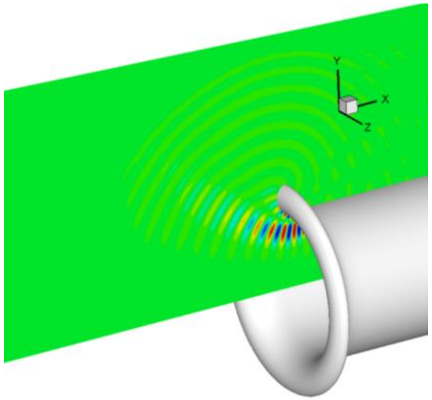
THE APPLICATION OF HARMONIC METHODS FOR THE CALCULATION OF THE TONE NOISE PROPAGATION THROUGH INLETS AND NOZZLES OF TURBOFANS

I.M. Druzhinin, V.I. Mileshin, ***A.A. Rossikhin***
Central Institute of Aviation Motors (CIAM)

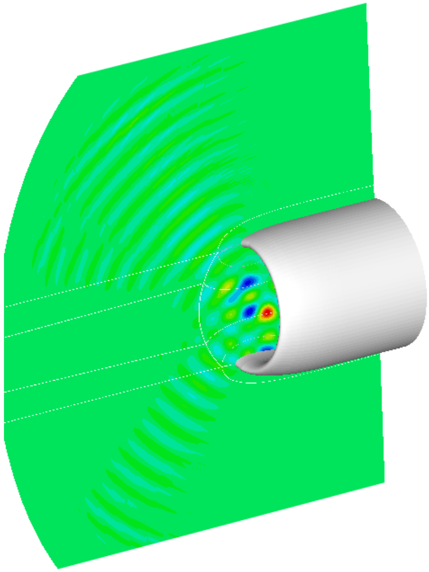
The calculation of the tone noise propagation through the inlet and the nozzle

The calculation of noise propagation through the inlet and the nozzle is an important part of tone noise calculations. It can be performed simultaneously with the interaction calculation – direct approach, or after the interaction calculation – hybrid approach



Direct approach

Takes into account the reflections from the inlet and the nozzle



Hybrid approach

Can be performed using more effective computational methods, thus reducing the computational cost

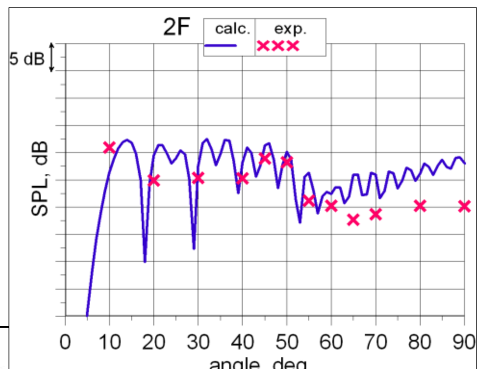
More flexible, as can use the results of one interaction calculation with different inlet and nozzles

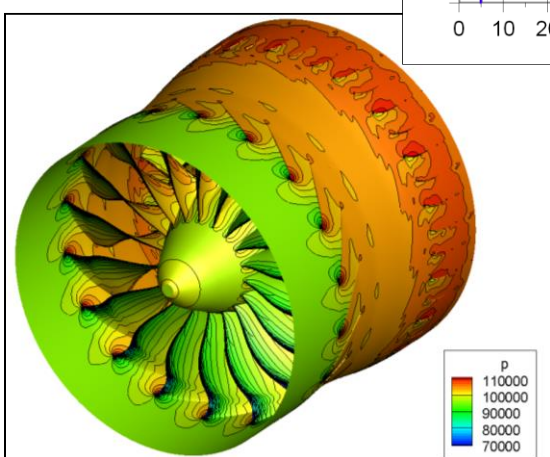
The program package 3DAS

A computational method for analysis of turbomachinery tone noise in the near and far acoustic fields was developed in CIAM. The method is based on the numerical solution of non-linear and linear 3D inviscid equations, solved for perturbations, using numerical methods of computational acoustics. It is implemented in CIAM’s program package 3DAS.

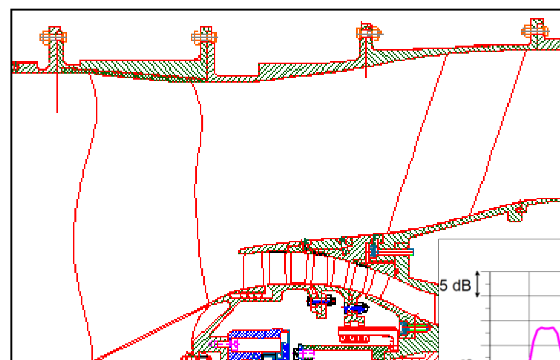
The method can be used for:

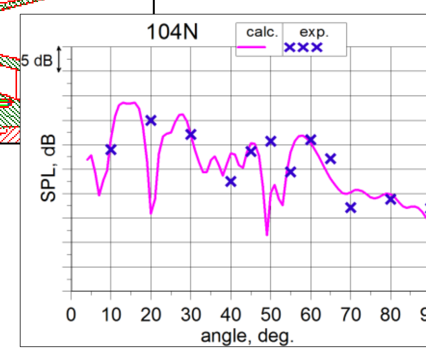
- Simulation of tone noise generated by ducted classical and counter-rotating fans in the near and far acoustic fields.





- Simulation of tone noise of open counter-rotating fans in the near and far acoustic fields.





- Simulation of tone noise of low pressure compressors

Numerical scheme

- Space discretization is constructed using the DRP scheme (Dispersion Relation Preserving Scheme) generalized to the finite volume method. This scheme is the optimized for aeroacoustic purposes fourth order scheme with stencil containing seven points. (C. Tam, J. Webb, 1993)

- Optimized 6-step Runge-Kutta Scheme of the 4th order of HALE-RK (High-accuracy large-step explicit Runge–Kutta) type is used for time discretization of equations

- Numerical system of equations also contains dissipative terms of second and fourth orders (O. Vasilyev, 1998) . In the nonlinear case numerical system of equations contains adaptive dissipation terms with simple pressure sensor (A. Jameson, W. Schmidt and E. Turkel, 1981)

- Calculations can be performed both in time and in frequency domains

- The method based on the Ffowcs-Williams and Hawkings equation with a penetrable data (integration) surface is used to predict tone noise in the far field, using results of the calculations in the near field.

- MPI library is used for parallelization

Harmonic methods

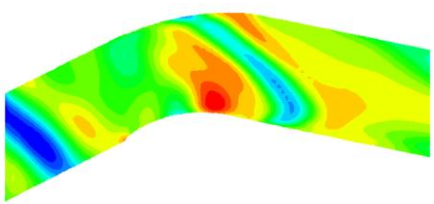
The harmonic methods are based on the assumption that the flow field in a turbomachine can be represented as a harmonic series on time

$$u(x,y,z,t) = u_0(x,y,z) + \sum_{k=1}^{Ng} \tilde{u}_k(x,y,z) \cdot e^{i(\omega \cdot t)}$$

Ng – a number of harmonics under consideration

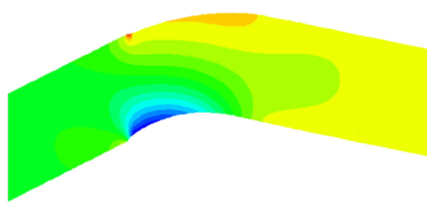
The unsteady problem can be reduced to Ng×2+1 steady problems

