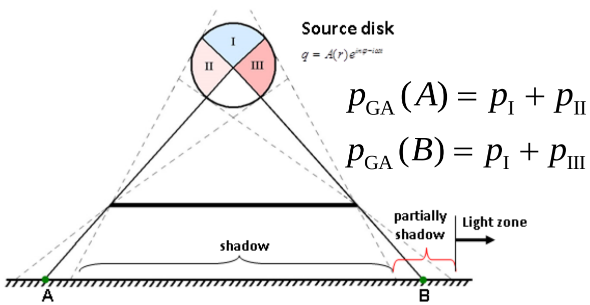


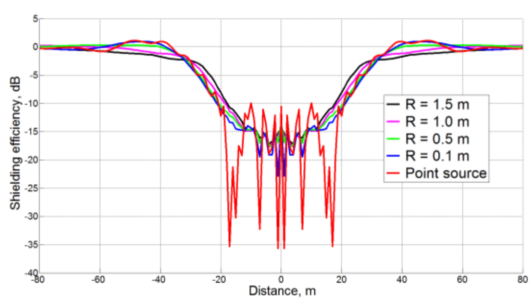








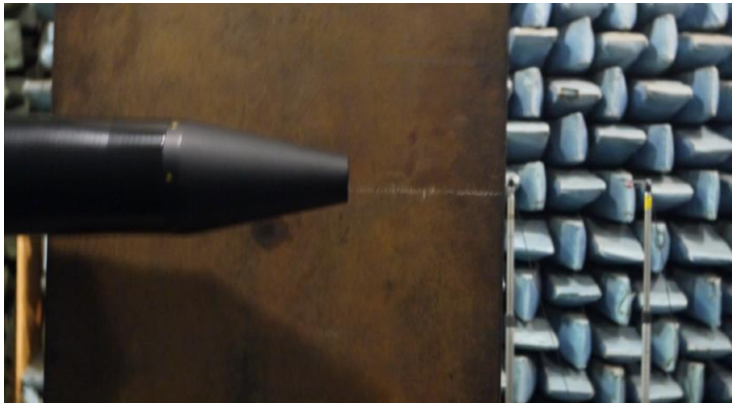


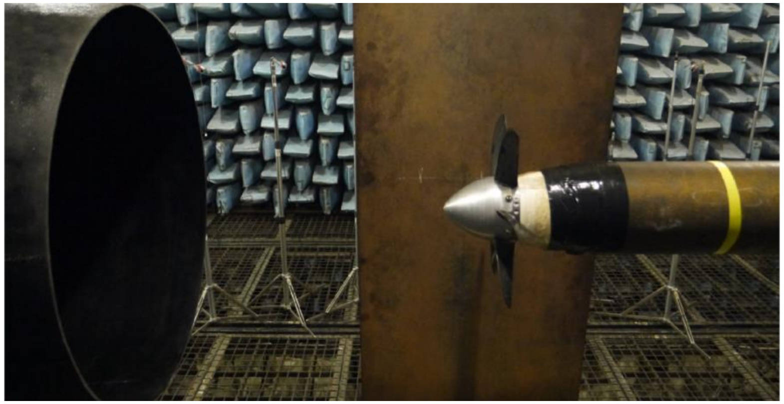


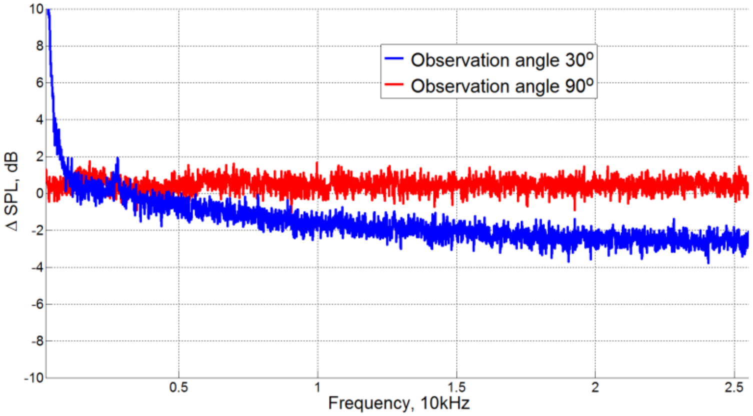
1. Diffraction pattern is determined essentially by source noncompactness for both tone and broadband noise
2. Tone noise shielding depends on azimuthal number of incident sound mode
3. Asymmetrical diffraction pattern appears for shielded rotating modes
4. If rotating modes scatter on screen edges, then noise amplification appears due to sharp directivity

Motivation and Background - II

Another investigations were dedicated to the effect of source noncompactness on shielding effect for *the case of mean flow presence* (AIAA Paper 2016 – 3014)





