Synthetic jets influence on noise level and it's spectral properties for off-design supersonic jet using RANS/ILES-method

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Introduction

Motivation: Reducing of the potential core length of supersonic jets is required in various applications. This can be achieved by using two techniques: passive control (chevron jets, lobed mixers etc.) and active control (fluid injection from the micro jets to main jet). Synthetic jets (SJ) may become one of efficient control technic for supersonic jets control. Unfortunately this type of active control is insufficiently studied because of complexity or even impossibility of experimental investigation. LES based method has ability to obtain necessary characteristics of flow, such as pressure and velocity pulsations in mixing layer, noise in near and far fields, spectra of pressure pulsations.

Purpose: investigation of SJ operating modes on potential core length, flow in mixing layer and near and far fields noise.

RANS/ILES high resolution method

Main features of RANS/ILES-method (Lyubimov D.A., High Temperature, 2012, 50(3), 420-436)[1]:

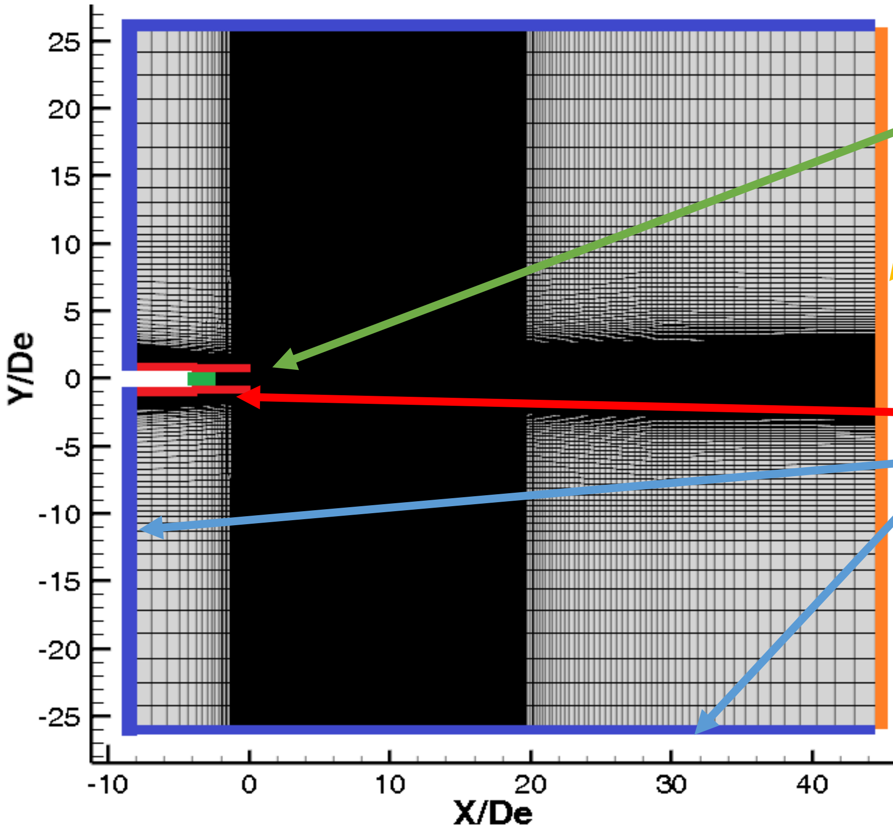
- Roe`s flux difference splitting method
- Monotonicity-preserving scheme MP9 [A. Suresh, H.T. Huynh, JCP 1997, V.136, P.83-99] with upwind 9th-order approximation in smooth regions for calculating flow parameters on cell faces. It makes possible to calculate supersonic flows with shocks without modification of the method.
- LES with implicit SGS-model (ILES): the scheme viscosity performs a function of a subgrid scale (SGS) model.
- In ILES region, the distance in dissipative term of Spalart–Allmaras turbulence model is changing:

RANS region: $\tilde{d} = d, d \leq C_{ILES}\Delta_{MAX}$ $\quad \nu_t = \nu_{tRANS}$

ILES region: $\tilde{d} = 10^{-6}L_{ref}, d > C_{ILES}\Delta_{MAX}$ $\quad \nu_t = 0$

Simulation parameters

NPR	T_0, K	U_j, m/s	T_j, K	M_j	Re
4	300	444	202	1.56	2.07×10^6

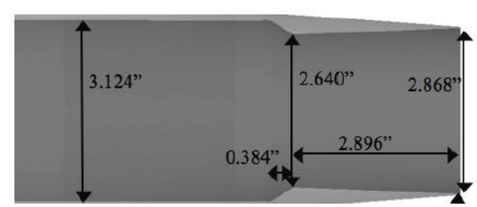


Nozzle inlet: stagnation temperature, pressure and velocity direction.

Outside boundary: fixed static pressure, other parameters have zero derivatives with respect to normal to the boundary.

Nozzle walls: wall function/slip.

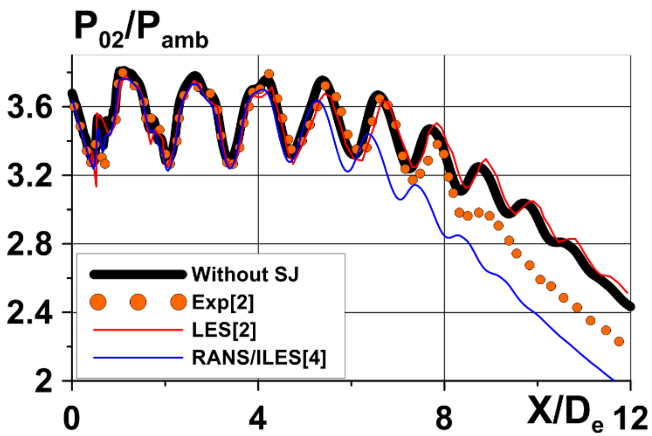
Outside boundary: the far field asymptotic of the jet.



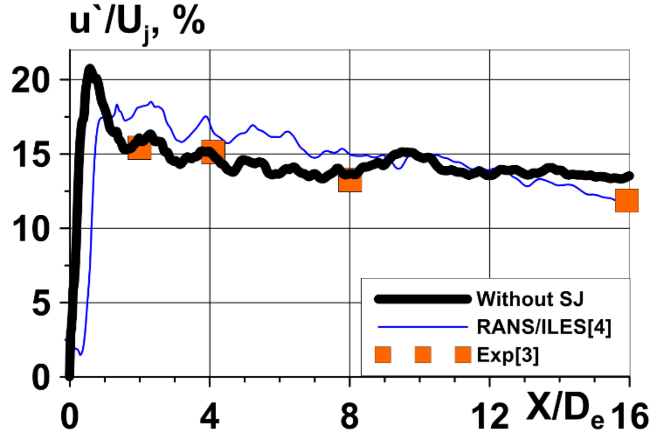
Nozzle geometry[2]

Calculations are carried out on structured grid containing 40×10^6 cells that showed good agreement with available experimental data and calculations.