$$u(x,y,z,t)$$

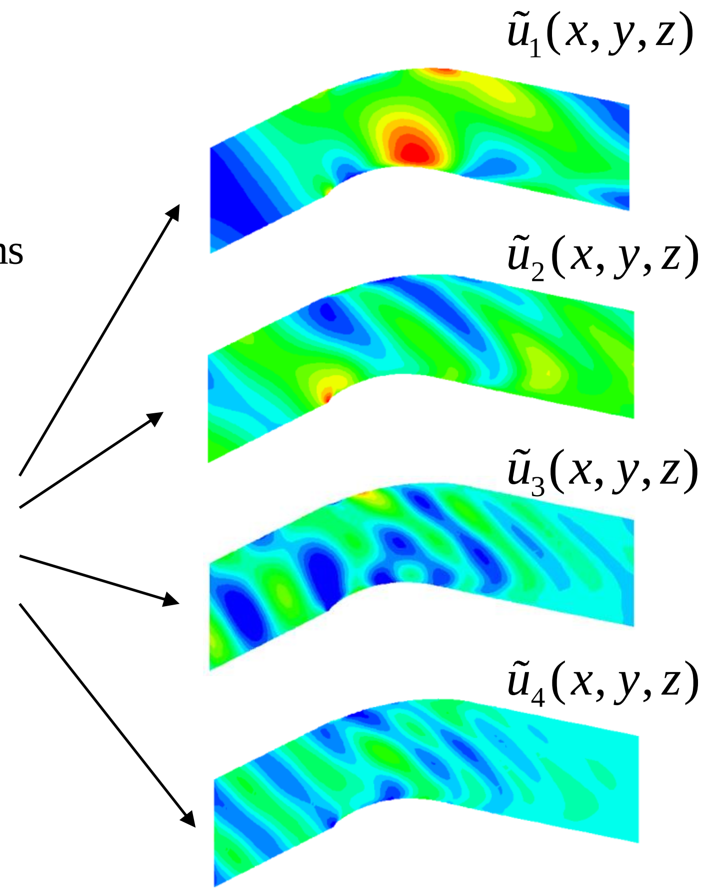


$$=$$

$$u_0(x,y,z)$$



$$+\sum_{k=1}^{Ng}$$



In the linear approximation the equations for different harmonics are independent

The solutions for steady problems can be obtained using the methods of convergence acceleration, developed in the framework of steady CFD

In general harmonic representation describes the evolution of the system in time more precisely than an unsteady solution

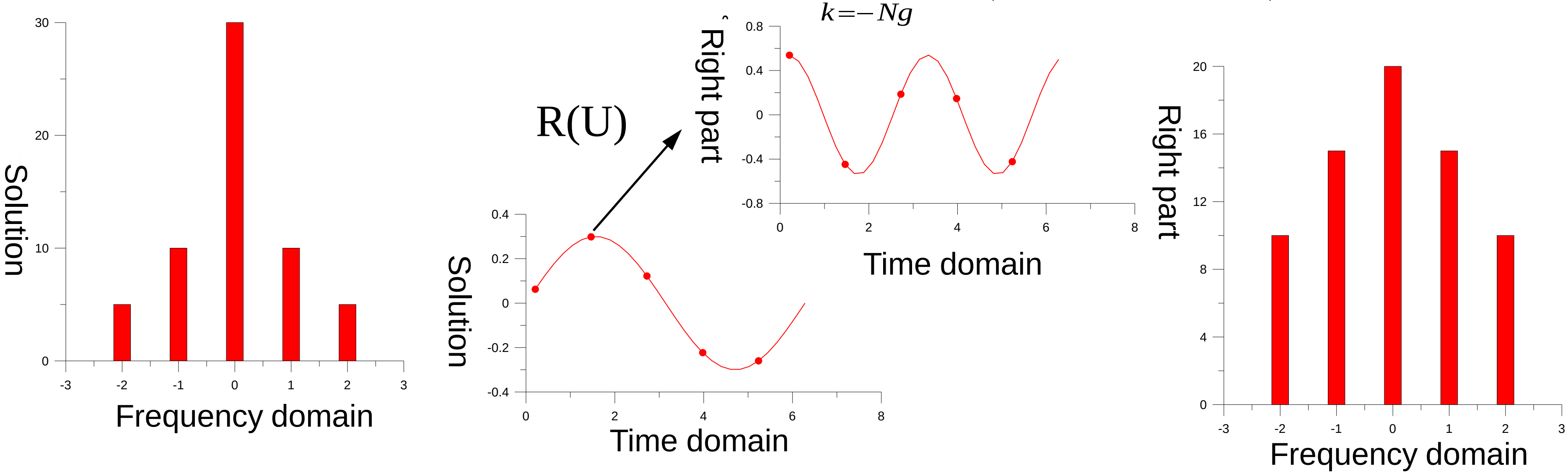
Harmonic balance method

In the nonlinear approximation the equations for harmonics are not independent. The fluxes depends on all harmonics, participating in the calculation.
According to the harmonic balance approach the fluxes in the frequency domain can be obtained by Fourier transformation of the fluxes in time domain, calculated at some specified time moments.

$$\vec{U}'(x,y,z,t) = \sum_{n=-Ng}^{Ng} \vec{U}'_n(x,y,z)\cdot e^{-i\cdot\omega\cdot n\cdot t}$$

$$-i\omega n \sum_{n=-Ng}^{Ng} \vec{U}'_n(x,y,z)\cdot e^{-i\cdot\omega\cdot n\cdot t} + \vec{R}\left(\vec{U}'(x,y,z,t)\right) = 0$$

$$-i\omega n \vec{U}'_n + \vec{R}'_n = 0 \qquad \vec{R}'_n(x,y,z) = \sum_{k=-Ng}^{Ng} \vec{R}'\left(\vec{U}'(x,y,z,t_k)\right)\cdot e^{i\cdot\omega\cdot n\cdot t_k}$$



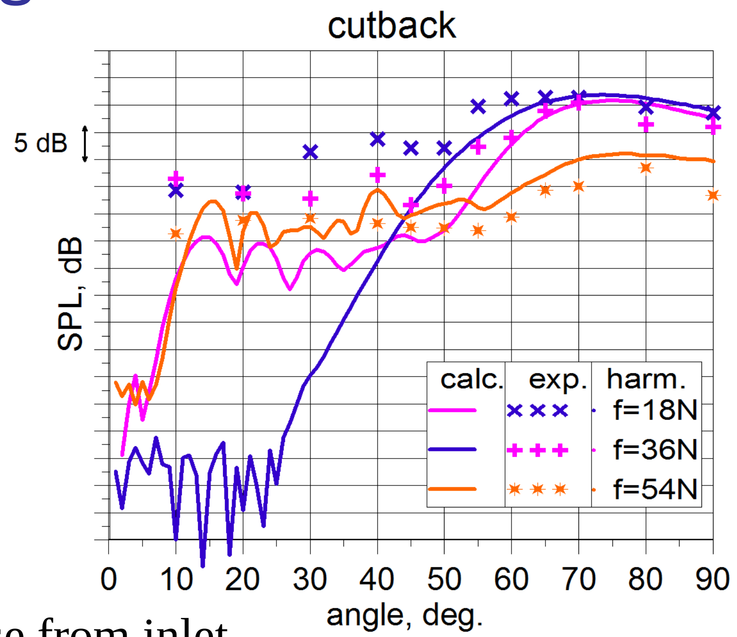
Applications

High bypass ratio fan at cutback conditions

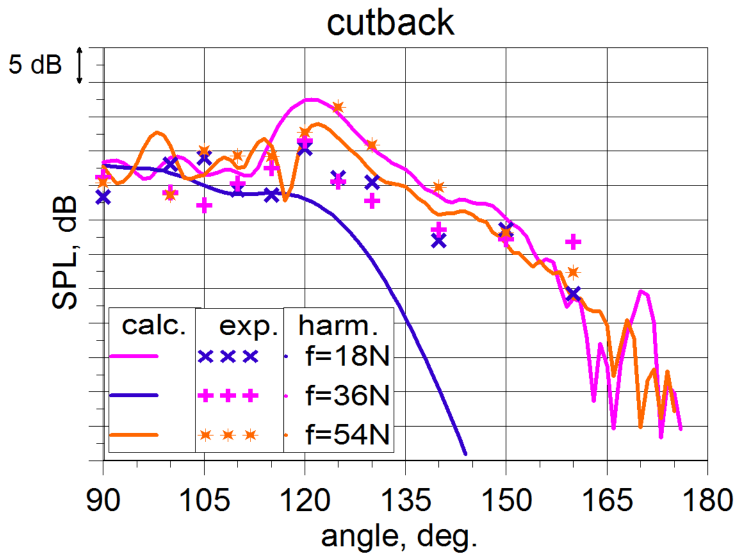
The fan has 18 blades in the rotor and 43 vanes in the stator of bypass duct.

