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On the possibility of active control of instability waves in unexcited turbulent jets

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Moscow, Russia,

Outline

- Introduction
- Artificial instability waves (AIW) , AIW control strategy
- NIW control idea, Overview of LES-results,
- Data analysis in the jet shear layer
- Data analysis in the jet near field
- Experimental data
- NIW Control strategy
- Conclusion

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Development of the Strategy of Active Control of Instability Waves in Unexcited Turbulent Jets

I. V. Belyaev, O. P. Bychkov, M. Yu. Zaitsev, V. A. Kopiev, V. F. Kopiev, N. N. Ostrikov, G. A. Faranosov*, and S. A. Chernyshev

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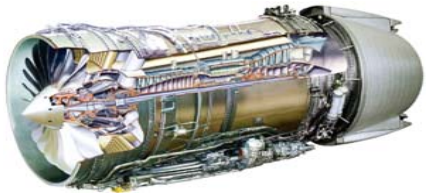
Examples of active/passive control of jet noise

Jet noise

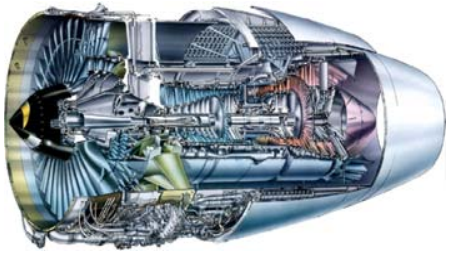
Lighthill's theory – acoustic power ~ U^8

Jet noise reduction – **increasing of BPR**

D-30KP

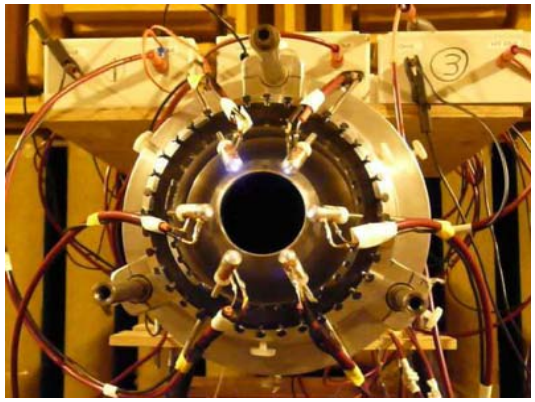


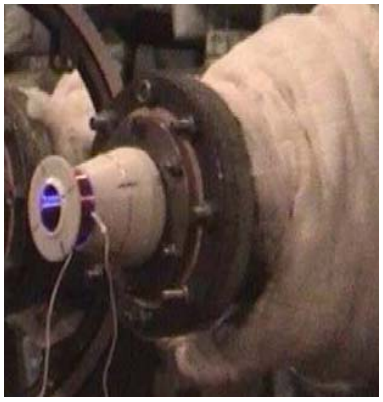
PS-90A

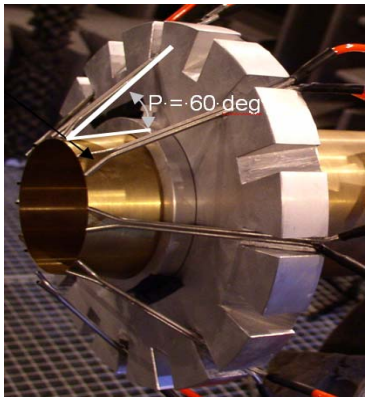


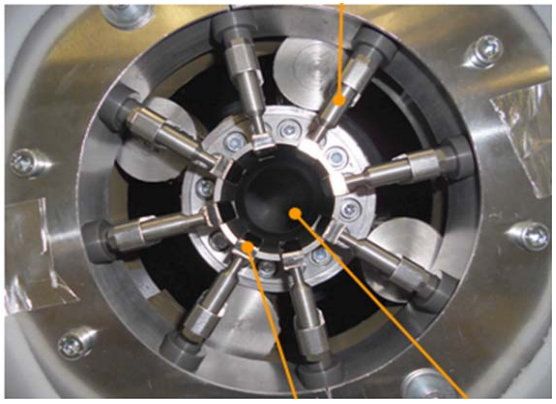
PD-14

Active jet noise control

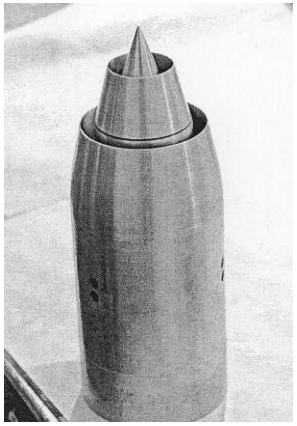




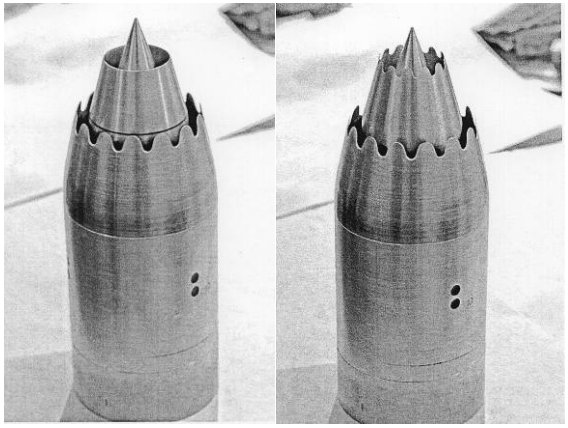




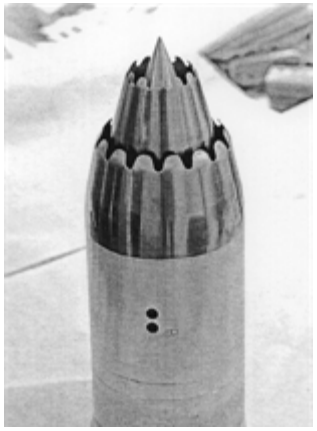
Nozzles with chevrons



Nozzles without chevrons



Chevrons directed streamwise

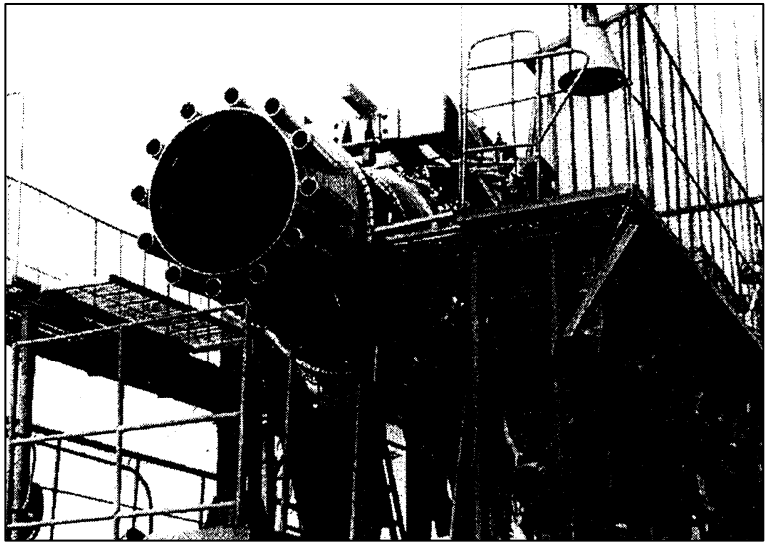


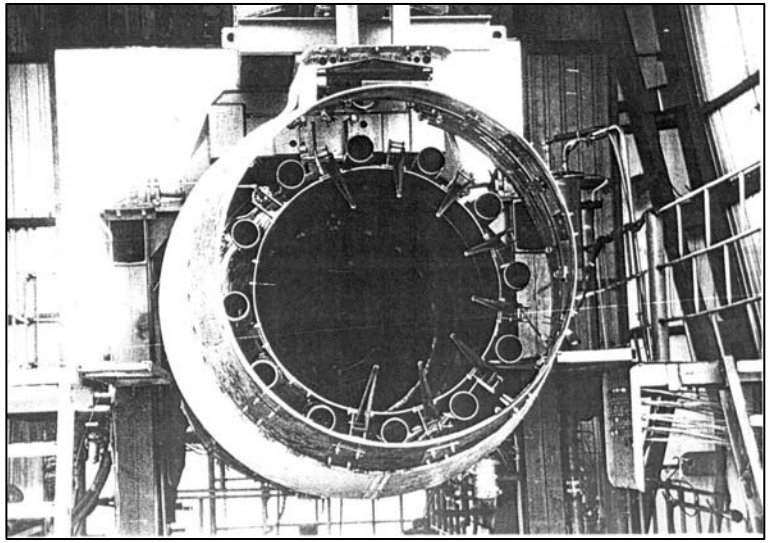
Chevrons deflected into the flow

Full-scale jet noise control - High TRL

Concept: It is known that low frequency noise excitation leads to broadband intensification of jet noise, vice versa high frequency excitation leads to noise suppression (at least for not very high amplitude of excitation) – low TRL experiments in anechoic chamber. Therefore high frequency excitation could be considered as a way for jet noise reduction

High TRL realization of this active control concept is presented on the picture for Nikolay Kuznetsov's type engine (NK): small-size jets located around main jet radiate more high-frequency noise compared the main jet, which acting on the main jet give mentioned suppression effect up to 3dB.





Instability wave control

AIW and NIW

Artificial instability waves (AIW)

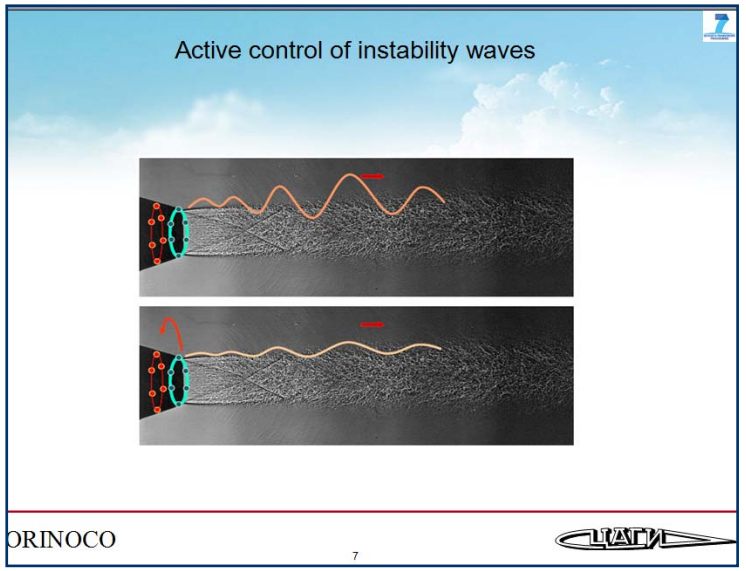
AIW are tone excited NIW (natural instability waves).

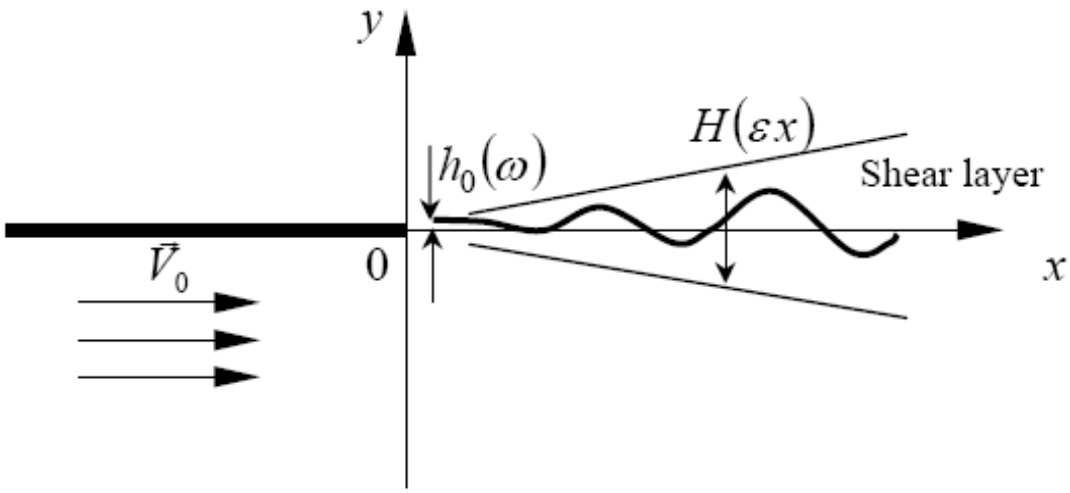
AIW as multiple increased NIW are dominates in the narrow frequency band.

AIW have the same properties as NIW

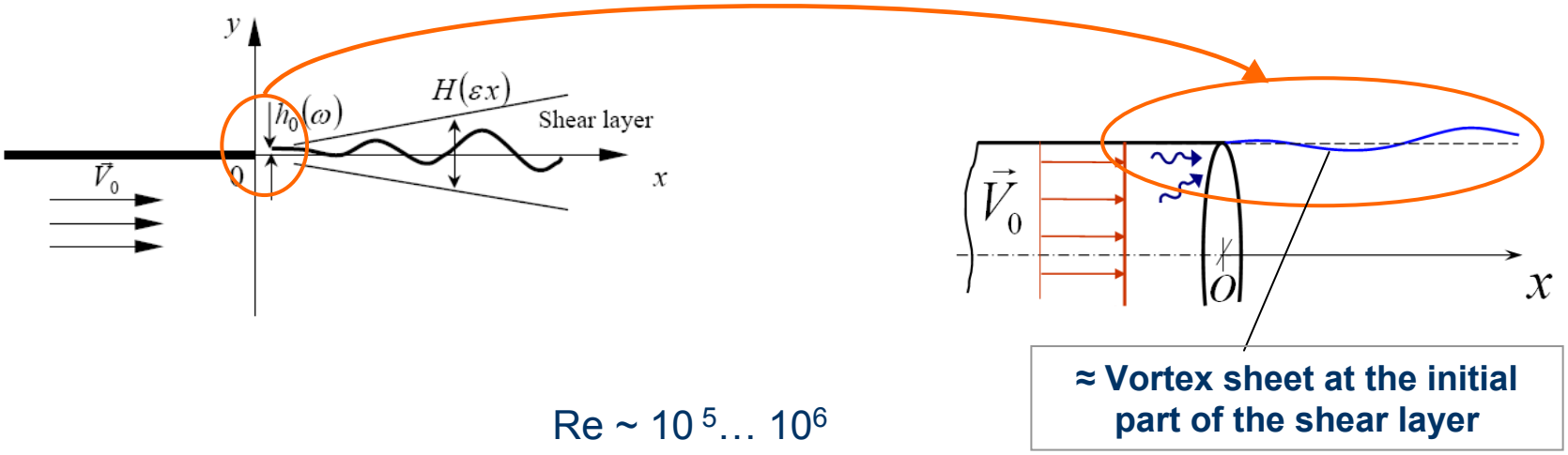
Benefits:

- Easy to measure (hotwire, PIV)
- Easy to generate
- Easy to control




y
$H(\varepsilon x)$
$h_0(\omega)$
Shear layer
$\vec{V}_0$
0
x

Kelvin-Helmholtz instability waves (IW) in jet shear layer



Re ~ 10^5… 10^6

≈ Vortex sheet at the initial part of the shear layer

Sedel'nikov T.K. The frequency spectrum of the noise of a supersonic jet // Phys. Aero. Noise Moscow: Nauka. 1967 (Trans. 1969 NASA TTF-538, P.71-75.)

Tam C.K.W., Burton D.E. Sound generated by instability waves of supersonic flows // J. Fluid Mech. 1984. V.138. P.249-295.

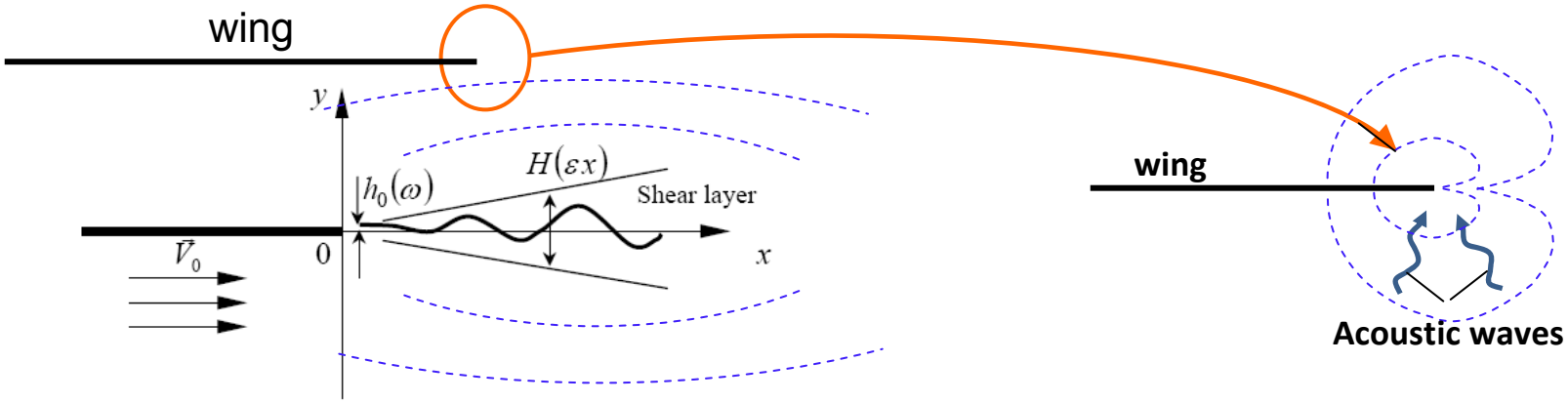
Crighton D.G., Huerre P. Shear-layer pressure fluctuations and superdirective acoustic sources //J. Fluid Mech. 1990. V.220. P.355-368.

Suzuki T., Colonius T. Instability waves in a subsonic round jet detected using a near-field phased microphone array // J. Fluid Mech. 2006. V.565. P.197-226.

Zaitsev M.Yu., Kopiev V.F., Chernyshev S.A. Experimental investigation of the role of instability waves in noise radiation by supersonic jets // Fluid Dynamics. 2009. V.44, N.4, P.587-595.

Morris P.J. The instability of high speed jets // Int. J. Aeroacoustics. 2010. V.9. N.1-2. P.1-50

Kelvin-Helmholtz instability waves (IW) in jet shear layer



$Re \sim 10^5 \ldots 10^6$

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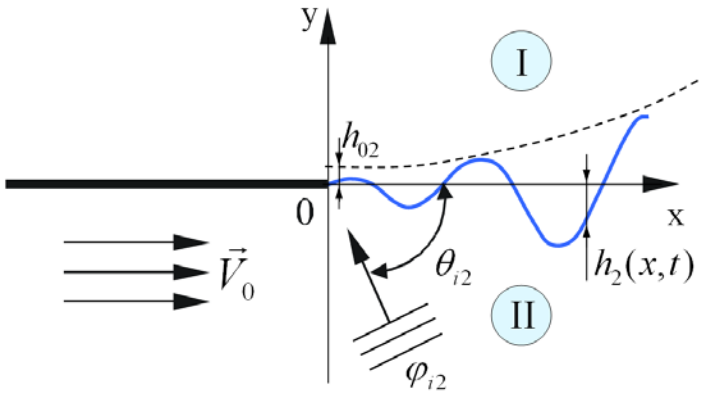
Governing Eqs for 2D problem



$$\begin{cases} \Delta\varphi_I + k^2\varphi_I = 0, & y > 0 \\ \Delta\varphi_{II} - \left(-ik + M\dfrac{\partial}{\partial x}\right)^2 \varphi_{II} = 0, & y < 0 \end{cases}$$

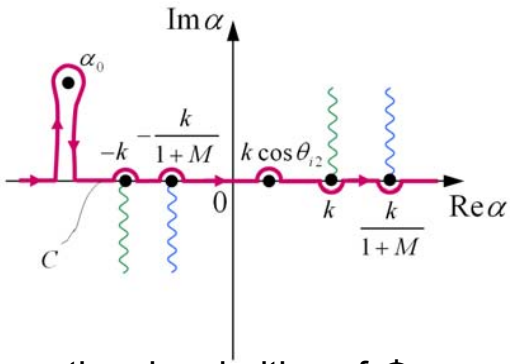
$$\varphi \sim exp\left(i\alpha x - ikct\right)$$

$$\varphi \sim exp\left(-\gamma y\right)$$
$$\varphi \sim exp\left(\beta y\right)$$

$$\gamma = \sqrt{\alpha^2 - k^2}$$
$$\beta = \sqrt{\left(\alpha(1+M)+k\right)\left(\alpha(1-M)-k\right)}$$

$$\Phi(\alpha, y, k) = \int_{-\infty}^{+\infty} \varphi(x, y, k)\exp(i\alpha x)dx$$

$$\varphi(x, y, t) = A \cdot e^{-ikct} \int_C \Phi(\alpha, y, k) e^{-i\alpha x} d\alpha$$



$$\Delta\left(k, \alpha\right) \equiv k^2\beta + (k + M\alpha)^2\gamma = 0$$ ← Roots of this Eq. are the singularities of Φ

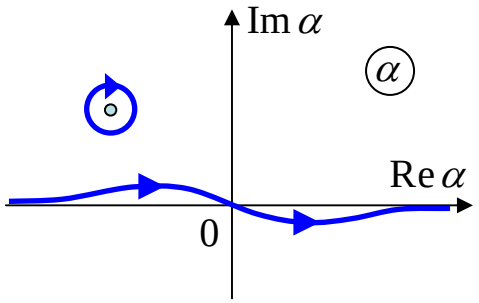
$$p_{inner}(\vec{r},t) = B \cdot e^{-i\omega t} \int_{-\infty}^{+\infty} f_{inner}(\alpha, y) e^{-i\alpha x} d\alpha$$

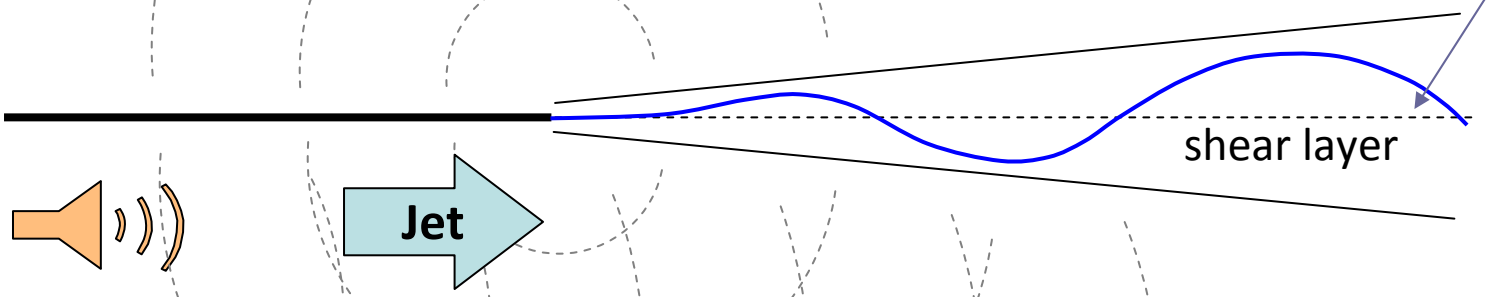
Acoustic part

$$p_{inner}(\vec{r},t) = B \cdot e^{-i\omega t} \int_{C} f_{inner}(\alpha, y) e^{-i\alpha x} d\alpha$$

$$p_{iw2}(\vec{r},t) = B \cdot \hat{f}_{inner} e^{-i\omega t - i\alpha_0 x - \gamma_0 y}$$

Hydrodynamic part





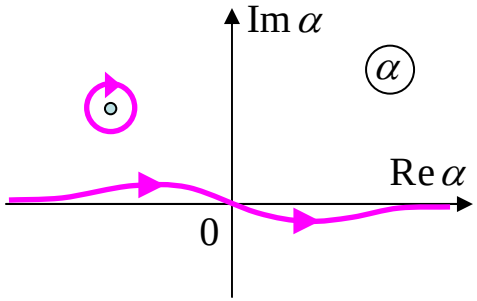
Full solution contains the incident wave, diffraction field and instability wave which together satisfy the Kutta condition near the edge.