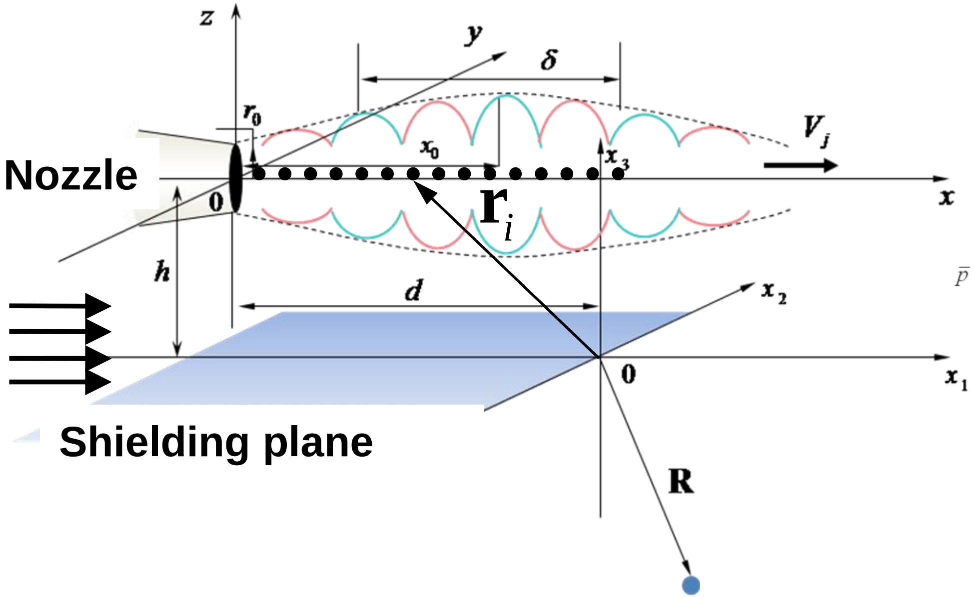


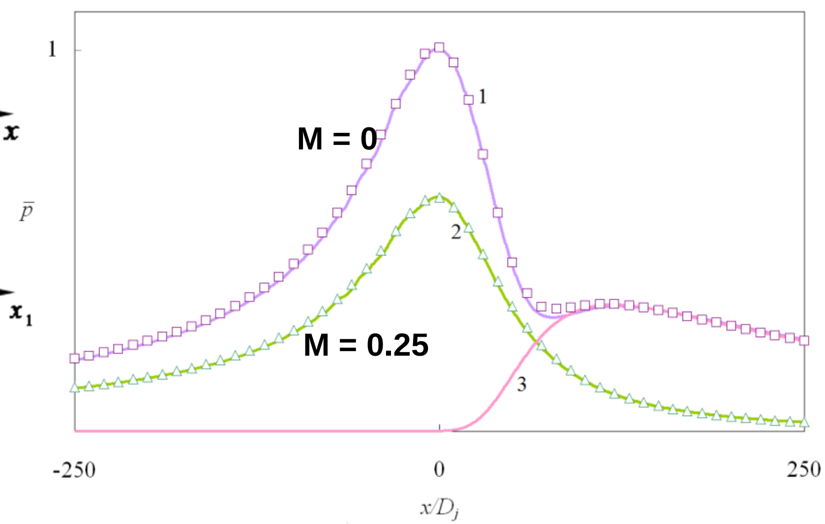
At low Mach number mean flow effect is weak for round jet noise shielding efficiency

The behavior of shielding efficiency for propeller tone noise is in a similar to one obtained in the previous work, where the case of co-flow absence was considered only. The mean flow effect on the shielding efficiency is large for propeller tone noise. The mean flow effect on the shielding efficiency for tone noise is rather difficult because the characteristics of propeller noise depend essentially on the co-flow velocity.

Motivation and Background - III

In paper Faranosov et al, (AIAA 2016-2932) theoretical approach to the jet-wing interaction noise is considered. For a zero mode instability wave comparison of the results obtained by the Wiener-Hopf technique (symbols) and the GTD method (lines) for static and flight conditions were performed.





The main purpose of this paper is to calculate by means of GTD the shielding efficiency of noise radiated by an instability waves describing by a more general model

Instability wave concept for jet noise prediction

Tam's theory has the following features:

•Long-waves turbulent disturbances within jet mixing layer are represented as stochastic sum of wave packets. Each wave packet is an eigen-solution to linearized Euler equations over mean jet flow.

•The typical form for wave packet as follows: $p = A_0(\omega, n)\,\exp\left(-i\int_0^x \alpha(x)dx\right)\cdot\exp(-i\omega t + in\varphi)\cdot p(r,x)$

It is characterized by individual real frequency, azimuthal number and initial amplitude considered as parameters. While, the spatial complex wave number along *x* axis is obtained from solution to spatial stability problem.

•There are several eigen-solutions of this problem for each real frequency and azimuthal number. The theory takes into account only waves having the most grows of amplitude at given frequency and azimuthal number. These waves correspond with Kelvin-Helmholtz instability and are named as *instability waves*. The others eigen-solutions are neglected.

•Due to the linearized problem is considered, the initial amplitude of each instability wave packet is free parameter that is chosen for agreement with experimental data. Moreover, due to self similarity of mixing layer near the round nozzle orifice, the distribution of initial amplitude is assumed as white noise.

These instability waves developing downstream from the nozzle lip have the most phase velocity over other disturbances within mixing layer. This velocity is supersonic. That is why they give the main contribution in the noise radiation.

Conclusions extracted from experiments

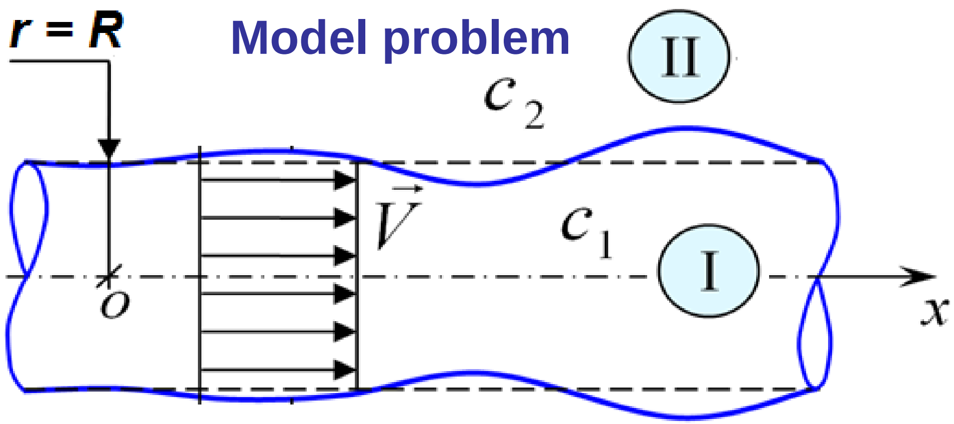
The main part of the mixing noise in supersonic jets is radiated by instability waves developing downstream from the nozzle lip

A comparison of the theoretical calculations and the measured data shows that for the azimuthal n = 0, 1, and 2 harmonics, which contribute most to the jet noise, the theoretical results are in good agreement with the experimental data

Distribution of the initial amplitudes of the instability waves near the nozzle orifice over different azimuthal numbers and frequency bands is closely to white noise.

Instability waves in subsonic jets

Model problem



The form of eigen solution

$$p_{1,2}(r,\varphi,x,t) = \tilde{p}_{1,2}(r)\exp(-i\omega t - i\alpha x - in\varphi)$$

Governing equations

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p_2}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 p_2}{\partial \varphi^2} + \left(k_2^2 - \alpha^2\right)p_2 = 0, \qquad r > R$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p_1}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 p_1}{\partial \varphi^2} + \left(\left(k_1 + M\alpha\right)^2 - \alpha^2\right)p_1 = 0, \quad r < R$$

$$M = \frac{V_0}{c_-}, \qquad k_{1,2} = \frac{\omega}{c_{1,2}}$$

Basic equations for pressure disturbances

$$\frac{\partial^2 p}{\partial t^2} - c_2^2 \Delta p = 0, \qquad r > R$$

$$\left(\frac{\partial}{\partial t} + V_0\frac{\partial}{\partial x}\right)^2 p - c_2^2\Delta p = 0, \qquad r < R$$

Boundary conditions

$$p_1\big|_{r=R} = p_2\big|_{r=R}$$

$$c_2^2\left(\frac{\partial}{\partial t} + V_0\frac{\partial}{\partial x}\right)^2 \frac{\partial p_2}{\partial n}\bigg|_{r=R} = c_1^2\frac{\partial^2}{\partial t^2}\left(\frac{\partial p_1}{\partial n}\right)\bigg|_{r=R}$$

1. Disturbances should decrease as $r \to \infty$ at each moment t
2. Disturbances are created by the sources located at the tangential discontinuity (causality)