Rotor of the fan model. Front view

Calculation was performed in frequency domain. The aim was to obtain directivity diagrams for first three harmonics of blade passage frequency

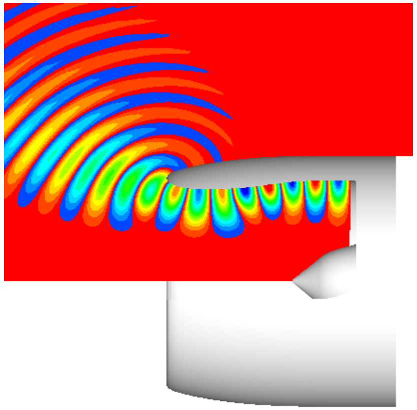


Noise from inlet



Noise from nozzle

2.5D Method of tone noise propagation calculation



When geometry of the problem and mean flow field are axisymmetric, inviscid equations for disturbances can be reduced to the set of equations for circumferential harmonics of disturbances. In the linear case this equations are independent

Lets assume

$$\vec{U}'(t,x,r,\varphi) = \sum_k O^5(\varphi)\vec{U}_k(x,r)e^{im_k\varphi - i\omega_k t}$$

$U_m(x,r)$ - Field of k- circumferential mode

$O^5(\varphi)$ matrix, describing rotations

Then, 2.5D equation can be represented in the form

$$-i\omega_k\vec{U}_k + \frac{\partial \vec{E}_k'(U)}{\partial x} + \frac{1}{r}\frac{\partial (r\vec{F}_k'(U))}{\partial r} = -O_{m_k}\vec{G}_k'(U)$$

In many cases the solutions can be described by quite small number of circumferential harmonics, so the reduction of 3D problem to the set of 2D problems can lead to the saving of computational resources.

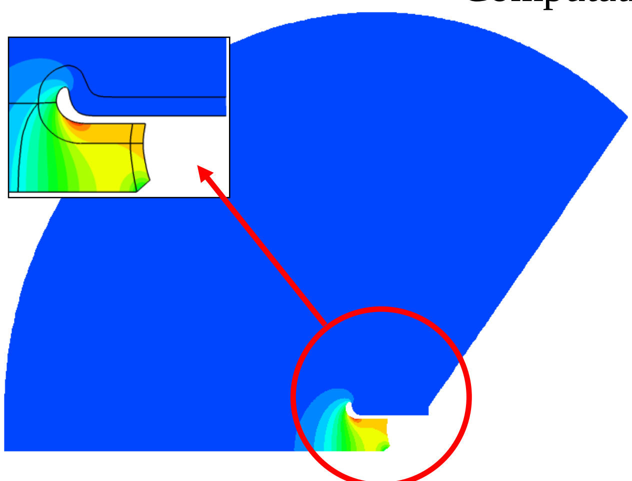
In the nonlinear approximation the fluxes can be calculated using harmonic balance approach

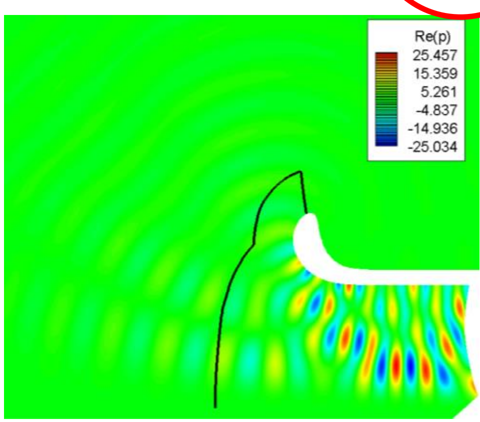
Applications of the method to the calculations of tone noise propagation through inlets

In the linear approximation the method can be used for calculation of tone noise propagation through the inlet.

Noise of the counter-rotating fan in the far field

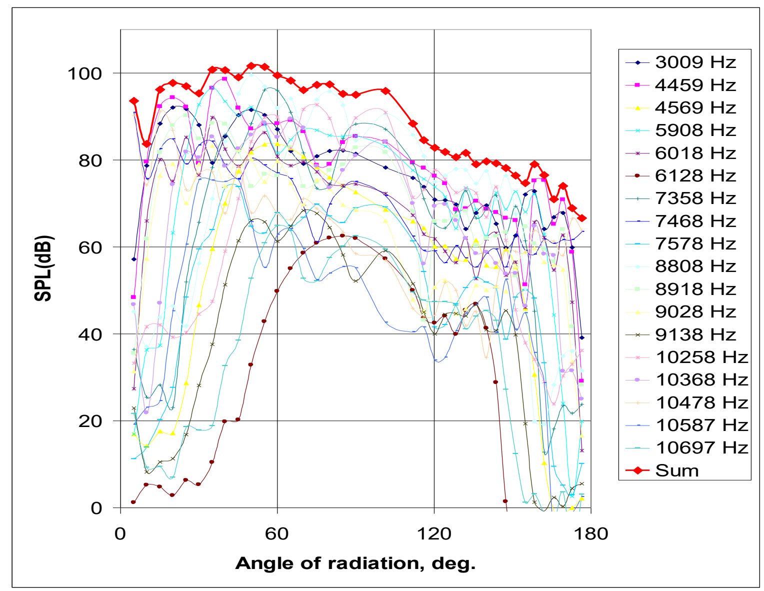
Computational domain





Real part of static pressure
f = 3009.4 Hz, m = 4

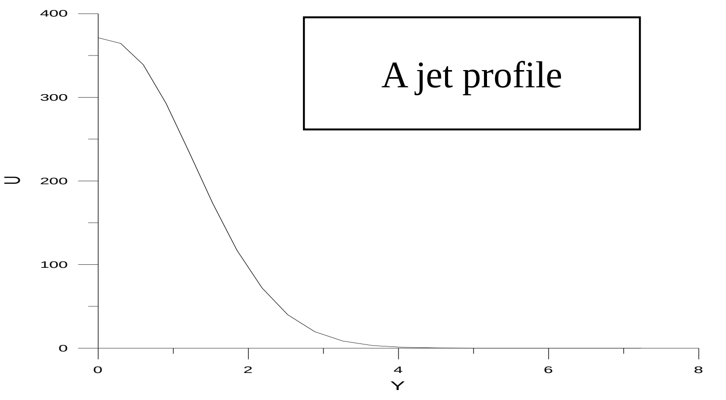
Directivity diagrams for circumferential modes

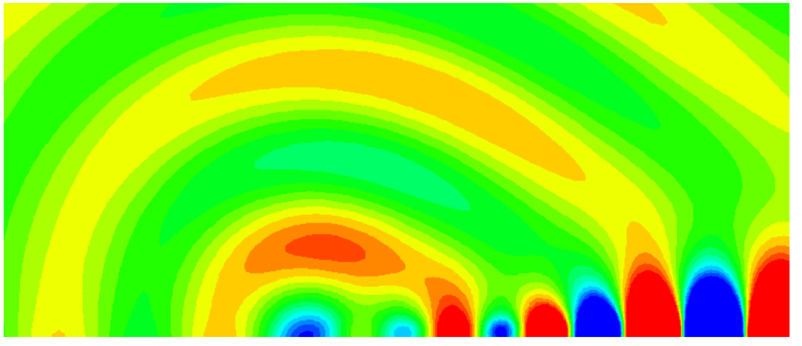


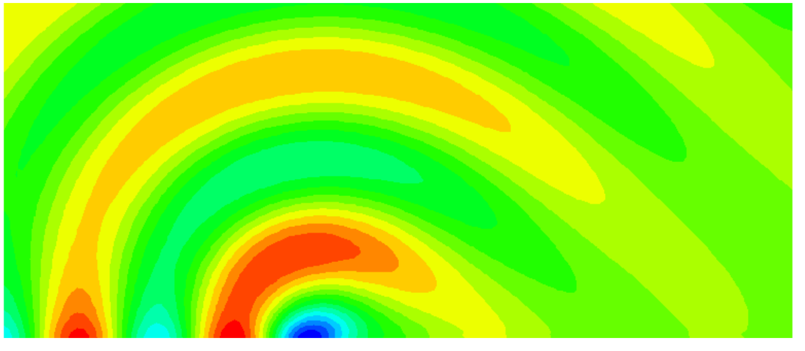
Similar calculations by means of other methods are more demanding in terms of computational resources

Applications of the method to the calculations of tone noise propagation through nozzles

Gradient term suppression (GTS)







