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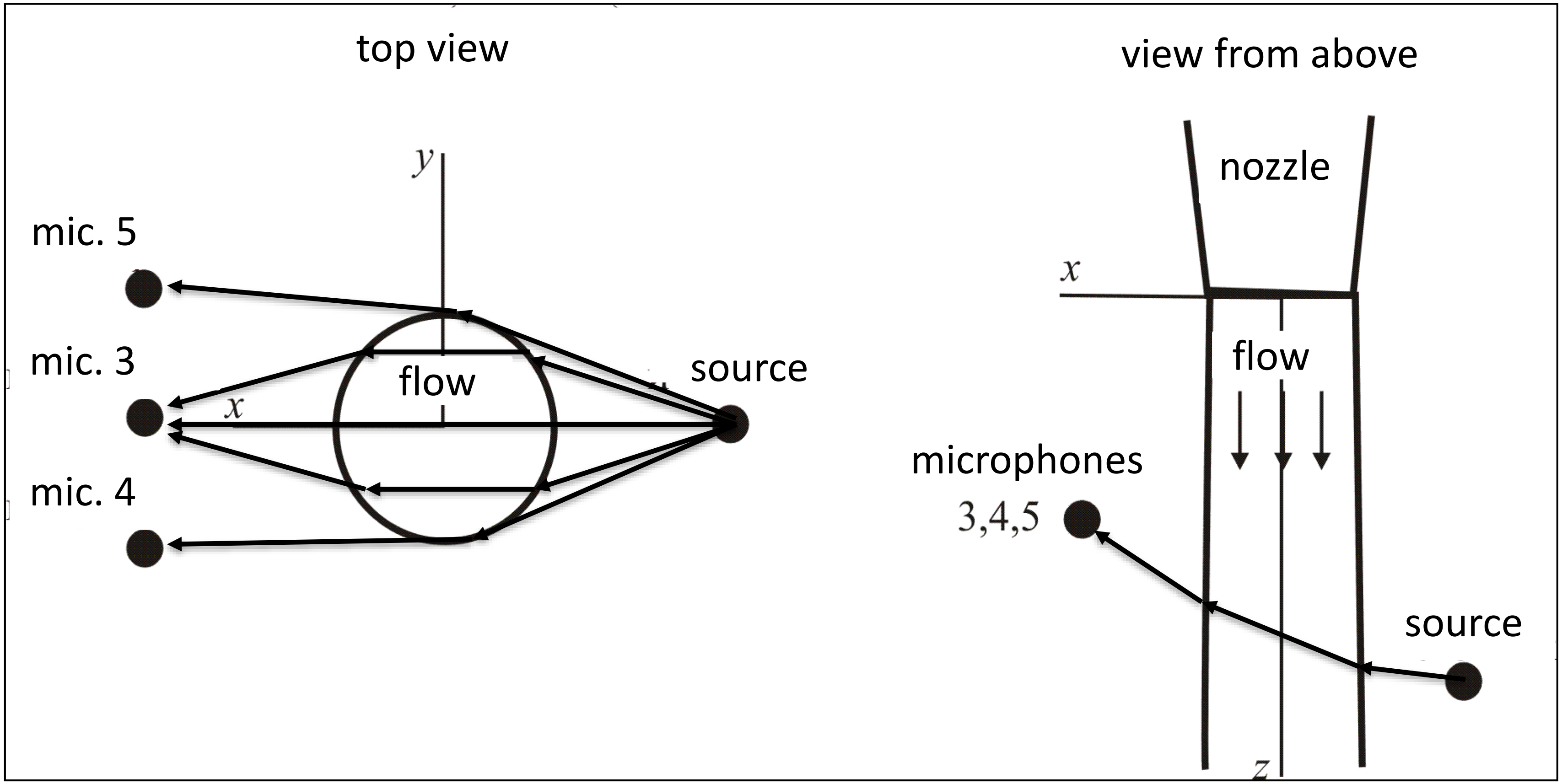
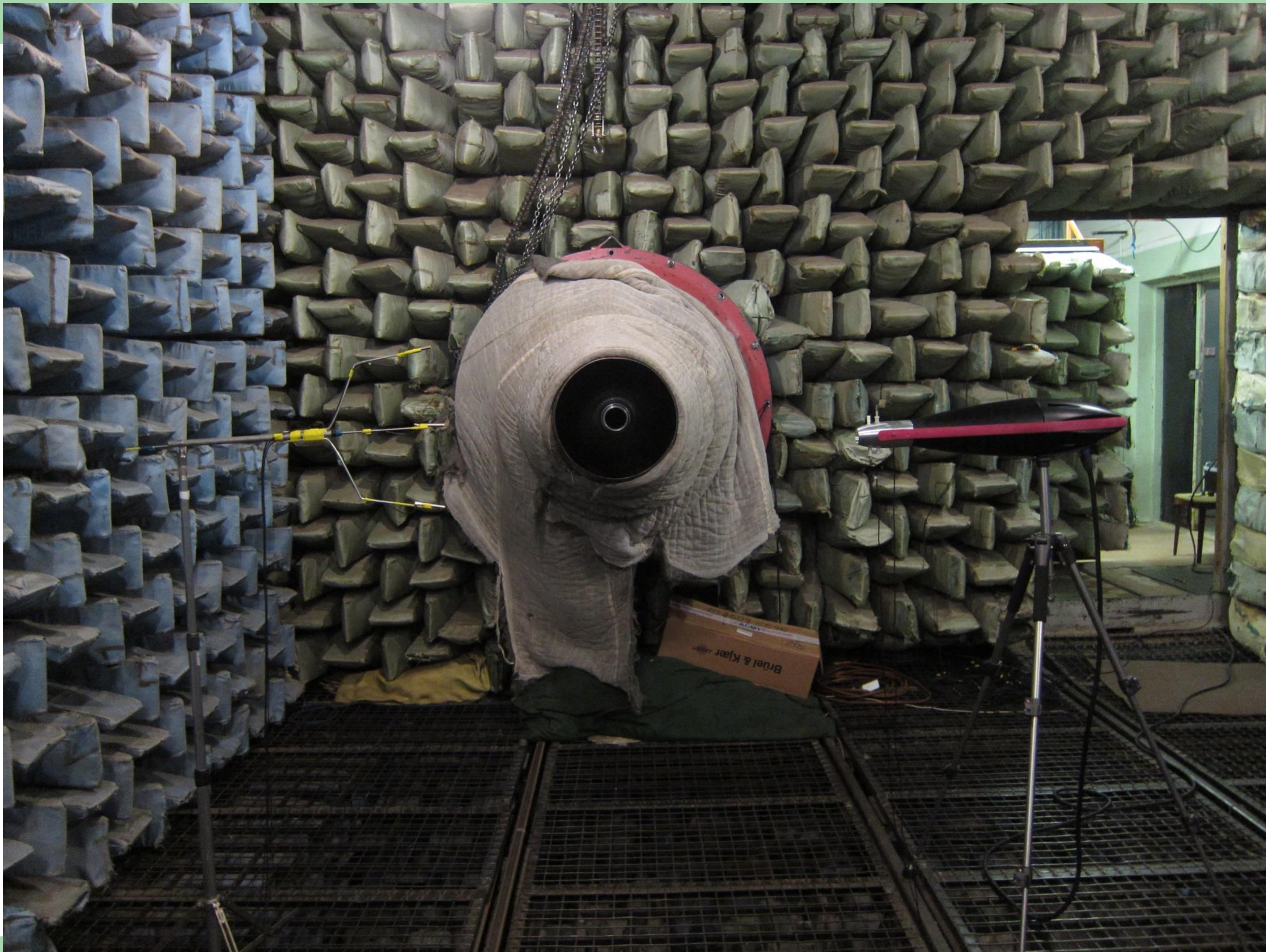
AIR FLOW EXPLORATION USING ACOUSTICAL MLS-SIGNAL