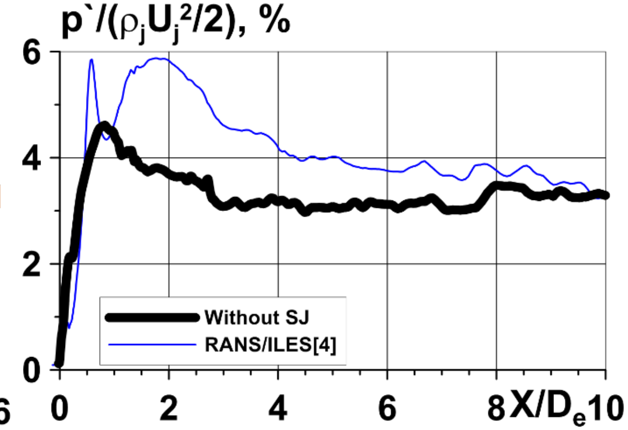
Comparison with experimental data and calculations



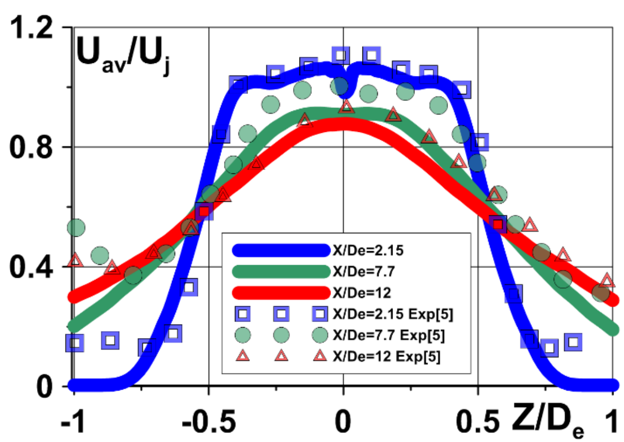
Total pressure behind a normal shock wave distribution along jet axis



Distribution of longitudinal velocity pulsations in mixing layer



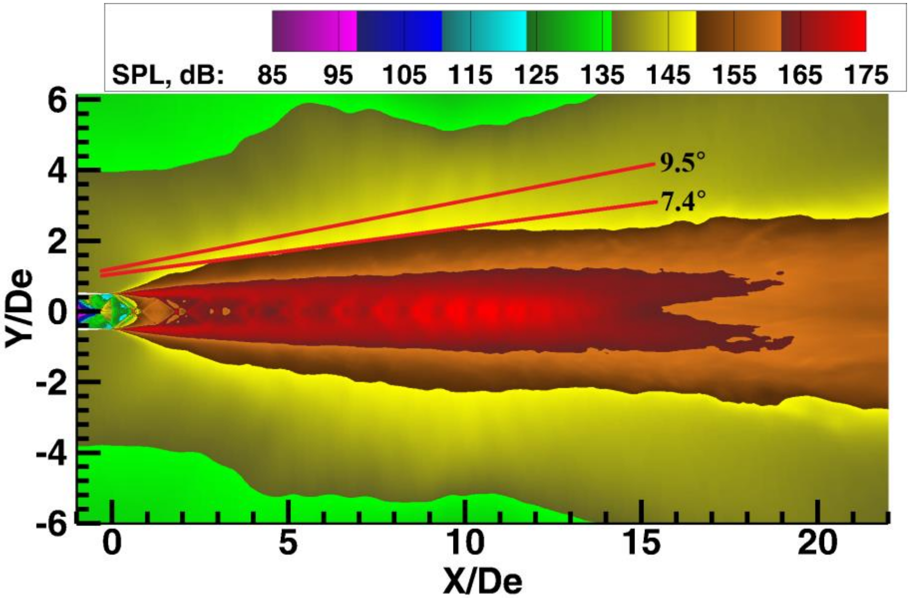
Distribution of static pressure pulsations in mixing layer



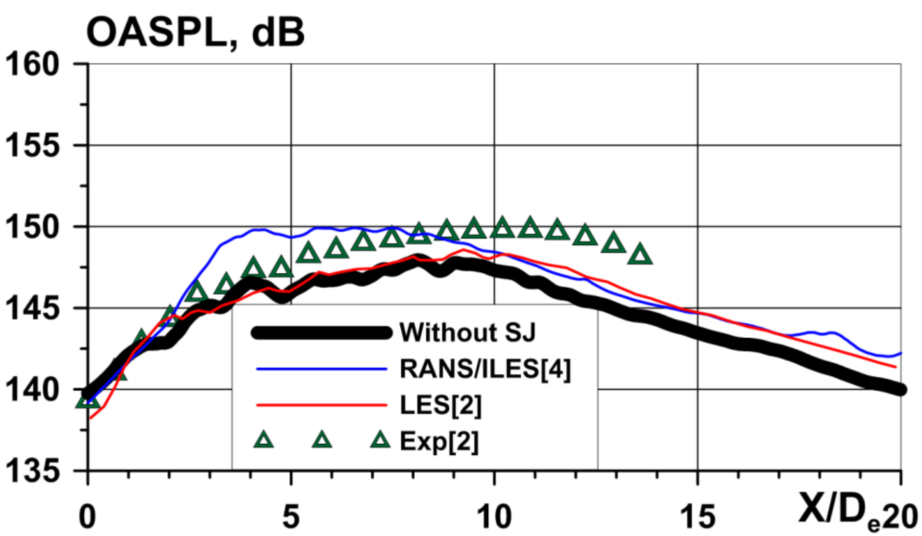
Distribution of longitudinal velocity in transverse direction

- Comparison current simulation (cell number 40×10^6) with RANS/ILES simulation [4] (cell number 4×10^6) and LES [2] (cell number 59×10^6).
- Current simulation doesn't show such an expressed peak in static pressure pulsations distribution comparing with previous RANS/ILES simulation.
- Total pressure is slightly overestimated, but velocity pulsations show great agreement.
- The agreement between simulation data and experiment [2, 3, 5] is very good.

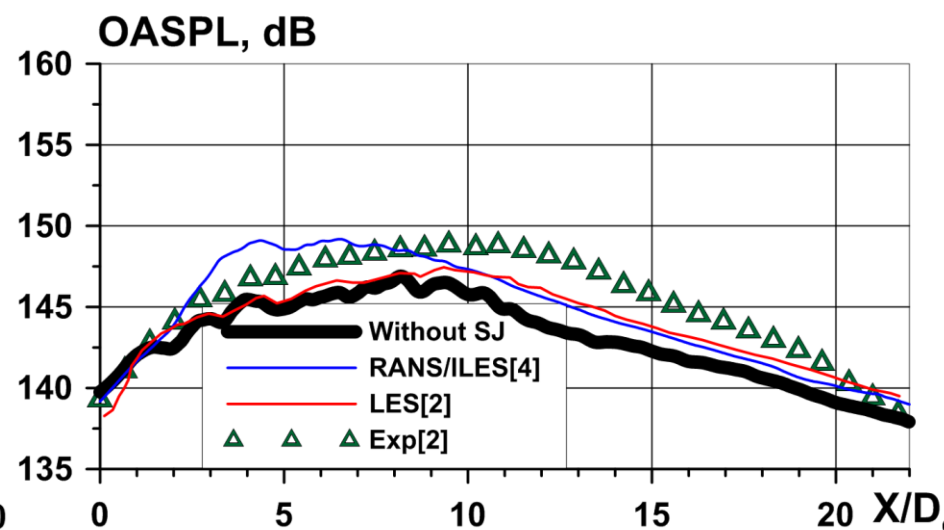
Near field noise



- Noise level in near field was calculated along two lines with angle of slope $7.4°$ and $9.5°$.
- There is a good agreement for all flow characteristics between computation and experimental data up to $X/D_e = 10$. After that there is a slight overestimate of the total pressure and underestimate of noise level in near field.