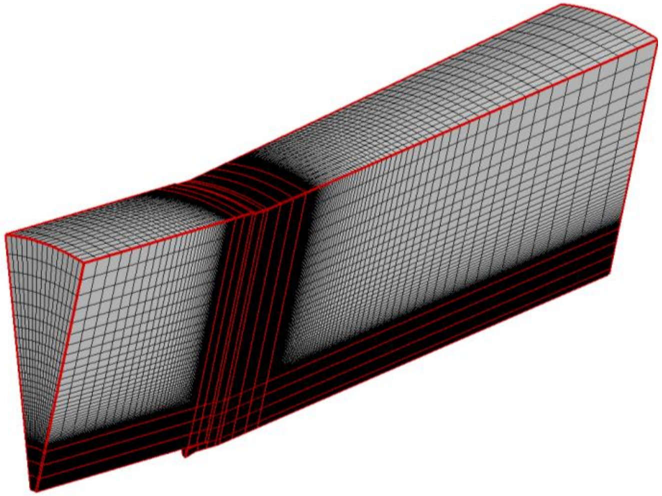
The linearized sound propagation equations, when used in the time-domain, can suffer from stability issues if the mean shear flow contains non-zero velocity or density gradients

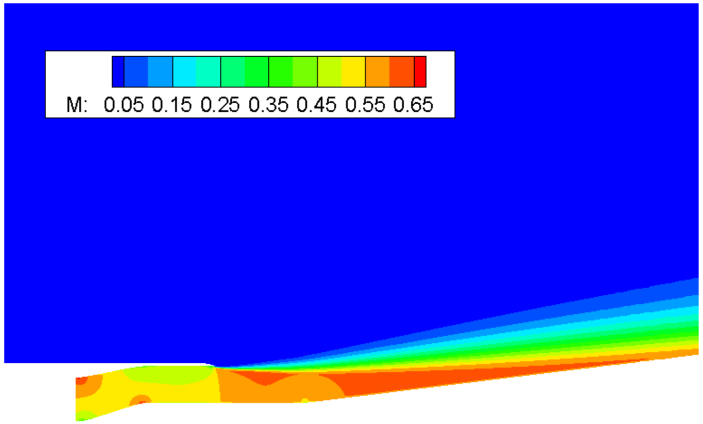
The situation, is much more serious in the frequency domain, where numerical instabilities can lead to the blow-up of the solution

To avoid this problem the method, called gradient term suppression is used in conjunction with 2.5D method

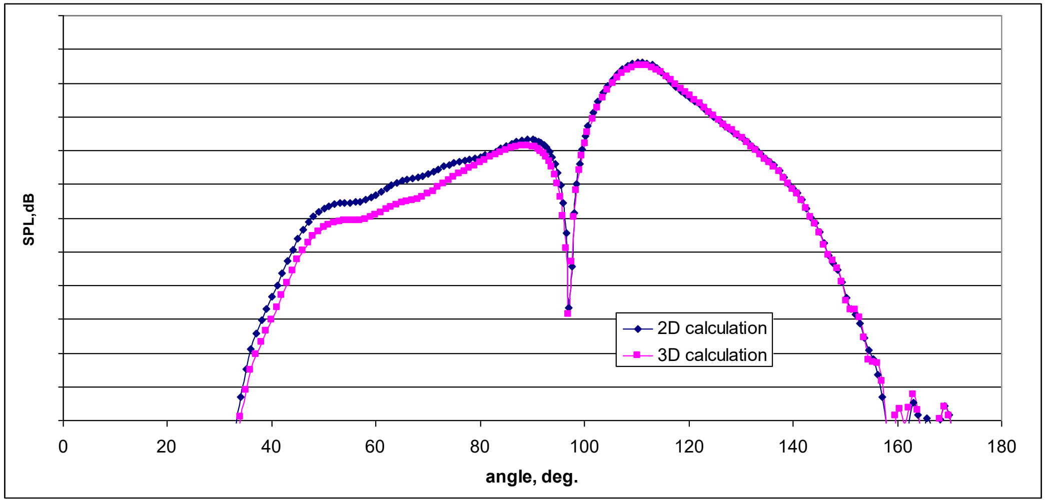
Validation of the method

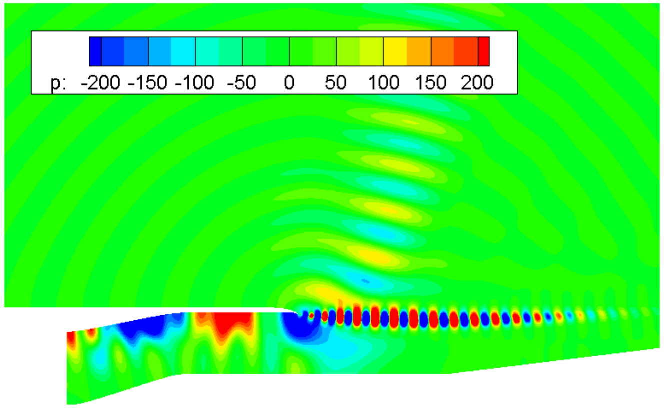
The comparison between 3D and 2.5D calculation with gradient term suppression





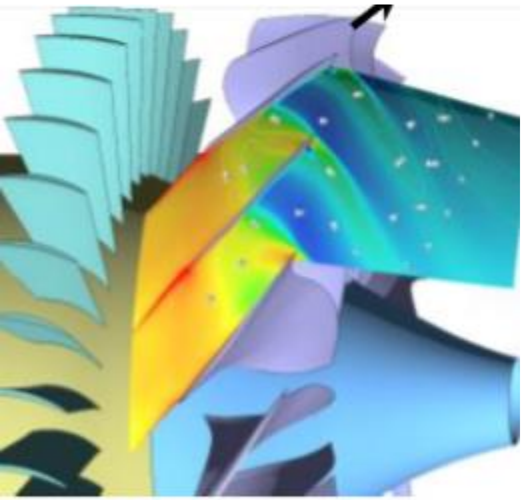
Mean flow field





Pressure pulsations
f = 2094 Hz, m = 16

Nonlinear approach for the calculation of tone noise propagation through the duct



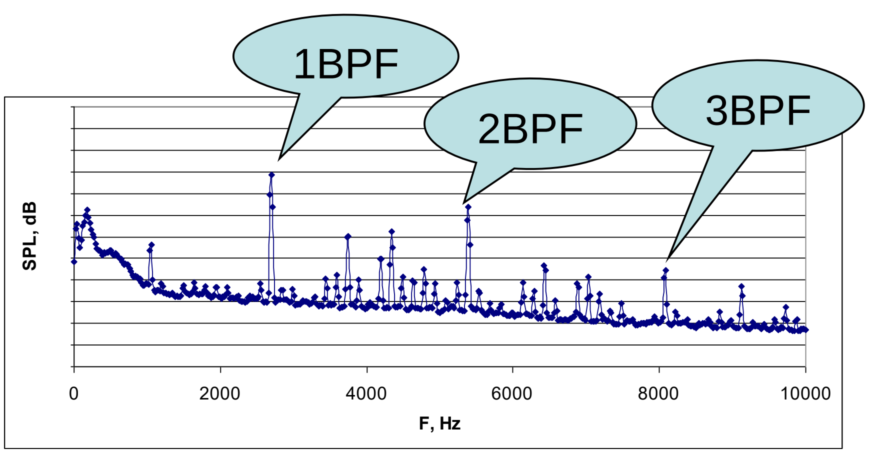
For cutback and sideline operational conditions of modern aviation engines the shock structure, arising on the blades of the fan rotor can propagate upstream through the inlet and eventually to the far field.

This leads to the formation of “buzz-saw” noise. It contains both strong tones, corresponding to harmonics of blade passing frequencies of rotor, being just noise of rotation, and tones on harmonics of shaft rotation frequency, caused by the geometry defects.