Features of Instability Waves Near the Orifice of Round Jet

Solutions of governing equations

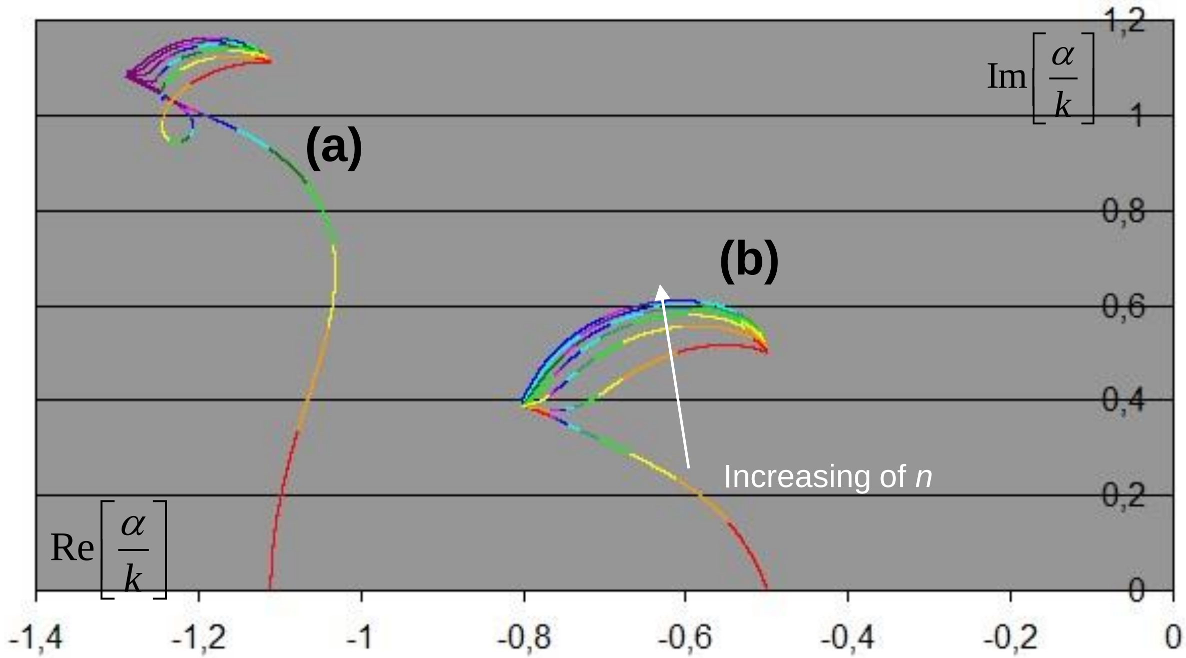
$$p_2 = \sum_{n=0} A_n H_n^{(1)}(i\beta_2 r)e^{in\varphi}, \qquad r > R$$

$$p_1 = \sum_{n=0} A_n J_n^{(1)}(i\beta_1 r)e^{in\varphi}, \qquad r < R$$

$$\beta_2 = \sqrt{\alpha^2 - k_2^2}, \qquad \beta_1 = \sqrt{\alpha^2 - (k_1 + M\alpha)^2}$$

Dispersion relation with respect to unknown spatial eigen wave number

$$(k_1 + M\alpha)^2 (i\beta_2 R) H_n'^{(1)}(i\beta_2 R) J_n(i\beta_1 R) -$$
$$-k_2^2 H_n^{(1)}(i\beta_2 R)(i\beta_1 R) J'_n(i\beta_1 R) = 0$$

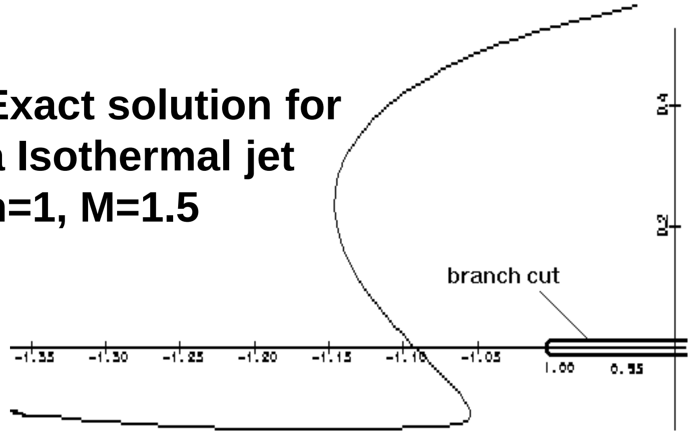


Dependence of spatial wave number α for instability wave with azimuthal numbers *n*=0,1,…,6 on Strouhal number. (a) M=0,9 ; (b) M=2,0

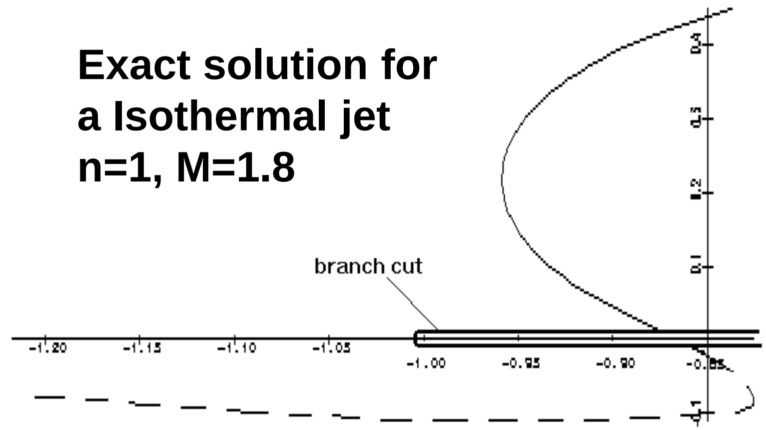
1. **Different azimuthal modes as eigen-solutions are independent from each others**
2. **There is degeneracy for azimuthal modes with n and –n azimuthal numbers**