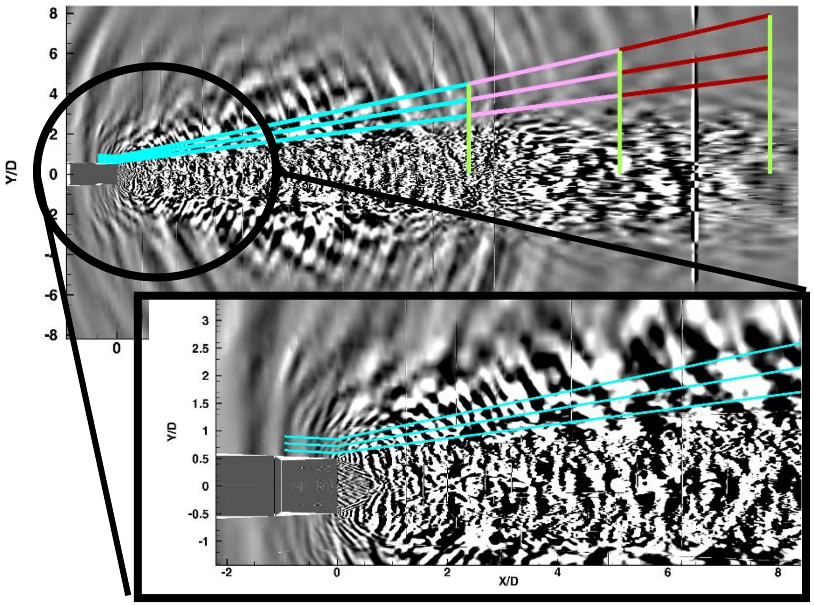


Pressure fluctuations along line 7.4°

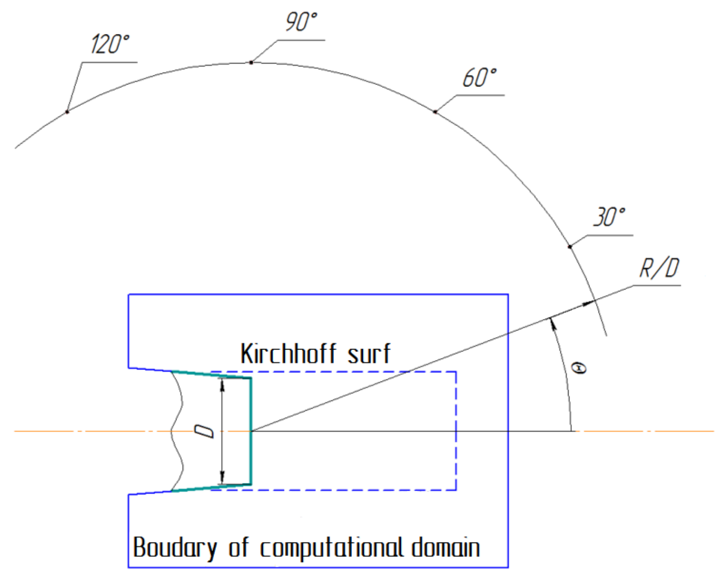


Pressure fluctuations along line 9.5°

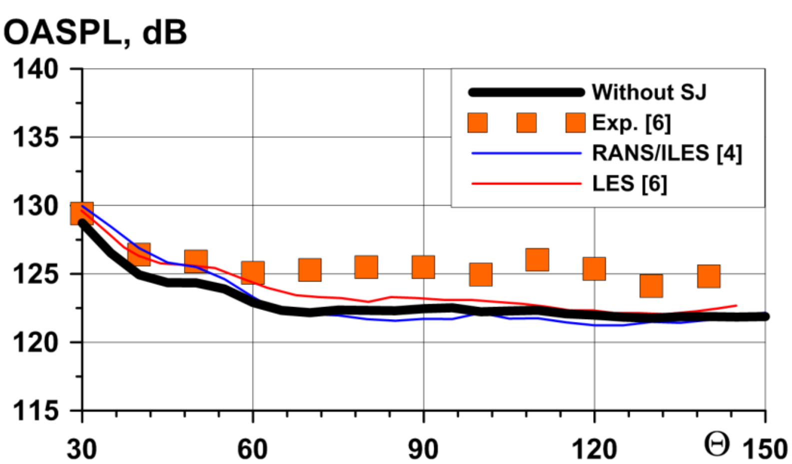
Far field noise



Kirchhoff surfaces



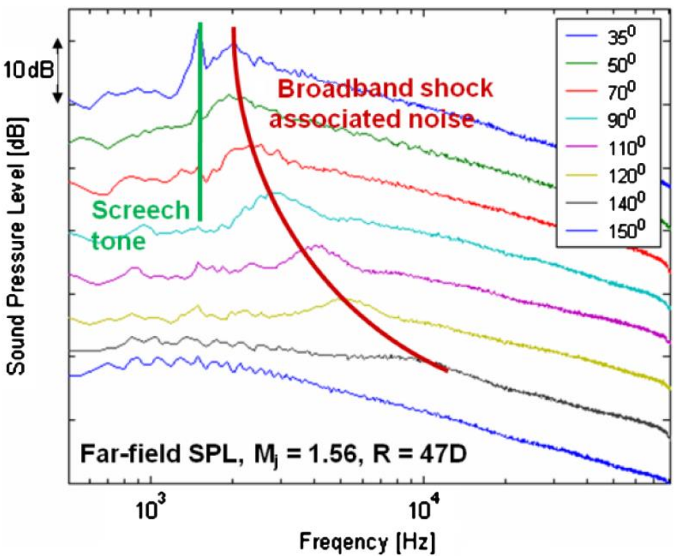
Observation angle measured from downstream direction



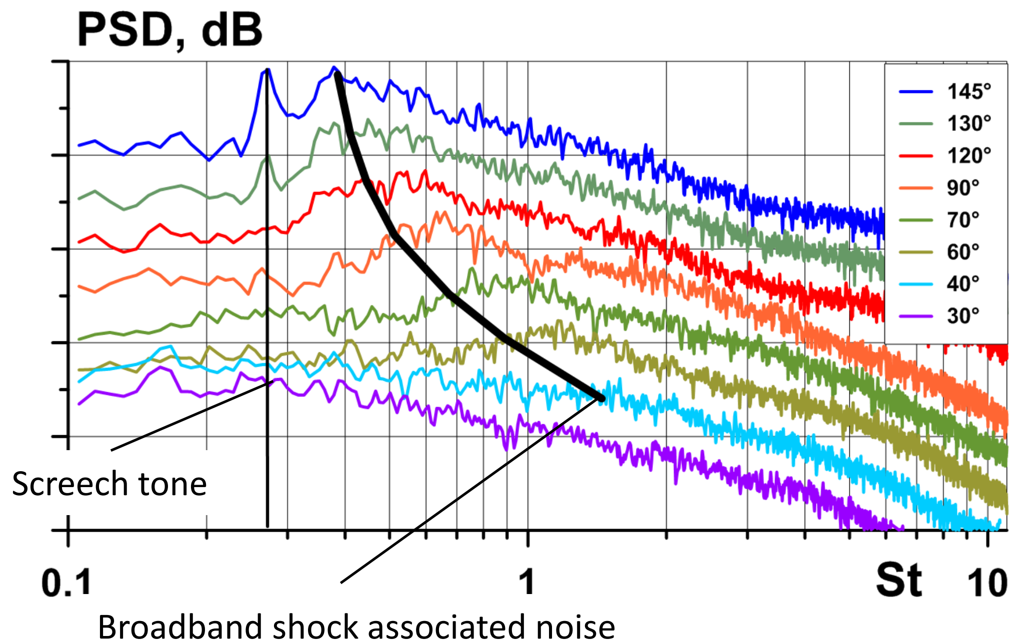
Overall sound pressure level in far-field

- The FWH-method was used for calculation of far-field noise. 9 Kirchhoff surfaces covers jet and mixing layer up to $X/D_e = 32.5$.
- The average was made over outflow disks.
- To recalculate parameters from Kirchhoff surfaces forward time stepping method was used.
- Destination to observer is $\mathrm{R} = 47D_e$.