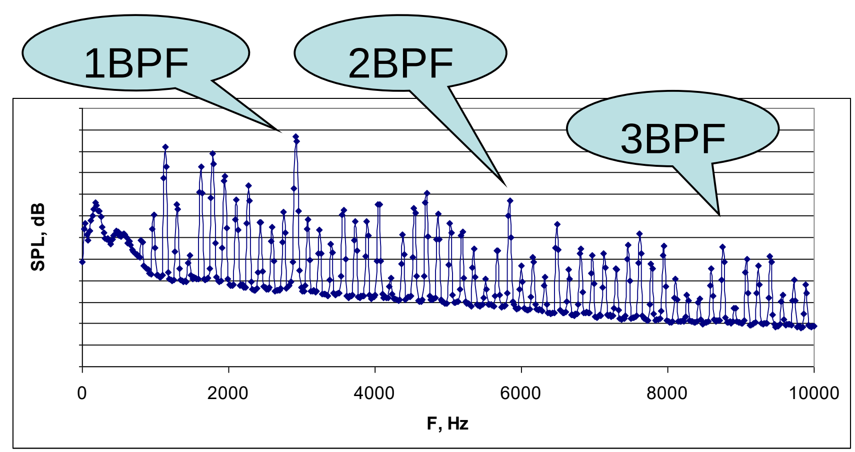
For low supersonic speeds the contribution of tones, caused by geometry defects is quite limited. That’s why it seems reasonable, to perform calculation of shock propagation only for BPF tones

Narrowband spectrum for direction 60 degrees

Cutback



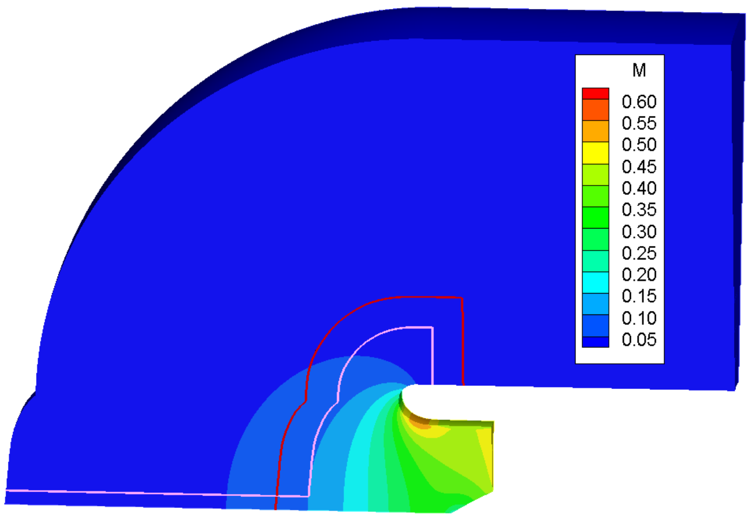
Sideline



Propagation of shock waves through the inlet

Example: tone noise of high bypass ratio fan at cutback operational conditions

First calculation was performed in time domain in nonlinear setup in one blade channel



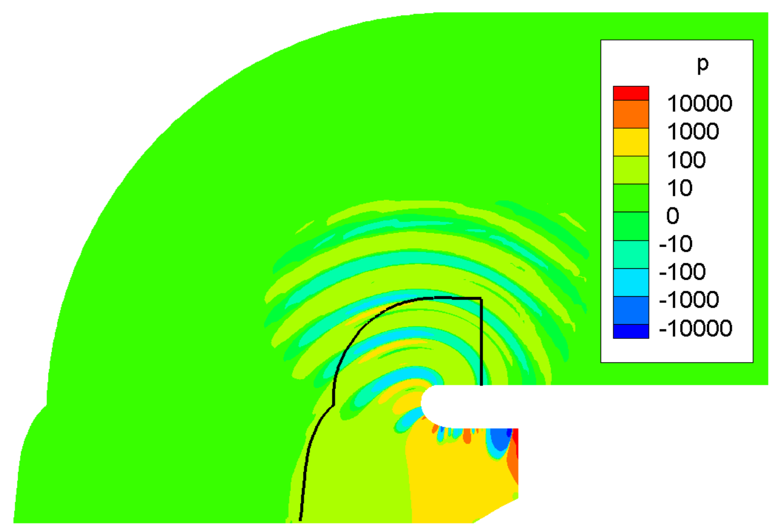
Steady flow field in the inlet for cutback

Red line – boundary of fine grid

Pink line – boundary between rotating and motionless parts

Instantaneous unsteady pulsations of flow field on the longitudinal section of computational domain for cutback

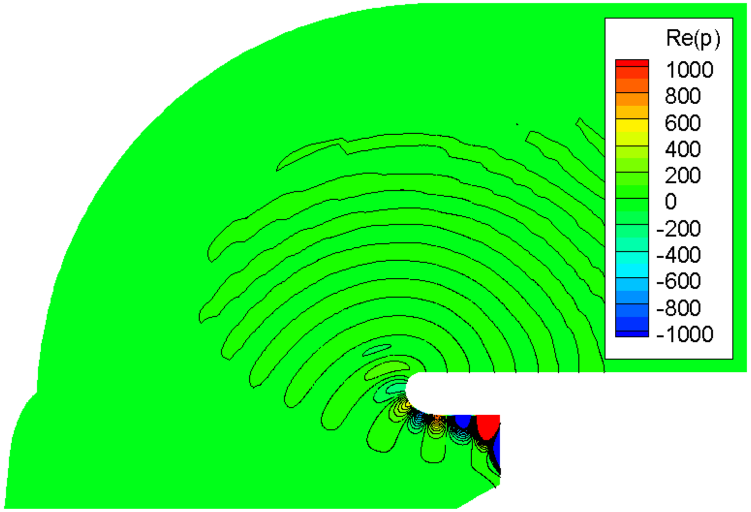
Black line –surface of integration



The inner part was rotated with the shaft of the fan so we could use local time step

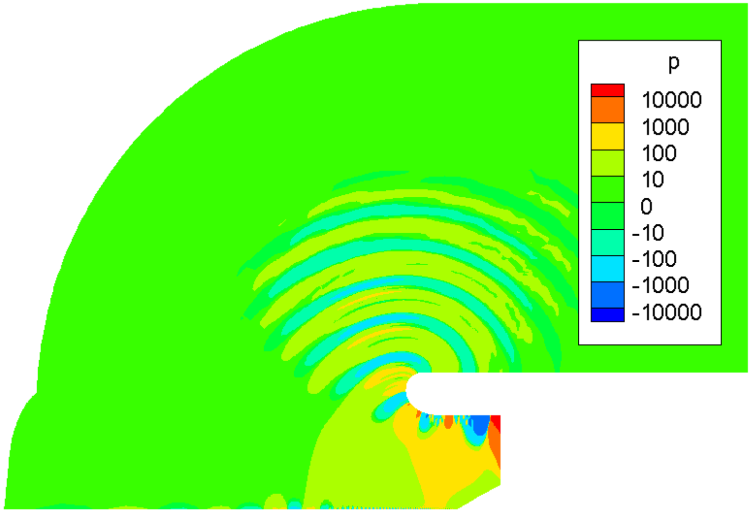
2.5D harmonic balance

In the frequency domain the calculation was performed on the longitudinal section of the inlet for the first ten harmonics of blade passing frequency



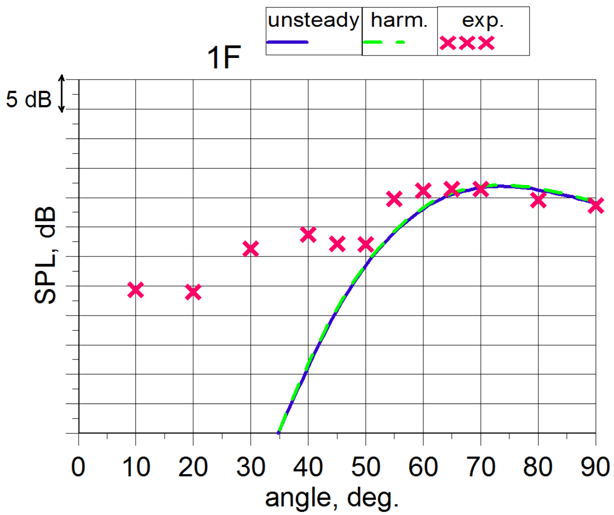
The field of real part of static pressure for the first harmonic of BPF

Reconstructed distribution of pressure pulsation on the longitudinal section of the inlet