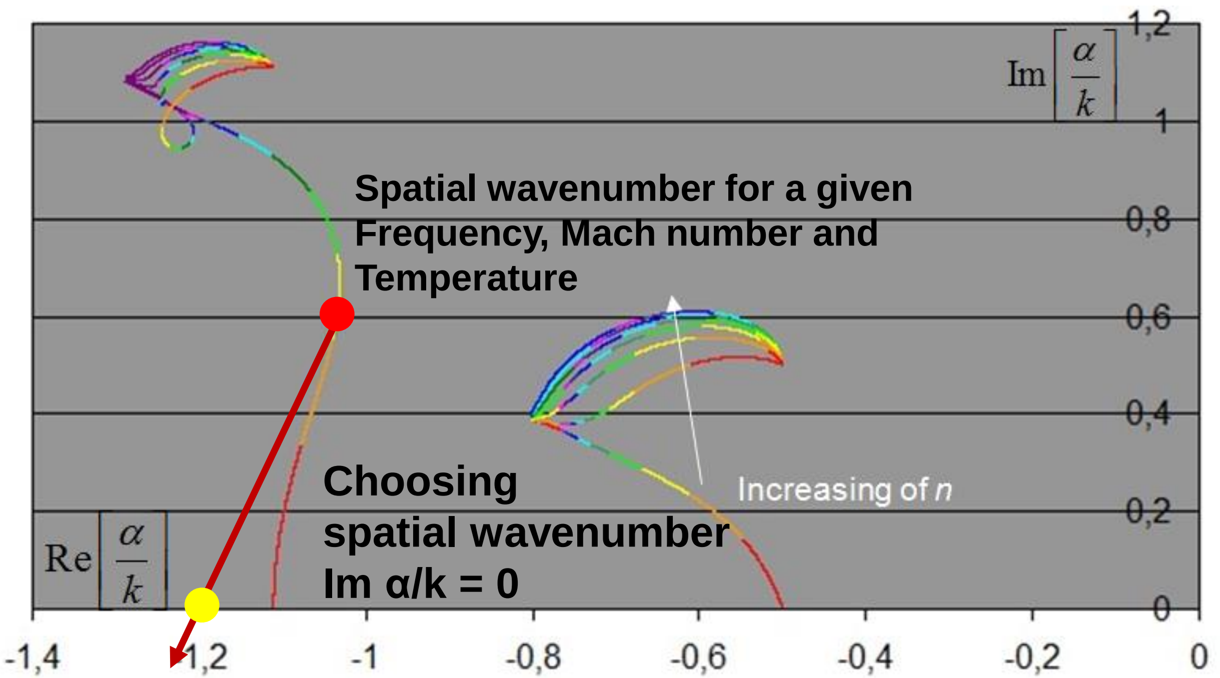
Spatial wavenumber evolution in complex plane and wavepacket parameters

Exact solution for a Isothermal jet n=1, M=1.5



Exact solution for a Isothermal jet n=1, M=1.8





Wavepacket length X, location of maximum amplitude x0 and spatial wavenumber at Im α/k = 0 choosing arbitrary.

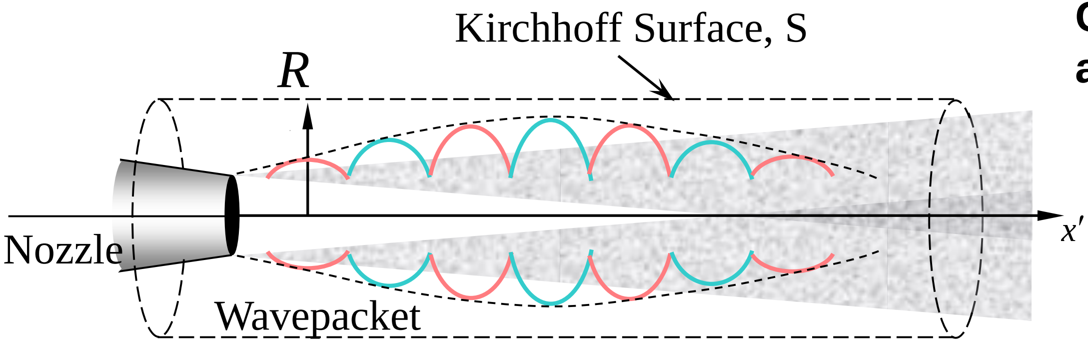
This makes it possible to vary the properties of the wavepacket with constant jet parameters.

Basic equations for a far field calculations

$$P(\mathbf{x}) = \int_S \left(G(\mathbf{x},\mathbf{y}) \frac{\partial P(\mathbf{y})}{\partial n} - P(\mathbf{y}) \frac{\partial G(\mathbf{x},\mathbf{y})}{\partial n} \right) d\mathbf{y}$$

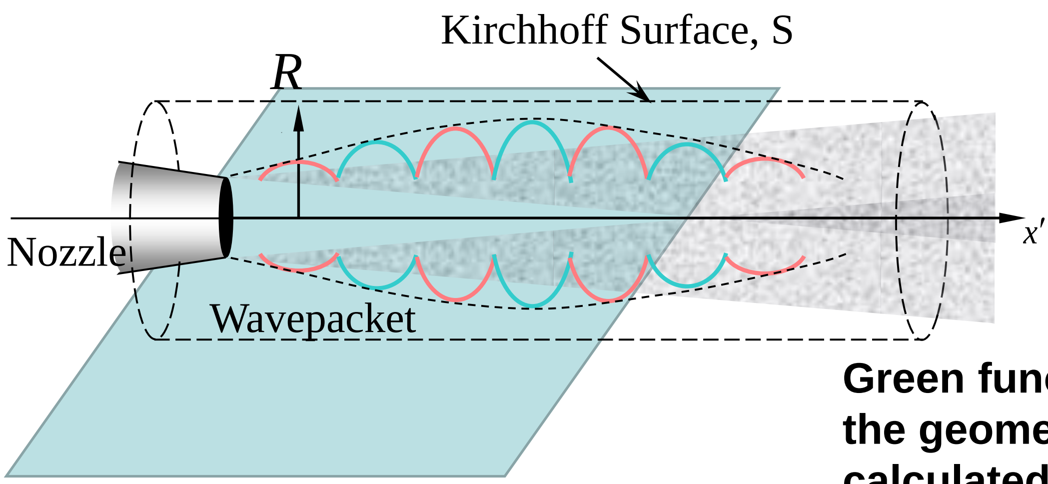
Functions $\frac{\partial P(\mathbf{y})}{\partial n}$ **and** $P(\mathbf{y})$

Calculated on Kirchhoff surface for a described Instability wave model



Green function for a free space

$$G(\mathbf{x},\mathbf{y}) = \frac{1}{4\pi} \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{|\mathbf{x}-\mathbf{y}|}$$



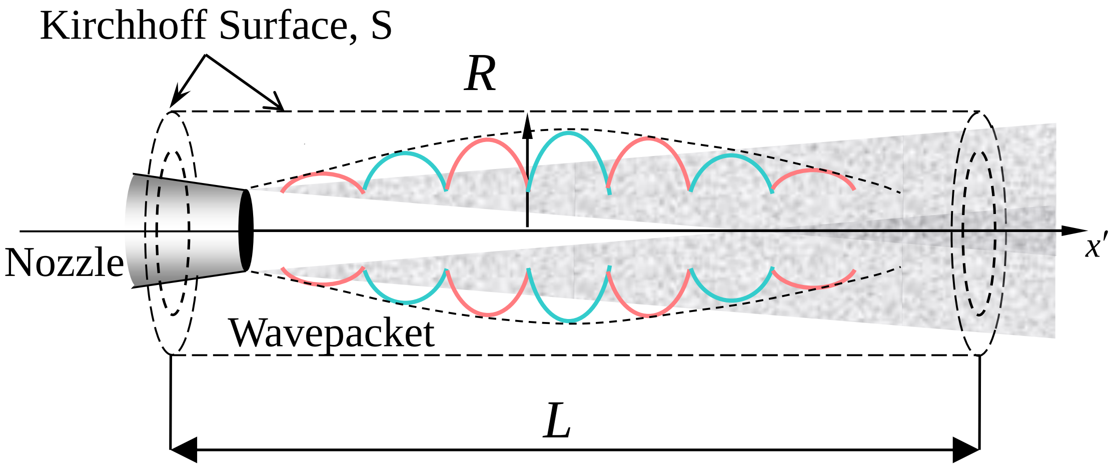
Green function for a shielding calculation

$$G(\mathbf{x},\mathbf{y}) = G_G(\mathbf{x},\mathbf{y}) + G_D(\mathbf{x},\mathbf{y})$$