Far-field acoustic spectrum



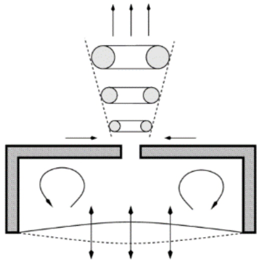
Typical far-field acoustic spectrum for an imperfectly expanded supersonic jet [7]



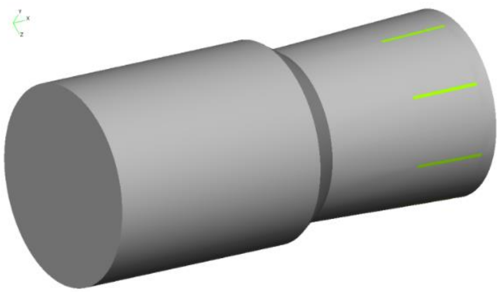
Noise spectra in several observation angles

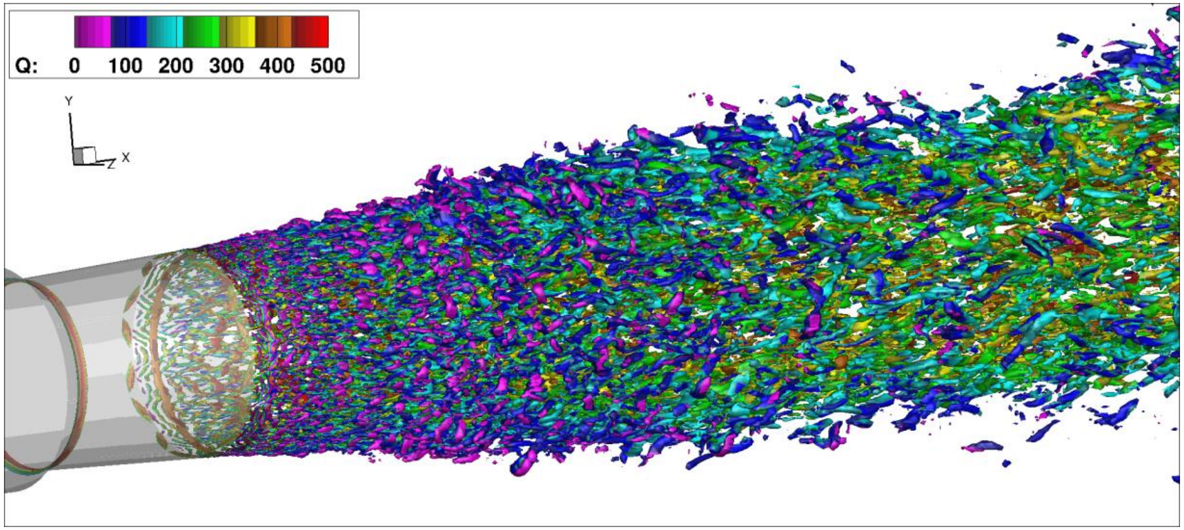
- Spectrum shifted 10dB each for clarity
- $PSD = 10\log_{10}(PSD_{raw}) - 20\log_{10}(2\cdot 10^{-5}) + 10\log_{10}(U_j/D_e)$
- $St = f\cdot\frac{U_j}{D_e}$
- Screech tone observed on Strouhal number $St = 0.267$

SJ application



Synthetic jets generator



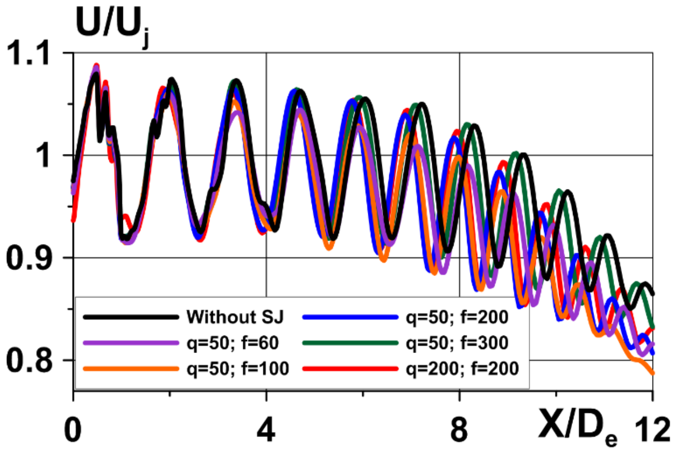


q, m/s	f, Hz	C_μ, %	St
50	60	0.022	0.27
50	100	0.022	0.45
50	200	0.022	0.90
50	300	0.022	1.35
200	200	0.35	0.90

Operating modes of SJ

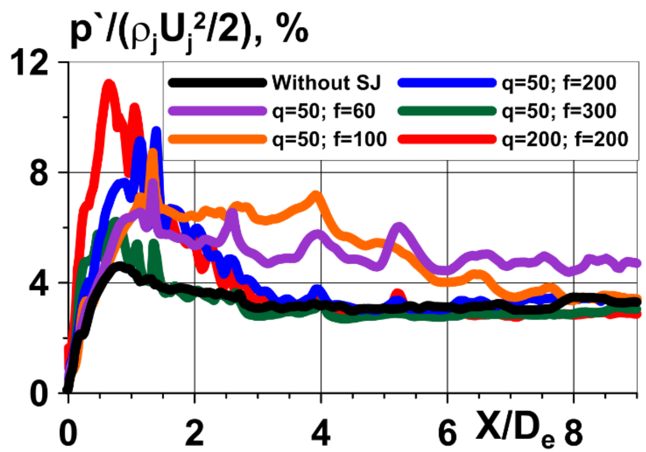
- Synthetic jets – jets with zero mass flow rate.
- SJ were injecting from eight rectangular slits inside nozzle with step of 45° in azimuthal direction.
- Simulations of SJ were carried out using approximate boundary conditions.
- C_μ, % - SJ effective coefficient of momentum: ratio of the total momentum of average velocity of SJ over one period to the momentum of the main flow velocity.

SJ influence on flow and mixing layer parameters

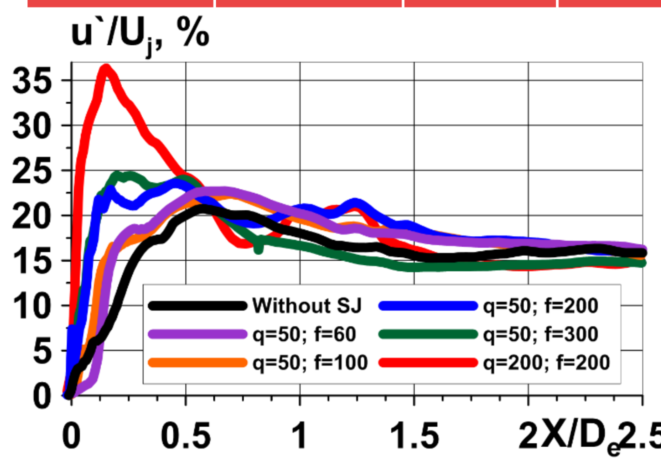


Distribution of averaged longitudinal velocity along jet axis

q, m/s	C_μ, %	f, Hz	St	Potential core length, X/D_e
Without SJ			0.267	9.354
50	0.022	60	0.27	7.24
50	0.022	100	0.45	7.12
50	0.022	200	0.90	8.02
50	0.022	300	1.35	9.2
200	0.35	200	0.90	8.11



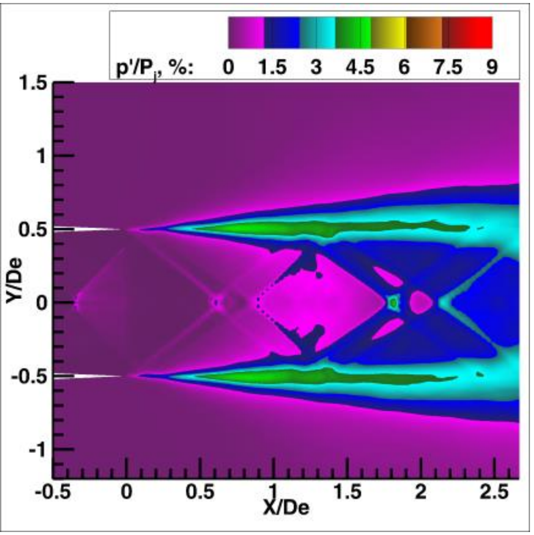
Distribution of static pressure pulsations in mixing layer