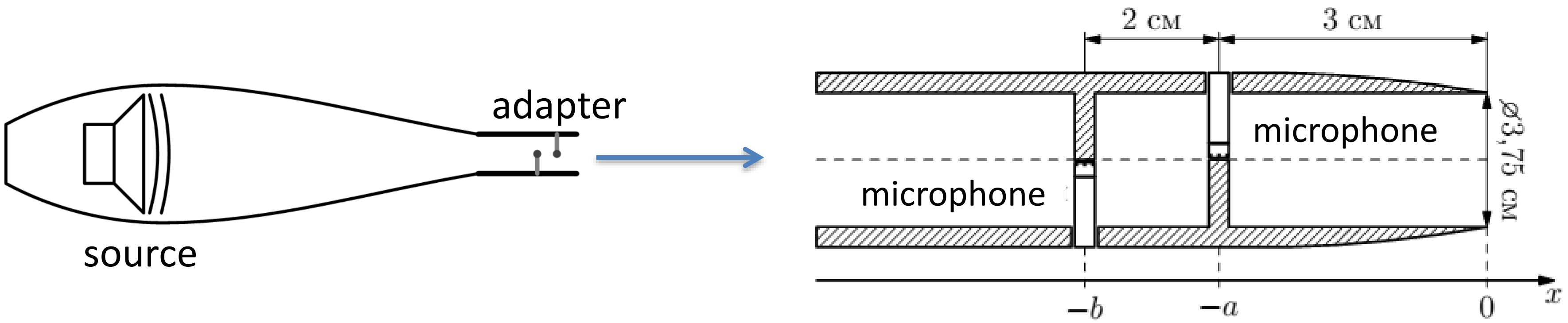
A.A. Belous [1], **A.I. Korolkov** [1],
A.V. Shanin [1], N. N. Ostrikov [2]
[1] Moscow State University, Moscow, Russia
[2] Central Aerohydrodynamic Institute (TsAGI), Moscow, Russia

Experimental setup




Brüel & Kjær

Geometry of velocity adapter



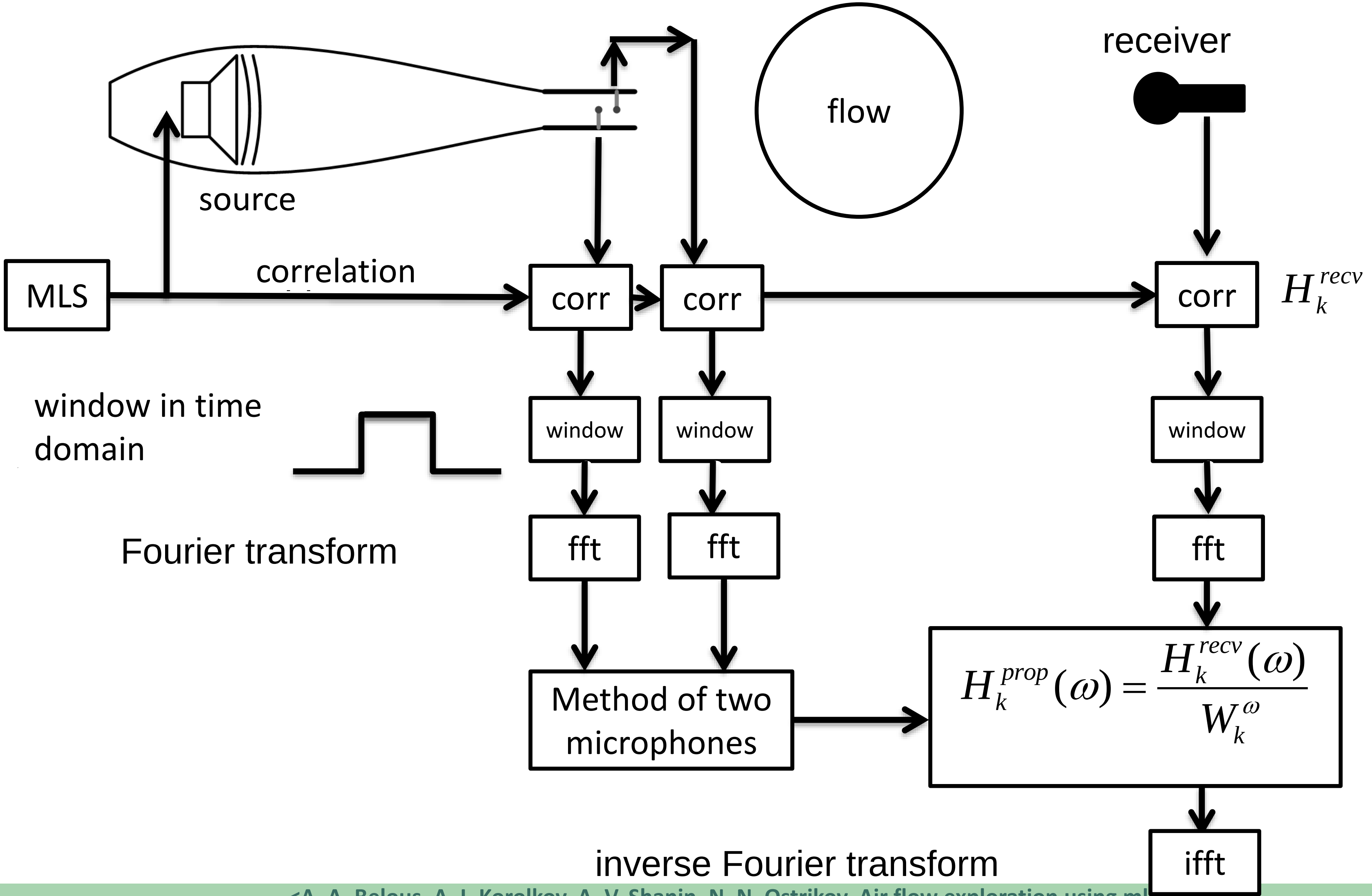
Volume velocity of the source is calculated using two microphones method