Therefore the instability wave initial amplitude is determined by the incident wave properties only.

$$p_{outer}(\vec{r},t) = A \cdot e^{-i\omega t} \int_{-\infty}^{+\infty} f_{outer}(\alpha, y) e^{-i\alpha x} d\alpha$$

Acoustic part

$$p_{inner}(\vec{r},t) = A \cdot e^{-i\omega t} \int_{C} f_{inner}(\alpha, y) e^{-i\alpha x} d\alpha$$



$$p_{iw1}(\vec{r},t) = A \cdot \hat{f}_{outer} e^{-i\omega t - i\alpha_0 x - \gamma_0 y}$$

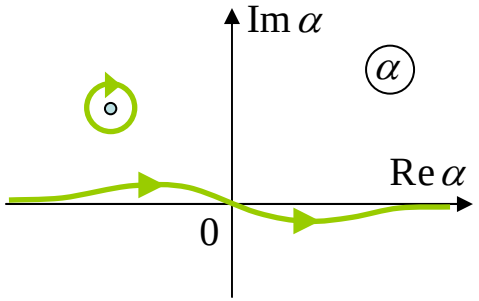
Hydrodynamic part

shear layer

Jet

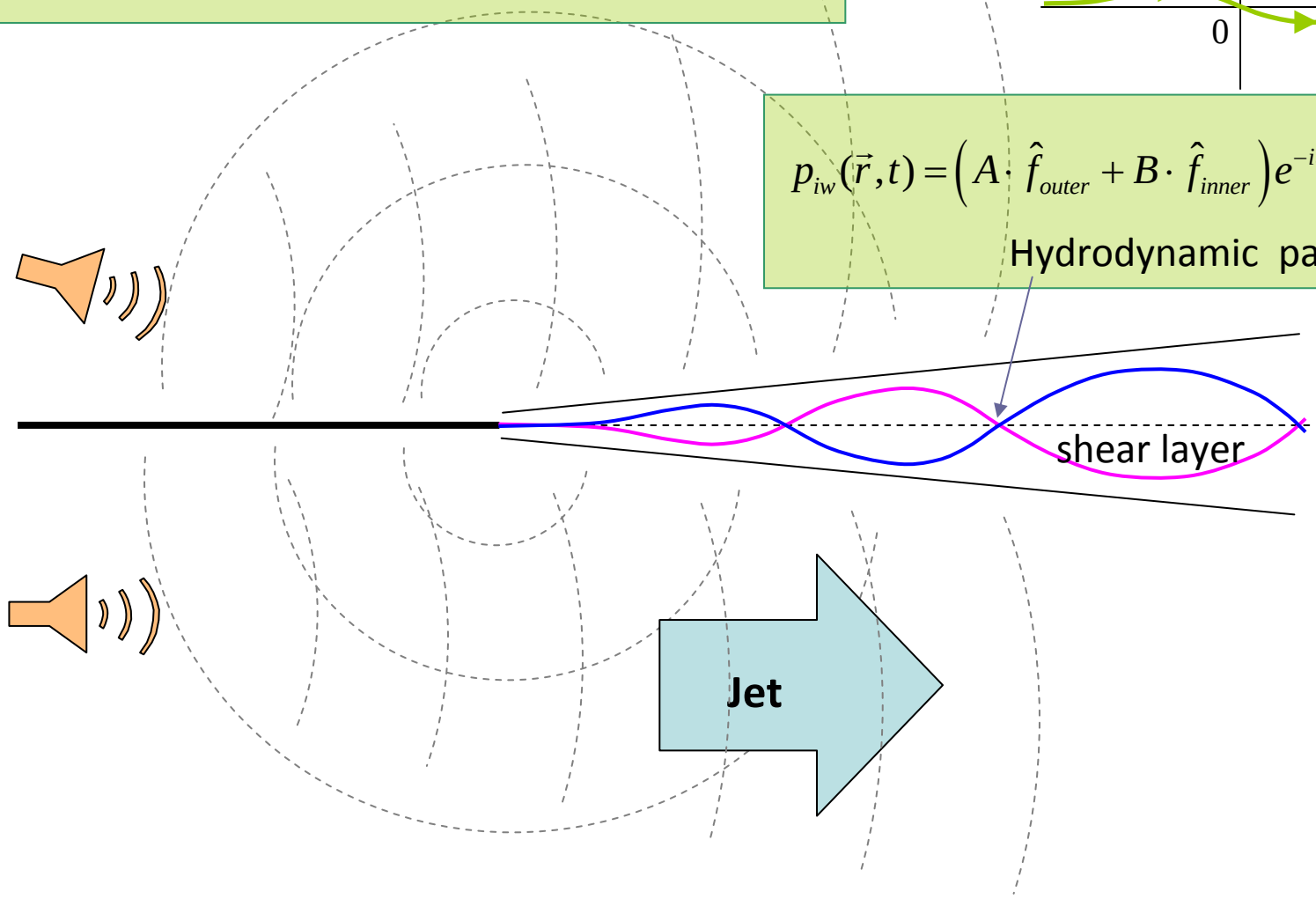
$$p(\vec{r},t) = e^{-i\omega t}\int_{-\infty}^{+\infty}\left(A\cdot f_{outer}(\alpha,y) + B\cdot f_{inner}(\alpha,y)\right)e^{-i\alpha x}d\alpha$$

Acoustic part



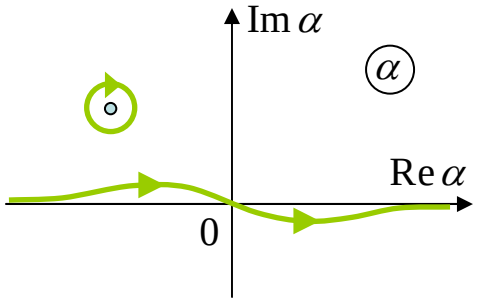
$$p_{iw}(\vec{r},t) = \left(A\cdot \hat{f}_{outer} + B\cdot \hat{f}_{inner}\right)e^{-i\omega t - i\alpha_0 x - \gamma_0 y}$$

Hydrodynamic part



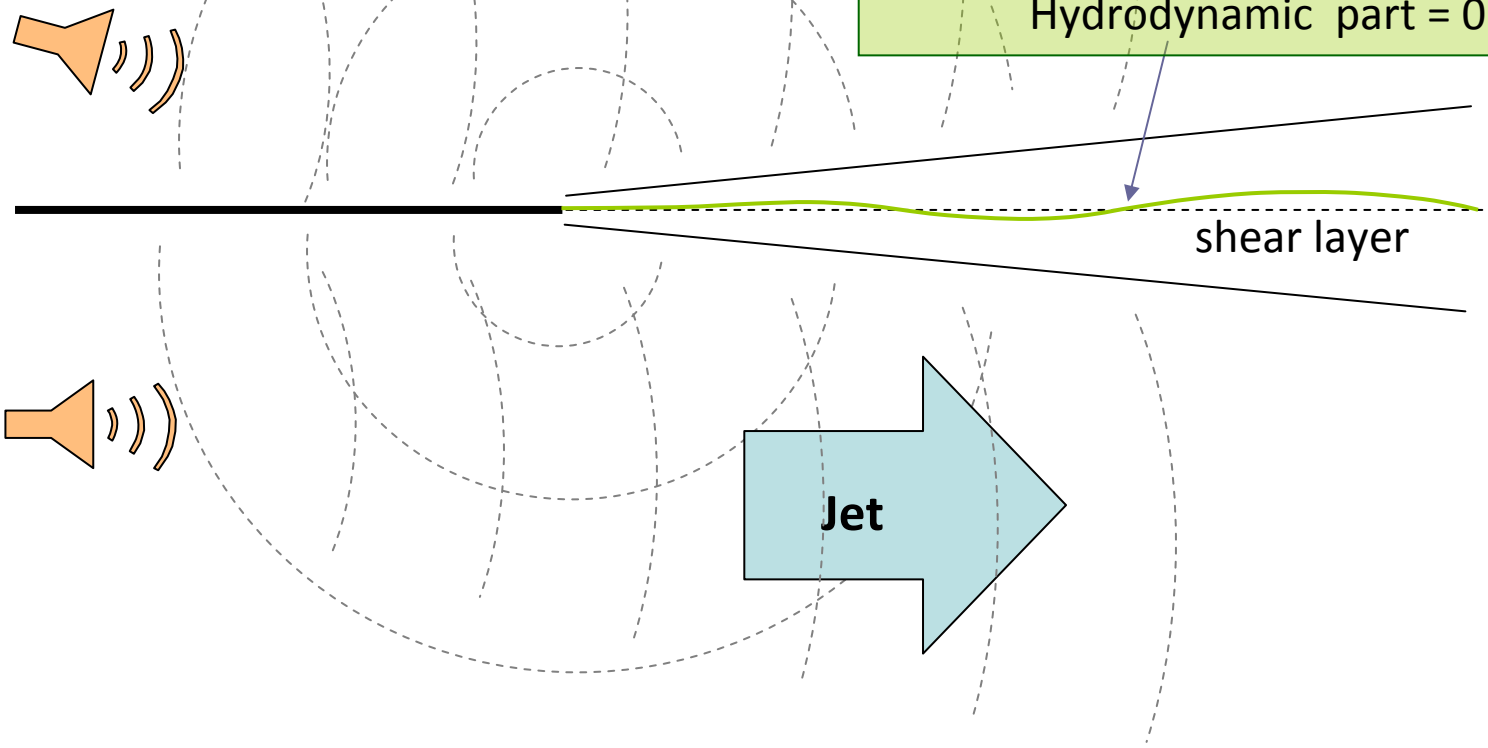
$$p(\vec{r},t) = e^{-i\omega t}\int_{-\infty}^{+\infty}\left(A\cdot f_{outer}(\alpha,y) + B\cdot f_{inner}(\alpha,y)\right)e^{-i\alpha x}d\alpha$$

Acoustic part ≠ 0

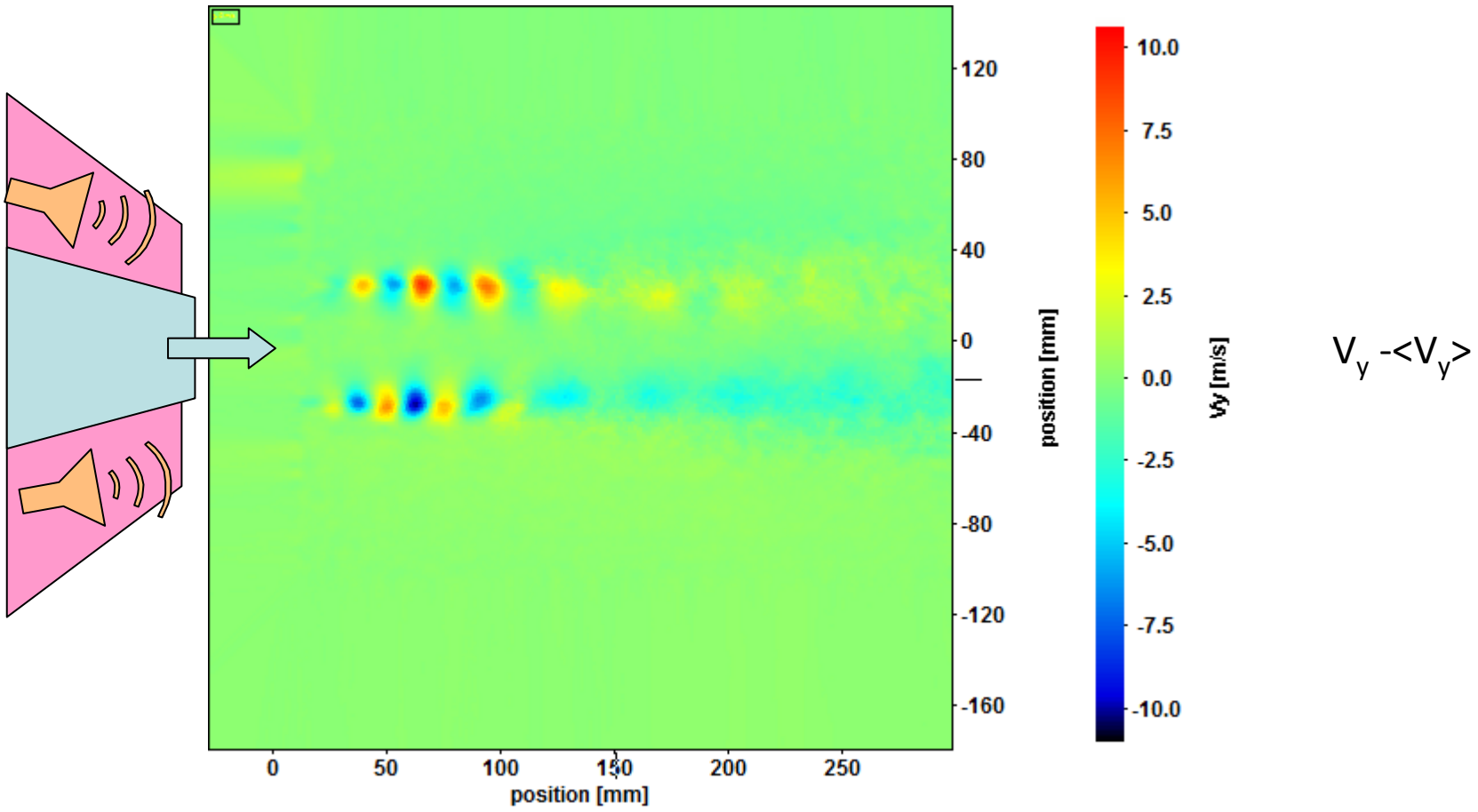


$$p_{iw}(\vec{r},t) = 0, \quad A = -B\cdot \hat{f}_{inner} / \hat{f}_{outer}$$

Hydrodynamic part = 0

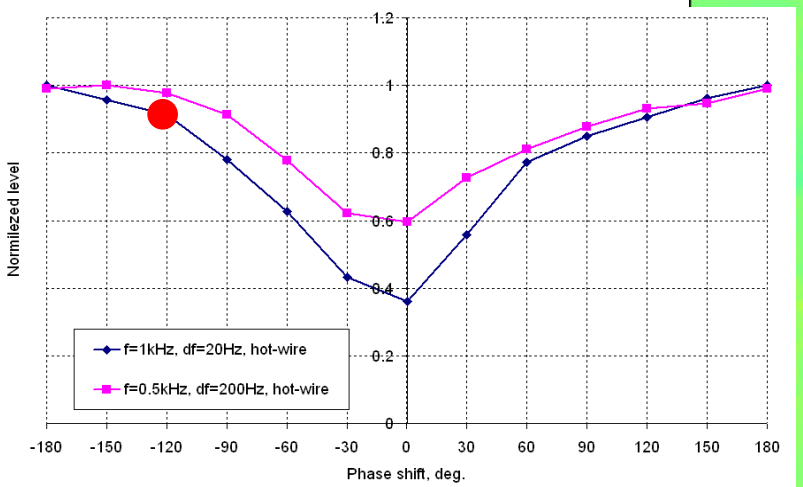


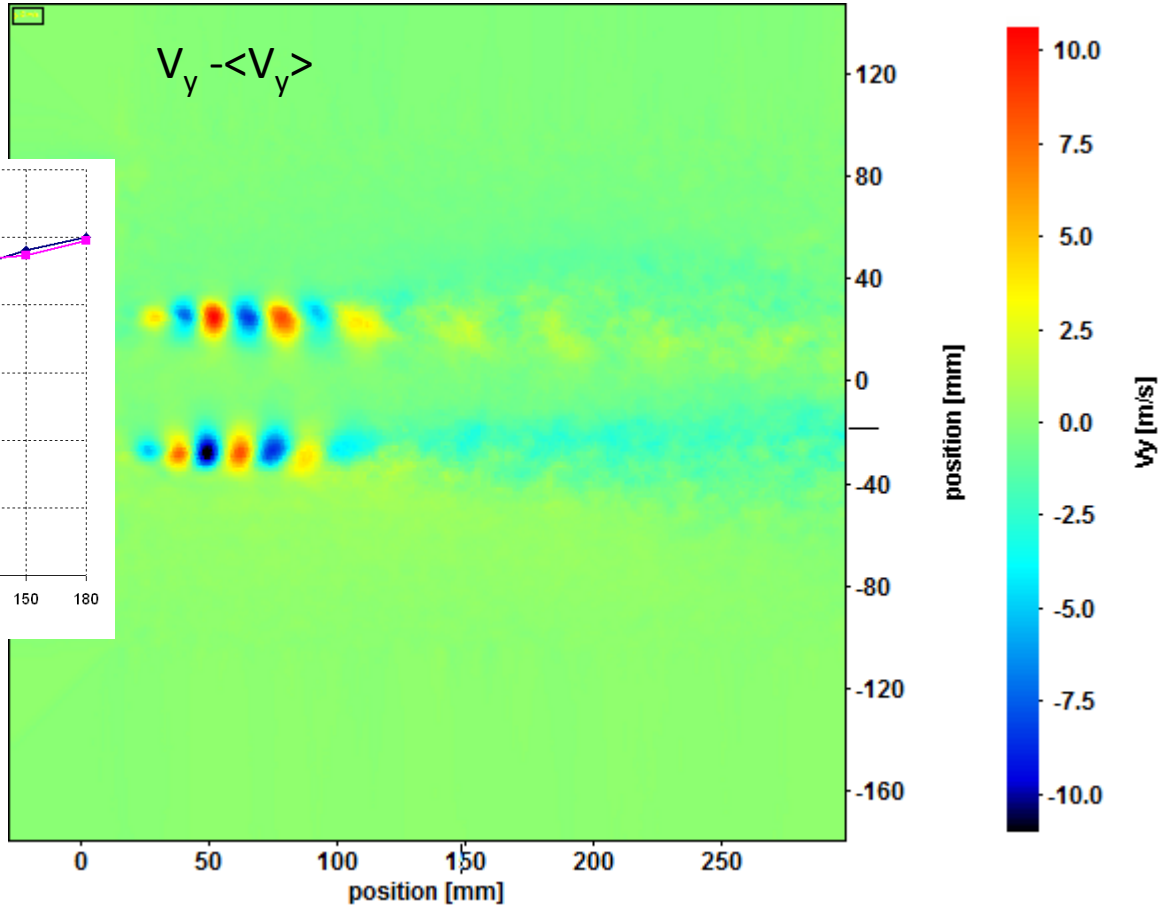
PIV measurements , $f_{exc}=f_{samp}$ =1kHz



Outer source

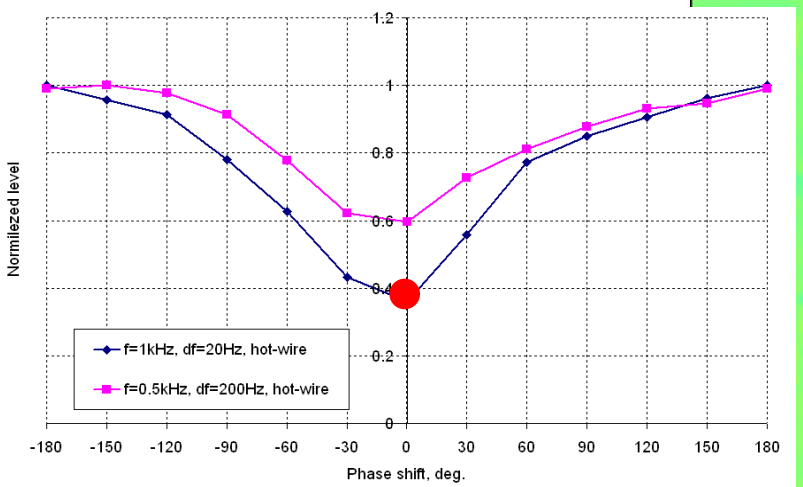
PIV measurements , $f_{exc}=f_{samp}$ =1kHz

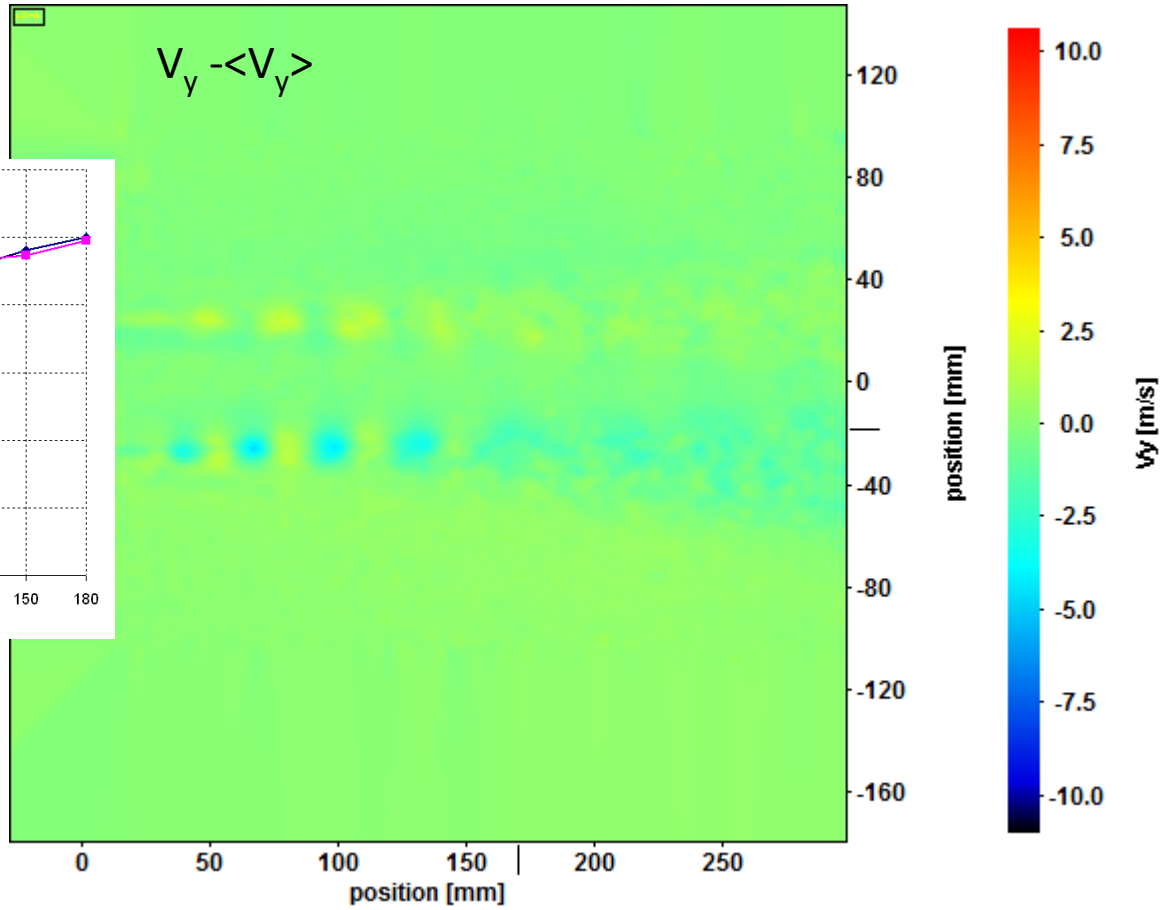




$\Delta\phi = -180^0$

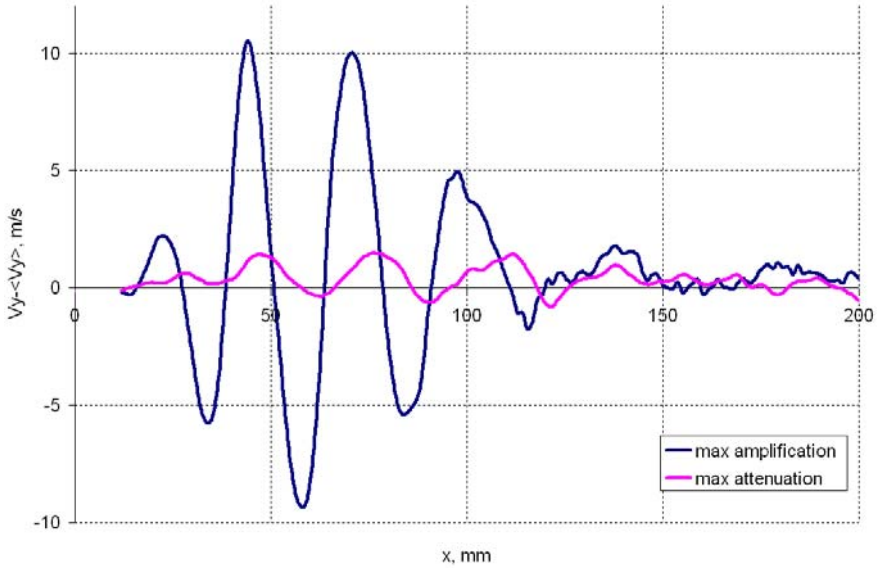
PIV measurements , $f_{exc}=f_{samp}$ =1kHz