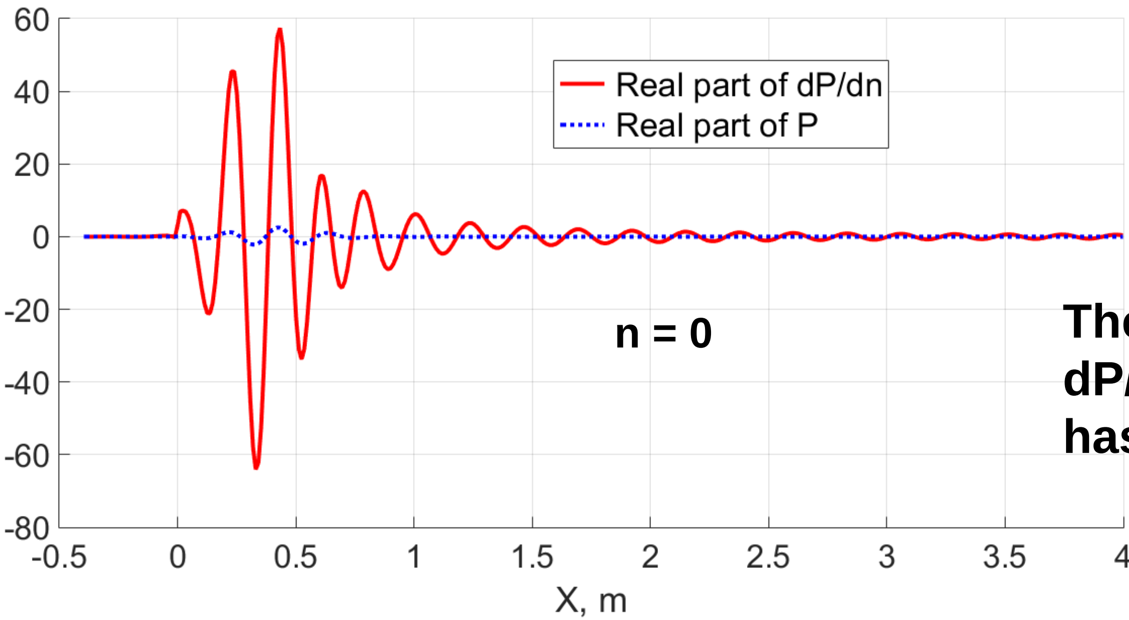
Green function for the geometrical field calculated by GTD

Green function for the diffracted field calculated by GTD

Kirchhoff surface construction

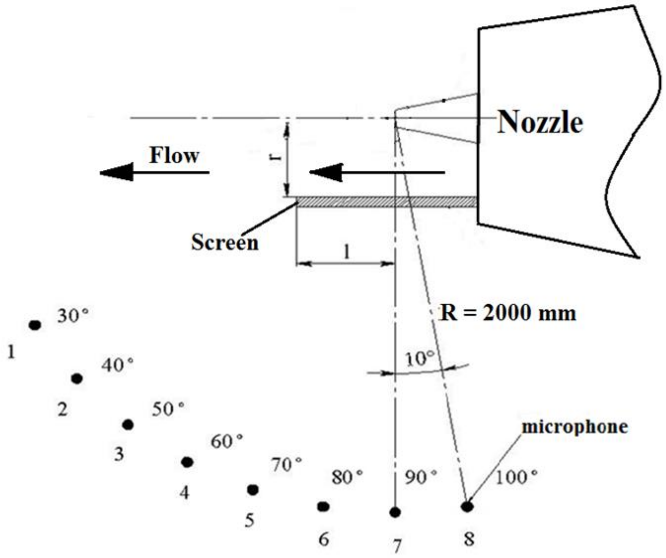


For a long wavepacket length of the Kirchhoff surface L enlarge up to 100D.
Short length of the Kirchhoff surface with the L=20D result in error in free field calculation.
It caused by with the significant oscillations of the pressure normal derivative along Kirchhoff surface.

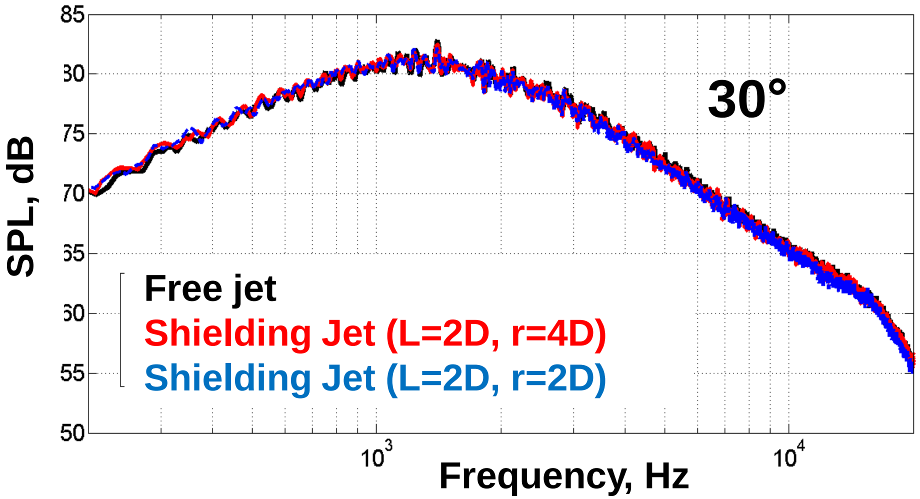


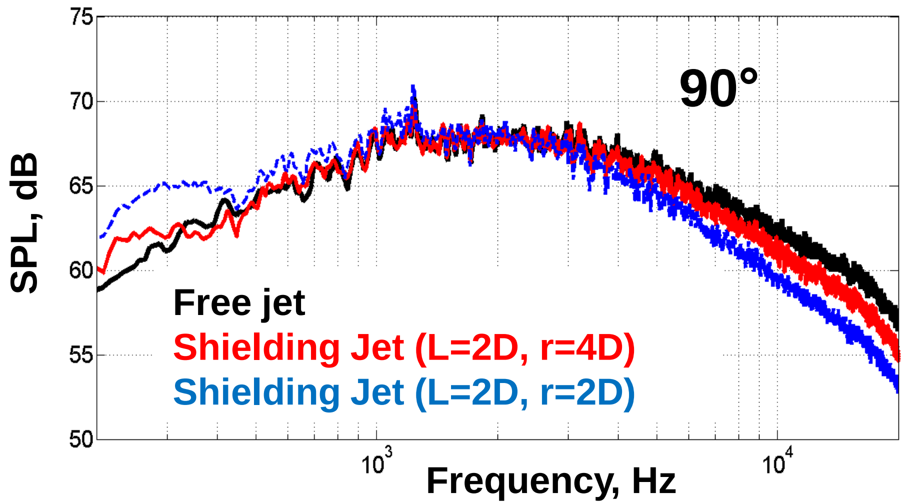
The image part of P and dP/dn on Kirchhoff surface has the same behavior