$$p^{\omega}(x) = A\mathrm{e}^{-ikx} + B\mathrm{e}^{ikx}$$

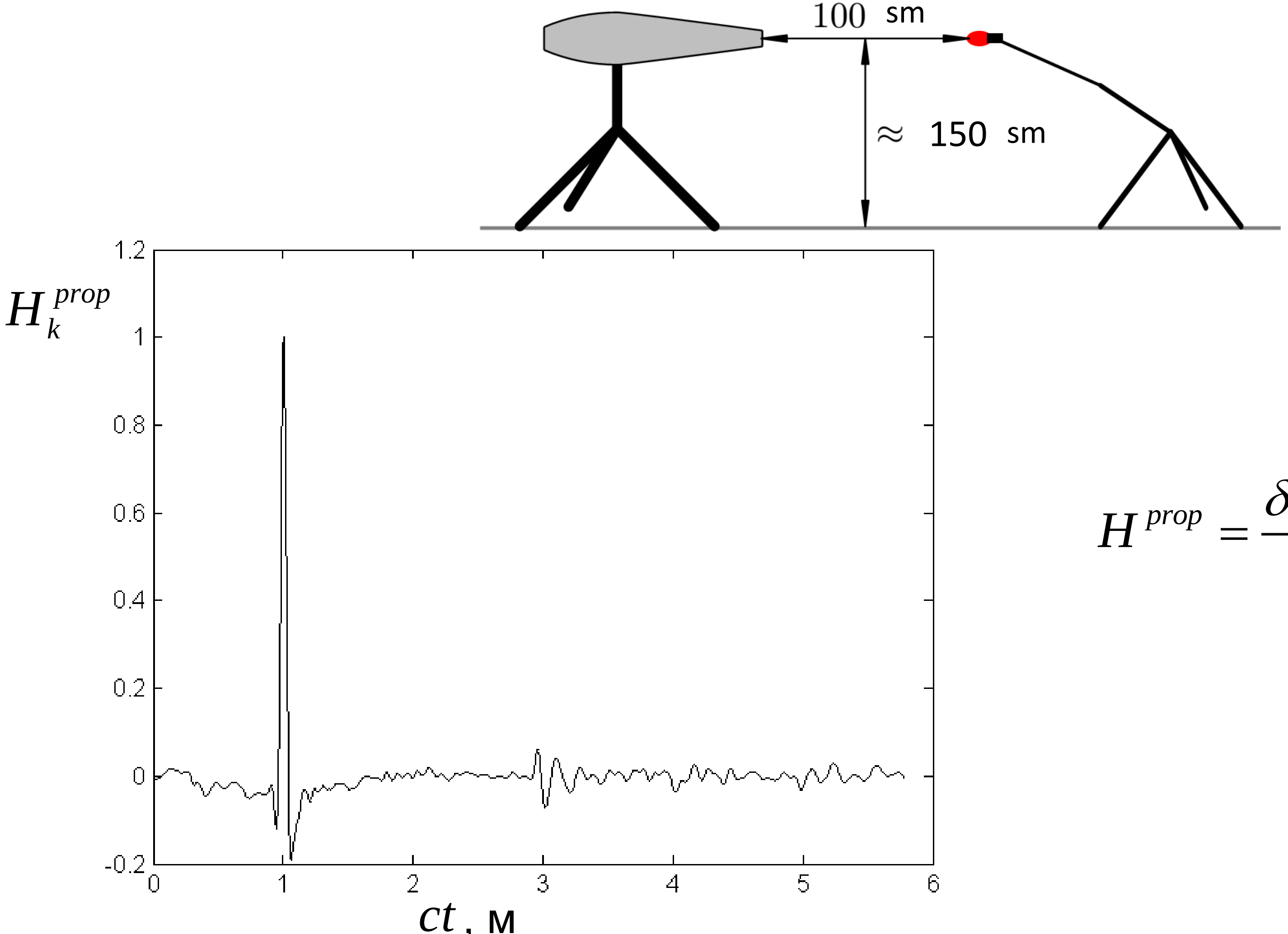
One can calculate coefficients A and B by measuring the pressure on each of two microphones. Then volume velocity can be calculated with help of Euler equations :