$\Delta\phi = -60^0$

PIV measurements , $f_{exc}=f_{samp}$ =1kHz

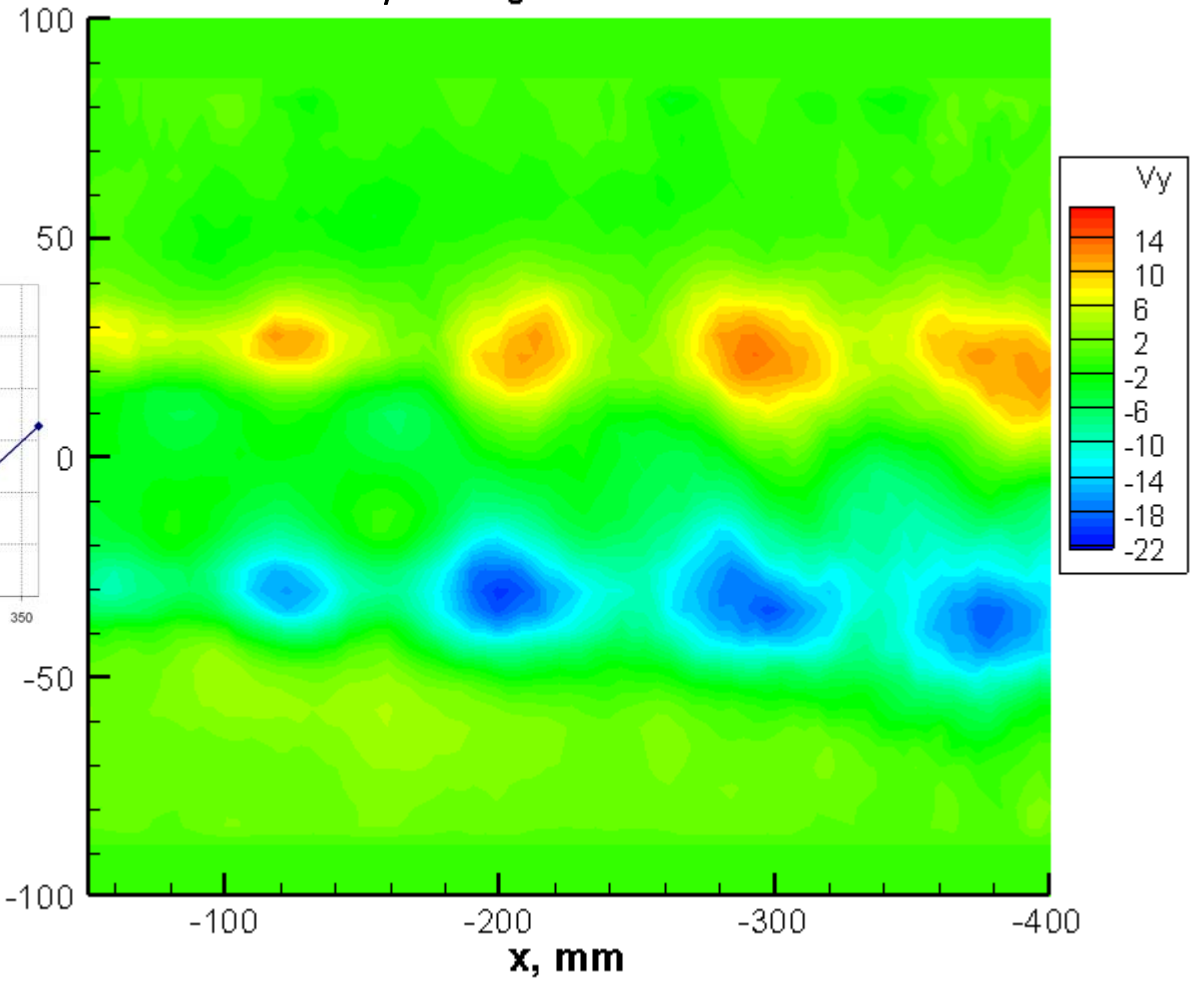


Profile of V_y-<V_y> along the lip-line

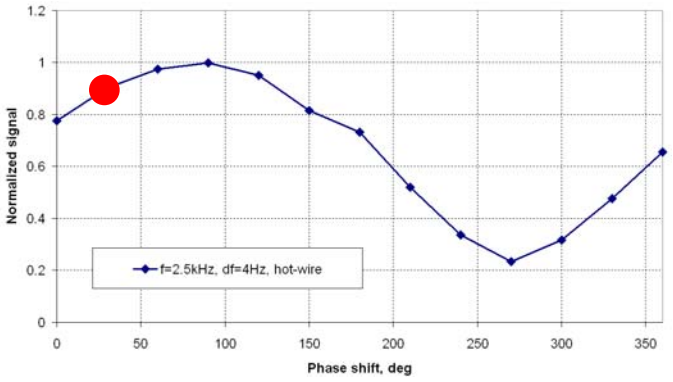
Jet velocity 280 m/s

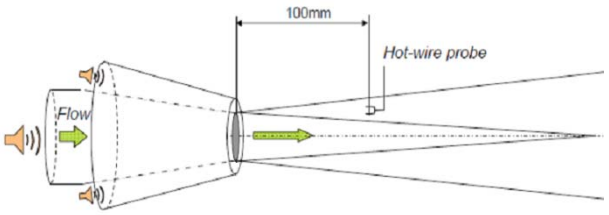
Measurements by TR PIV, $f_{exc}=f_{samp}$ =2.5 к Г ц

$\Delta\phi$ =30 deg



Measurements by hot-wire

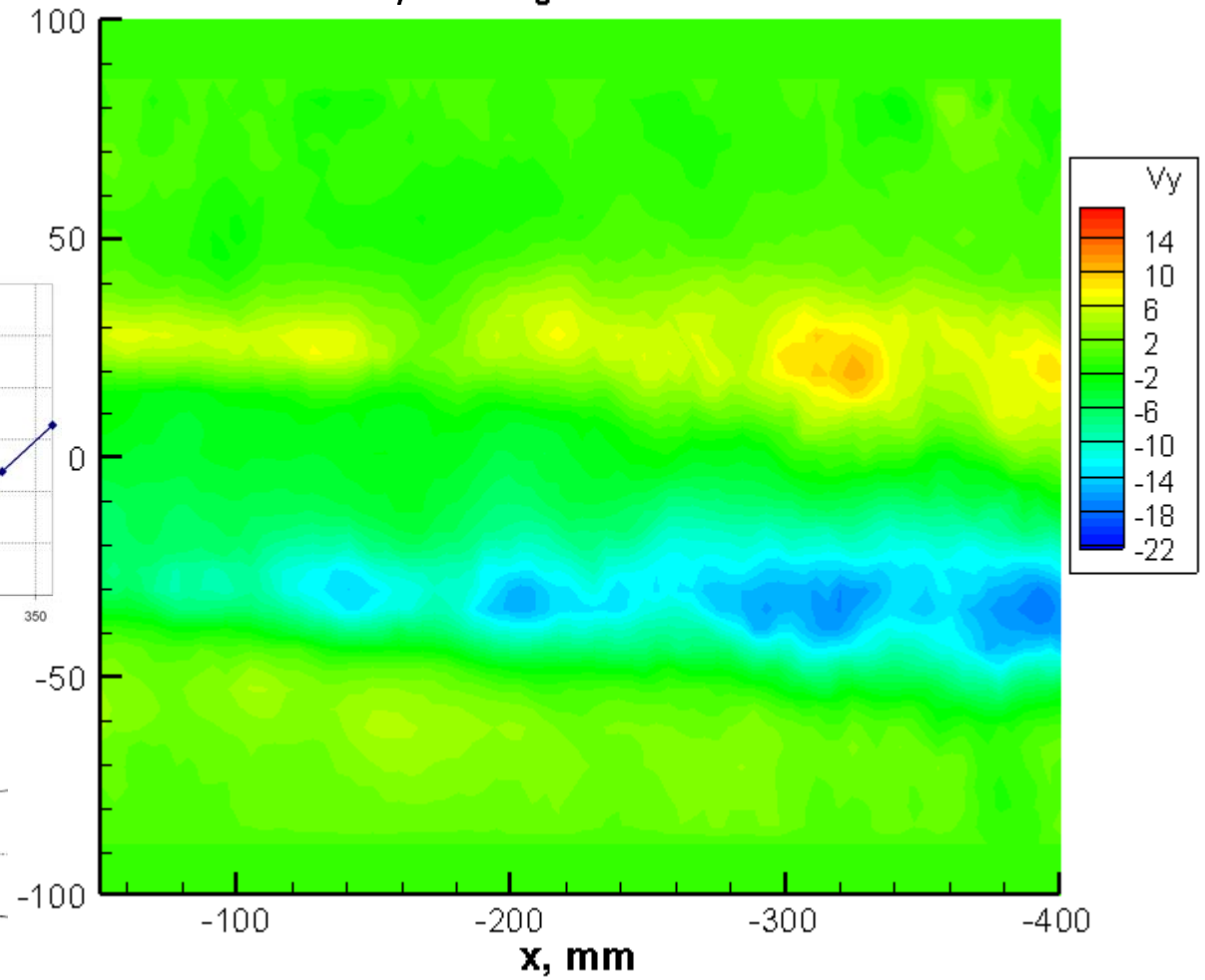




Jet velocity 280 m/s

Measurements by TR PIV, $f_{exc}=f_{samp}$ =2.5 к Г ц

$\Delta\phi$ =270 deg



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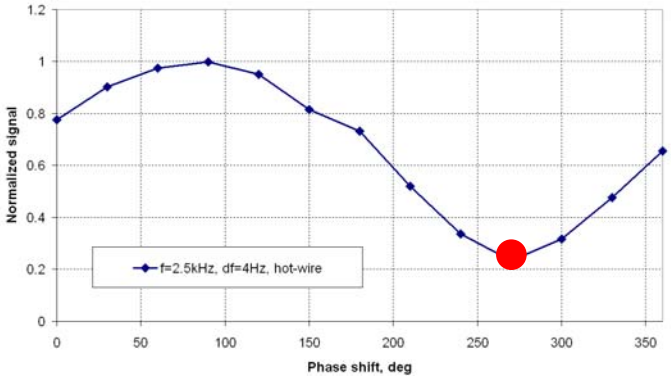
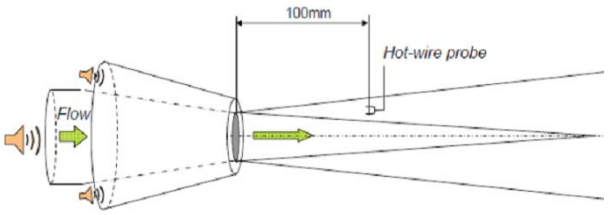
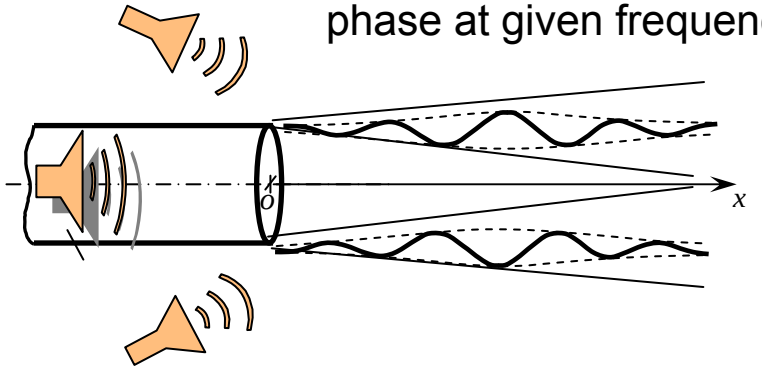


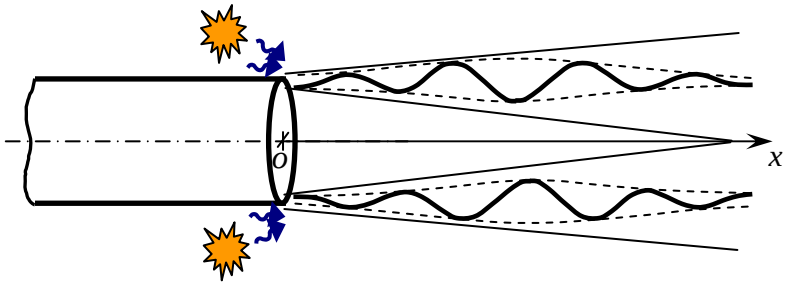


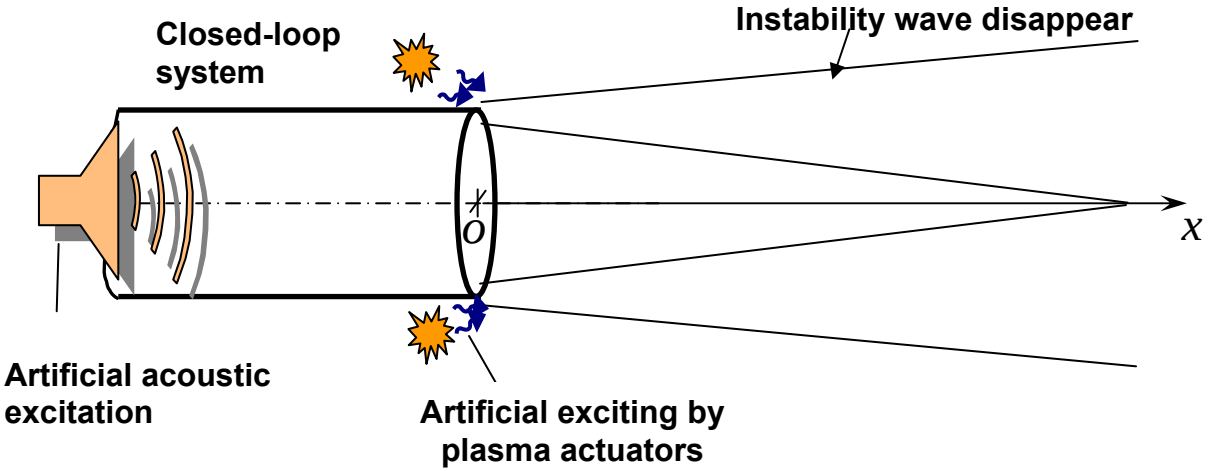
Plasma actuator for IW suppression

Artificial acoustic excitation characterized by amplitude and phase at given frequency



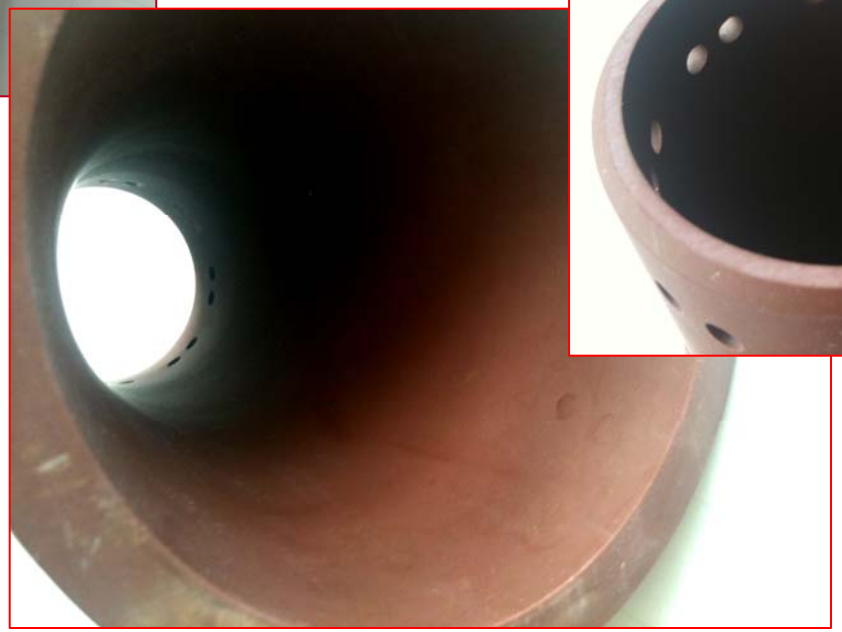
Artificial exciting by plasma actuators



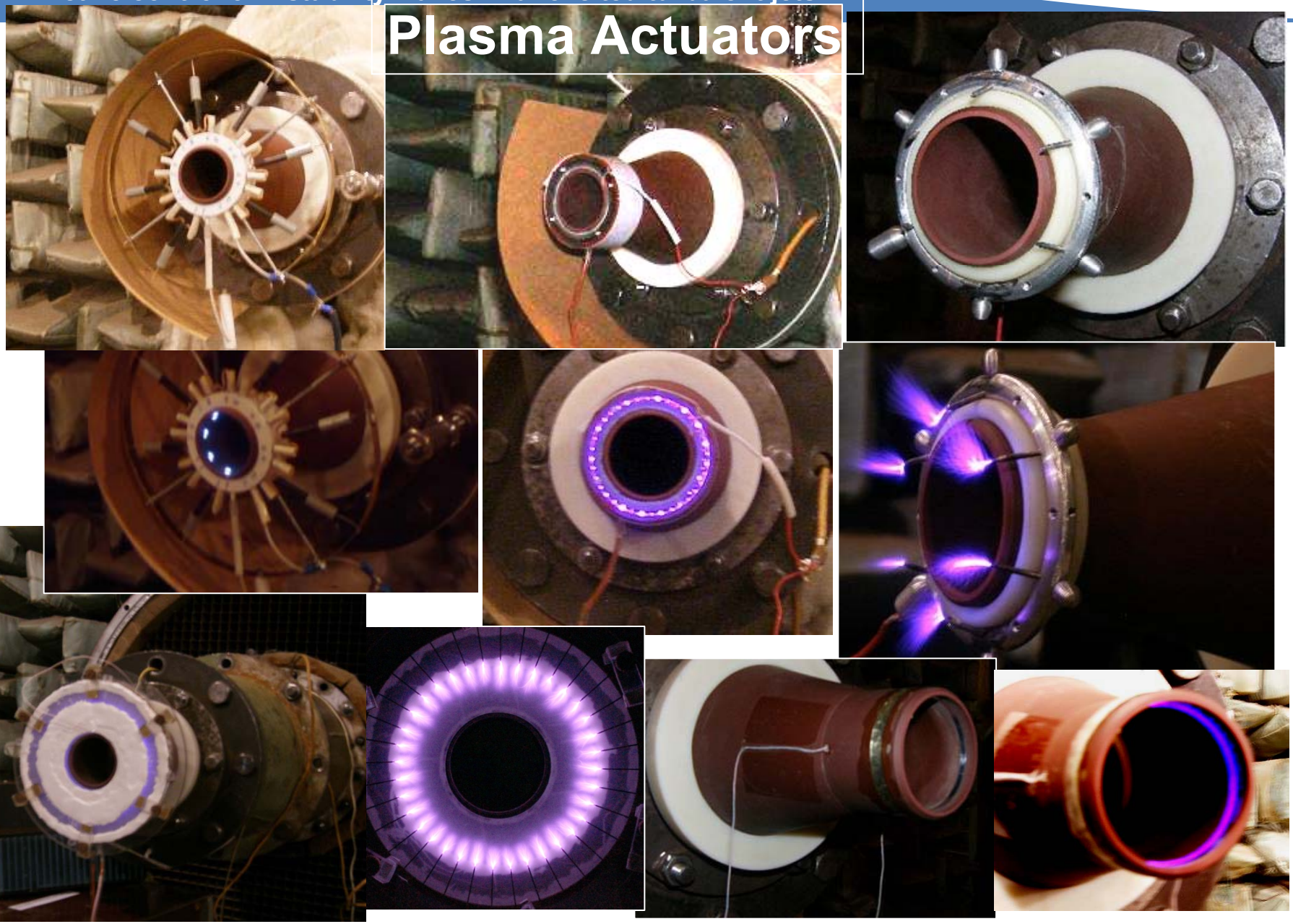


Witoszynski ceramic nozzles

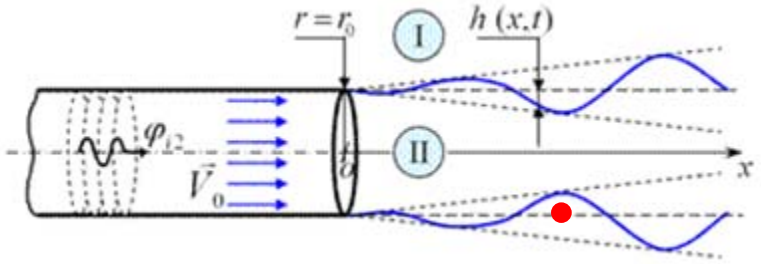
$$r(x) = \frac{r2}{\sqrt{1 - \left(1 - \left(\frac{r2}{r1}\right)^2\right) \frac{\left(1 - \frac{x^2}{L^2}\right)^2}{\left(1 + \frac{x^2}{L^2}\right)^3}}}$$



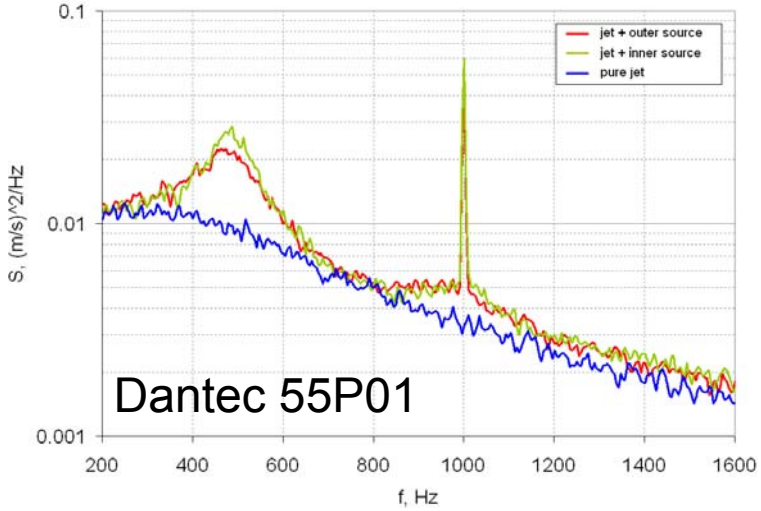
Plasma Actuators



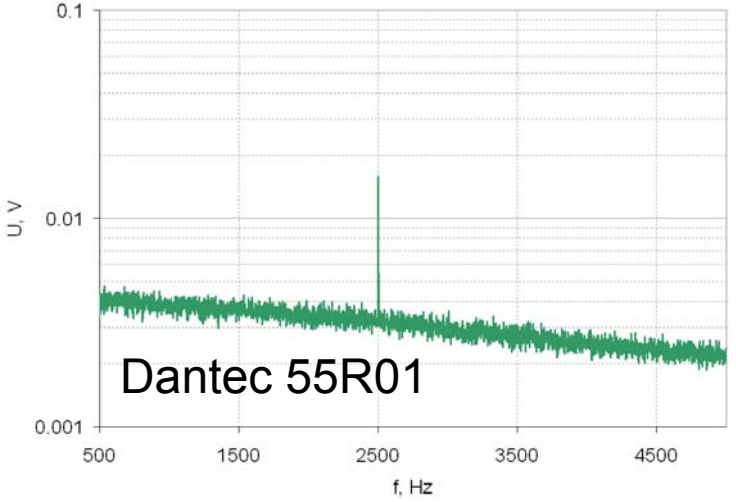
Hot-wire measurements



V=50 m/s, at f=1kHz

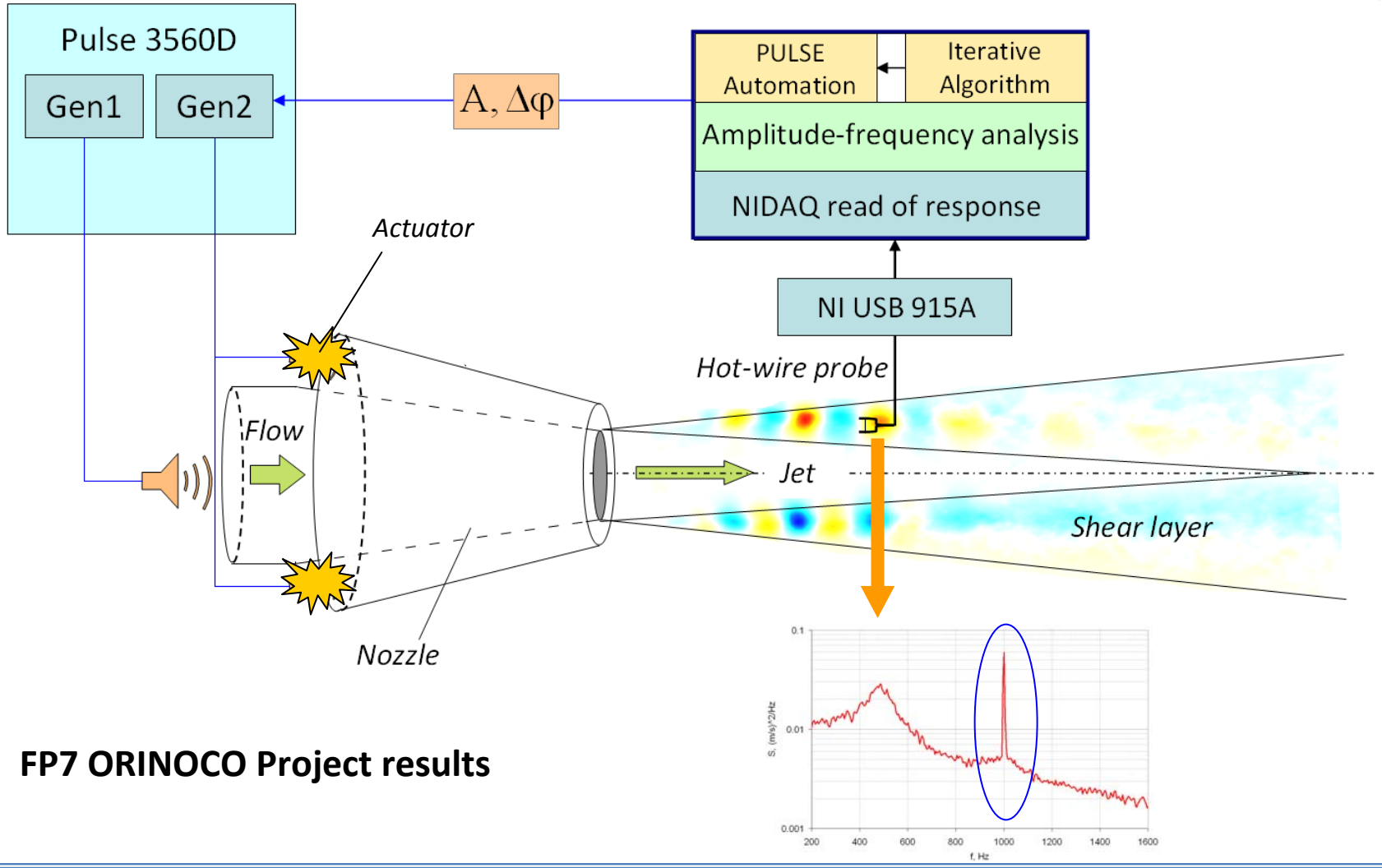


V=280 m/s, at f=2.5kHz



Closed loop AIW control system

Kopiev et al. (2013, 2014)



FP7 ORINOCO Project results

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- Introduction
- Artificial instability waves (AIW) , AIW control strategy
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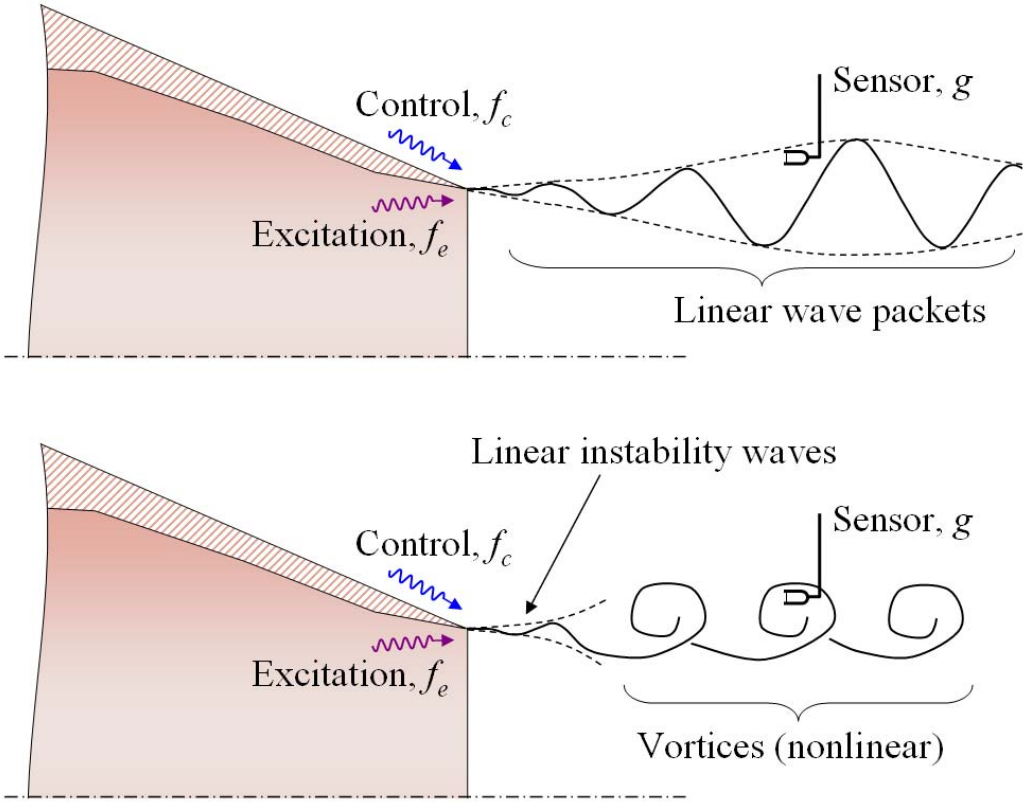
- Conclusion

How to control Natural Instability waves (NIW)?