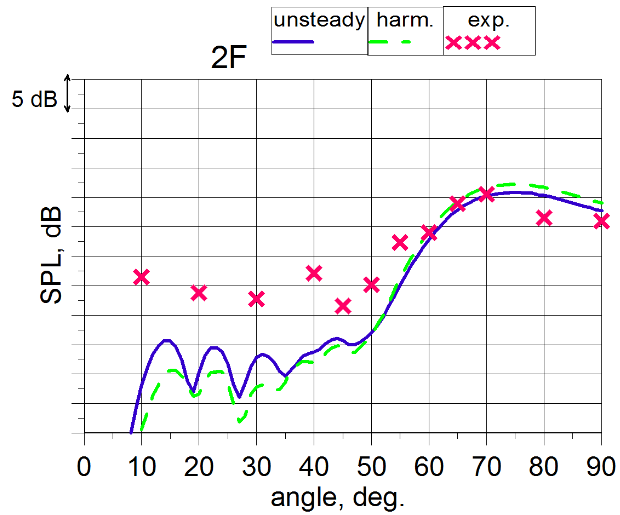


Directivity diagrams in the forward hemisphere

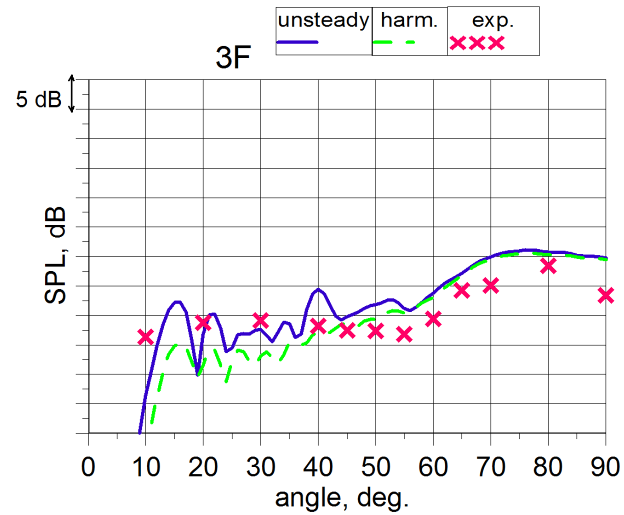
Shock waves give the main contribution to the tone noise in the forward hemisphere



1 harmonic of BPF



2 harmonic of BPF



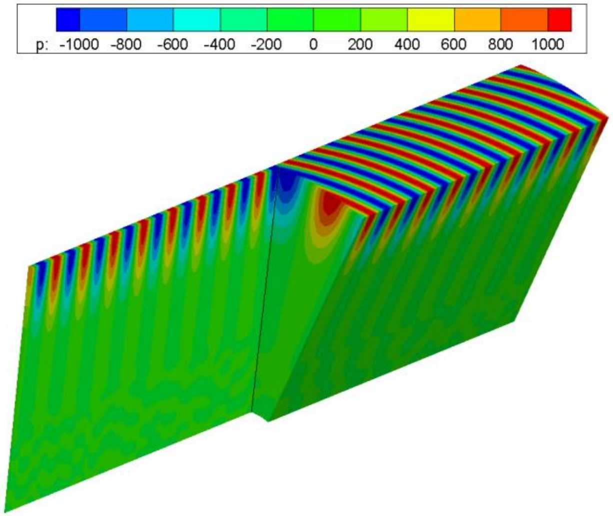
3 Harmonic of BPF

In the forward hemisphere satisfactory results were obtained near the maxima of directivity diagrams (45-90 degrees) for all three harmonics

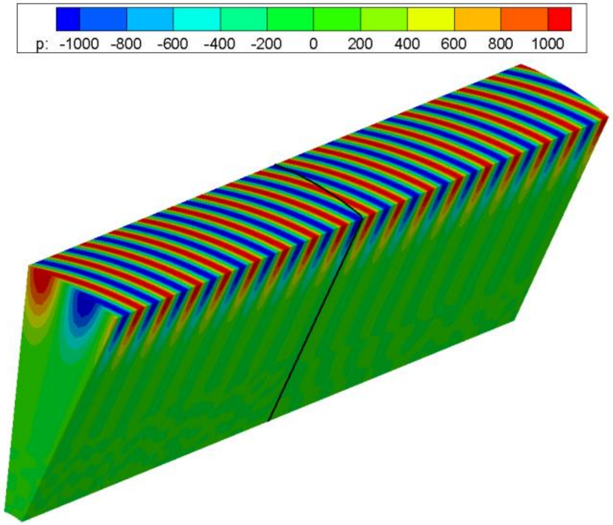
There is a good agreement between the results of calculations in the time and in the frequency domains except for small angles

3D-2.5D interfaces

The calculation can be performed not only for 3D and 2.5D computational separately, but also for their combinations. Special interfaces can transfer disturbances between 3D and 2.5D computational domains



Reconstruction of the 3D flow field

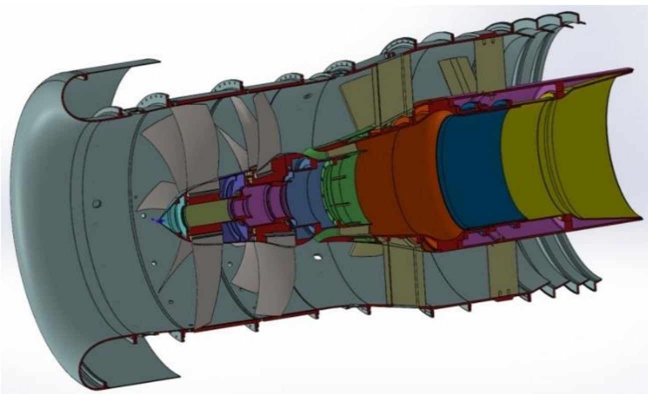


Reconstruction of pressure pulsations in the computational domain

The investigation of tone noise of counter-rotating fan

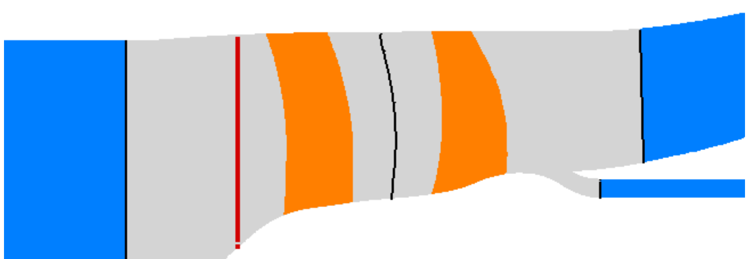
Counter-rotating fan at approach conditions

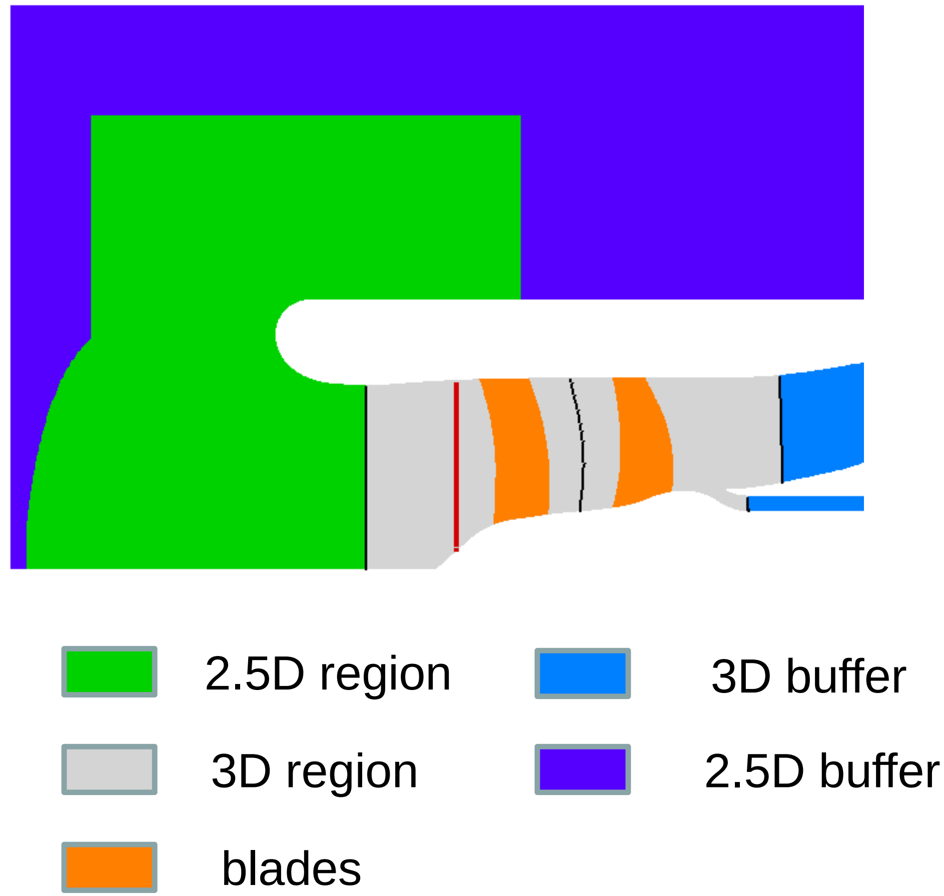
Computational domain for direct - 3D-2.5D calculation



Scheme of the fan model

Computational domain for the 3D calculation, being the first step of hybrid calculation