$$W^{\omega} = i\omega \frac{2\pi r^2}{\rho_0 c}(A - B)$$

Block diagram of the experiment



Check experiment without flow



$$H^{prop} = \frac{\delta(t - R/c)}{R}$$

Experiments with flow. Effects Observed

1. Noise generated by flow was much higher than signal from the source.

2. The amplitude of measured sound signal experienced variations due to the velocity pulsations in the flow.

3. Drift of acoustical signal along flow.

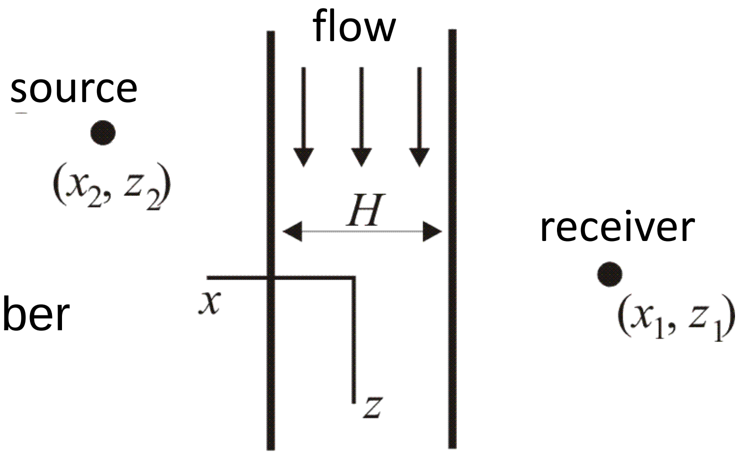
4. Sound focusing by cylindrical flow.

Signal delay. Geometric description.

Model equation with flow:

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\varphi=\left(M\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)^2\varphi$$

φ - acoustical potential, *M* – Mach number



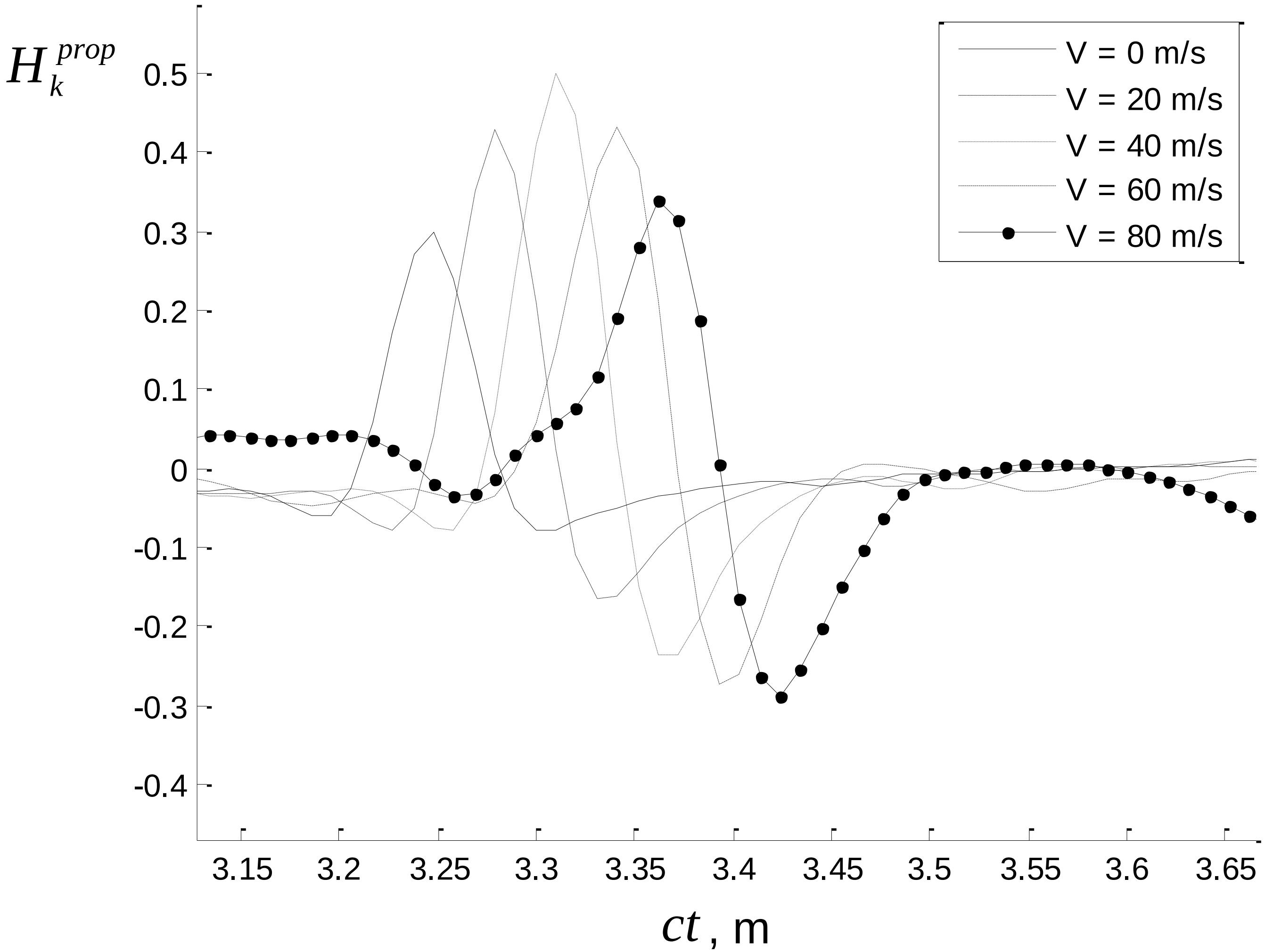
$$\phi=\iint A(\omega)\exp\{if(\omega,k_z)\}d\omega\, dk_z$$

$$f(\omega,k_z)=-\omega t+k_z(z_2-z_1)+(x_2-x_1-H)\sqrt{\frac{\omega^2}{c^2}-k_z^2}+H\sqrt{\left(\frac{\omega}{c}-Mk_z\right)^2-k_z^2}$$