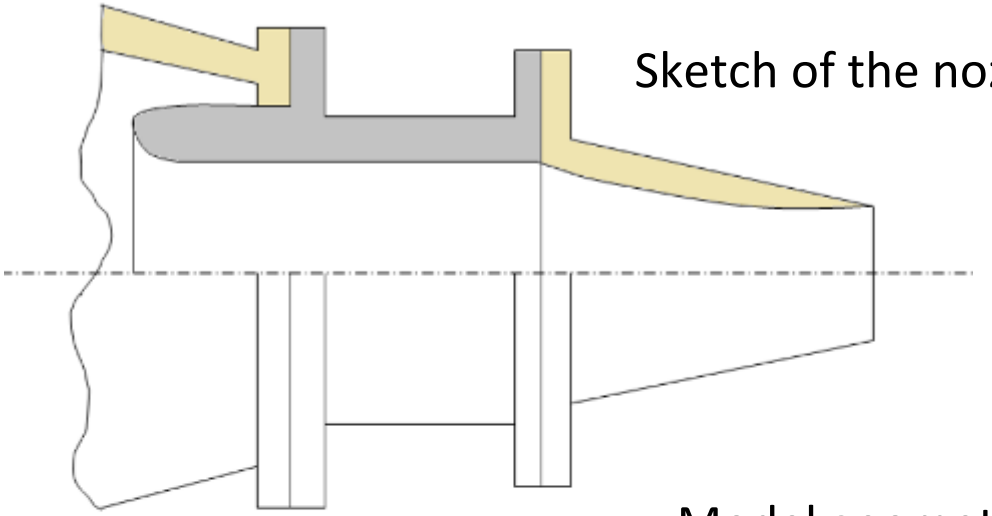
Instabilities in excited jet: nonlinear and linear regimes



Overview of LES-results

Profiled TsAGI nozzle

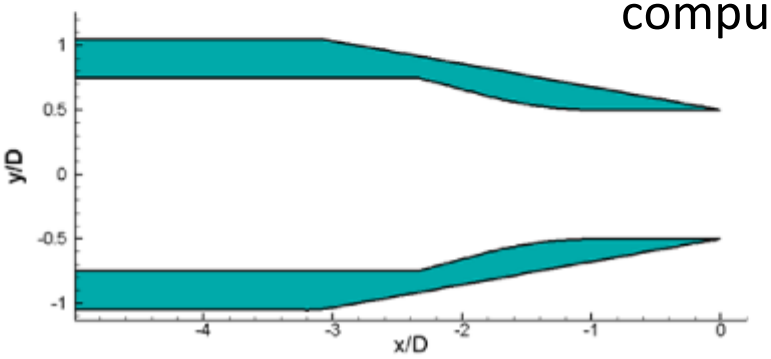
Sketch of the nozzle

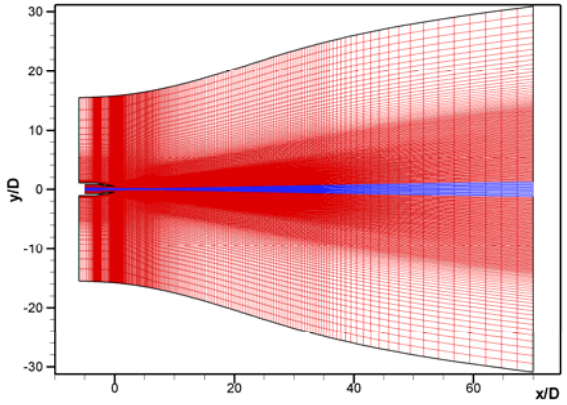


Operating conditions

V_{jet}=280 m/s
D=0.04 m
T*=290 K

Model geometry and computational mesh

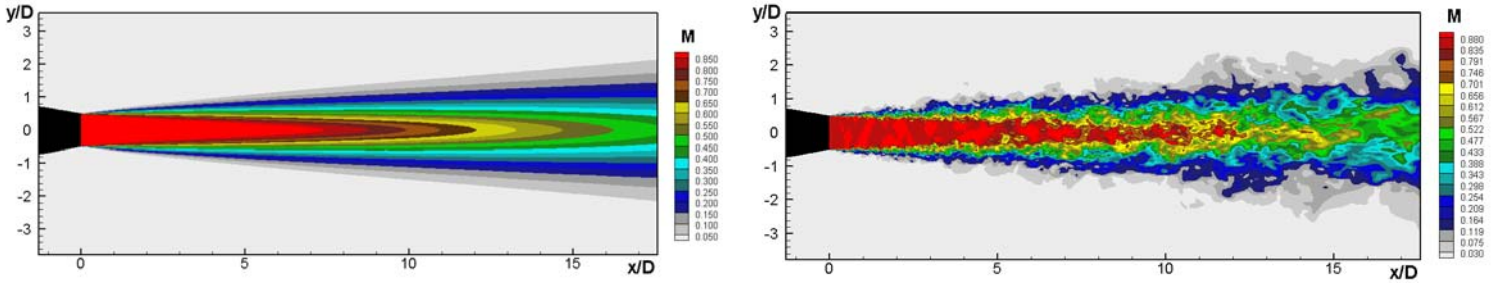




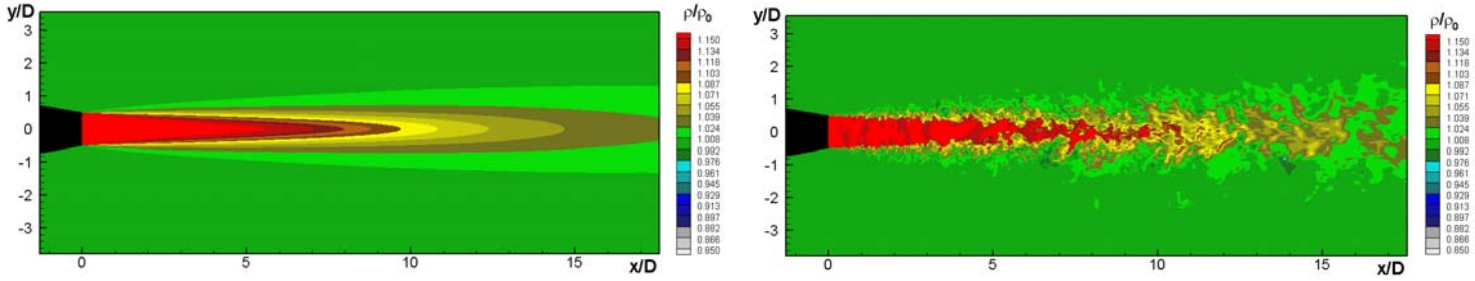
Simultaneous and averaged fields in symmetry plane

LES simulation by M.Shur and M.Strelets

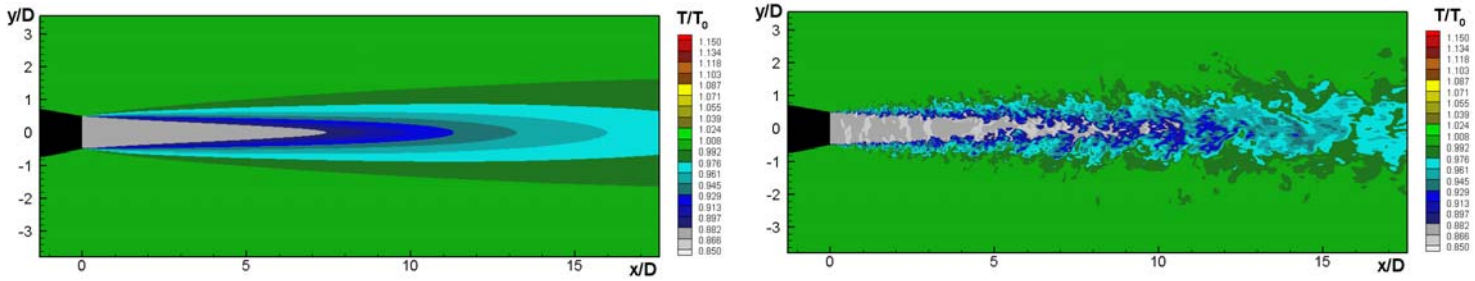
Mach number



Density

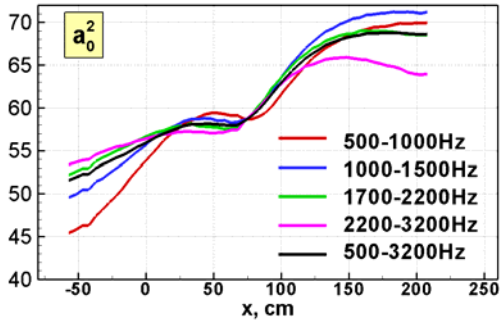


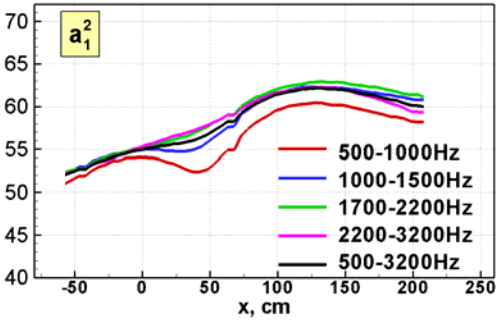
Temperature

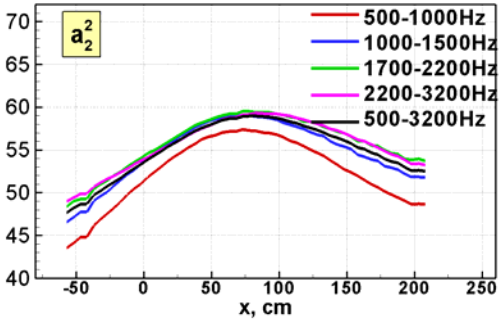


Validation of LES data in far acoustic field

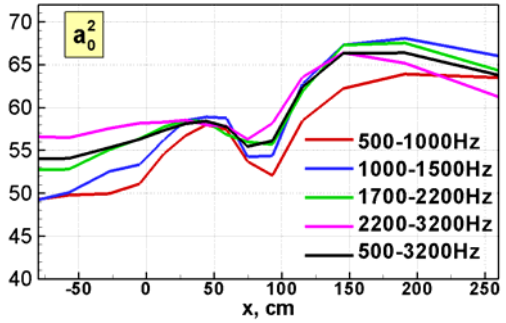
Experiment

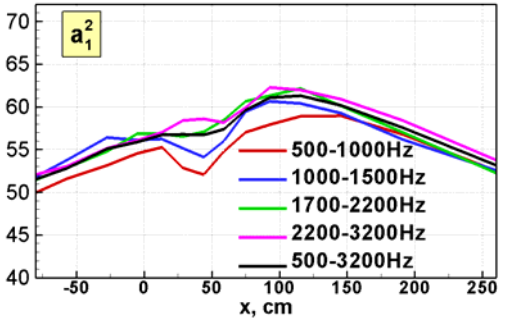


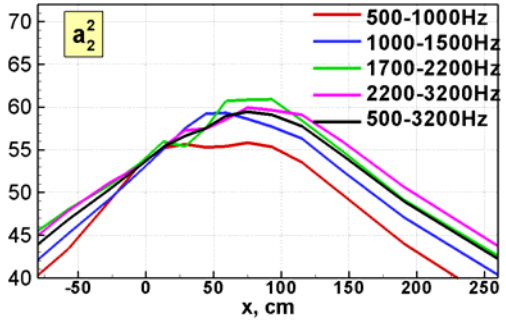




Simulation

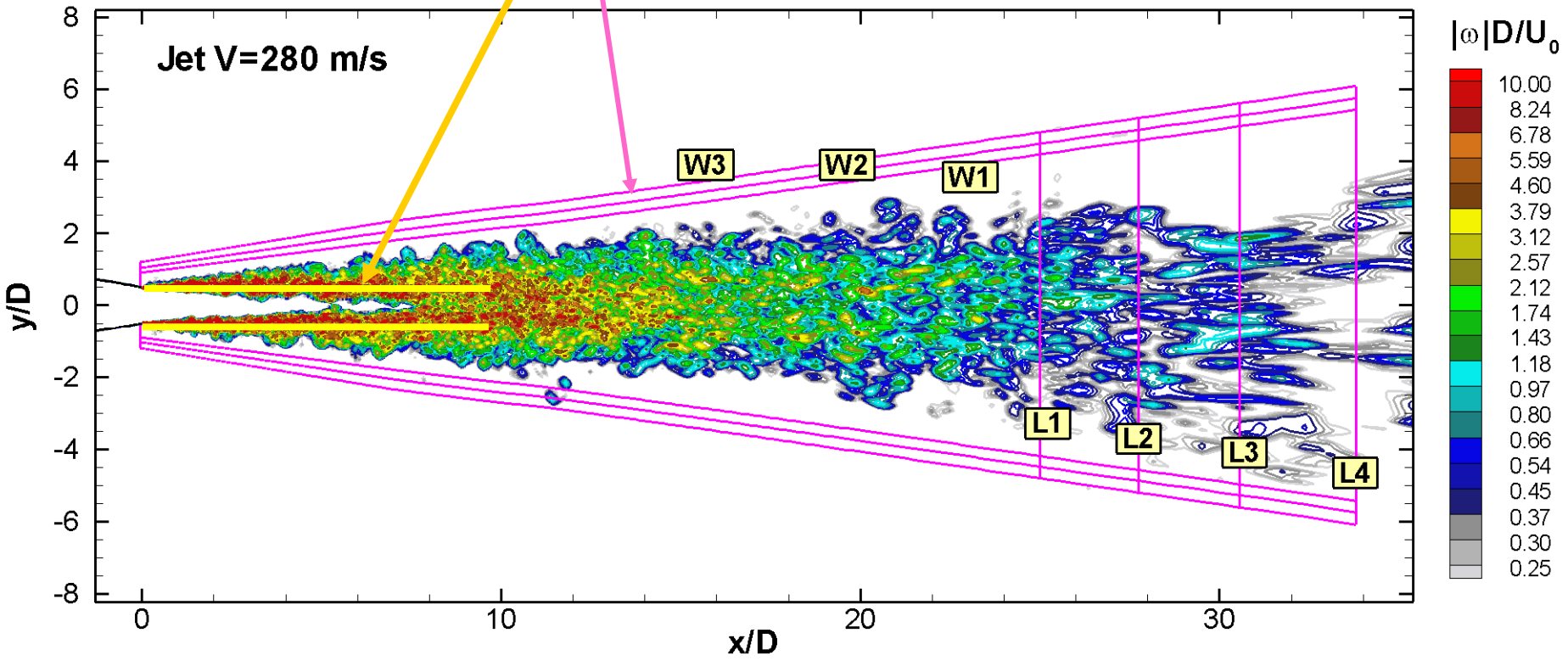






Surfaced with saved pulsations time histories

1. Cylindrical lip-line surafce
2. Control FWH surfaces in the jet near field



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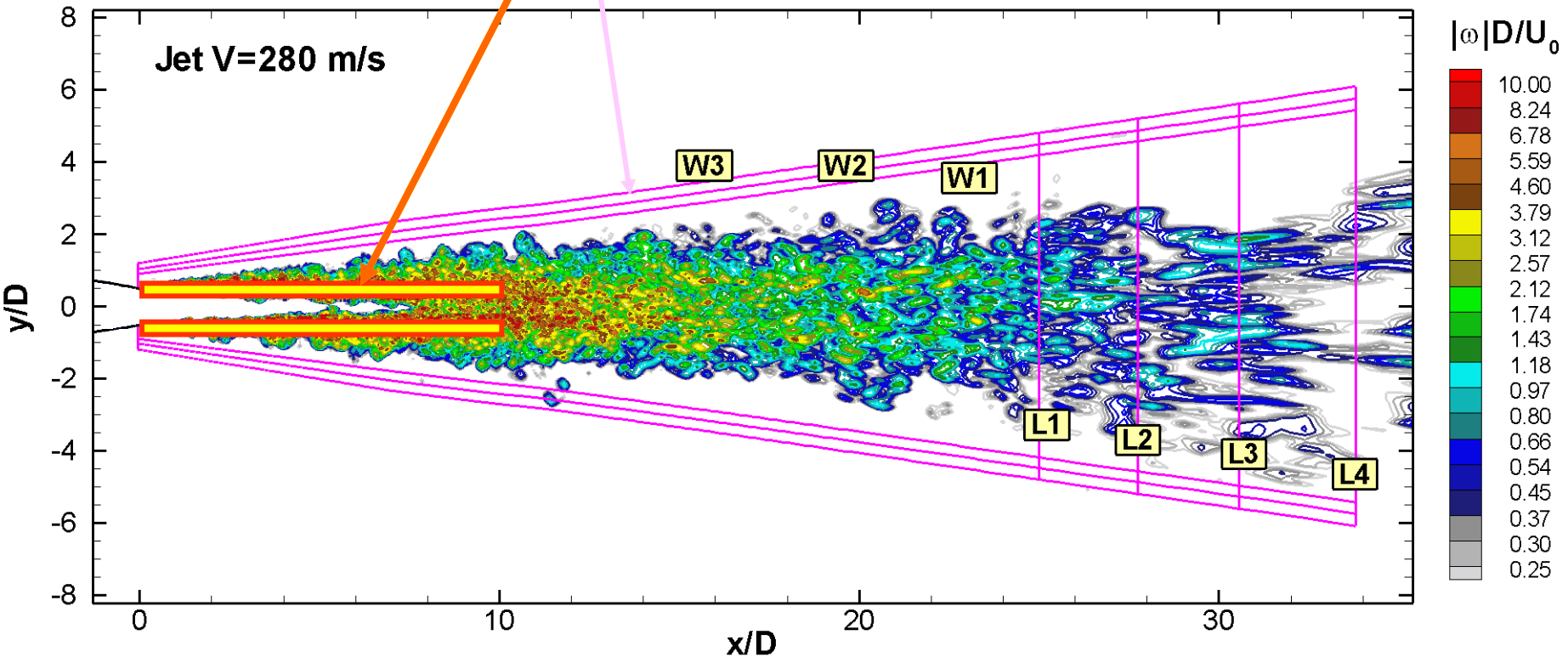
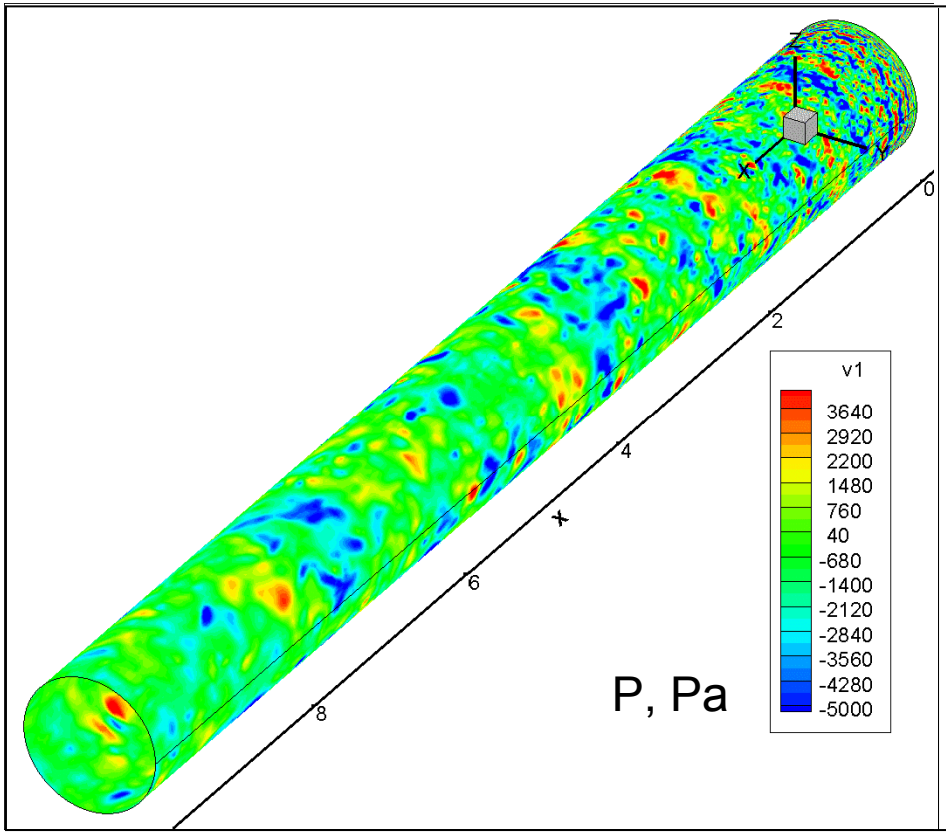
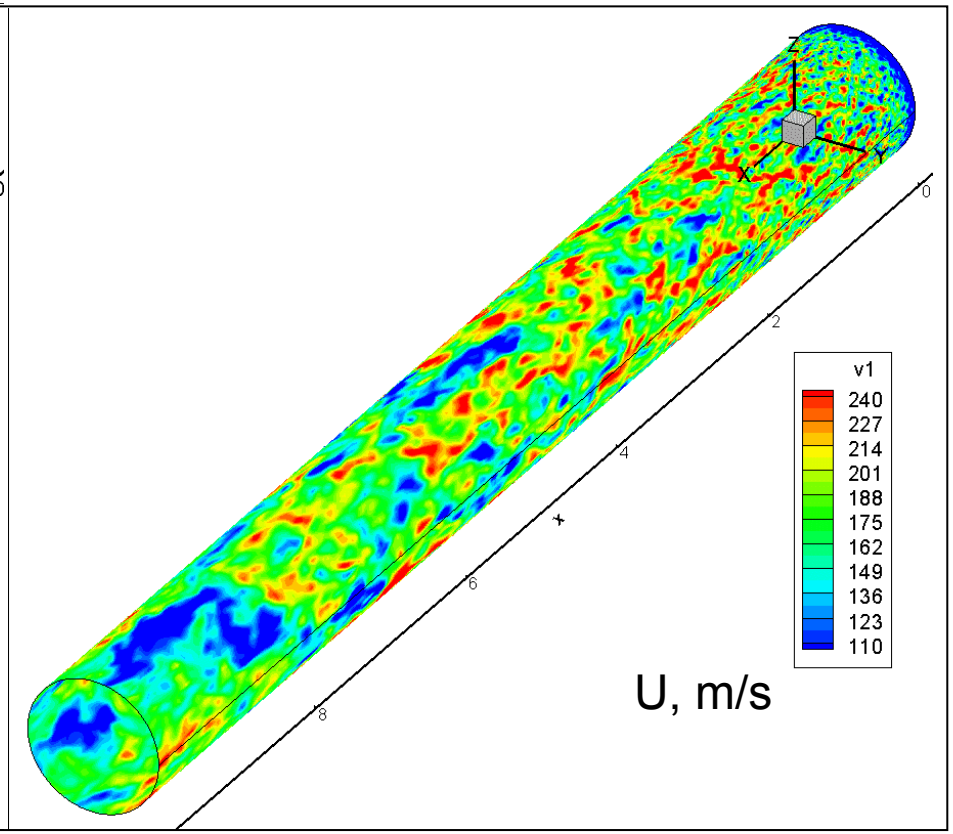