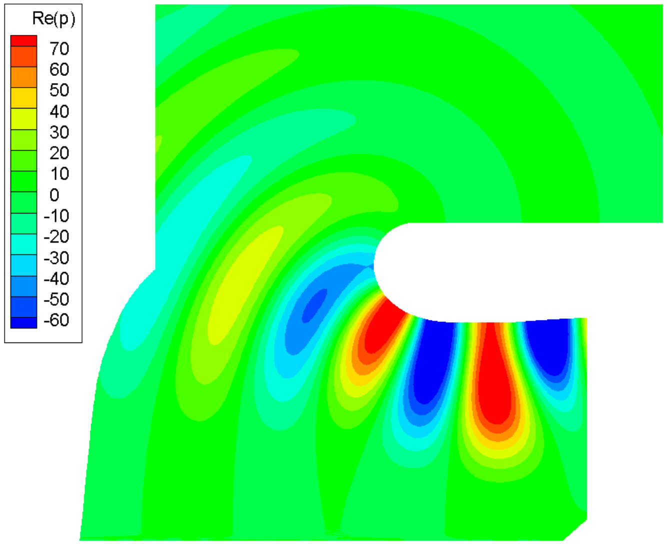
The calculation of noise propagation through the inlet

The calculation was performed for both computational setups.

After the convergence of the solution the modal analyses on the surface in front of the fan was performed

The results of the modal analyses were used for calculation of noise propagation through the inlet

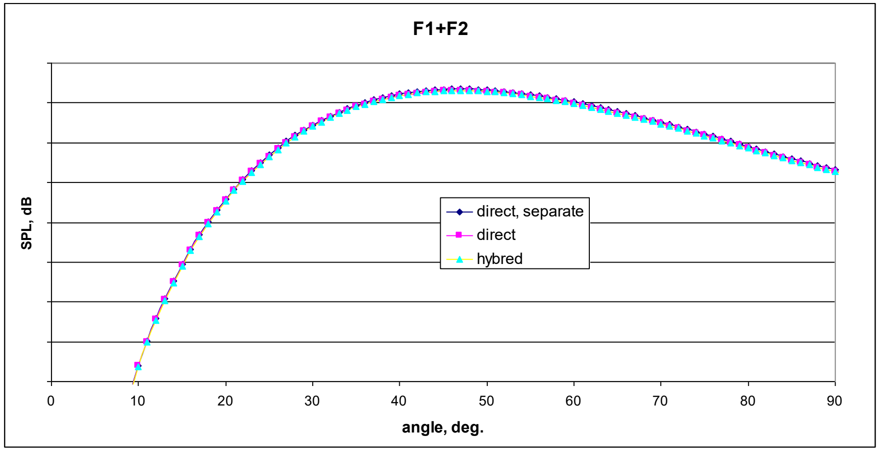
Finally three sets of data in the far field were obtained:
•Results of the direct calculations
•Results of the hybrid calculations based on the data obtained in the direct calculations
•Results of the hybrid calculations

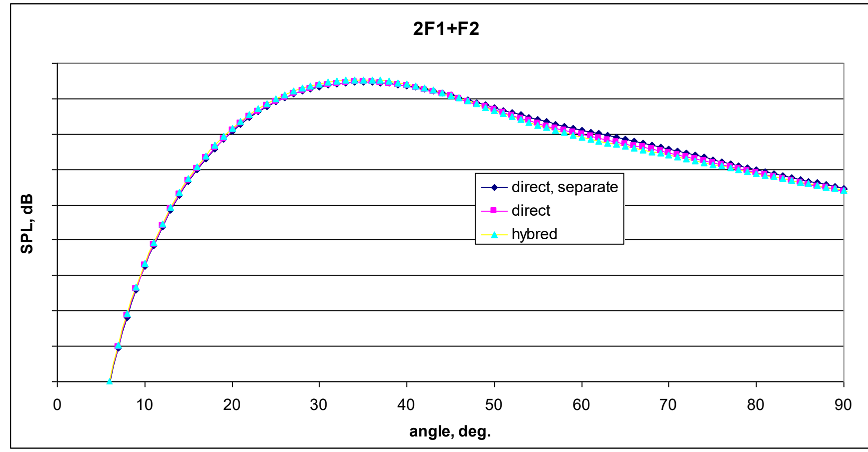


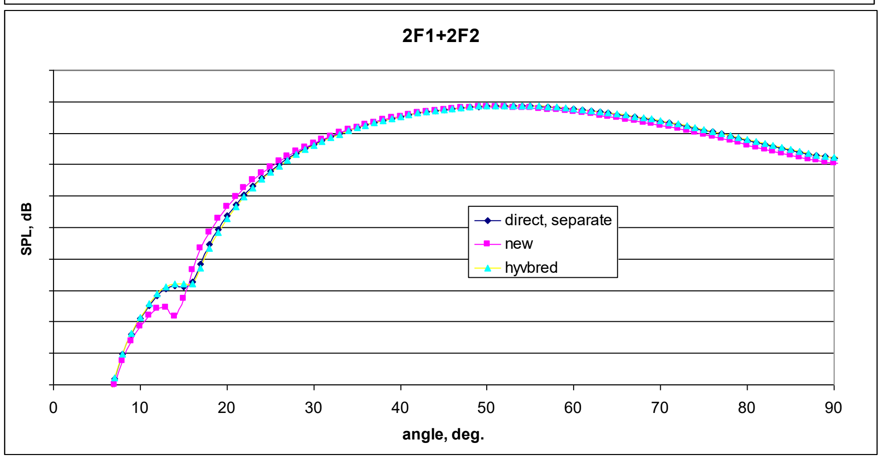
Real part of static pressure
f = 1054 Hz, m = 4

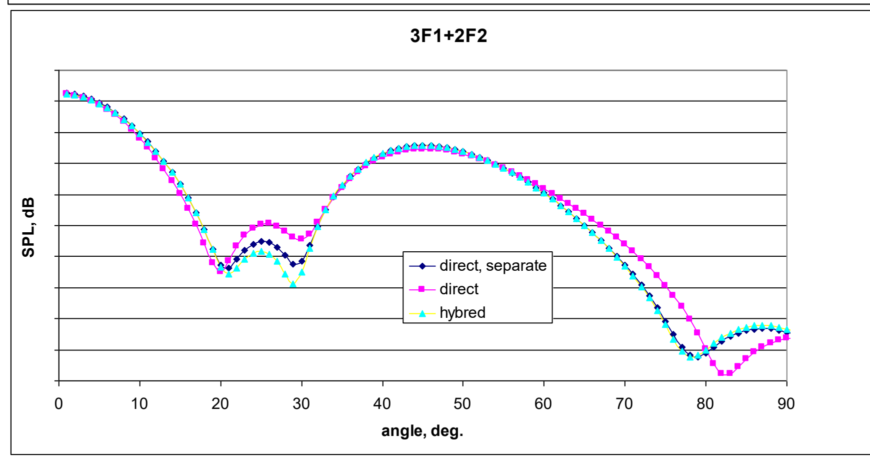
The results of the calculation in the far field

The results of the calculations for the first four harmonics









The calculations produced nearly identical results

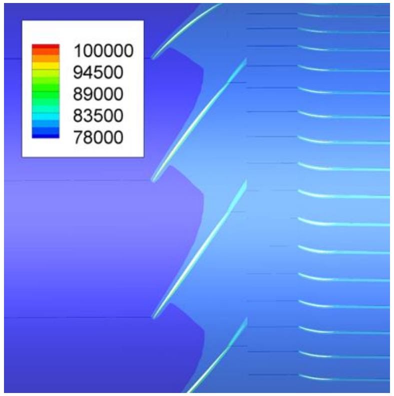
Conclusion

- In the current work the implementation of the 2.5D method in 3DAS (3 Dimensional Acoustics Solver) CIAM in-house solve is described. The method can be used either in the linear approximation, which is appropriate approach for the calculation of the propagation of an interaction noise, or it can be used in the nonlinear statement. In the latter case it can be used for the calculation of the propagation of shock waves, arising in the blades of the fan operating at supersonic tip speed, through the inlet. Also the method can be used for the calculation of pure multiple tone noise. The comparisons between the results of linear and nonlinear computations in the frequency domain performed with the method under consideration and the results of direct unsteady calculations of noise propagation through an inlet and a nozzle are presented. It is shown that the usage of harmonic methods makes possible to increase the speed of calculations retaining acceptable precision both in the linear and nonlinear statements.
- With the usage of 3DAS solver it is possible to combine 2D and 3D computations in one calculation. Special interfaces preserve the continuity of the solution on the boundary for the specified set of circumferential modes. This approach makes possible, for example, to perform the simulation of tone noise generation due to rotor-stator (rotor-rotor) interactions in the 3D setup and at the same time to model the propagation of disturbances through the inlet in the 2D setup. Such approach owing to a direct connection of calculations of interaction and propagation should provide the higher accuracy of the overall calculation, than the standard hybrid approach. Moreover the computational costs for carrying out of the given calculation not considerably surpass costs for carrying out of calculation of interaction between rows.