Stationary points of the integral: $\frac{\partial f}{\partial \omega}=0$ $\quad \frac{\partial f}{\partial k_z}=0$

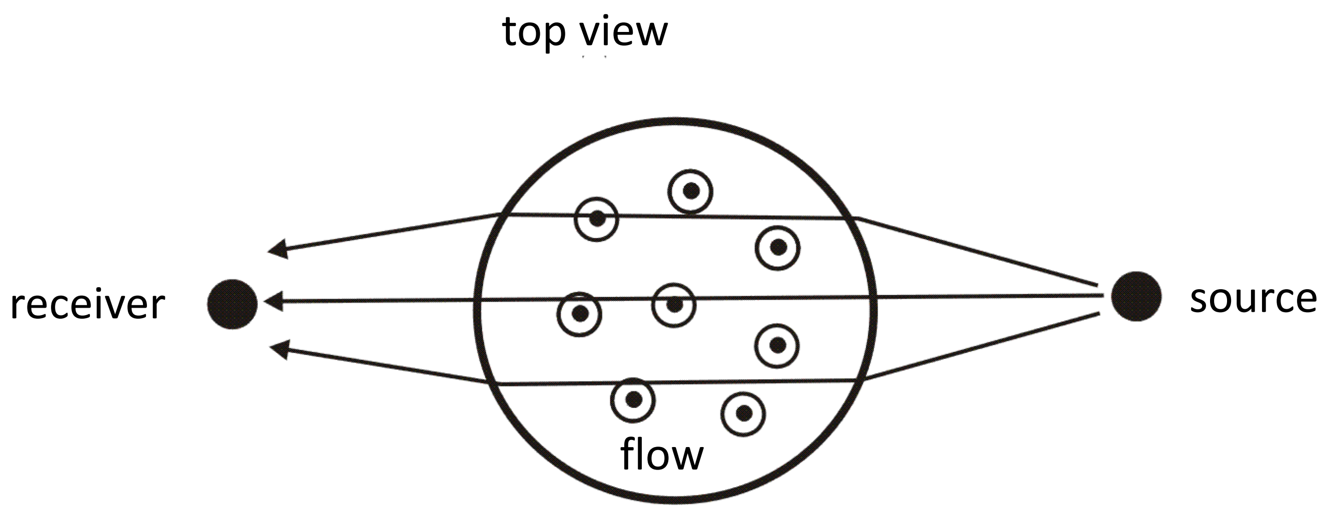
V = 0 m/s	V = 20 m/s	V = 40 m/s	V = 60 m/s	V = 80 m/s
ct = 3.280 m	ct = 3.310 m	ct = 3.339 m	ct = 3.366 m	ct = 3.394 m

Experimental results



Signal from microphone 3

Sound focusing by flow



The flow can be considered as acoustically denser media if projection of the acoustical ray is negative. It means that flow worked as collecting lens.

Numerical modeling. Lippmann-Schwinger equation

It is supposed that flow occupies cylindrical area and Mach number in it is constant. The following equation is satisfied:

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\phi=\left(M\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)^2\phi+\delta(\mathrm{t})\delta(x-x_1)\delta(y-y_1)\delta(z-z_1)$$

The field is represented as Fourier integral on variables z,t

$$\varphi(x,y,z)=\iint\tilde{\varphi}(x,y,k_z,\omega)\exp\{i(k_z z-\omega t)\}dk_z d\omega$$

Fourier image $\tilde{\varphi}$ satisfy following equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}-k_z^2\right)\tilde{\varphi}+\left(\frac{\omega}{c}-M(x,y)k_z\right)^2\tilde{\varphi}=\frac{1}{4\pi^2}\exp\{-ik_z z_1\}\delta(x-x_1)\delta(y-y_1)$$

Last equation can be rewritten in the following way:

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\omega^2}{c^2}-k_z^2\right)\tilde{\varphi}=\left[\frac{\omega^2}{c^2}-\left(\frac{\omega}{c}-M(x,y)k_z\right)^2\right]\tilde{\varphi}+\frac{1}{4\pi^2}\exp\{-ik_z z_1\}\delta(x-x_1)\delta(y-y_1)$$

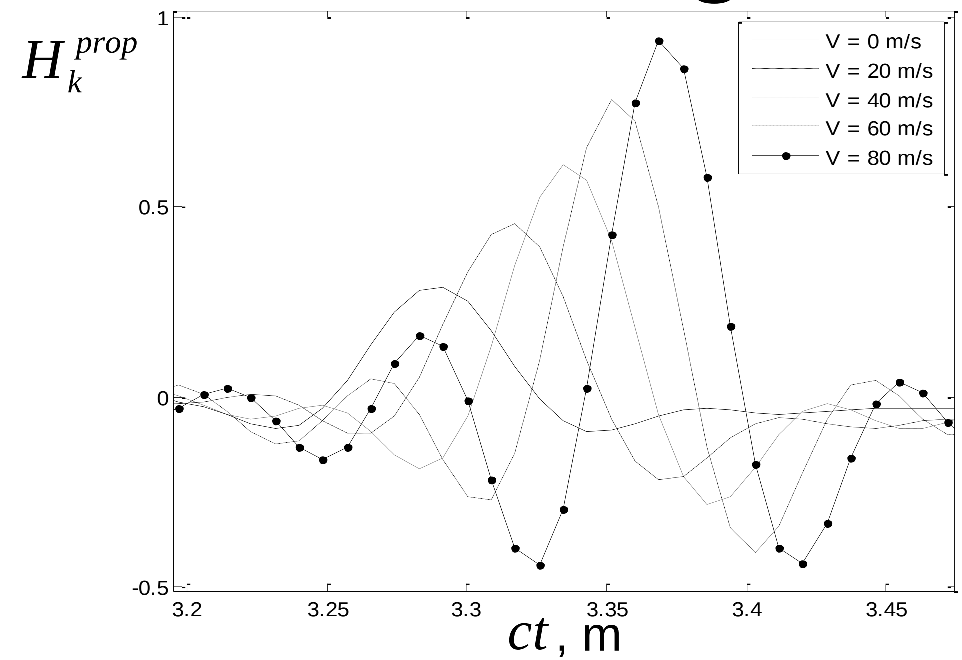
Let us use Lippmann-Schwinger method. Suppose that right side of this equation is known function and rewrite last expression as a integral equation:

$$\tilde{\varphi}(x_2,y_2,k_z,\omega)=\frac{\exp\{-ik_z z_1\}}{4\pi^2}G_{k_z,\omega}(x-x_1,y-y_1)+$$
$$\iint\left[\frac{\omega^2}{c^2}-\left(\frac{\omega}{c}-M(x,y)k_z\right)^2\right]\tilde{\varphi}(x,y,k_z,\omega)\,G_{k_z,\omega}(x_2-x,y_2-x)\,dxdy$$

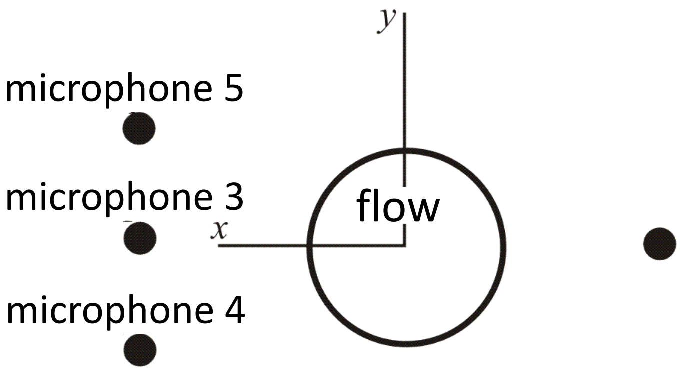
$$G_{k_z,\omega}(x,y)=H_0^{(1)}\left(\sqrt{x^2+y^2}\sqrt{\omega^2/c^2-k_z^2}\right)$$

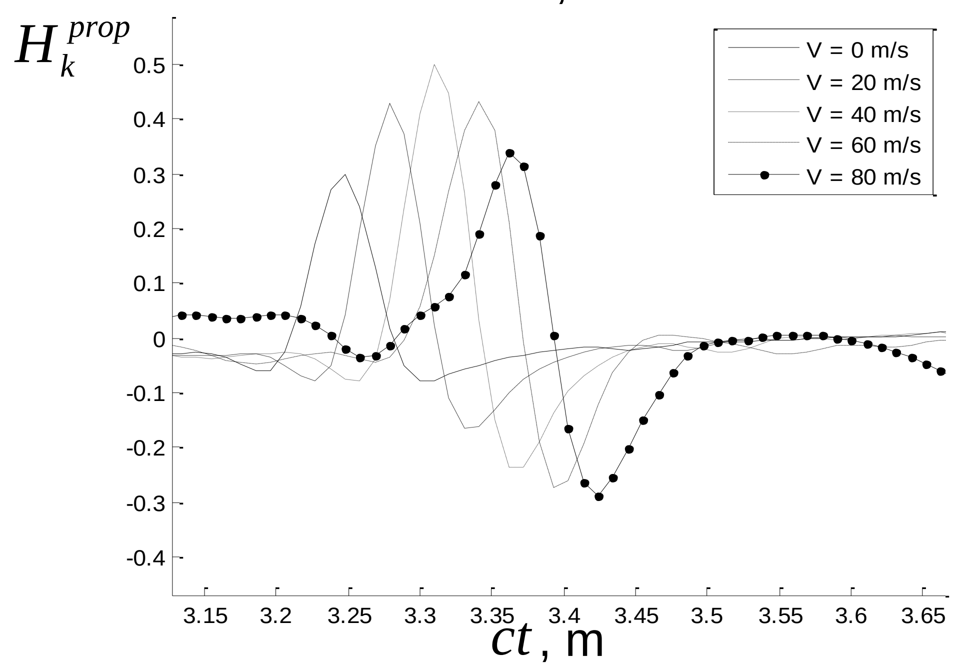
This equation was solved numerically. Grid step in plane (*x*,*y*) was 2 sm. Diameter of the flow was 40 sm.

Results of the numerical modeling



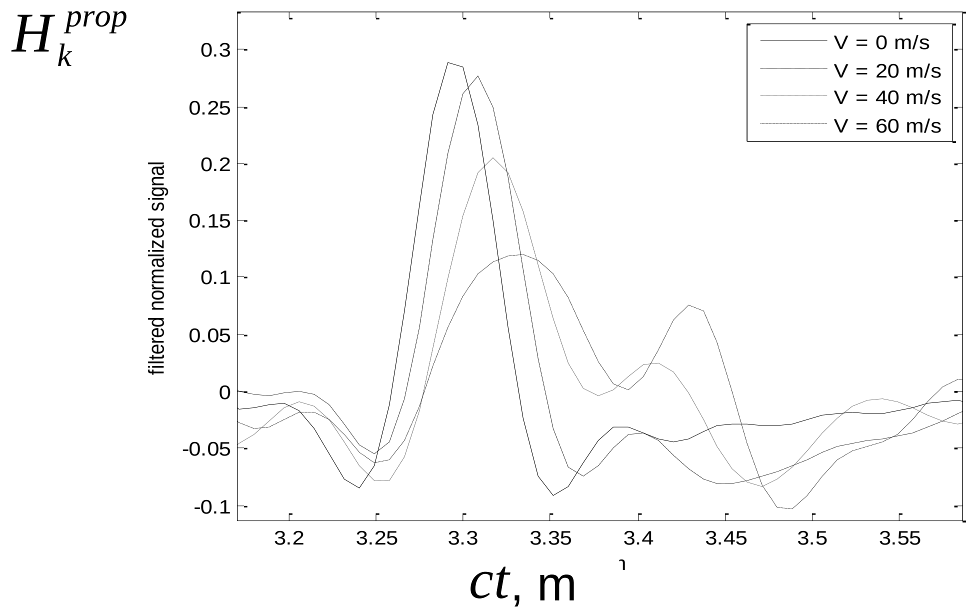
Numerical modeling for signal from microphone 3