Time evolution of pressure and axial velocity pulsations





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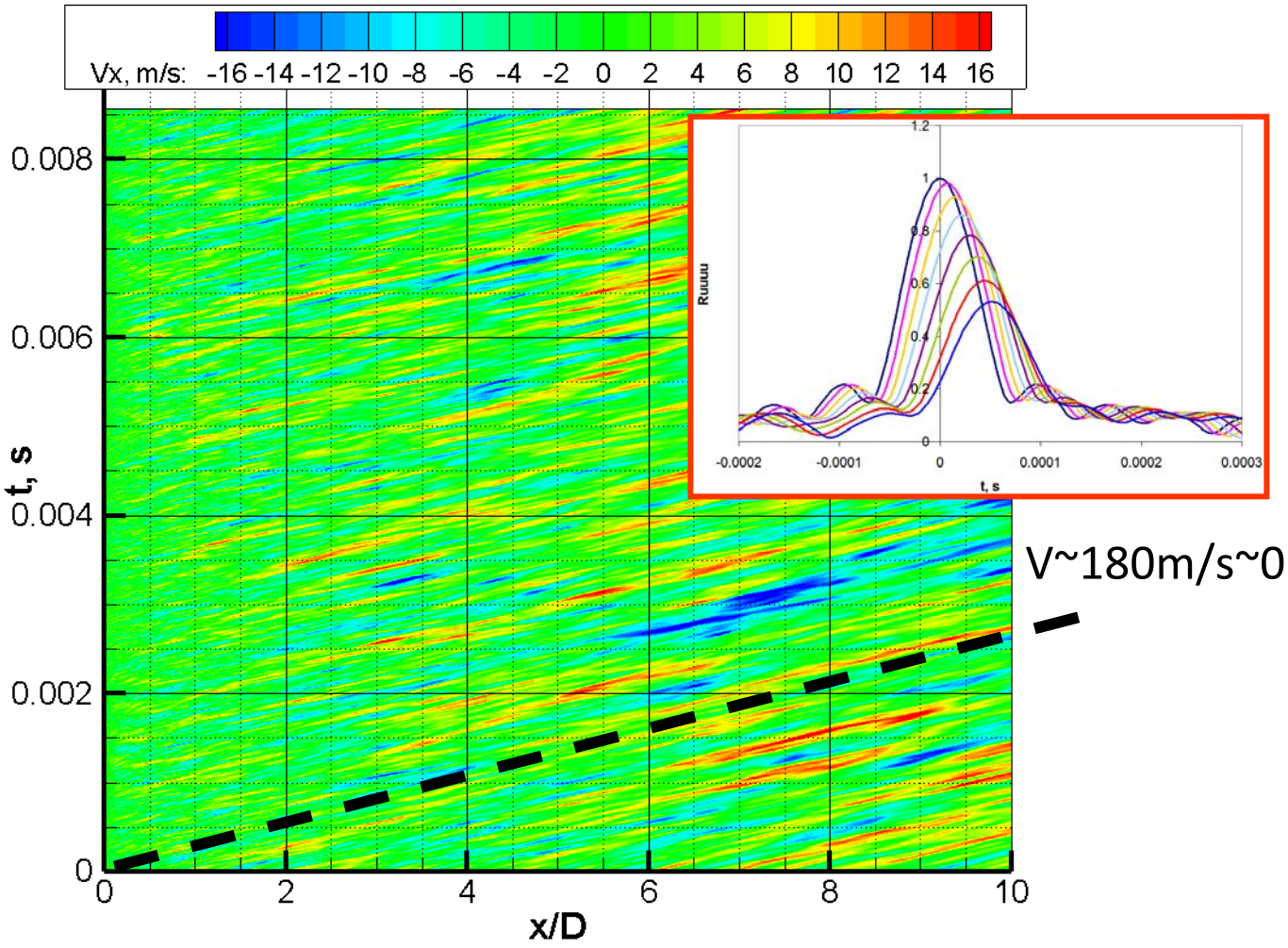
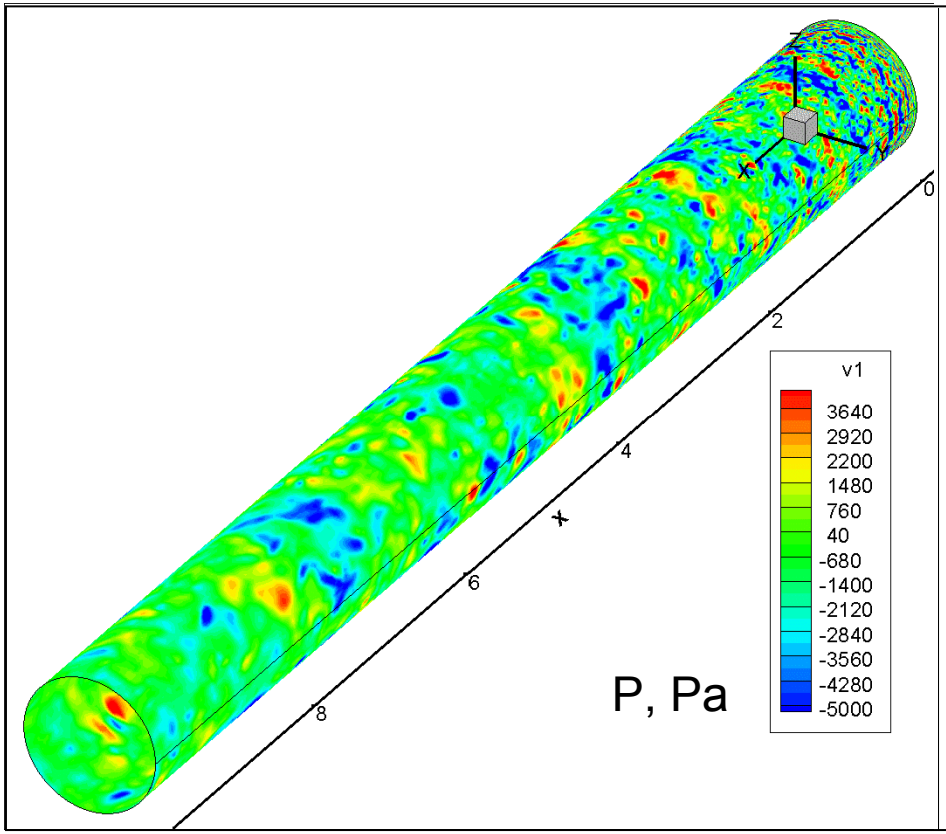
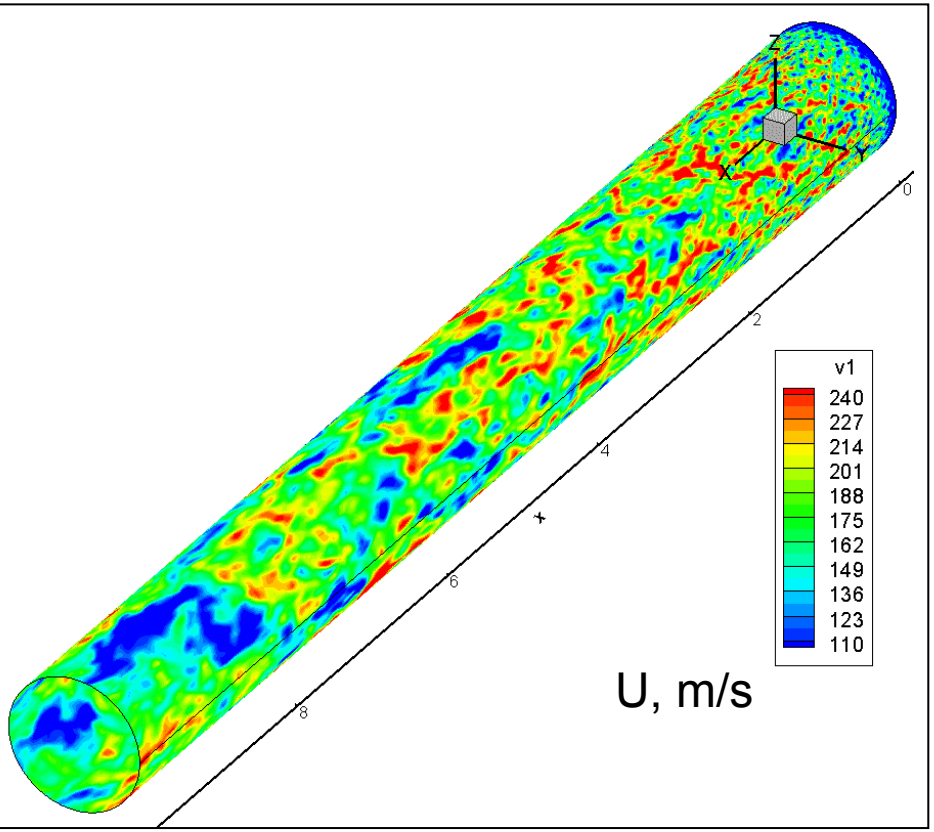


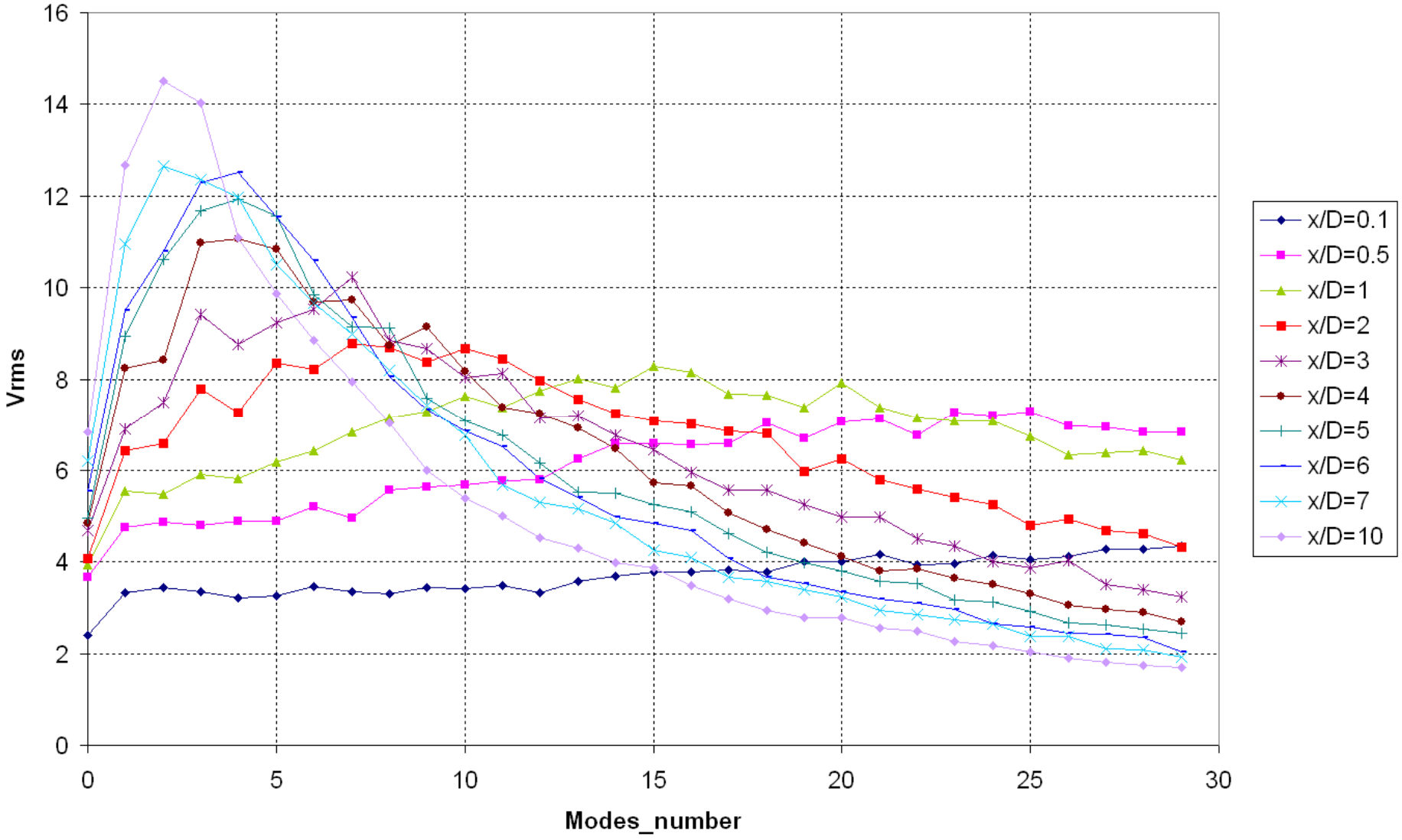
Time evolution of pressure and axial velocity pulsations



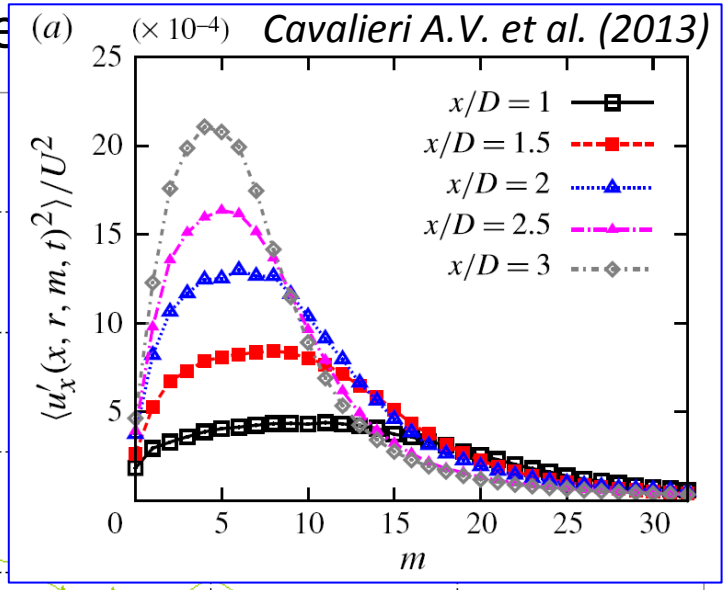


$$f(x,\theta,t) = \sum_{n=0}^{N} \left(f_n^{\cos}(x,t)\cos n\theta + f_n^{\sin}(x,t)\sin n\theta \right)$$

Modal content of velocity pulsations



Modal content of ve



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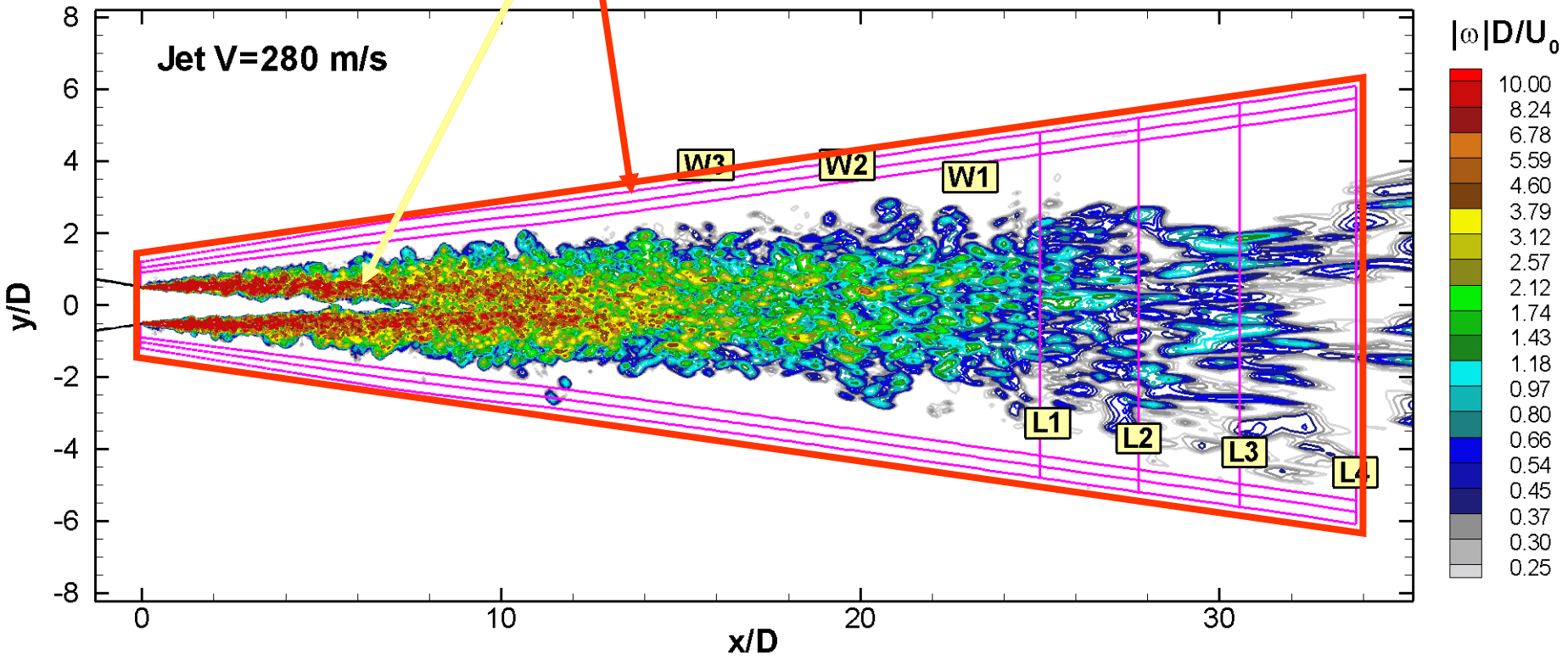
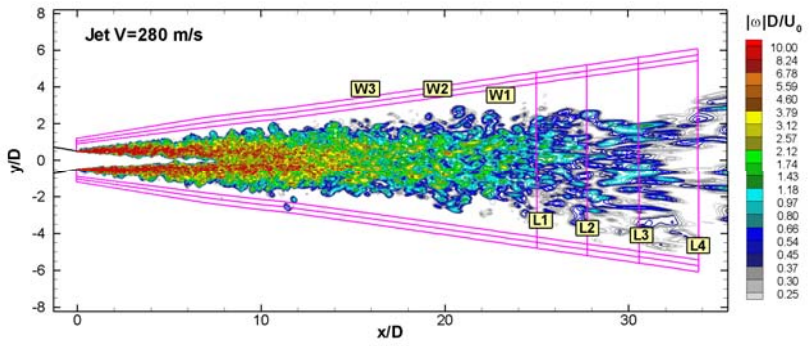
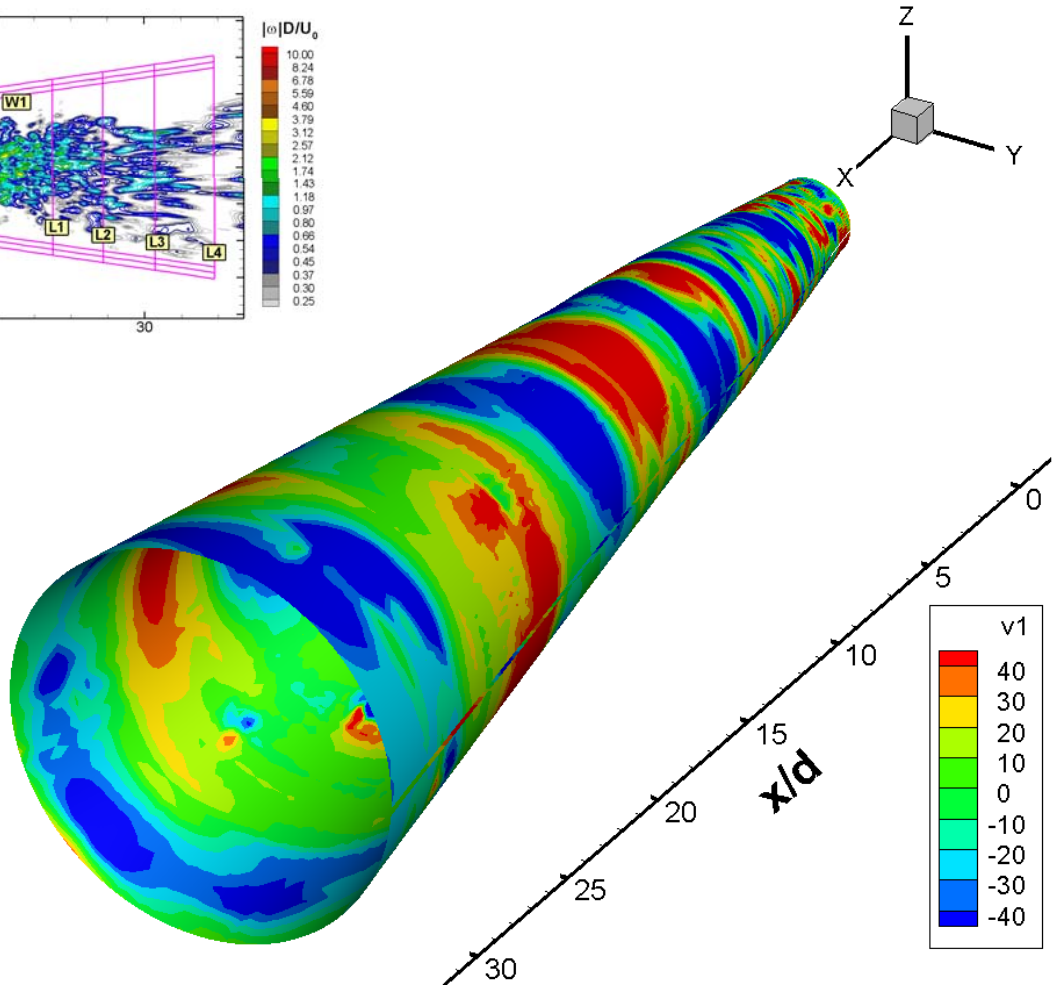
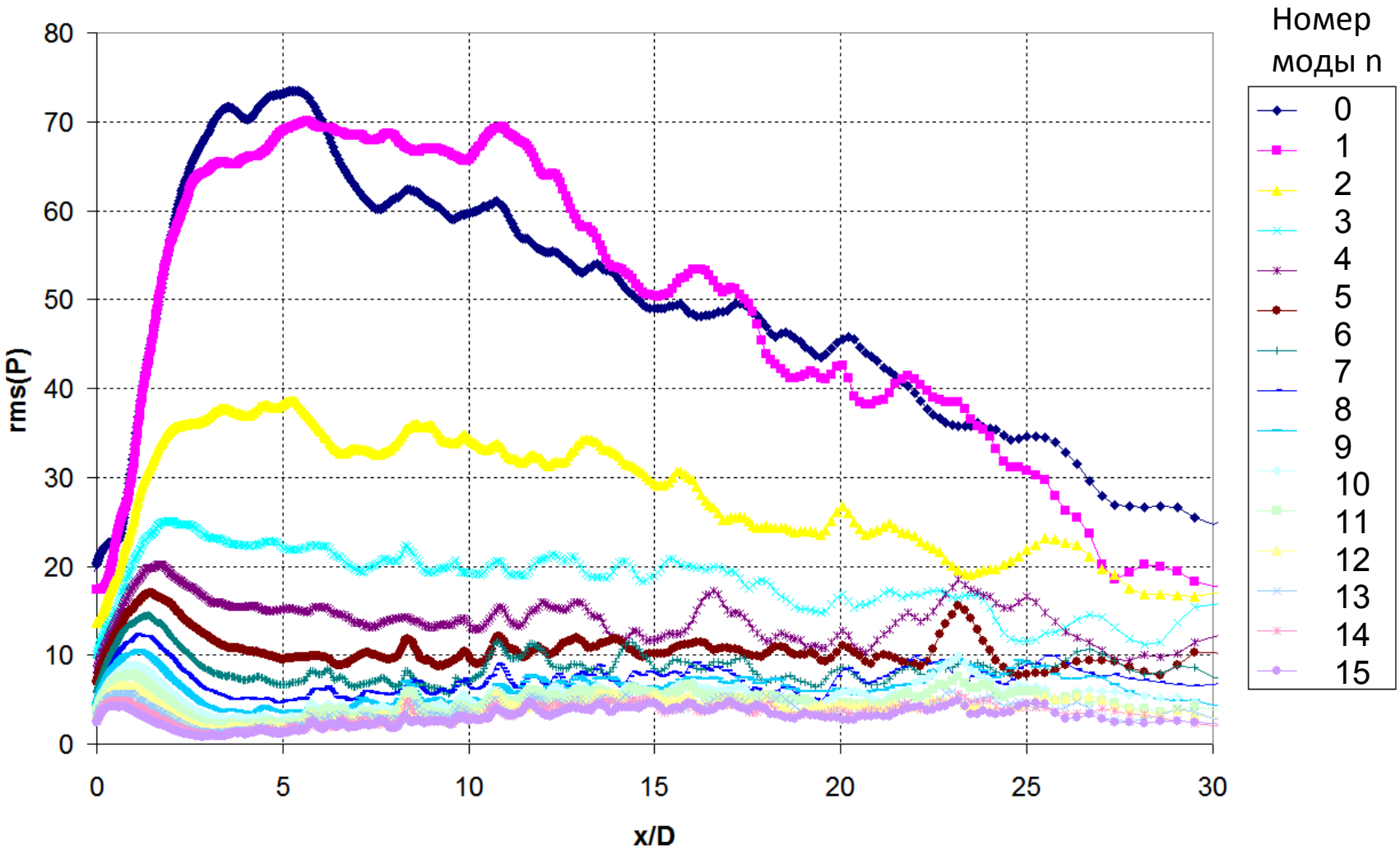