Experimental set-up for single jet noise shielding investigation

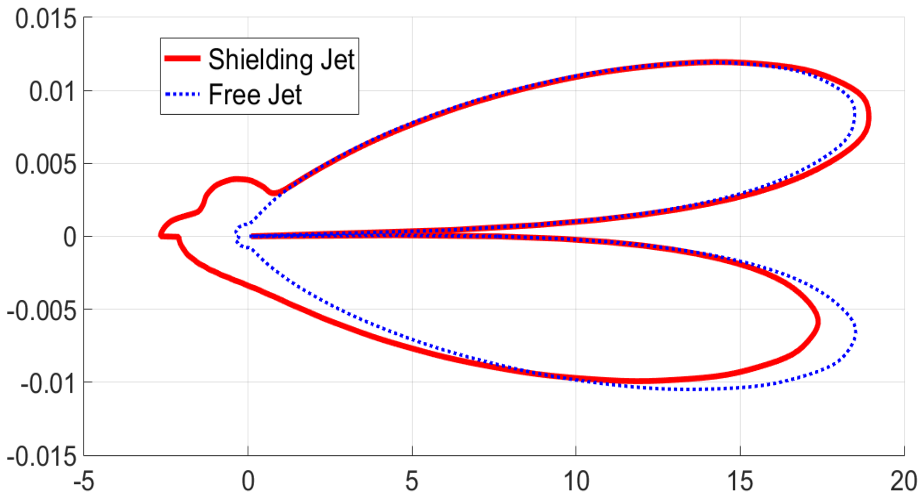


Screen position:
l = 2D, r = 2D; l = 4D, r = 2D,
l = 4D, r = 4D; l = 2D, r = 4D.
D – nozzle diameter (4 cm). V=0.9M

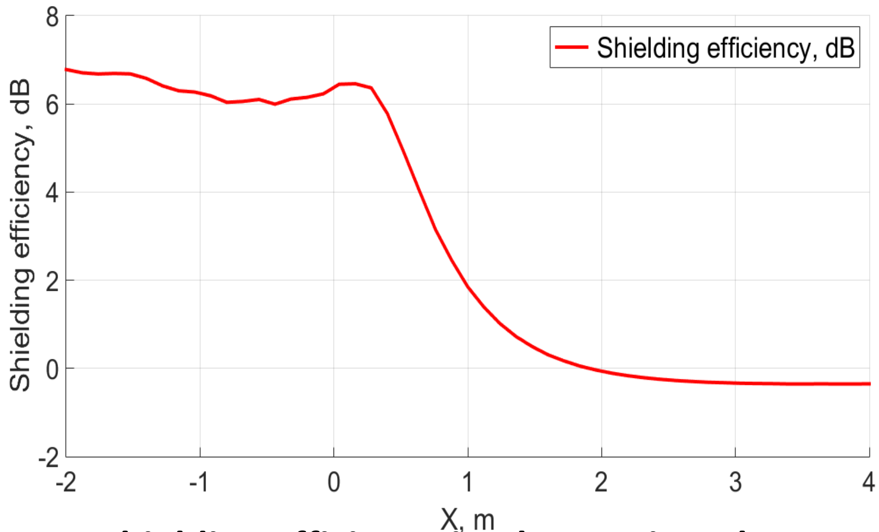




Shielding efficiency calculation for instability wave of zero mode (n=0)

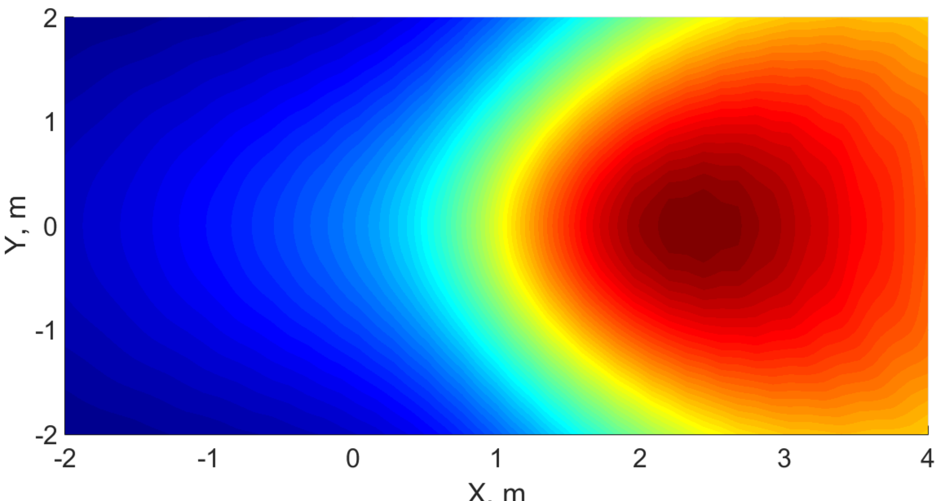


Polar directivity



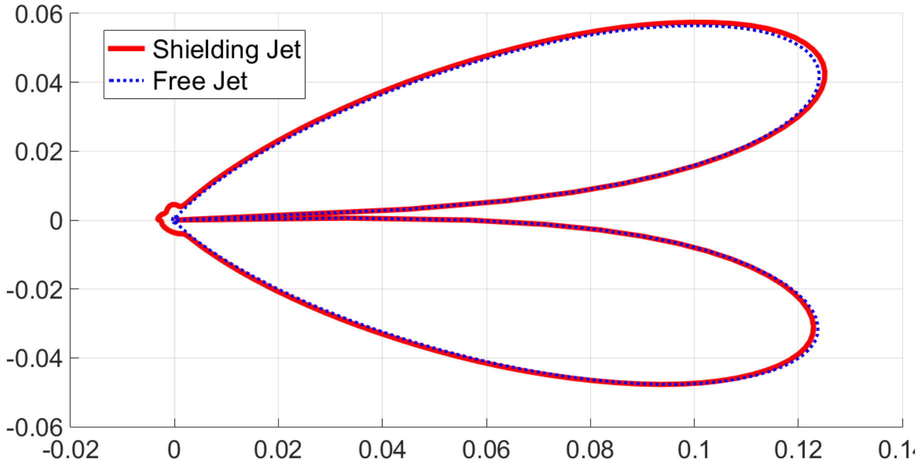
Shielding efficiency in observation plane