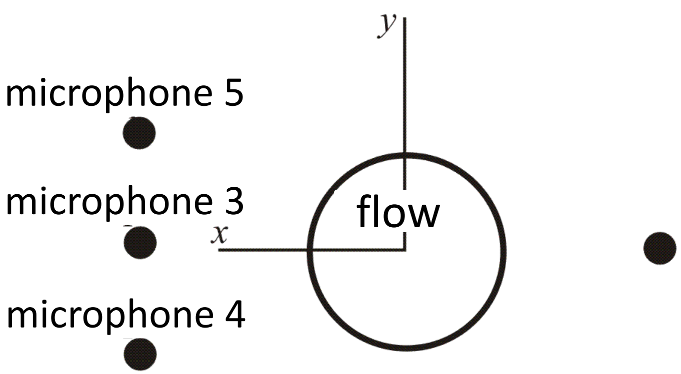


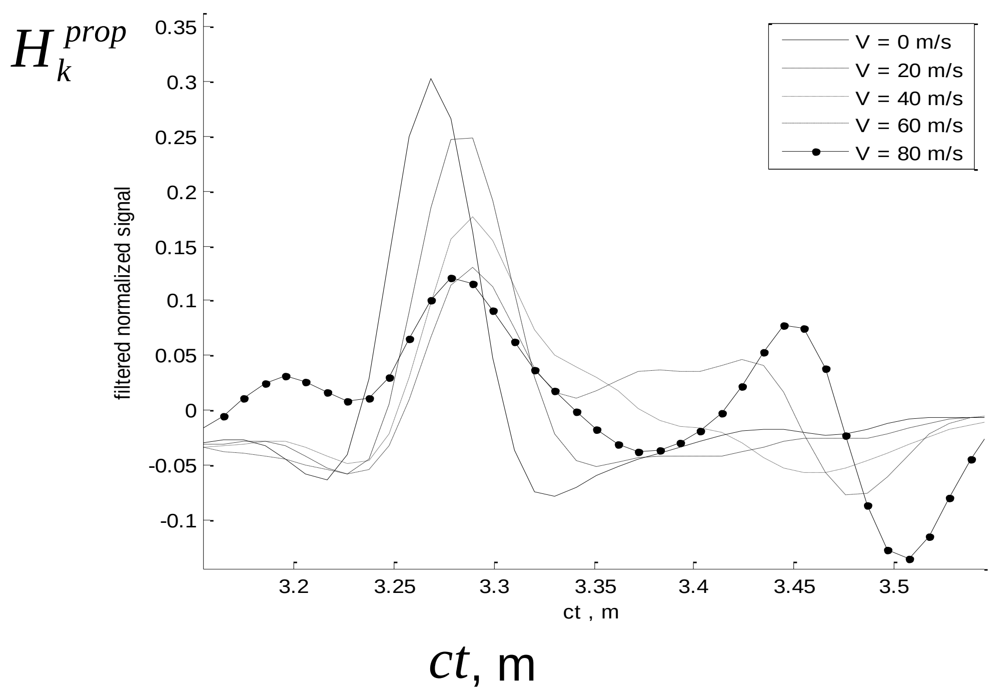


Experimental signal from microphone 3

Numerical modeling for signal from microphone 5







Experimental signal from microphone 5

Model parabolic equation with pulsations

The following parabolic equation for sound propagation in flow with pulsations is proposed:

$$\frac{\partial}{\partial z}\overline{\varphi} + \frac{1}{2ik}\Delta_{\perp}\overline{\varphi} = -k^{2}\Gamma_{\parallel}\overline{\varphi} + \Gamma_{\perp}\Delta_{\perp}\overline{\varphi}$$

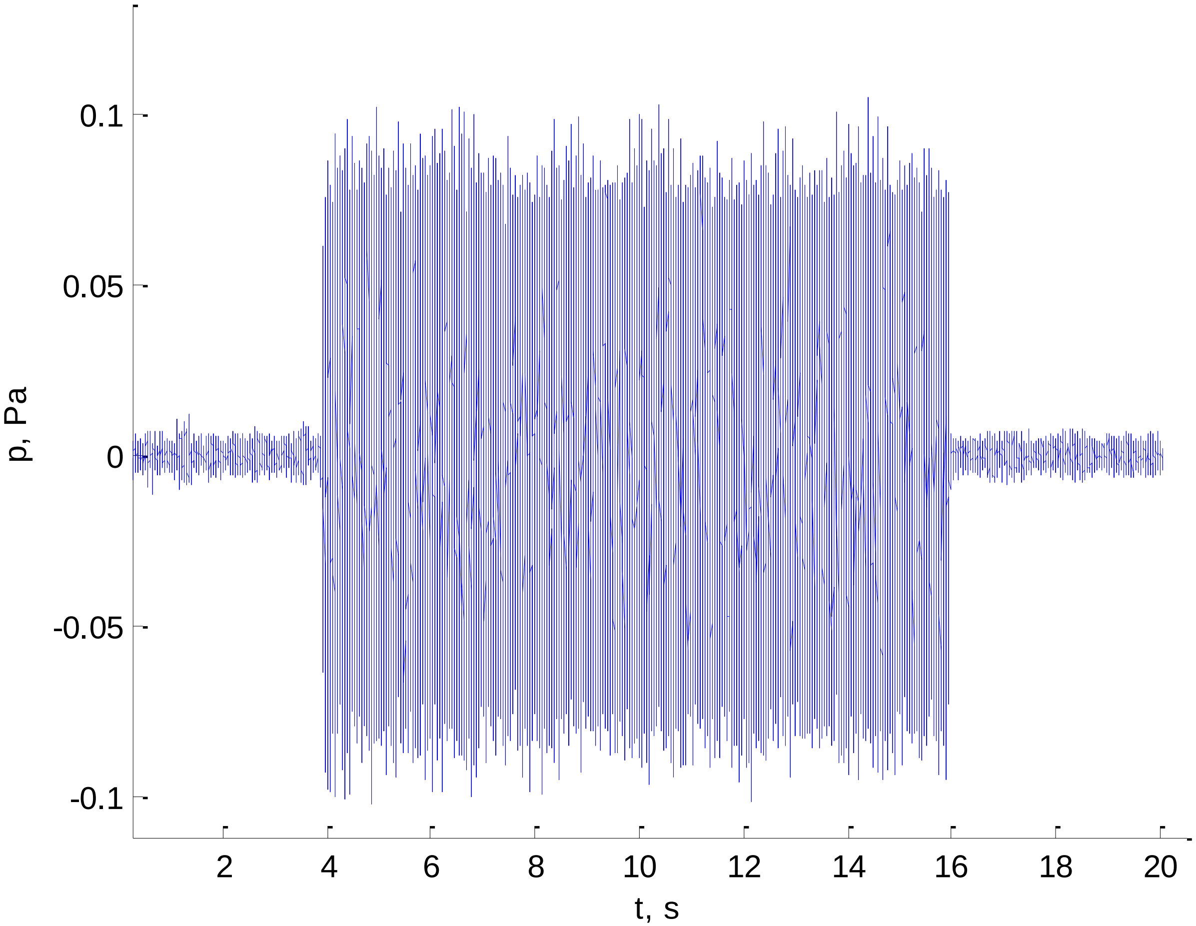
$\overline{\varphi}$ - average value of the acoustic potential,
z - direction of sound propagation,
$\Delta_{\perp}$ - Laplace operator in transverse coordinates,