Pressure pulsations in the near field



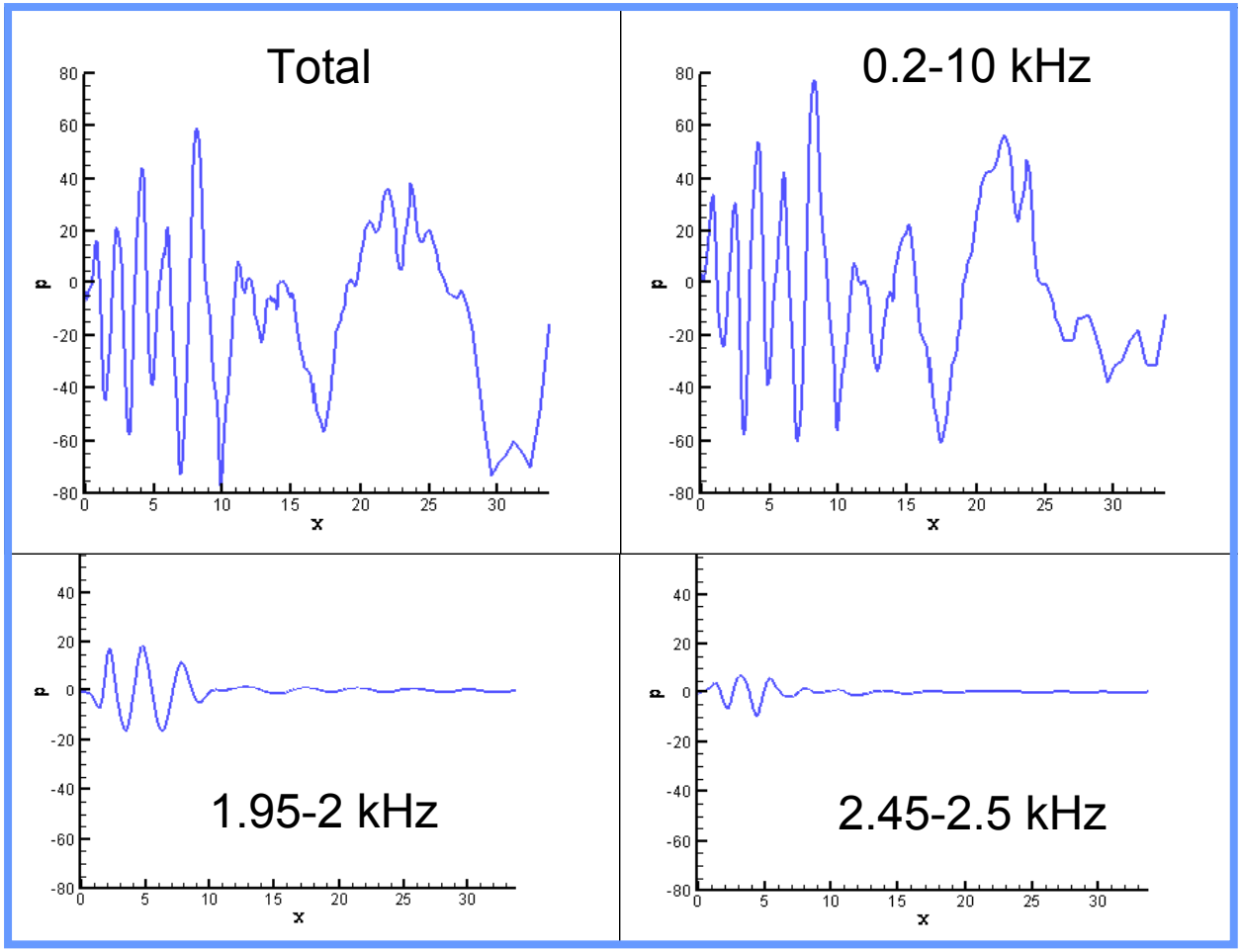


Modal content of pressure pulsations



Spatio-temporal evolution of pressure pulsations, n=0

FWH W1, filtering in frequency bands



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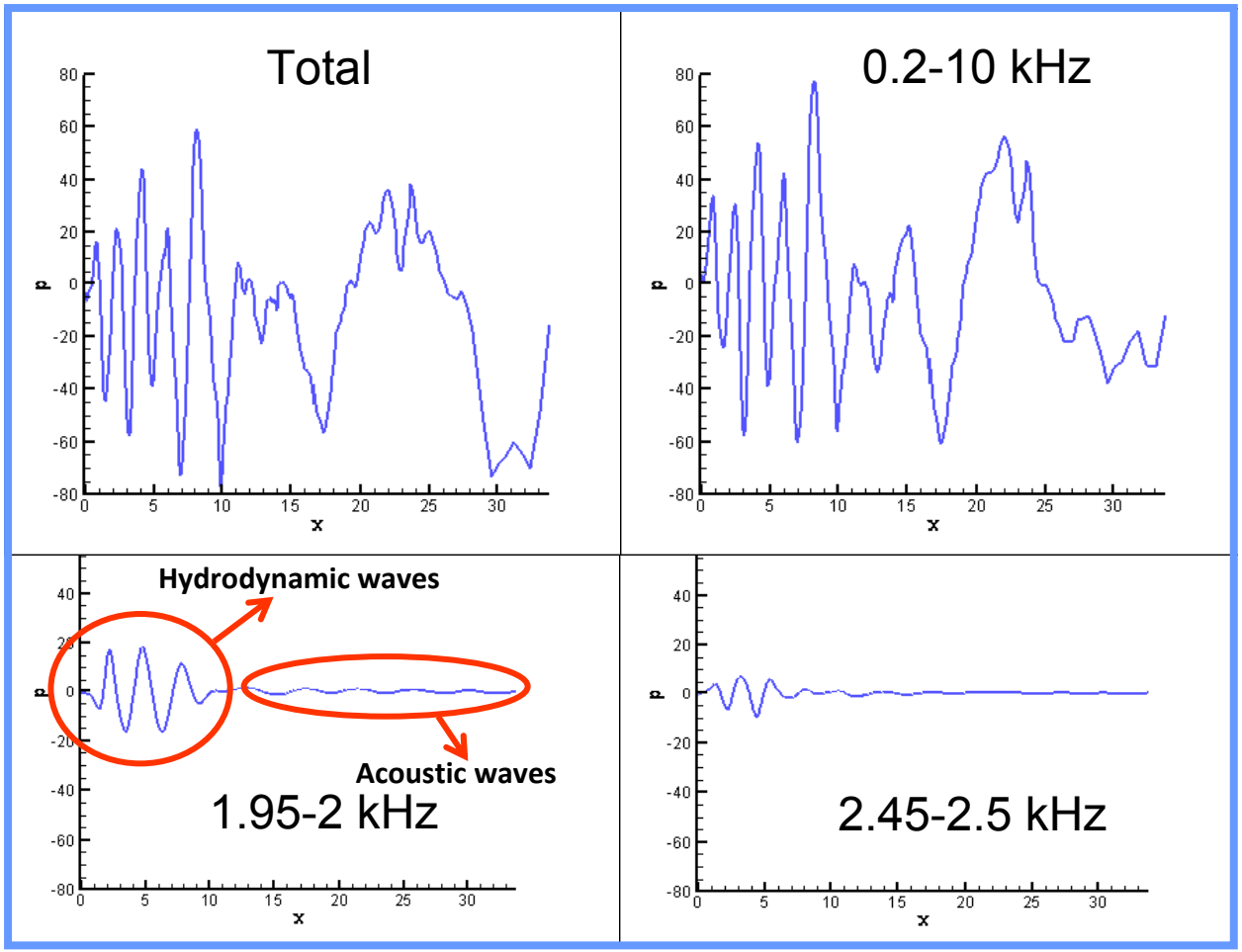
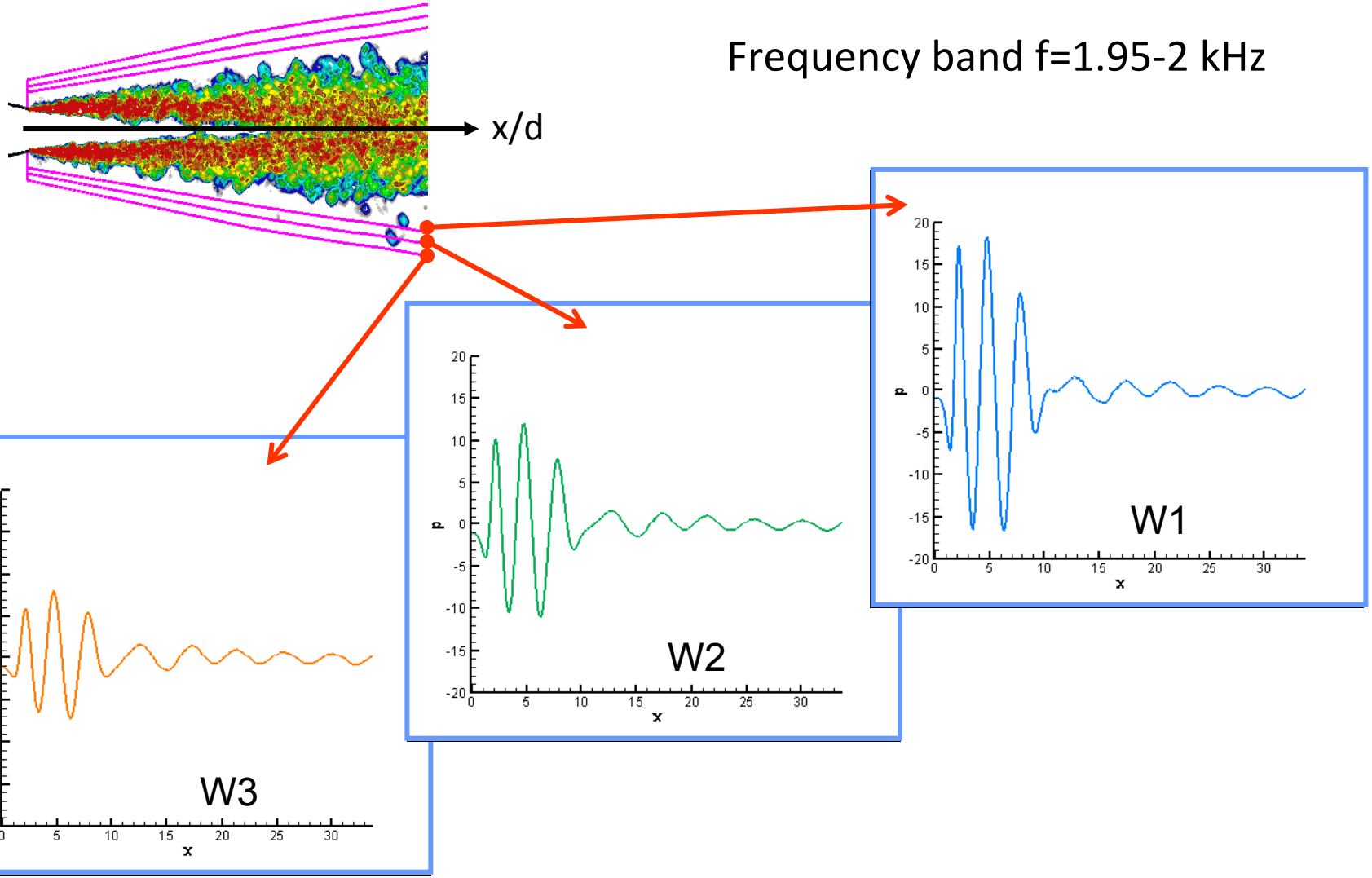
FWH W1, filtering in frequency bands



Spatio-temporal evolution of pressure pulsations, n=0

Frequency band f=1.95-2 kHz



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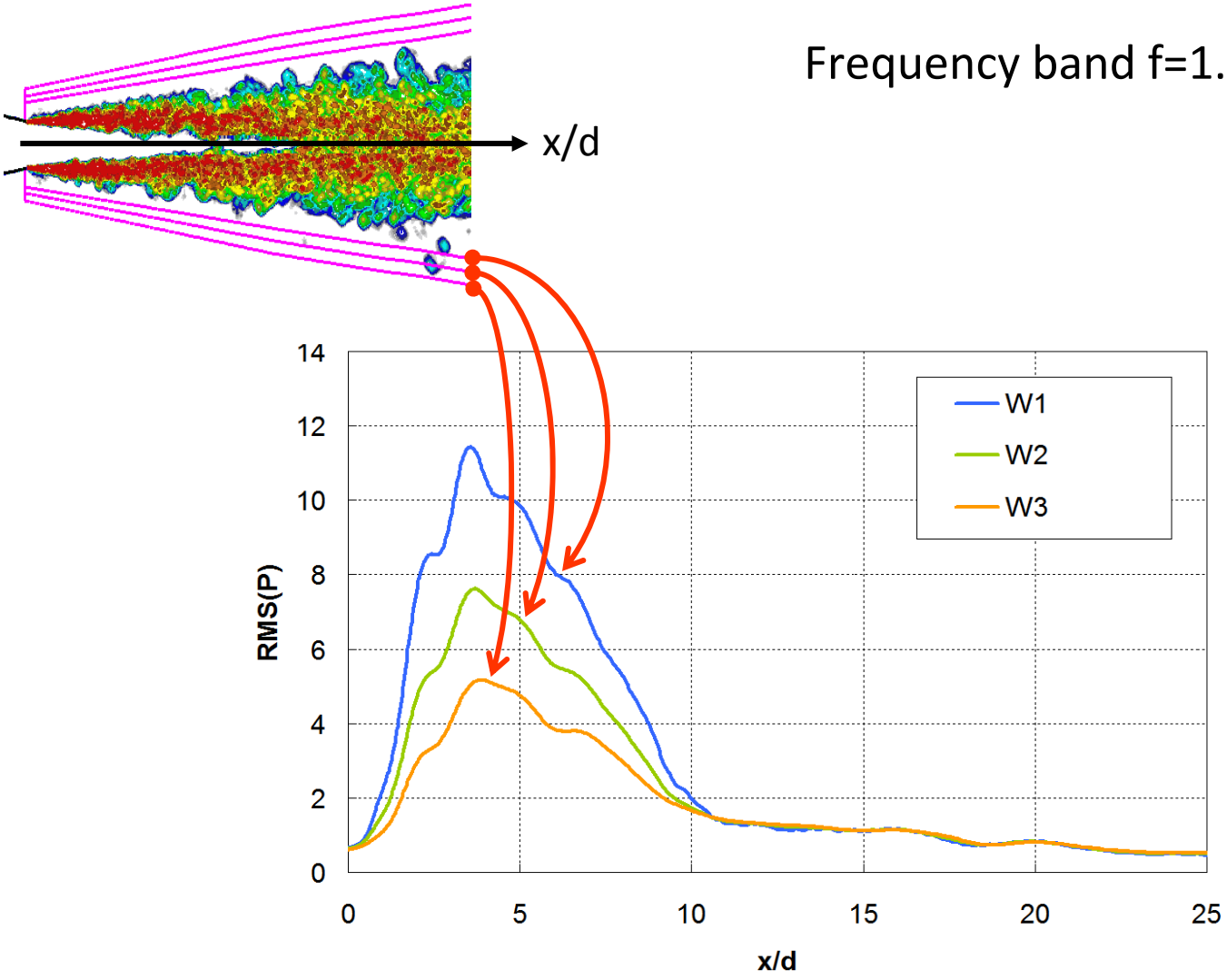
Frequency band f=1.95-2 kHz



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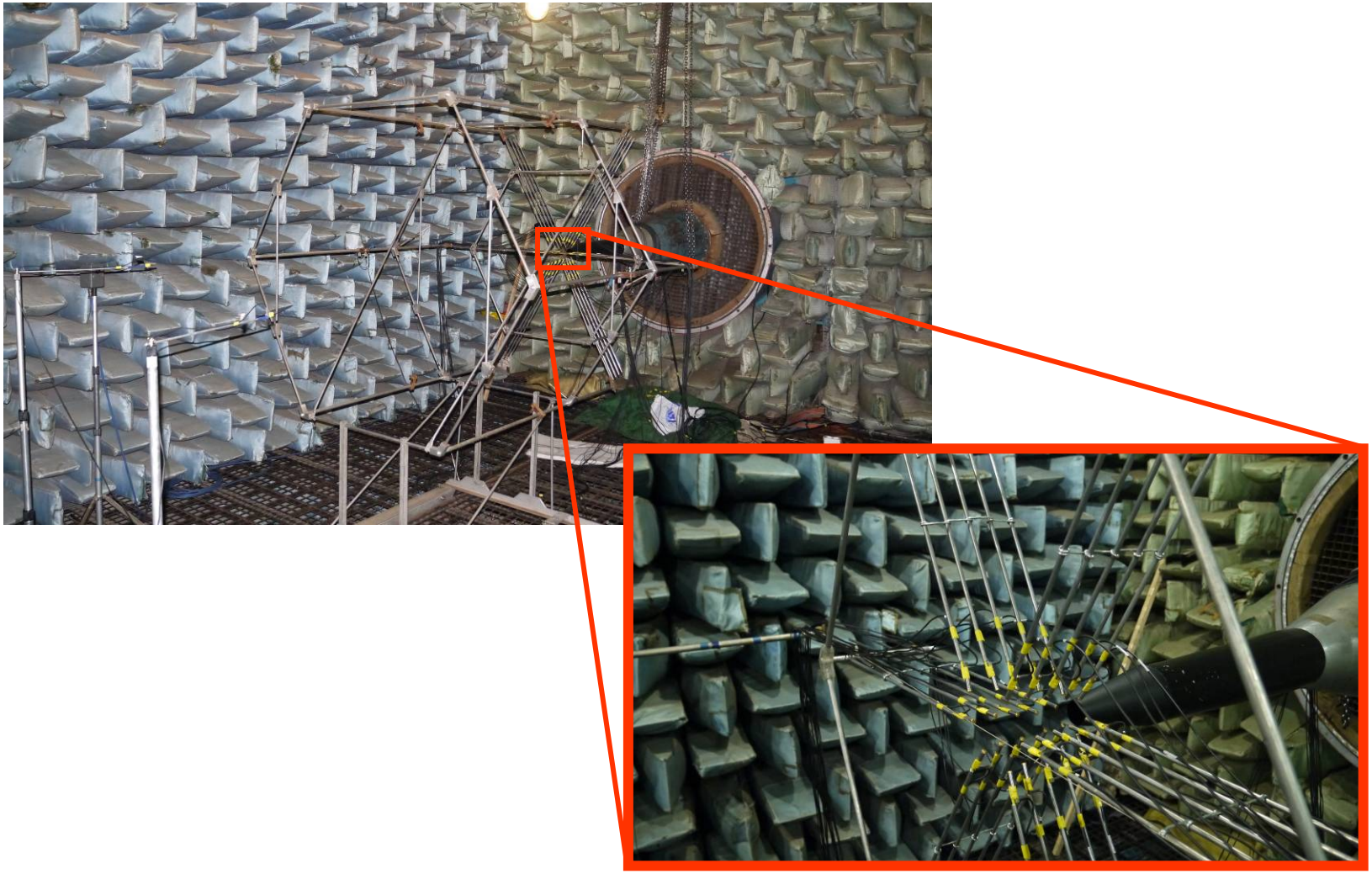
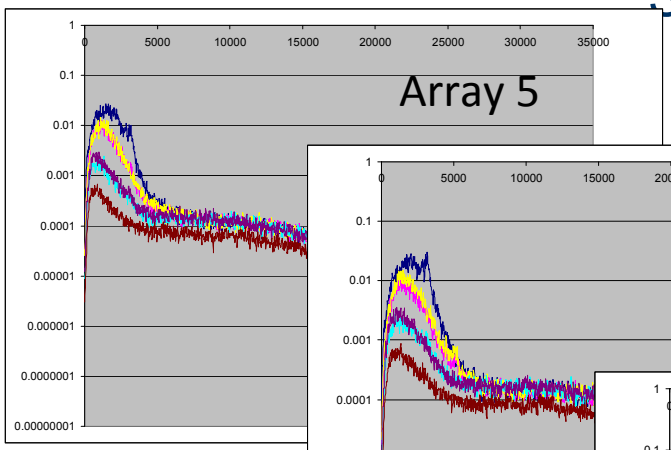
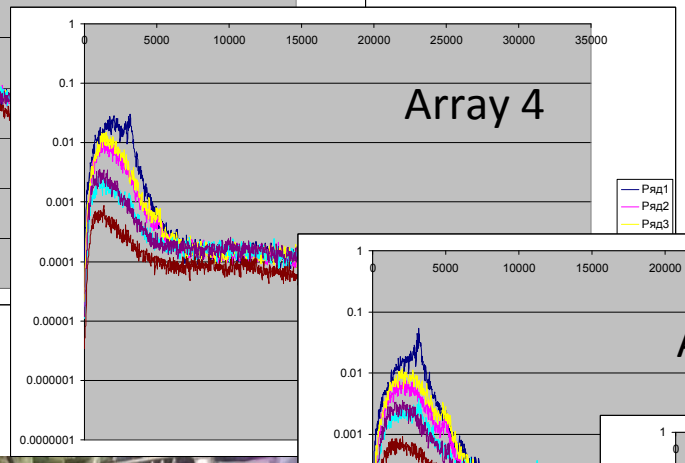
Near-field multi-microphone array