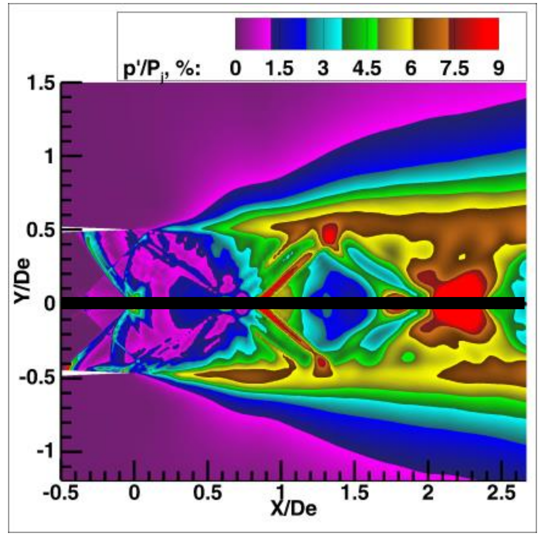
Distribution of longitudinal velocity pulsations in mixing layer

- Static pressure pulsations increase in mixing layer.
- Potential core is declay up to 25% on operating mode $q = 50\, m/s; f = 100 Hz$.
- Frequency of SJ exerts the greatest influence on the initial section comparing to amplitude.

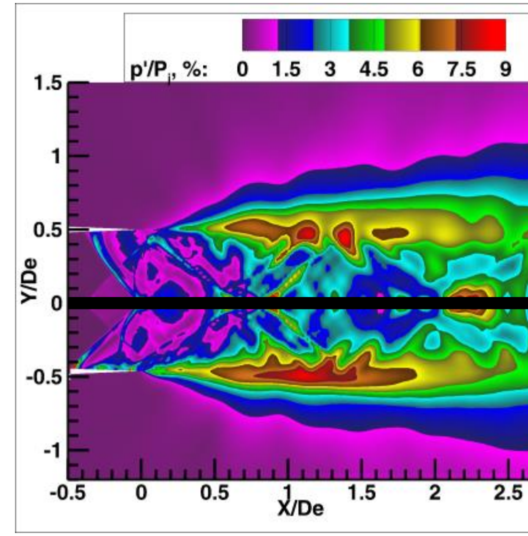
SJ influence on static pressure pulsations



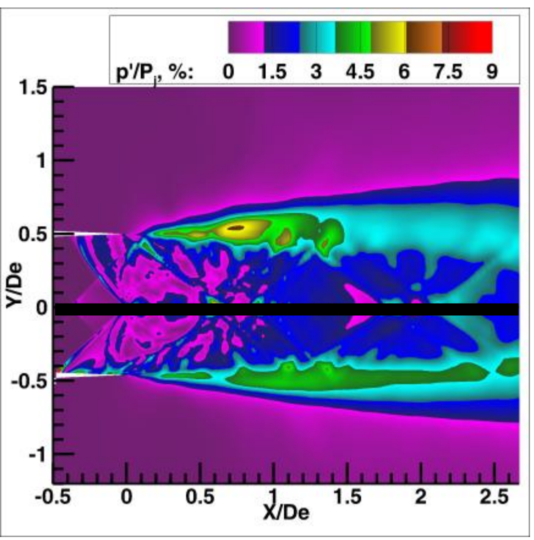
Without SJ



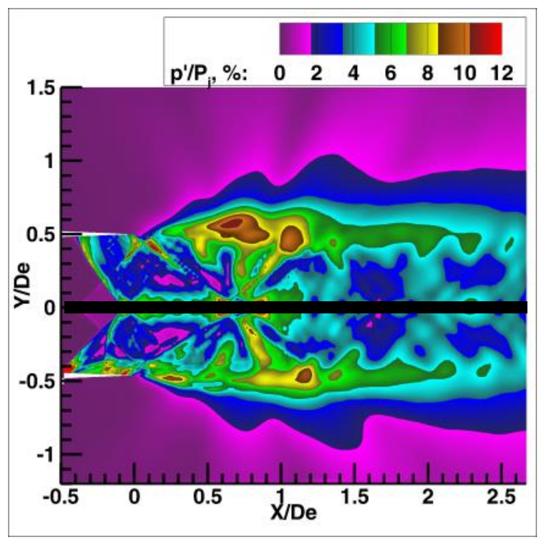
q=50; f=100



q=50; f=200



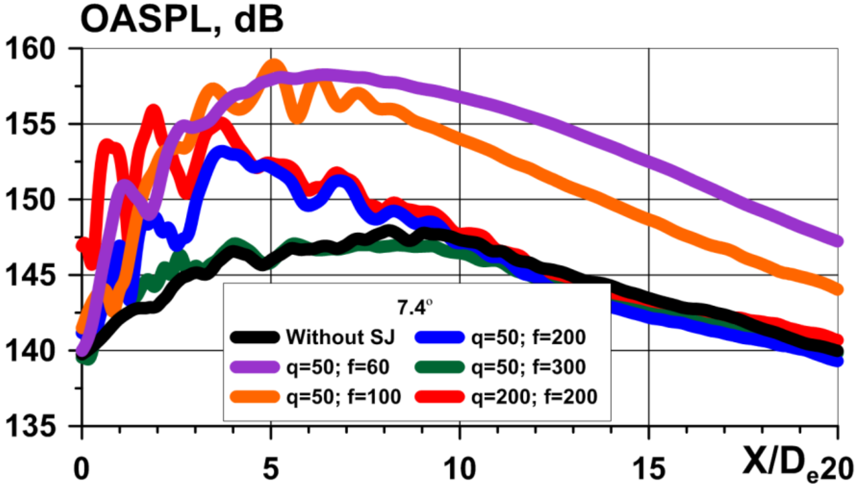
q=50; f=300



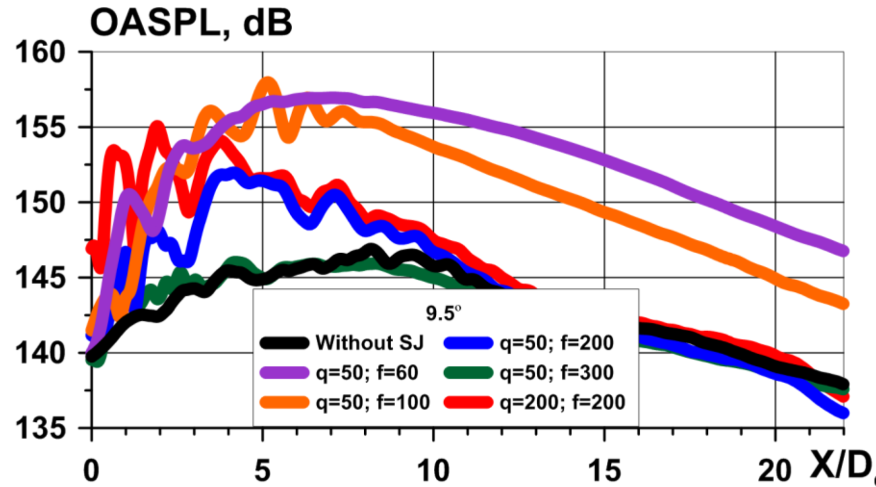
q=200; f=200

- Every figure divided by two parts: on the top: slice between SJ slits, on the bottom – through SJ slits
- Maximum of pressure pulsations appears between SJ slits.
- SJ application changes shock system in main jet
- The strongest pressure pulsations arise with operating mode q=50 m/s; f=100 Hz