Frequency = 1500 Hz;
x0 = 5D; X = 50D;
R=1.5D; L=75D;
Number of sources = 4960

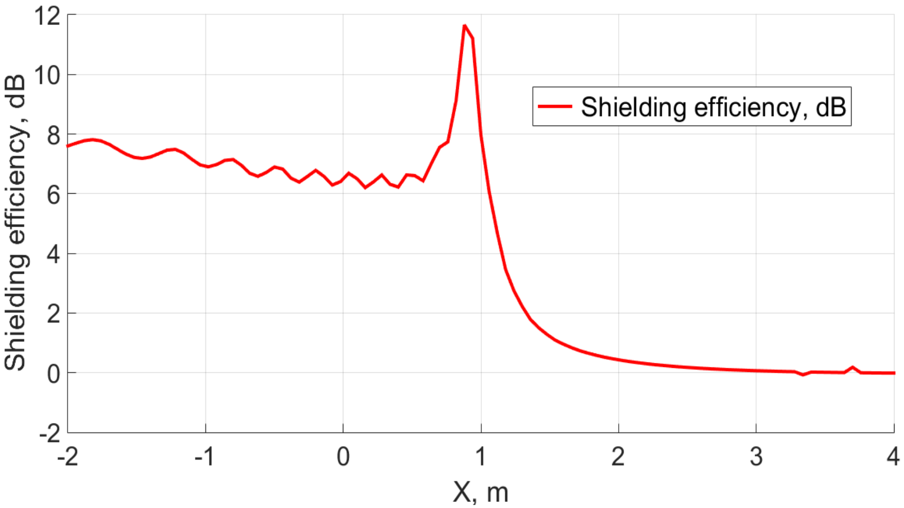


Noise distribution in observation plane X-Y under the screen

Shielding efficiency calculation for instability wave of zero mode (n=0)

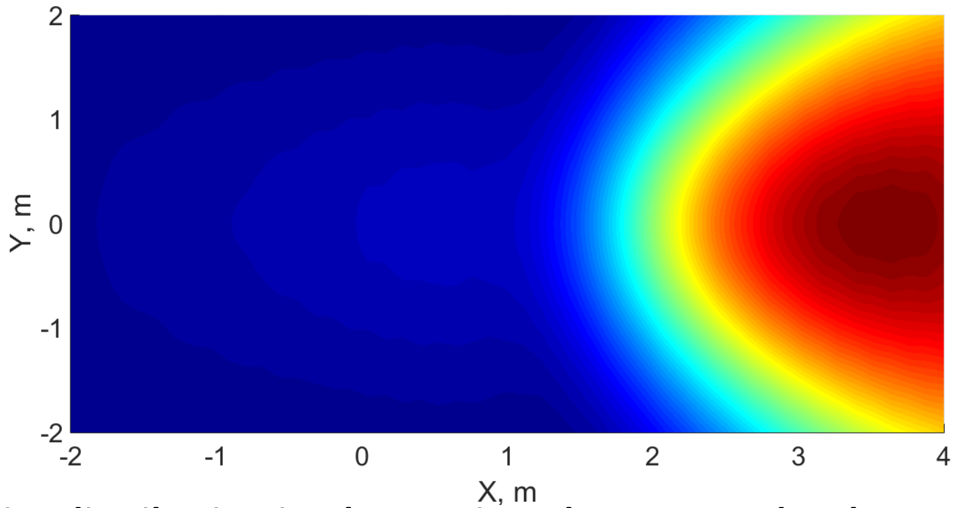


Polar directivity



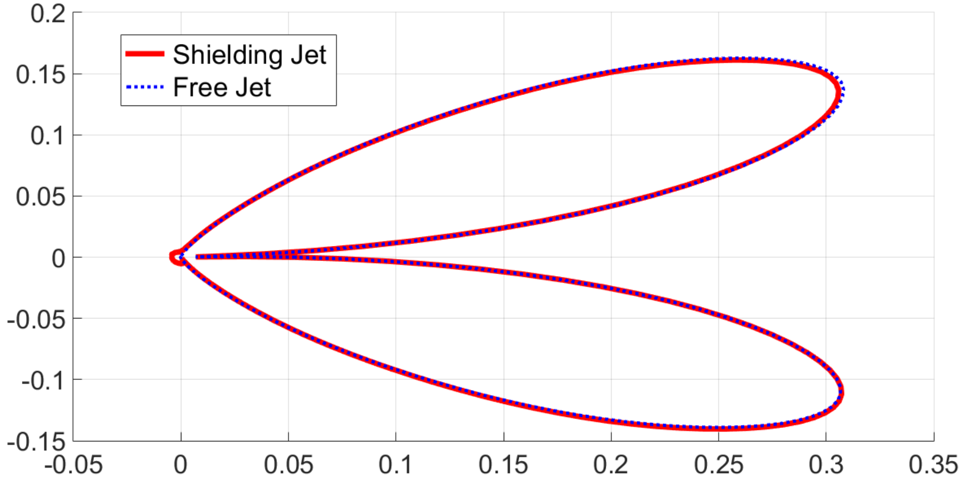
Shielding efficiency in observation plane

Frequency = 1500 Hz;
x0 = 10D; X = 50D;
R=1.5D; L=200D;
Number of sources = 6224

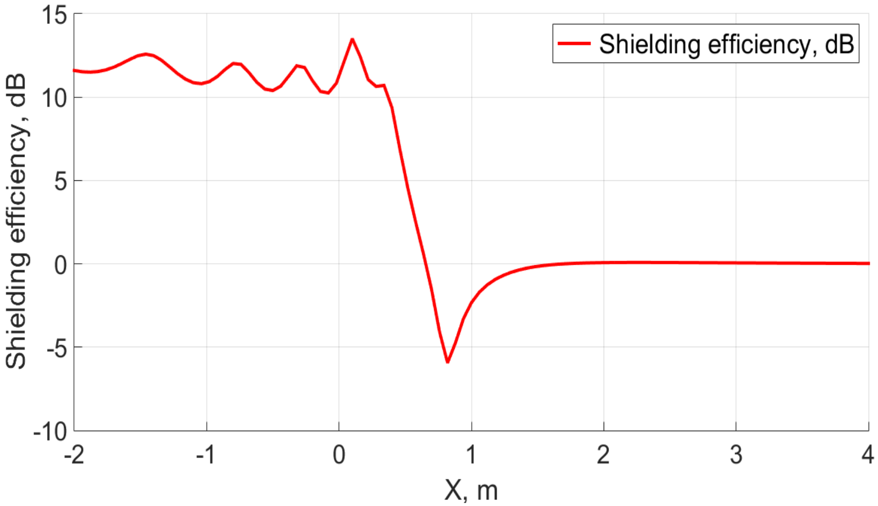


Noise distribution in observation plane X-Y under the screen

Shielding efficiency calculation for instability wave of first mode (n=1)