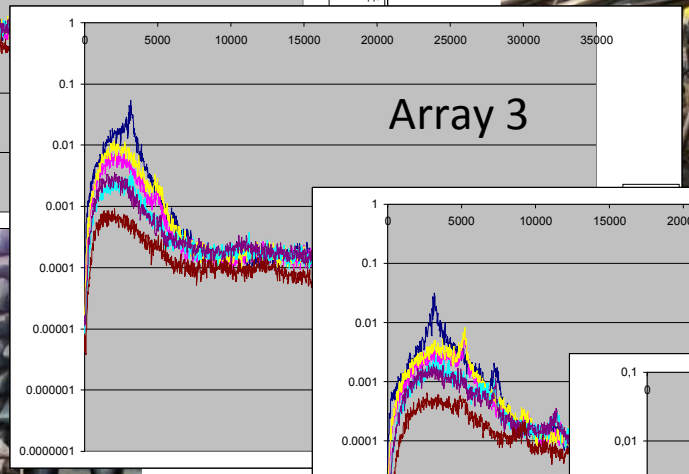


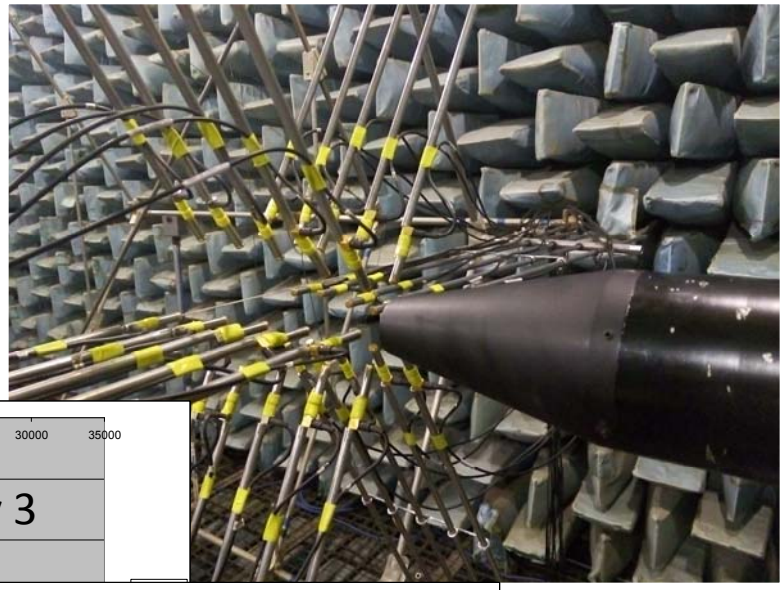
Spectra of modes

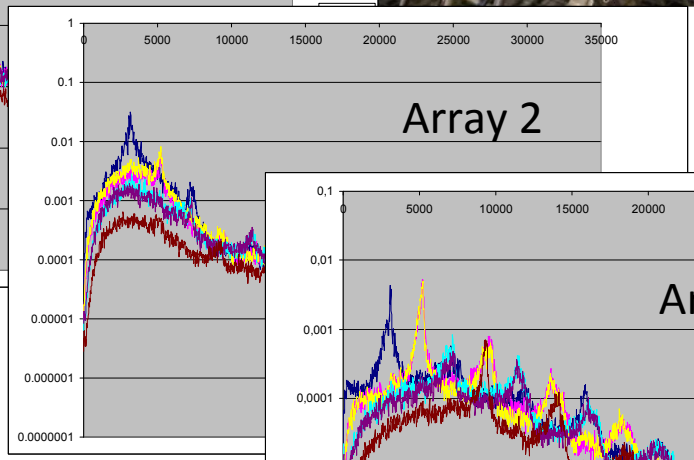
M=0.9

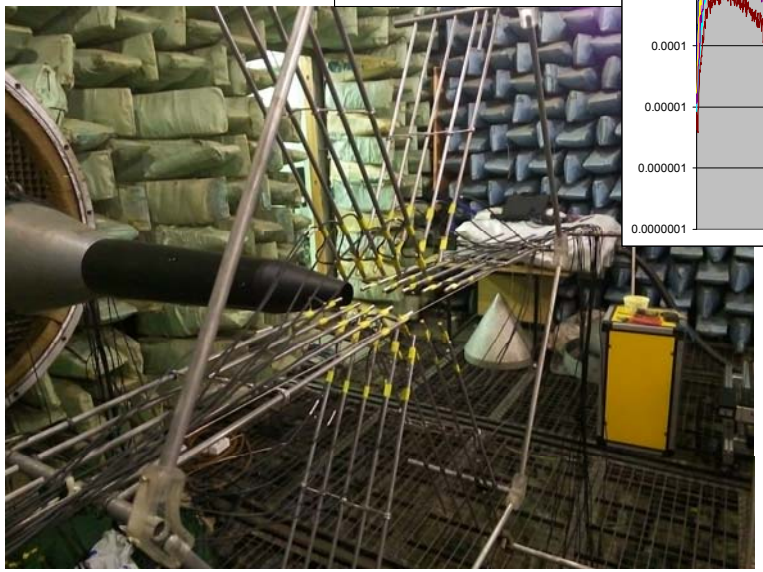


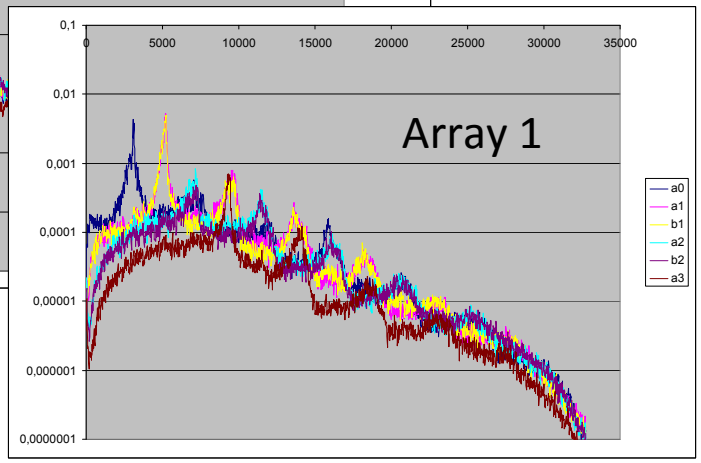




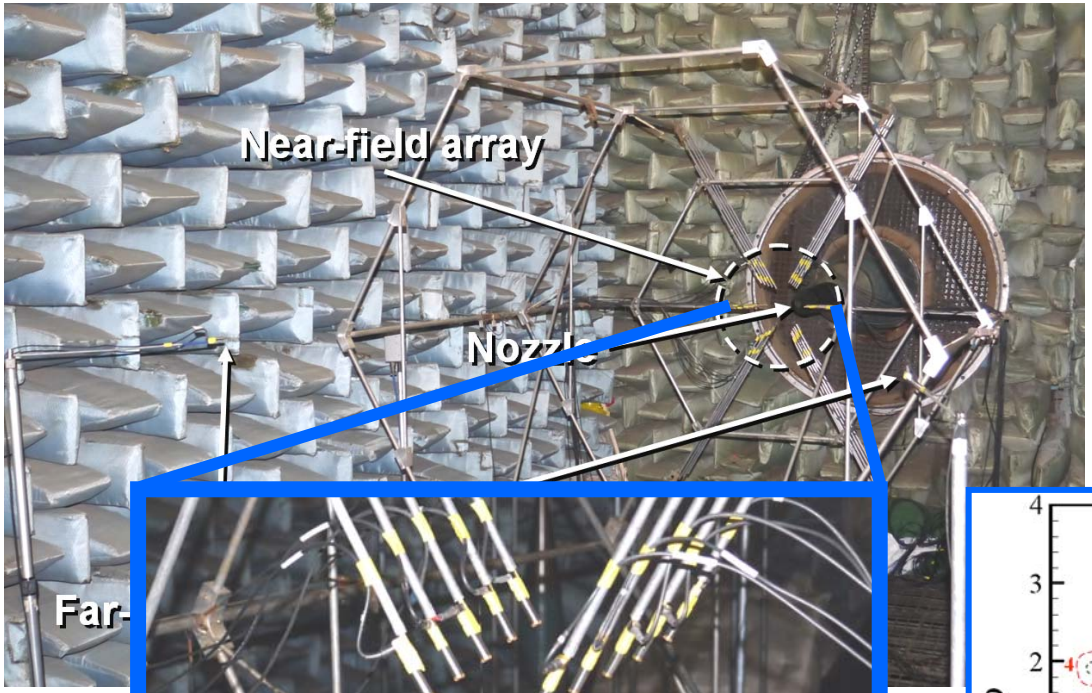


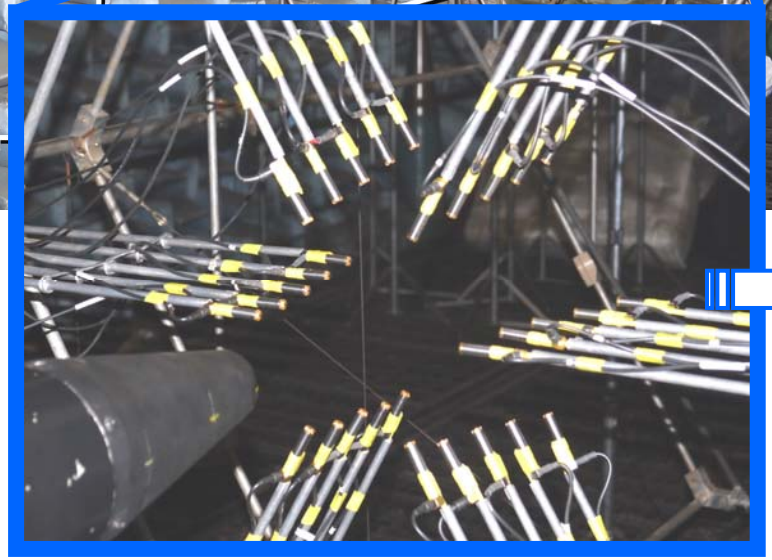






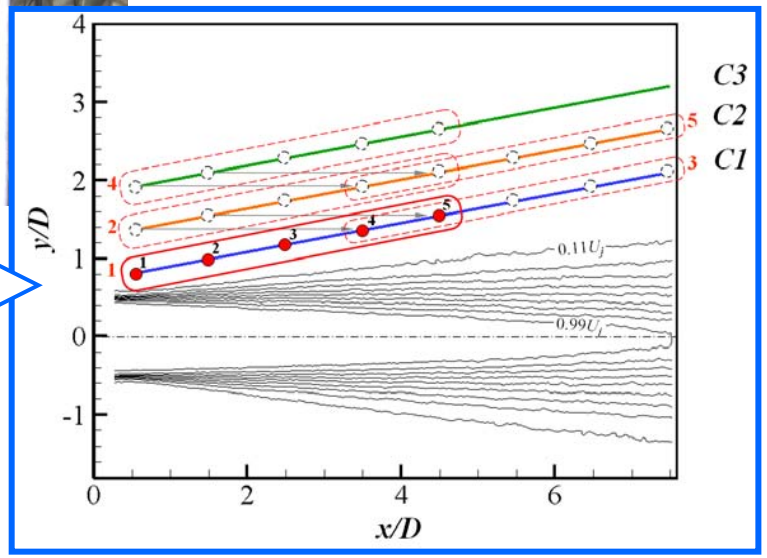
Near-field experiments





Round profiled nozzle D=40 mm
Jet Mach numbers:
M_j=0.4, 0.53, 0.6, 0.74, 0.82, 0.9

30 microphones:
- 3 conical surfaces (C1, C2, C3)
- 5 array positions
- x/D=0.5,1.5,…7.5



Near-field experiments

$p(x,R,\theta,t)$ — Raw signals

ADT

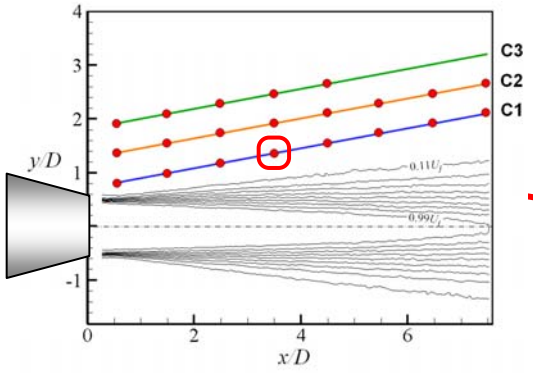
$$A_0(x,R,t)+\sum_{n=1}^{2}\left(A_n(x,R,t)\cos n\theta+B_n(x,R,t)\sin n\theta\right)+A_3(x,R,t)\cos 3\theta+\ldots$$

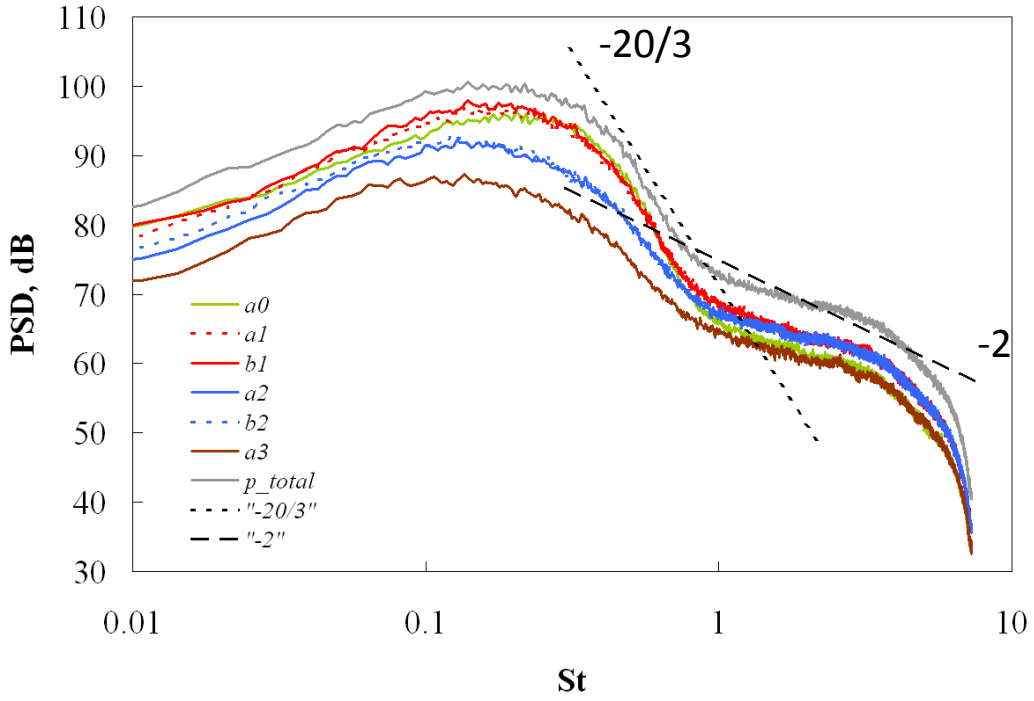
Azimuthal modes

PSD → $p_{total}(x,R,f)$

PSD → $a_{0,1,2}(x,R,f)$ $b_{1,2}(x,R,f)$

Typical near-field spectra of the total signal and its azimuthal modes. M_j = **0.53**

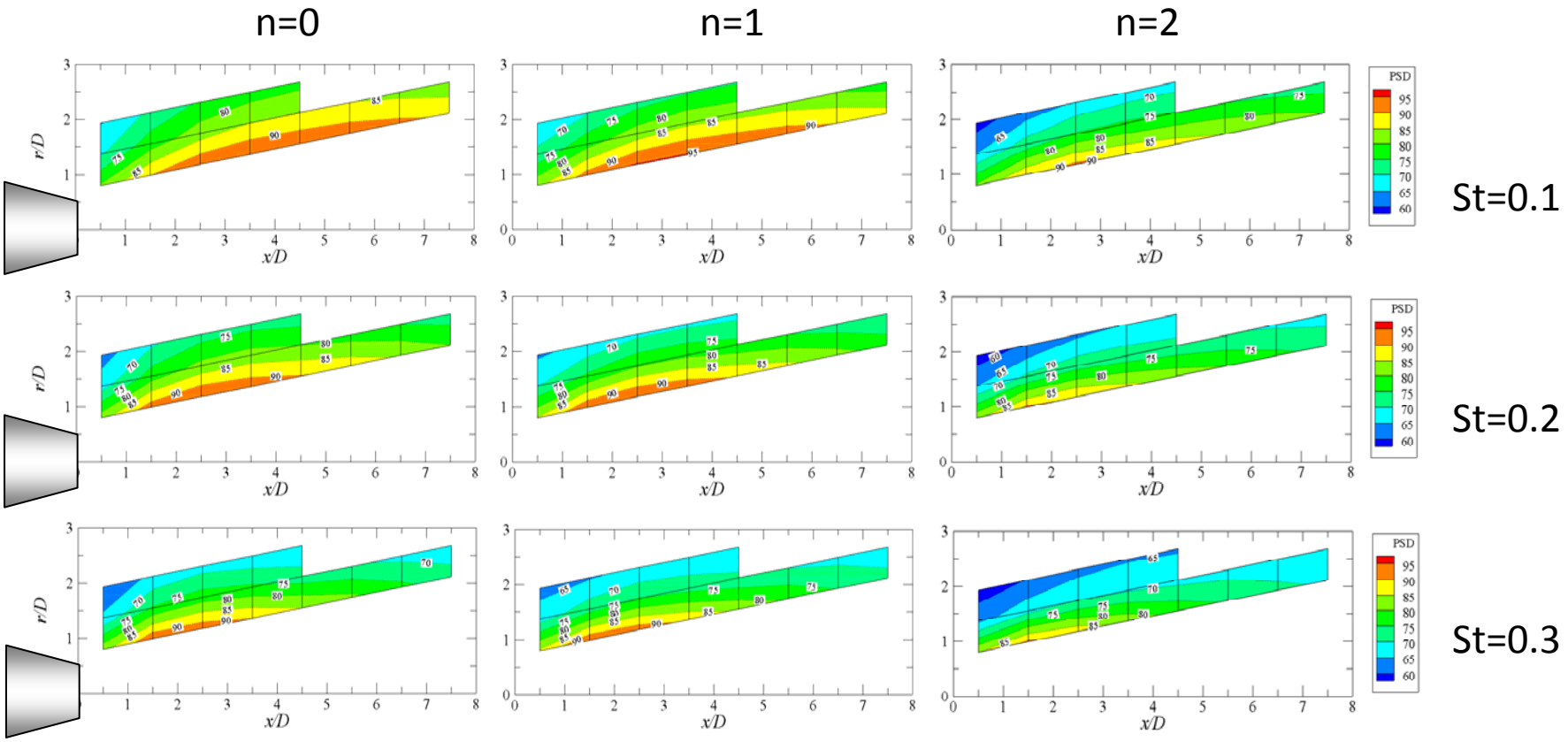




Arndt et al. 1997

Near-field experiments

Azimuthal modes M_j=0.53

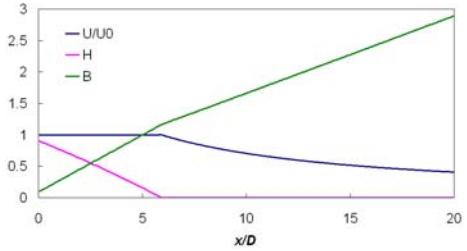


Near-field experiments

Azimuthal modes M_j=0.53

n=0

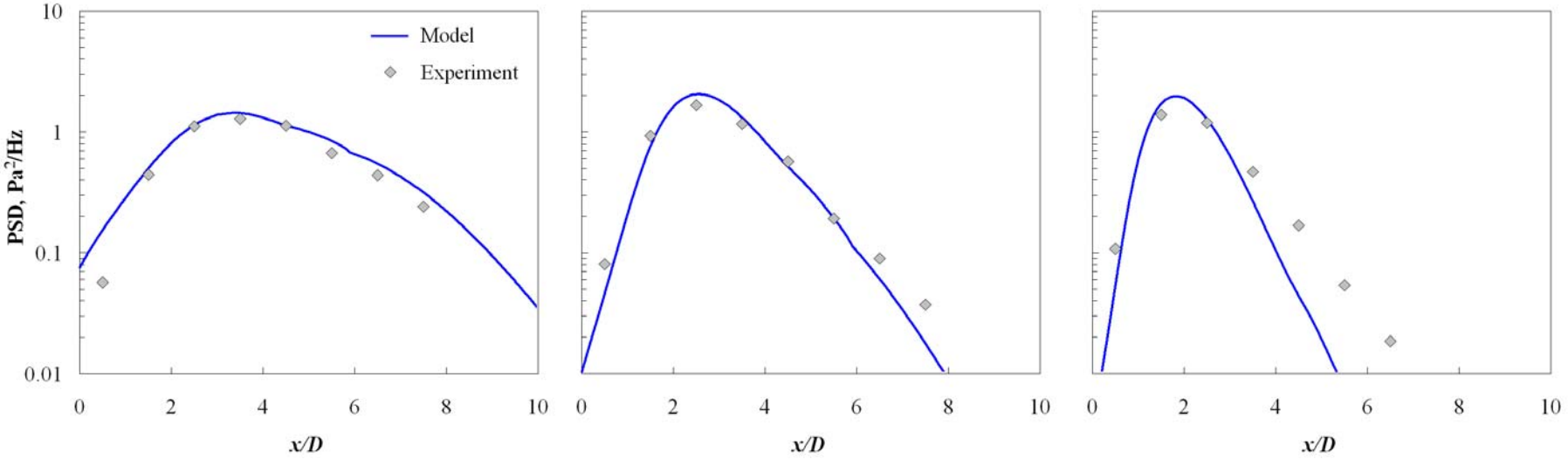
Linear stability analysis - generalized Tam's theory (AIAA 2006-2595)



$$p \sim A(0)\sqrt{\frac{I_1(0)}{I_1(s)}}\cdot exp\left(-\int_0^s \frac{I_0}{I_1} d\ s\right)\cdot exp\left(-i\int \alpha\ ds\right)$$

$$p = \int_{-\infty}^{\infty} g(\eta) H_n^{(1)}(i\lambda r)\, exp\ i\left(\eta z + \frac{\pi}{2}\right) d\ z$$

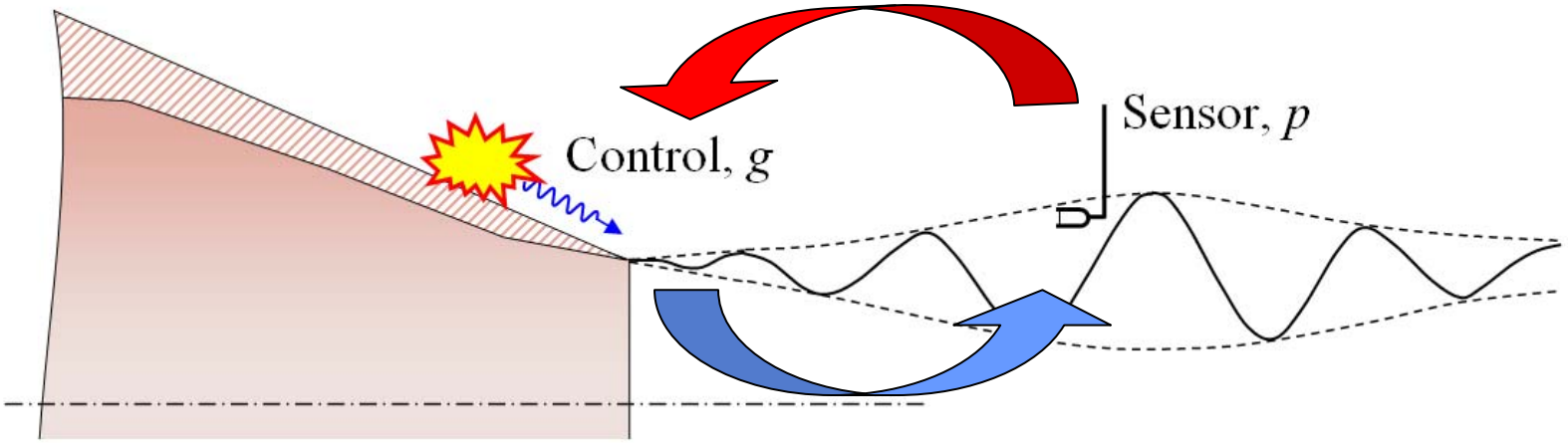
St=0.2 St=0.3 St=0.4



Outline

- Introduction
- Artificial instability waves (AIW) , AIW control strategy
- NIW control idea, Overview of LES-results,
- Data analysis in the jet shear layer
- Data analysis in the jet near field
- Experimental data
- NIW Control strategy
- Conclusion

Control strategy for NIW



Actuator – near the nozzle edge
Sensor – downstream from the nozzle exit

\+ • Effective control action – high receptivity of the shear layer

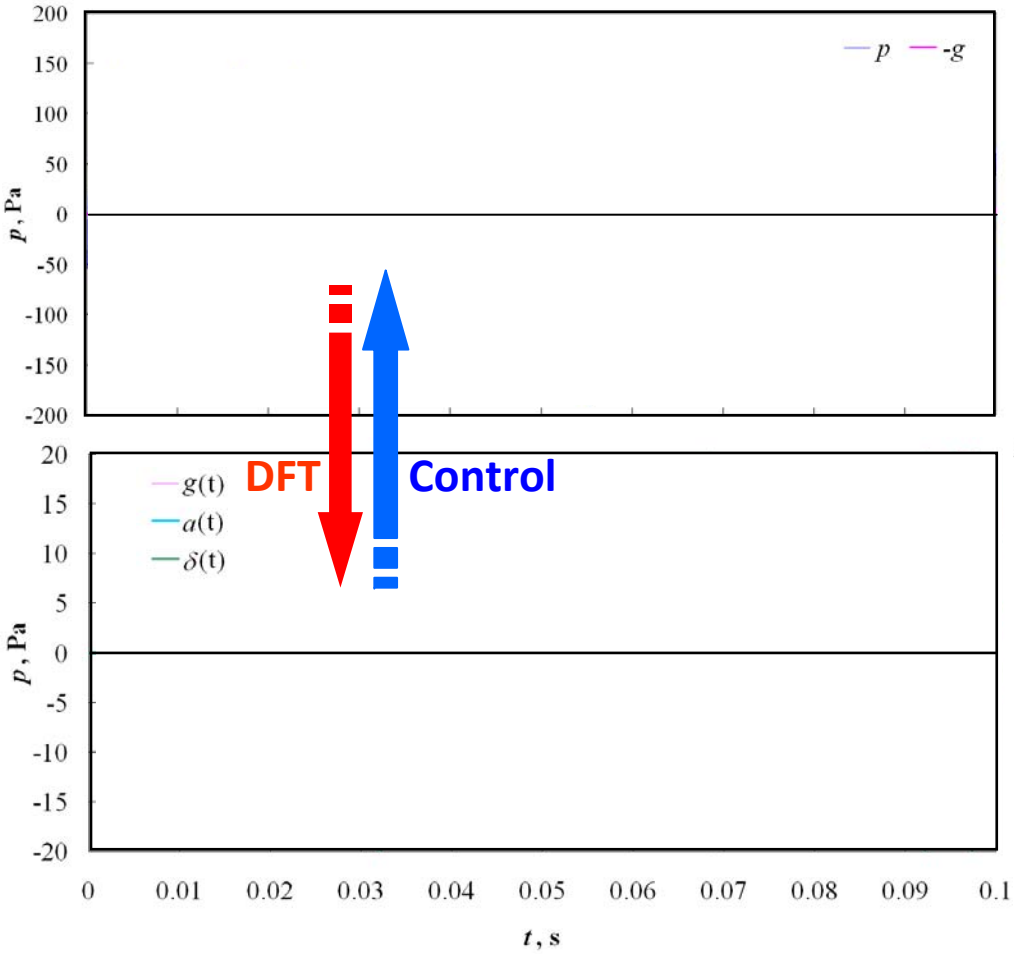
− • Inevitable time delay $\tau \sim D/V_c$, (τ~0.3 ms for M_j=0.53)