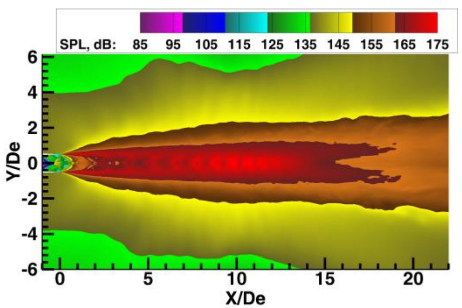
SJ influence on noise level in near field



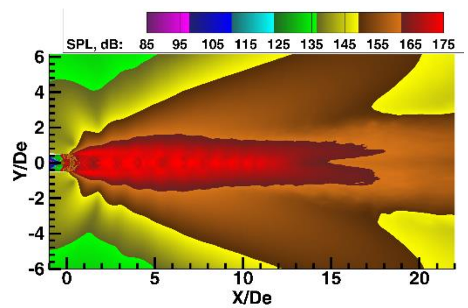
Pressure fluctuations along line 7.4°



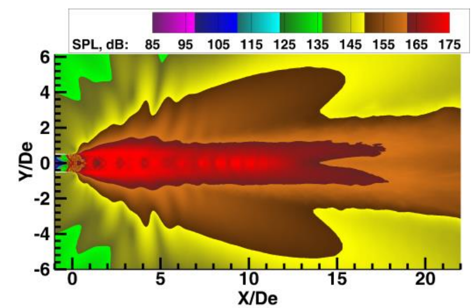
Pressure fluctuations along line 9.5°



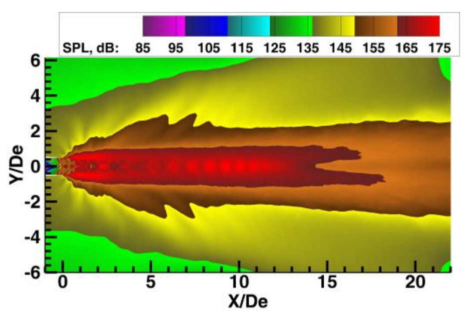
Without SJ



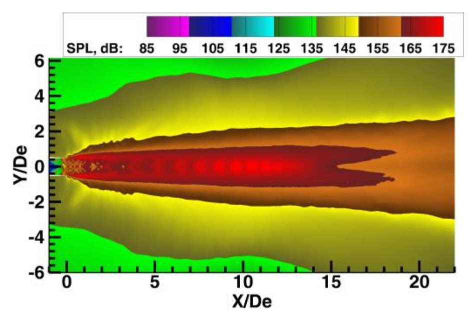
q=50; f=60



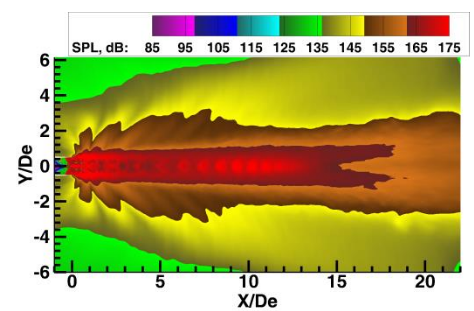
q=50; f=100



q=50; f=200

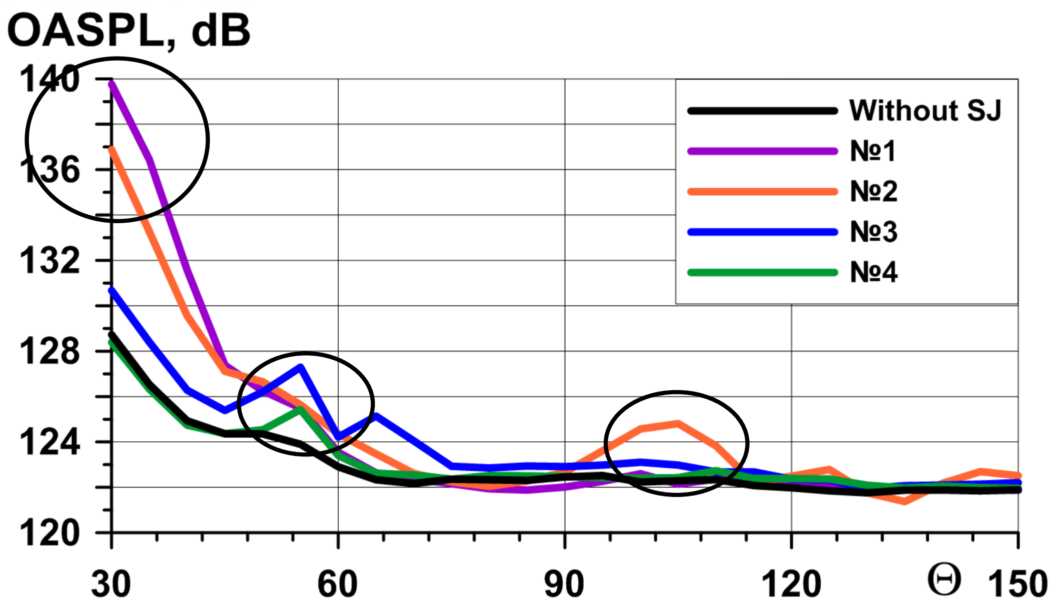


q=50; f=300



q=200; f=200

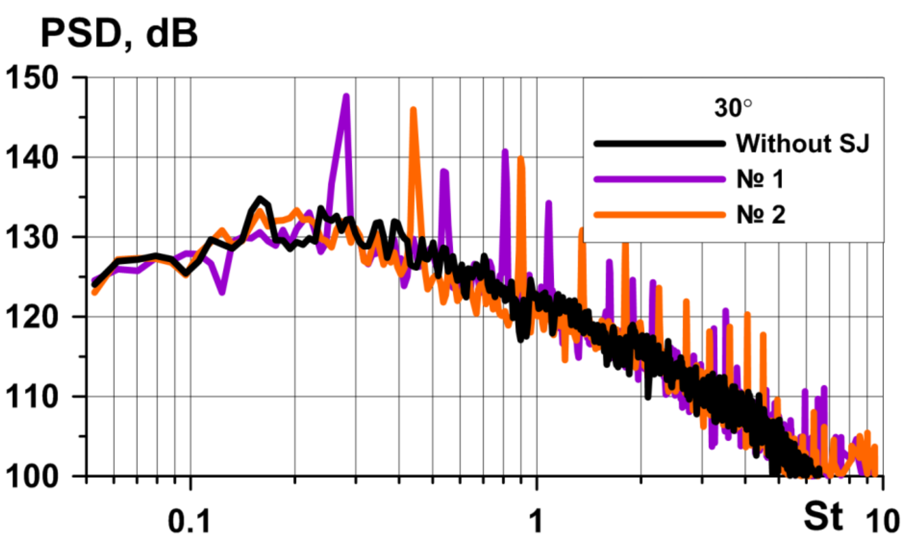
SJ influence on far-filed noise level



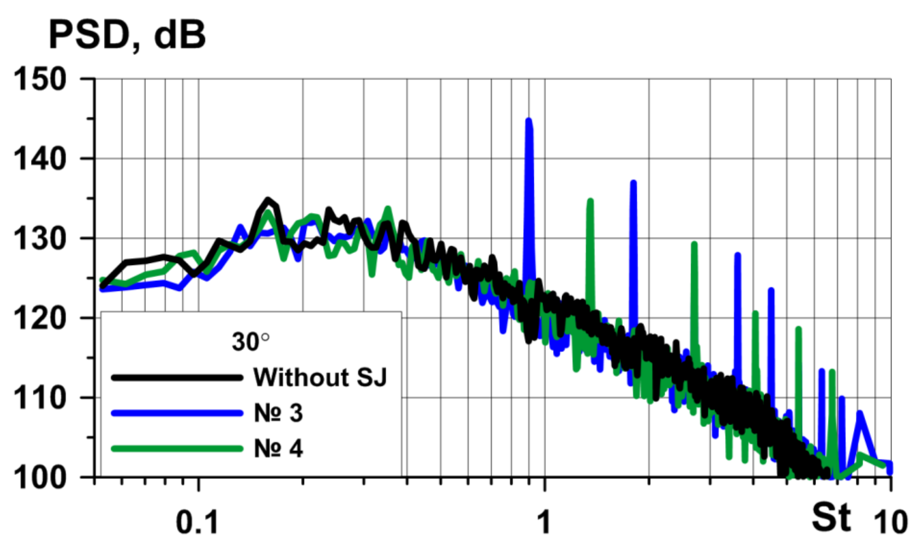
Overall sound pressure level in far-field