Polar directivity



Shielding efficiency in observation plane

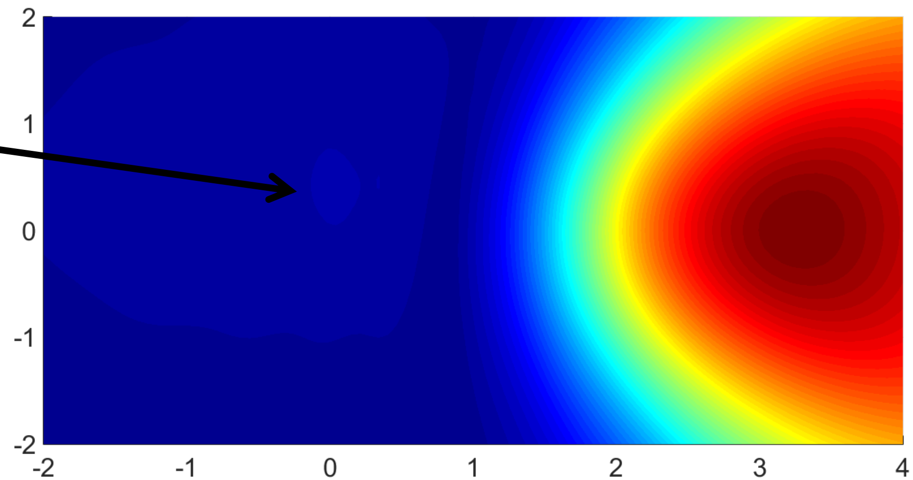
In geometrical shadow zone asymmetrical diffraction pattern appears

Frequency = 1500 Hz;

x0 = 10D; X = 50D;

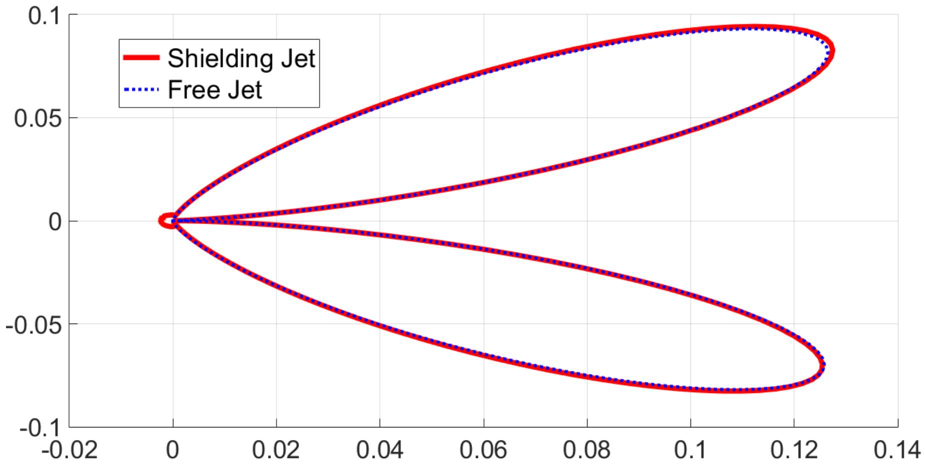
R=1.5D; L=35D

Number of sources = 2112

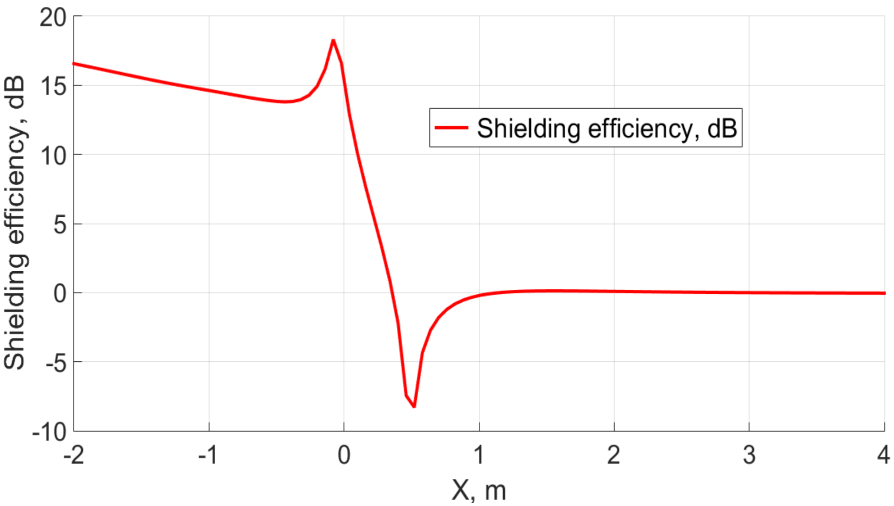


Noise distribution in observation plane X-Y under the screen

Shielding efficiency calculation for instability wave of second mode (n=2)



Polar directivity



Shielding efficiency in observation plane

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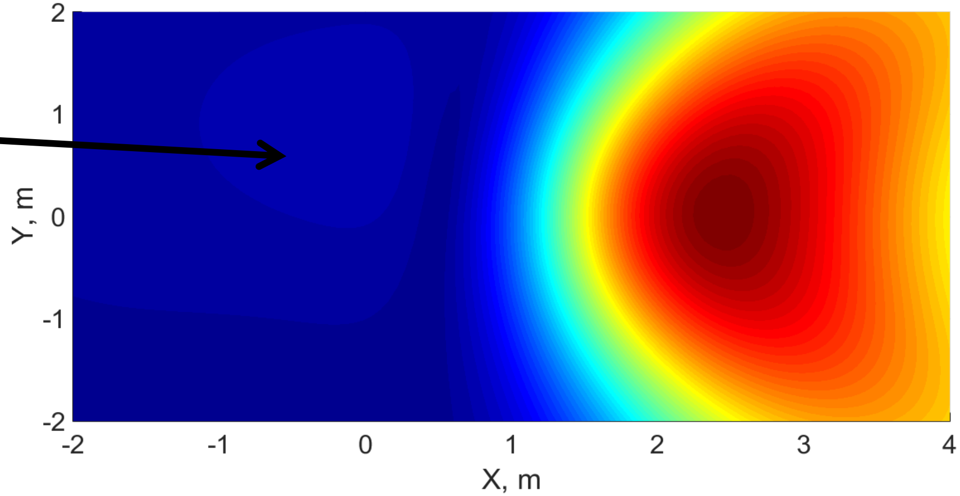

Noise distribution in observation plane X-Y under the screen

Conclusions

Based on Geometrical Theory of Diffraction (GTD) and Kirchhoff integral representation developed method for noise radiated by instability waves shielding efficiency calculation.

Proposed method suppose generalization for the case of flat polygonal shielding surfaces and different types of noncompact aviation noise sources for which Kirchhoff surface may be constructed.