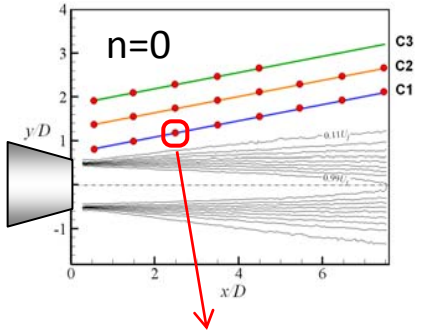
Control of model signal in a narrow frequency band

f_c=65.536kHz – sampling rate

N_{DFT} =2048 points – Δf=32 Hz

Control at St=0.3





$$p(t)$$

$$DFT[p(t)]_{t-T}^{t} \Rightarrow \begin{cases} a_j(t), \\ \delta_j(t). \end{cases}$$

$$g(t) = -\sum_j a_j(t)\cos\left(2\pi f_j t - \delta_j(t)\right)$$

Control of model signal in a narrow frequency band

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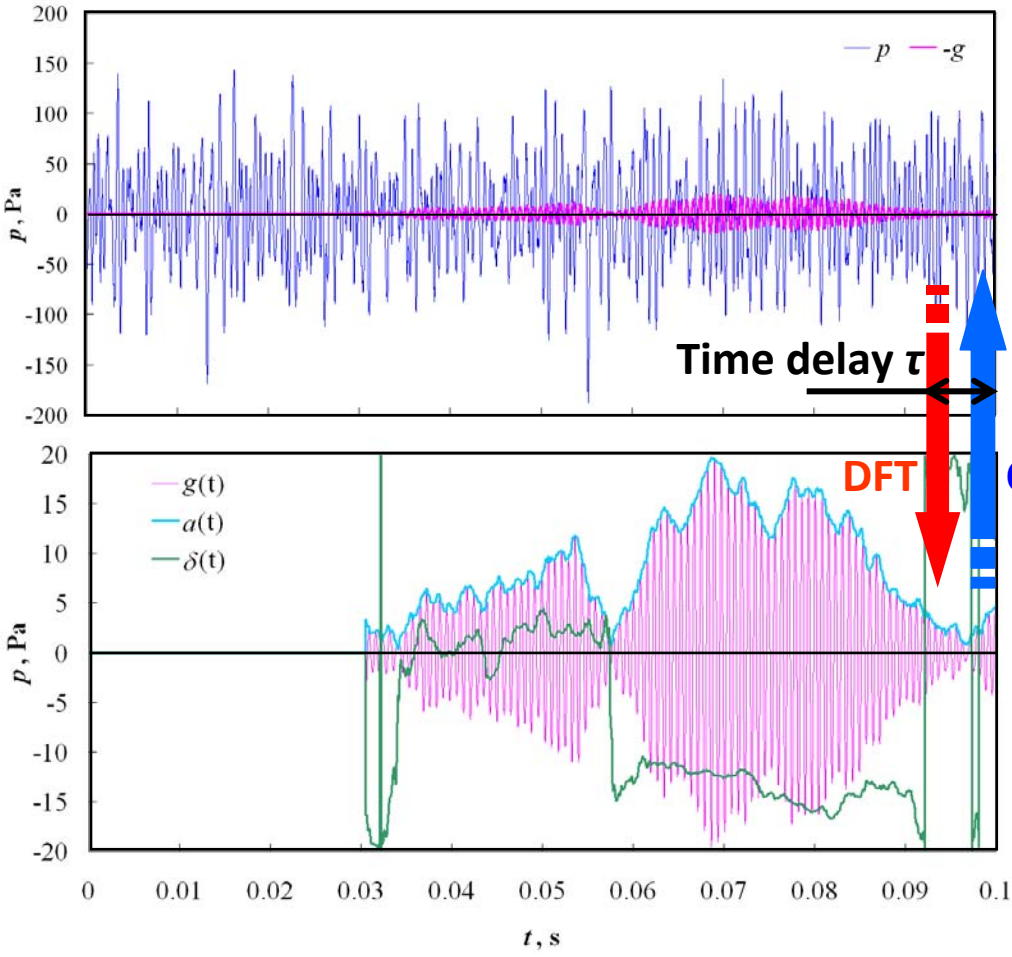
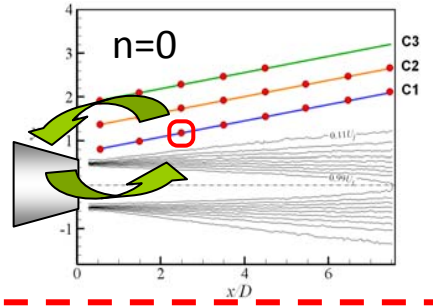
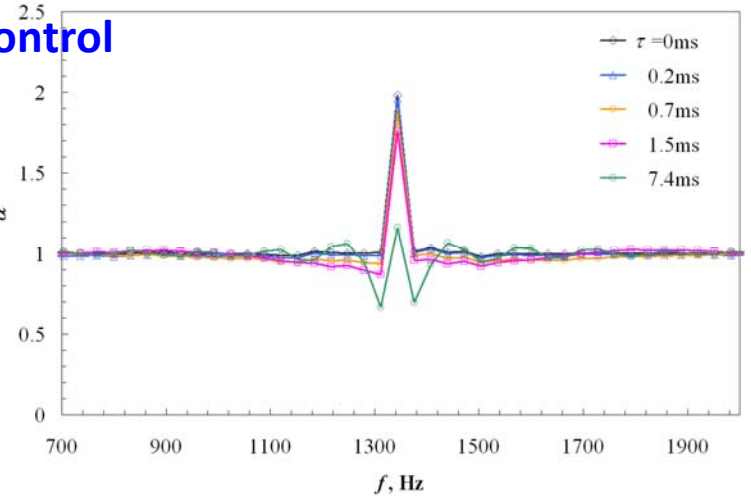




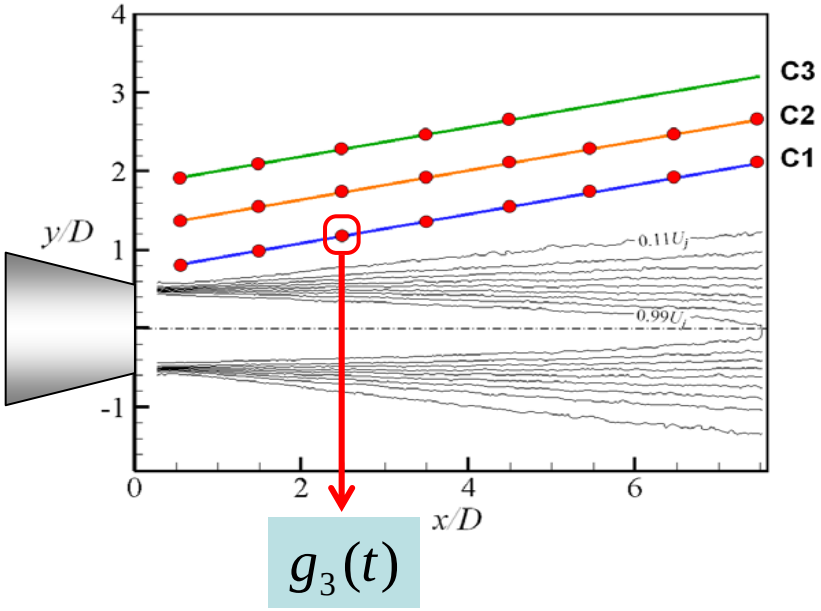
Time delay $\tau \sim D/V_c$

Suppression ratio for different time delays τ

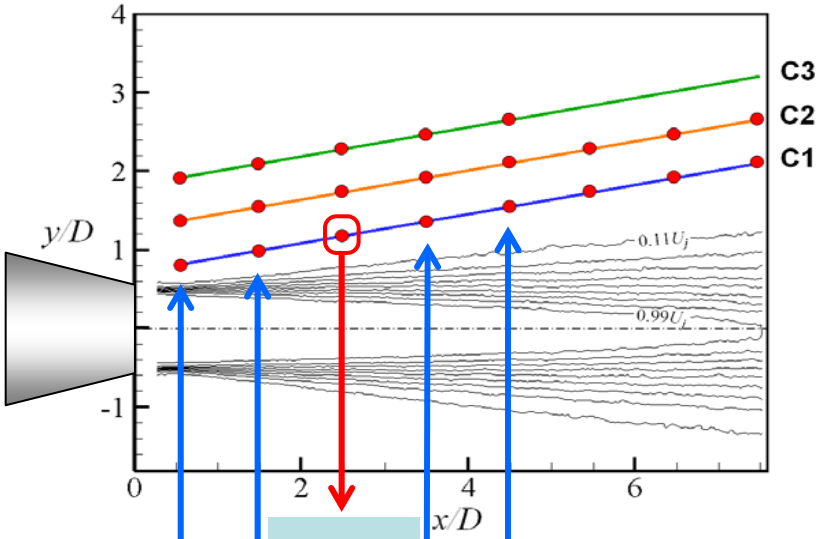
$$\alpha(f) = \frac{P_{control-OFF}(f)}{P_{control-ON}(f)}$$



Imitation of wavepacket control in a narrow frequency band



Imitation of wavepacket control in a narrow frequency band

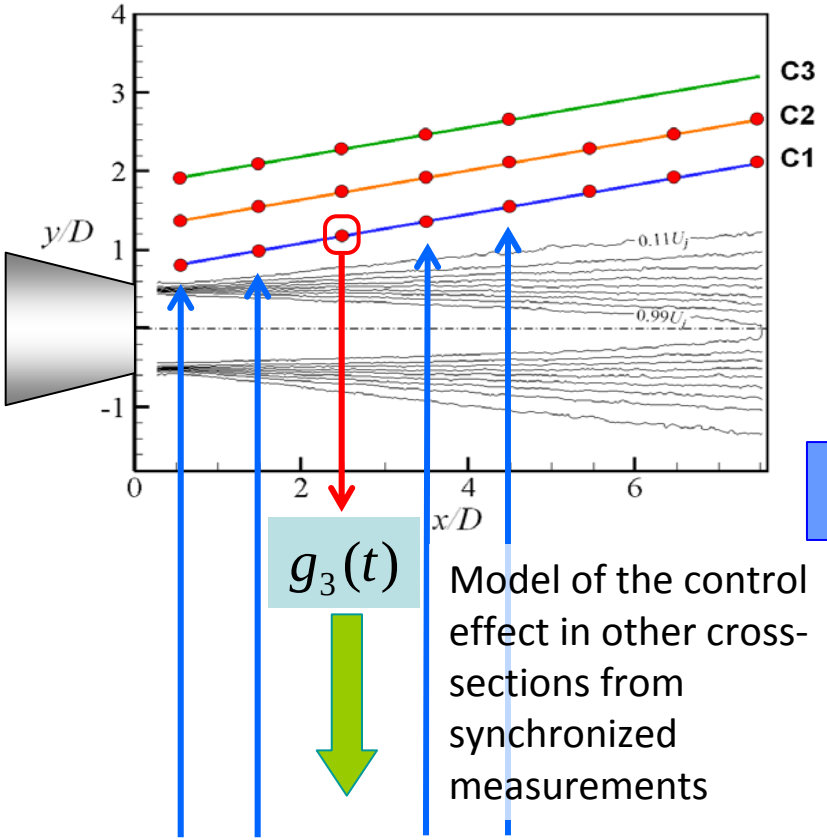


$g_3(t)$

Model of the control effect in other cross-sections from synchronized measurements

$$g_i(t) = \frac{\varphi(x_i / D)}{\varphi(x_3 / D)} g_3(t - \tau_{i3})$$

Imitation of wavepacket control in a narrow frequency band



$g_3(t)$

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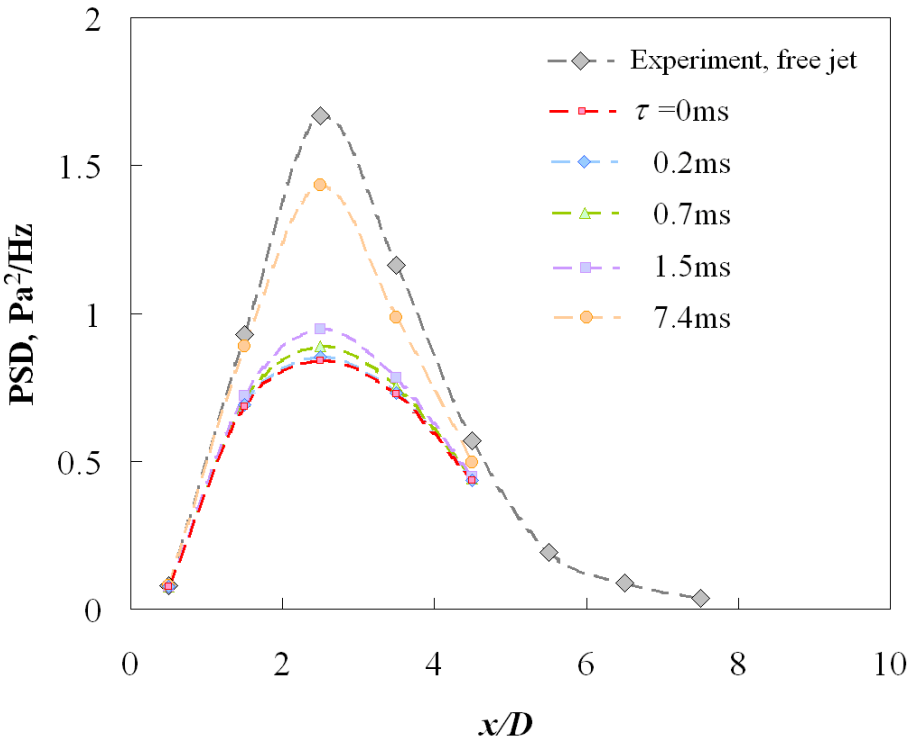
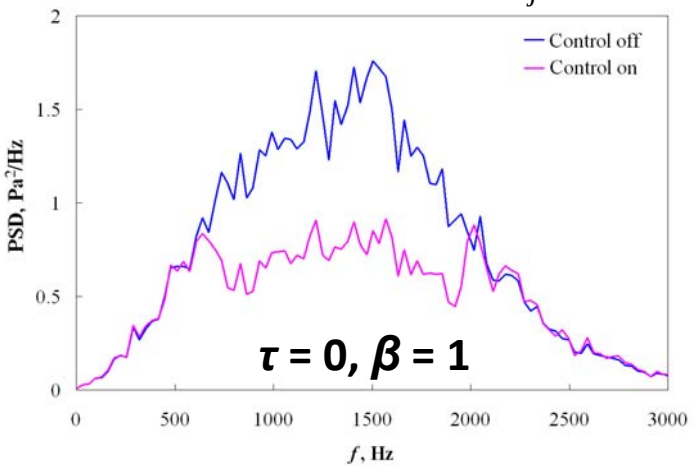
Effect of control on the wavepacket

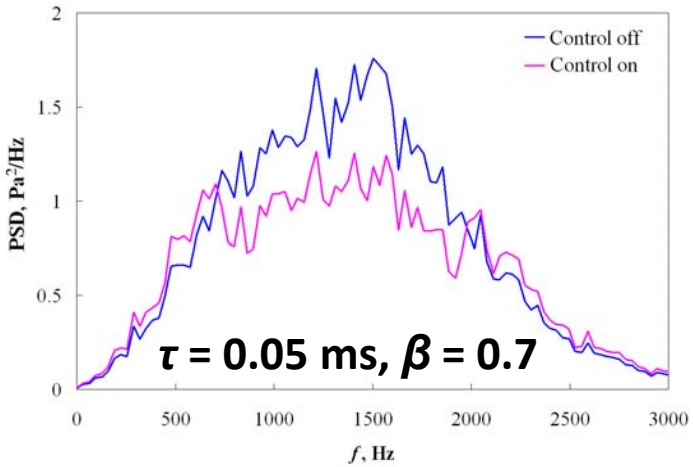


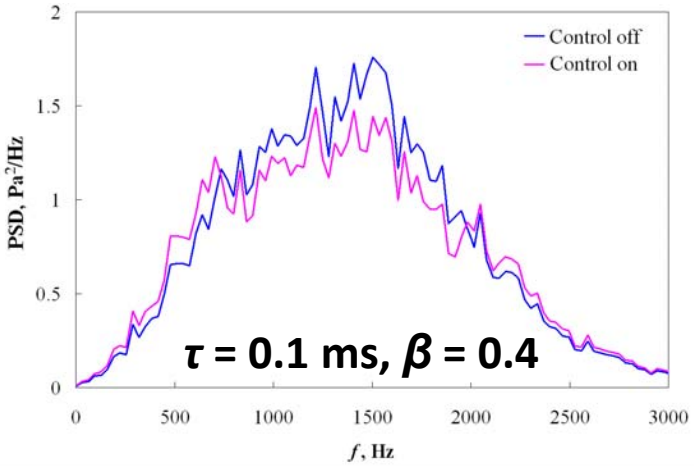
Effect of the delay at broadband control

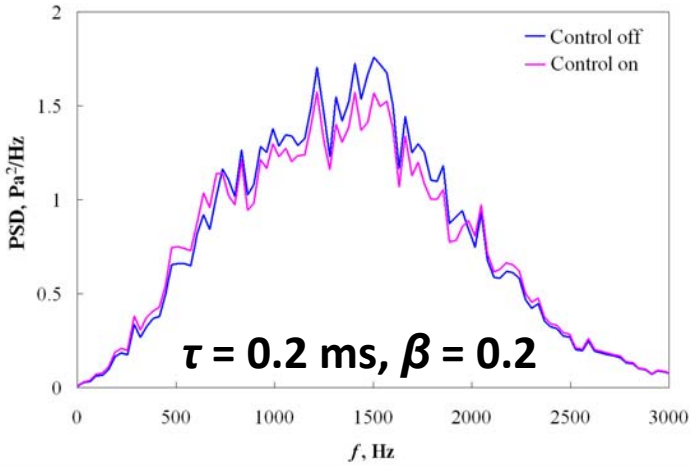
Spectra of the controlled and uncontrolled signals (0.7-2.0kHz)

$$g(t) = -\beta \sum_j a_j(t) \cos\left(2\pi f_j (t+\tau) - \delta_j(t)\right)$$









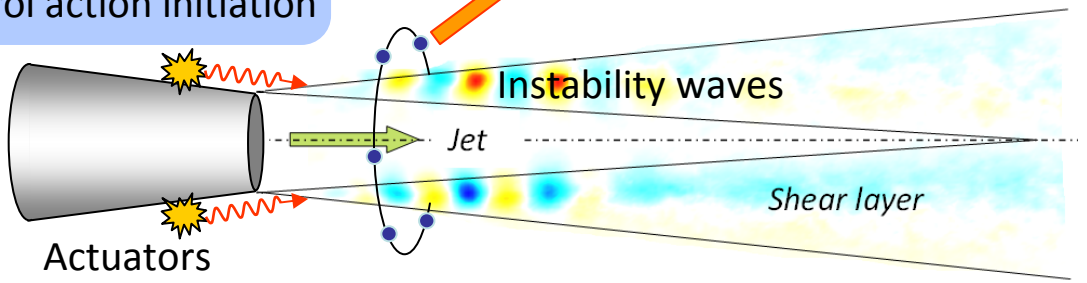
Control strategy

2 On-line filtering. Short-term prediction of the wavepacket parameters in the frequency band

3 Determination of the control action parameters (ampl.&phase)

1 Near-field IW detection – determination of axisymmetric wavepacket parameters in the frequency band (ampl.&phase)

4 Control action initiation



Control of real signal in a narrow frequency band, experimental setup TsAGI and JIHT RAS

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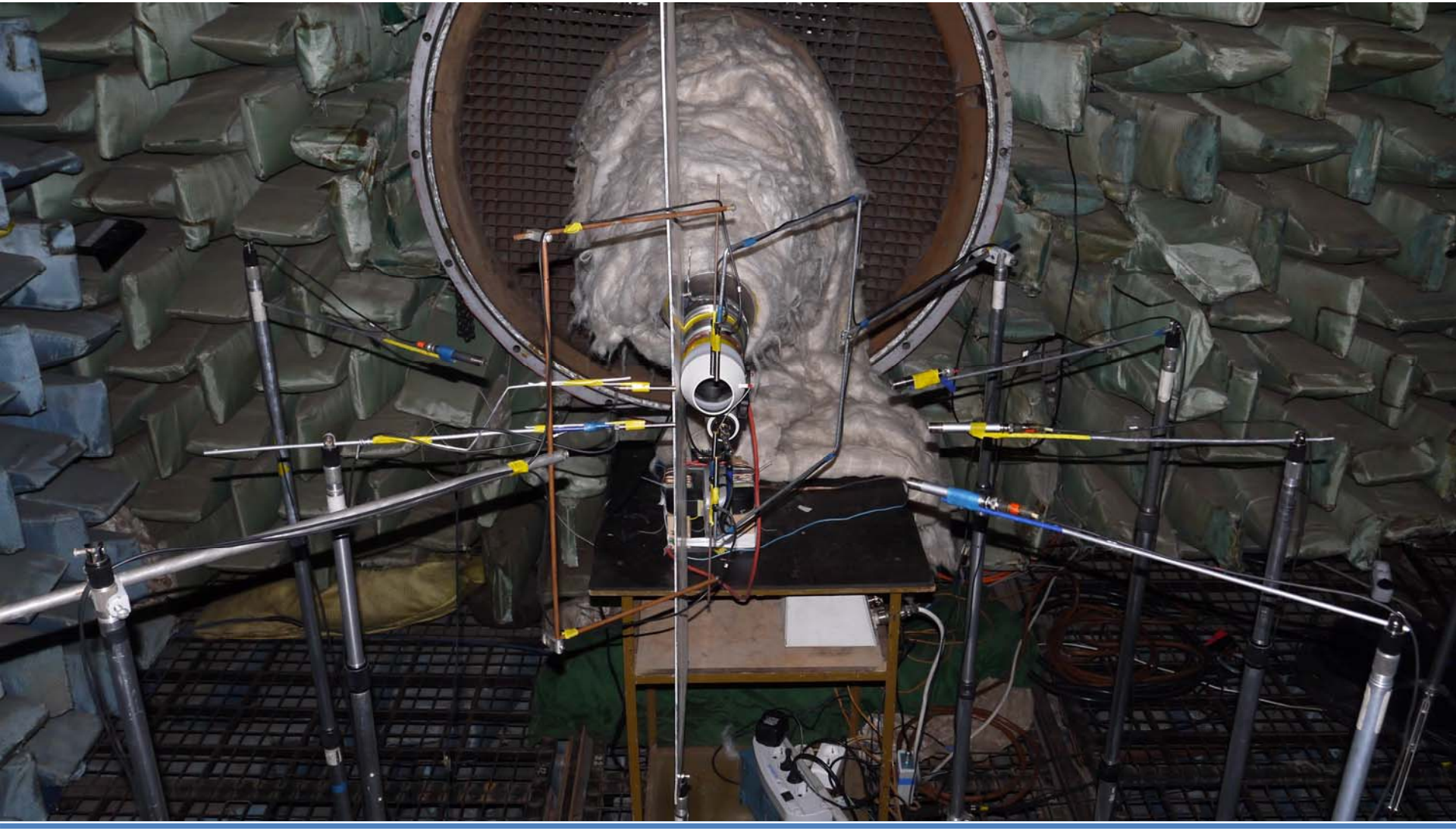

Conclusion

- The possibility of closed-loop control of artificially excited instability waves (AIW) by linear adjustment of the excitation and the control action is demonstrated.
- Analysis of the LES data was used to design microphone array for experimental detection of natural instability waves (NIW).
- It is shown that outside the shear layer, in the jet near field, there is a region containing footprints of large-scale structures related to the Kelvin-Helmholtz instability waves in the form of wave packets of 0, 1 and 2 azimuthal modes.
- It is shown on the model signal (axisymmetric mode) taken from the near-field measurements that such approach can lead to about twofold signal reduction (~3dB) in the given frequency band even for nonzero delay.
- It is shown that the integral effect of the control on the signal spectrum becomes negative despite the reduction in the given frequency band. This effect is related to the amplitude and phase errors introduced by the control. Reduction of the control amplitude and broadband action in the region of spectral maximum were proposed for mitigation of this time delay effect.
- It is demonstrated that the control signal defined by the measurements at one cross-section is able to suppress signals at different positions along the jet axis for moderate time delays, i.e. the control allows approximately twofold reduction of the wavepacket amplitude.