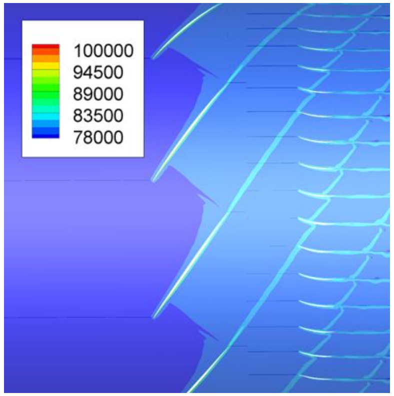
Calculation of turbomachinery tone noise using 3DAS code

Calculation scheme

Steady flow field calculation

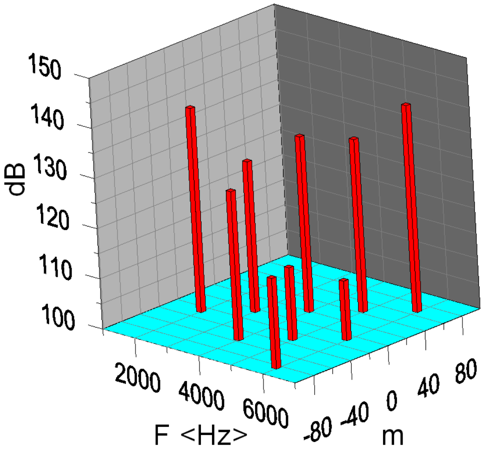


Unsteady calculation

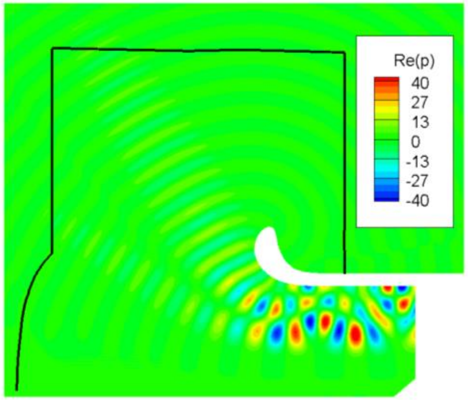


Cylindrical section – entropy function

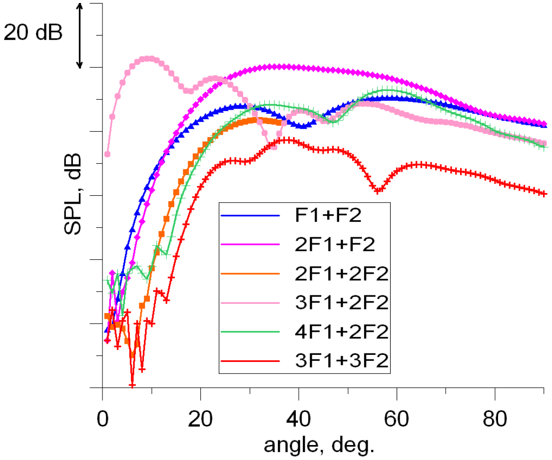
Modal analysis



Propagation calculation

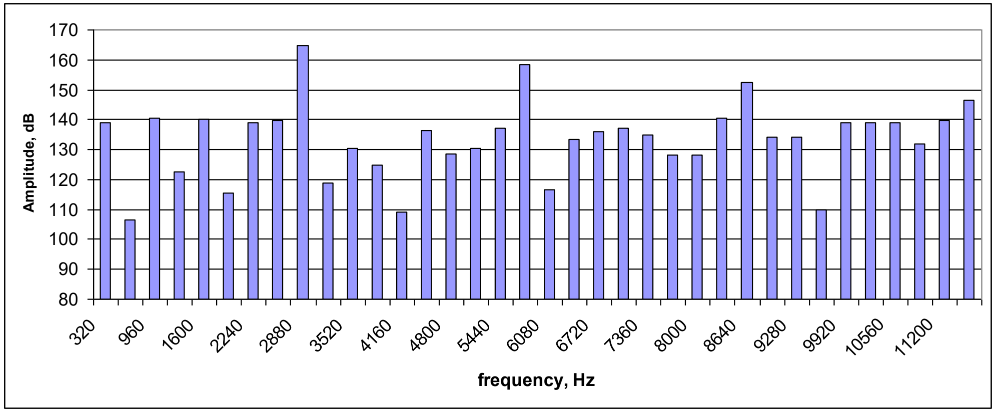


Calculation of pressure pulsations in the far field

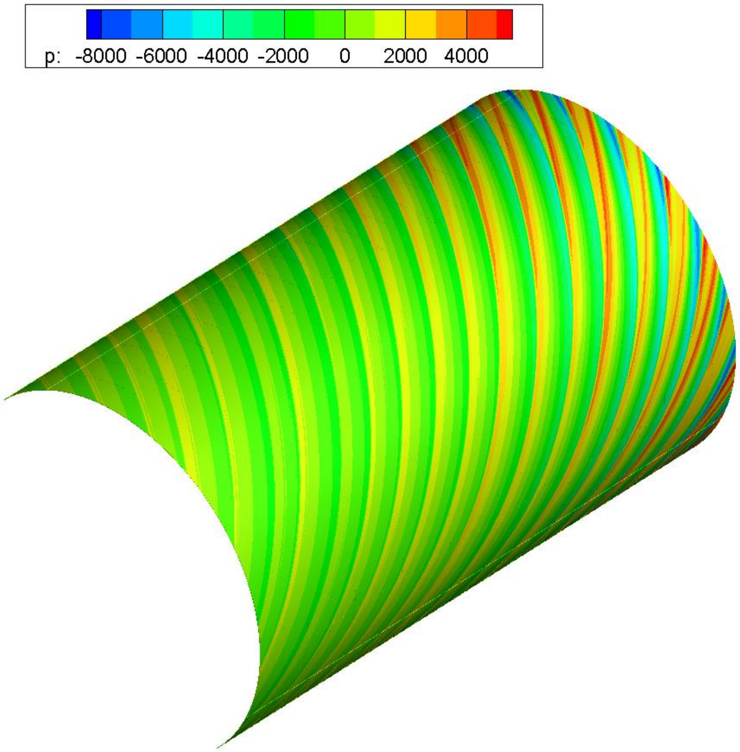


The application of the method to the complex sources

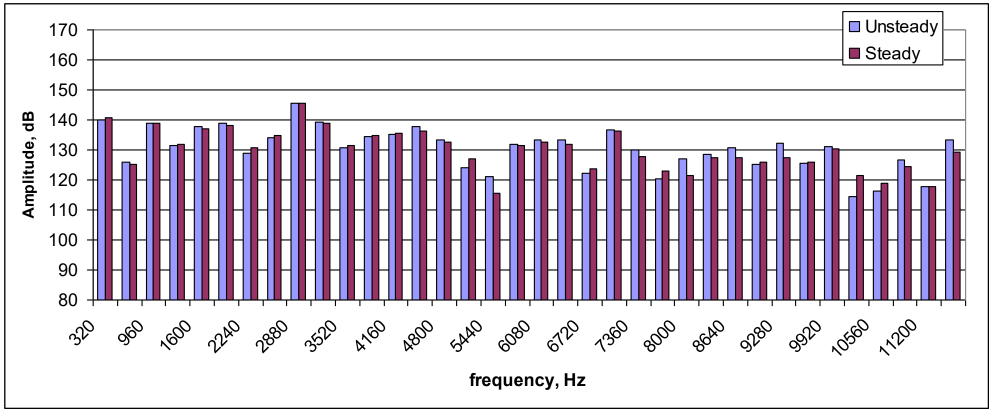
Initial spectrum



2D calculation



Comparison between the results of 2D and 1D calculations (the latter was performed in 2.5 D approximation)



The results seems satisfactory