№	q, m/s	C_μ, %	f, Hz	St
1	50	0.022	60	0.27
2	50	0.022	100	0.45
3	50	0.022	200	0.90
4	50	0.022	300	1.35

- Far-field noise calculation were carried out for SJ with operating modes:№1 - №4.($q = 50\ m/s;\ f = 60 - 300\ Hz$)

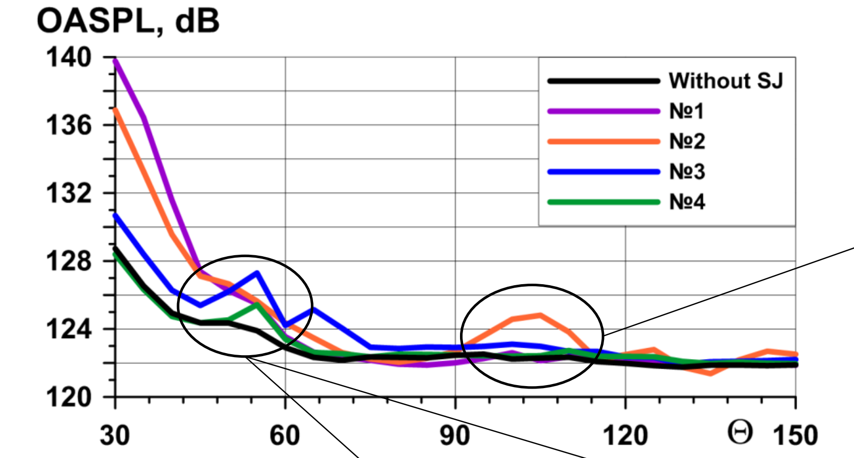


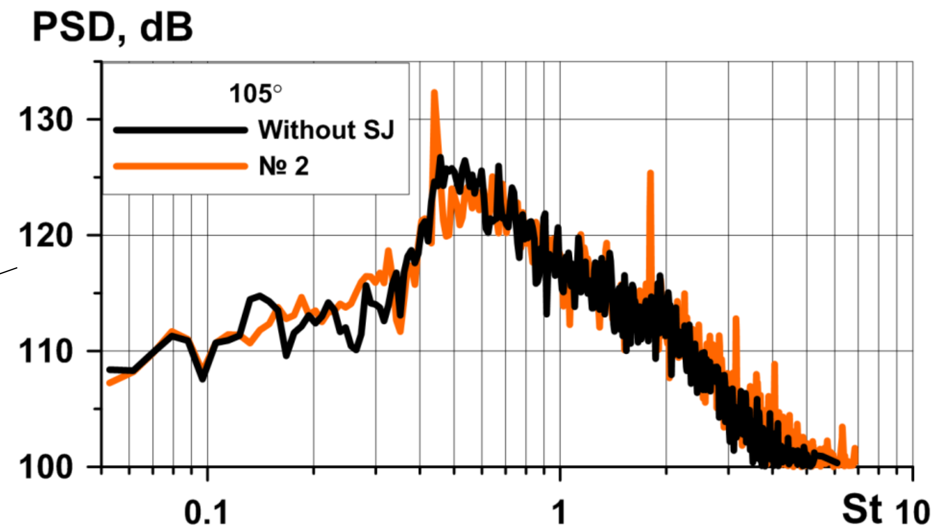
Power spectra density distribution at angle 30°



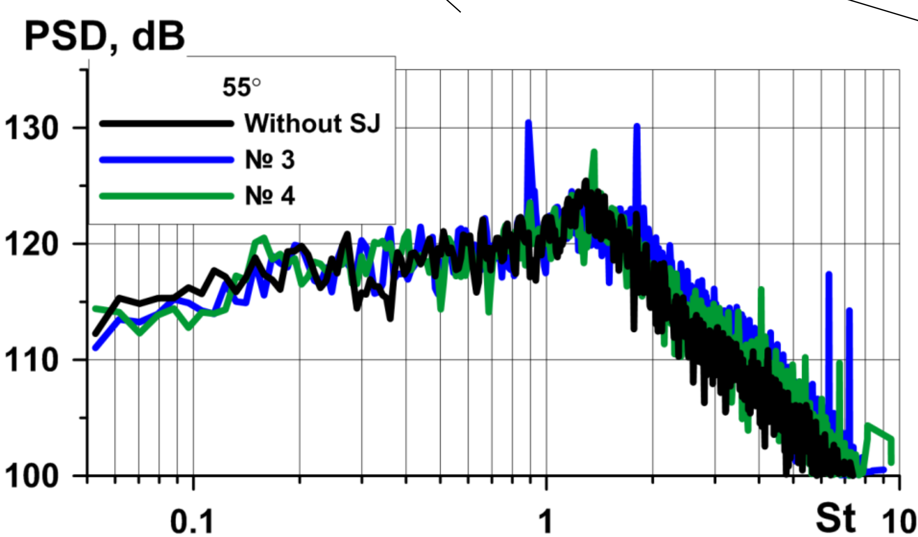
Power spectra density distribution at angle 30°

SJ influence on far-filed noise level

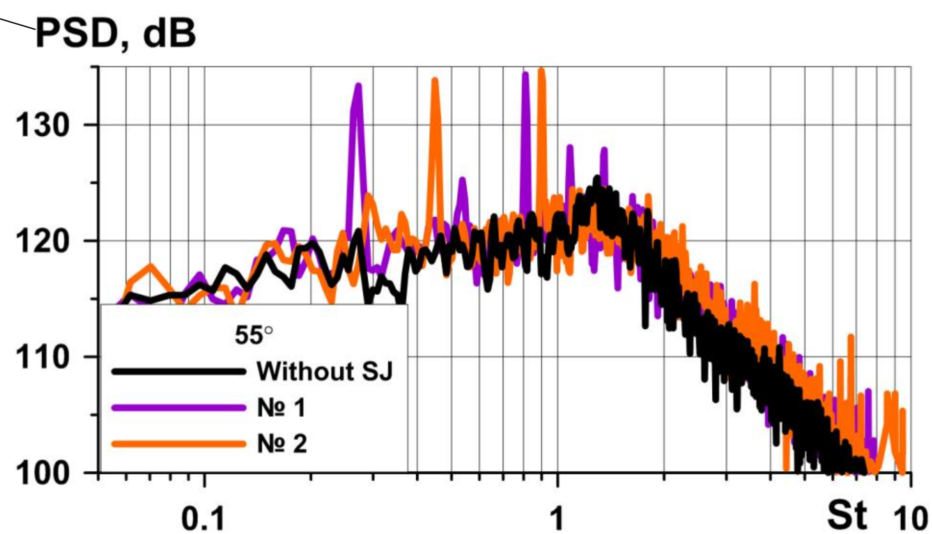




Power spectra density distribution at angle 105°

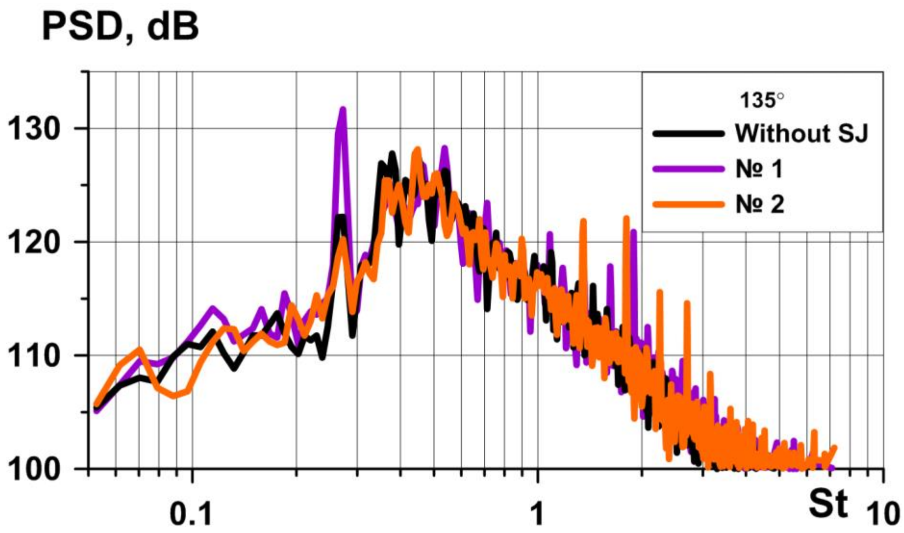


Power spectra density distribution at angle 55°

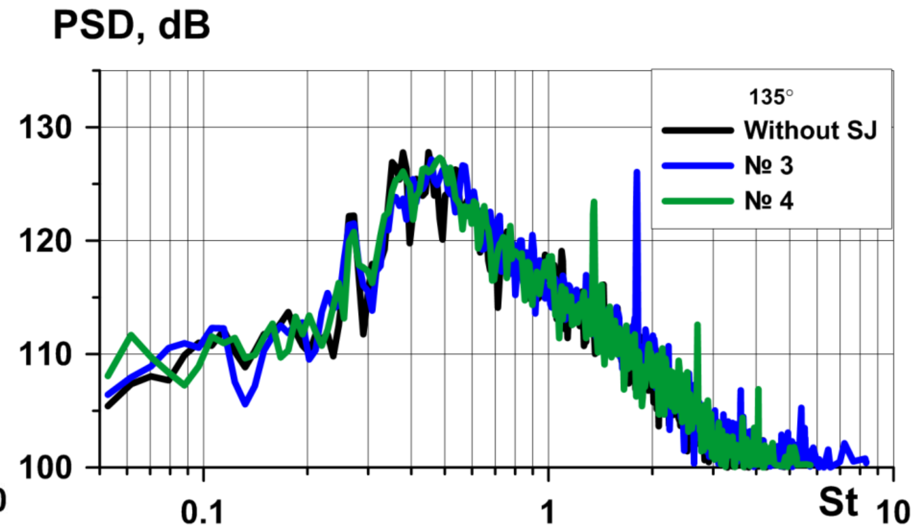


Power spectra density distribution at angle 55°

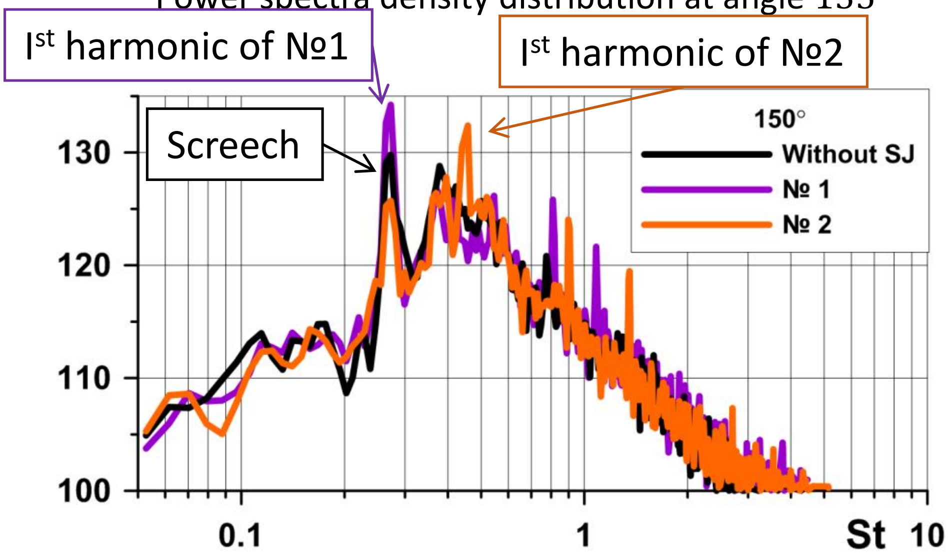
SJ influence on far-filed noise level



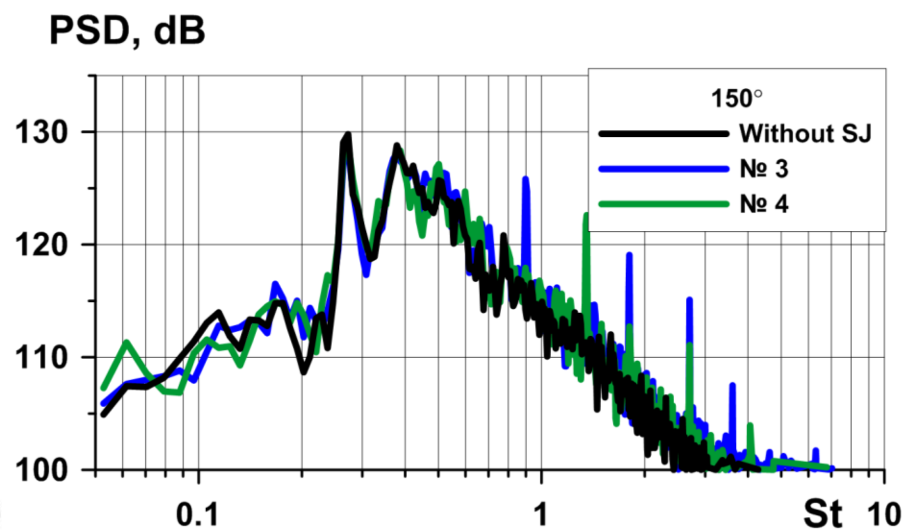
Power spectra density distribution at angle 135°



Power spectra density distribution at angle 135°



Power spectra density distribution at angle 150°



Power spectra density distribution at angle 150°

Conclusions and references

- Fine mesh with cell number 40×10^6 was used in this work because of good agreement with measurement data. Sufficiently small turbulence scales can be resolved with this mesh.
- The length of potential core is reduced at each of five synthetic jets operation mode. On operation mode $q = 50\ m/s$, $f = 100\ Hz$ potential core length reduced on 25%.
- SJ frequency has greater impact on flow than amplitude.
- Potential core reducing is accompanied by static pressure and velocity pulsation increasing in mixing layer. Apparently, SJ excitate flow in mixing layer region.
- Noise level increase in far-field depends on observation angle. If SJ frequency is close to frequency of PSD maximum on some of observation angles, then there is overall sound pressure level increase on this observation angle.
- On observation angle $150°$ there is 6 dB decrease in power of the screech for SJ operating mode $q = 50\text{м}/\text{с}$, $f = 100$. And on 2 dB for observation angle $135°$

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Thanks for attention