$$\Gamma_{\perp} \sim \frac{\overline{V_{\perp}^{2}}a_{\perp}}{c^{2}}, \qquad \Gamma_{\parallel} \sim \frac{\overline{V_{\parallel}^{2}}a_{\parallel}}{c^{2}}$$

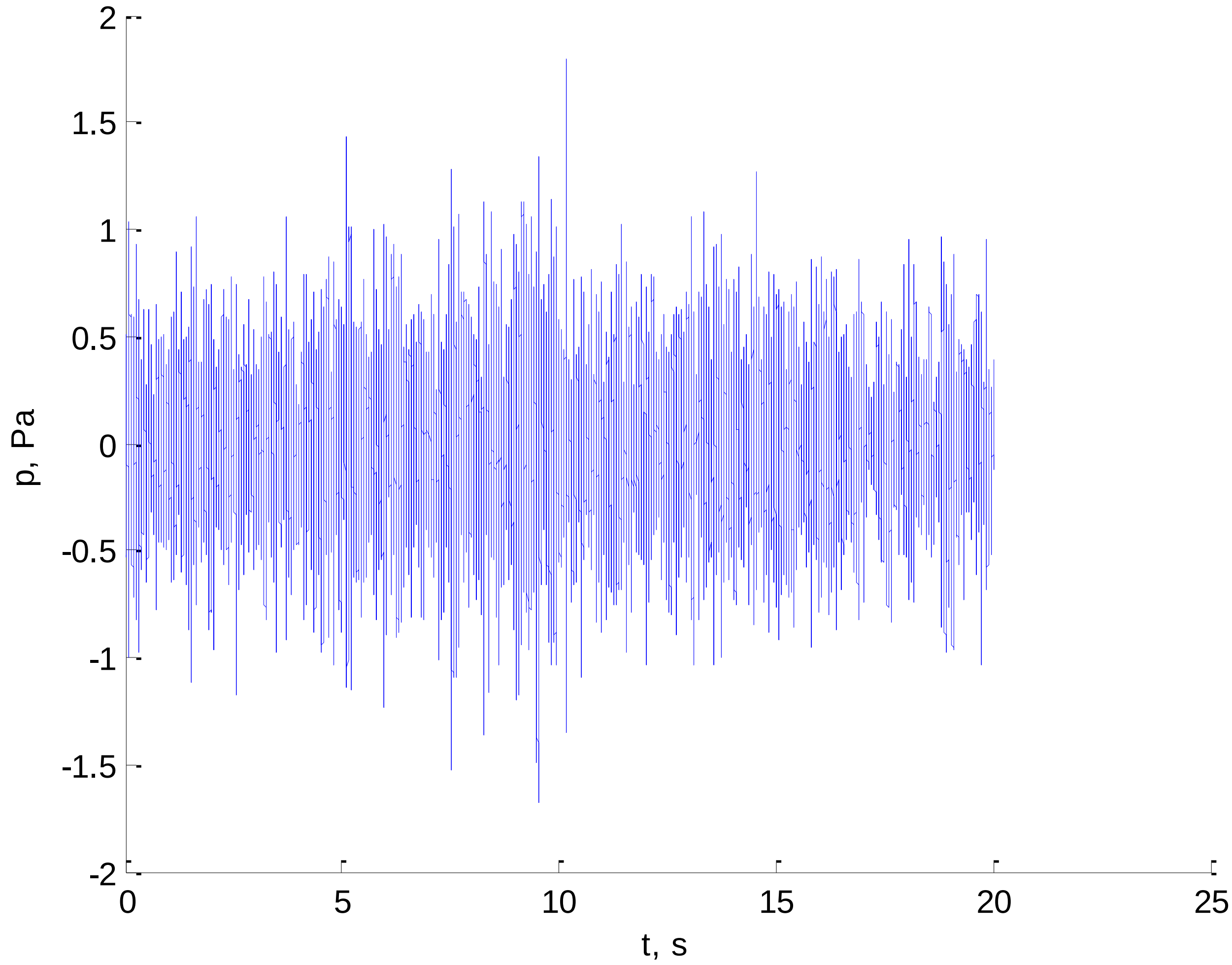
$a_{\perp}$ and $a_{\parallel}$ - characteristic values of the vorticity in longitudinal and transversal directions.

$\overline{V_{\perp}^{2}}$ and $\overline{V_{\parallel}^{2}}$ - mean square velocity pulsations in longitudinal and transversal directions.

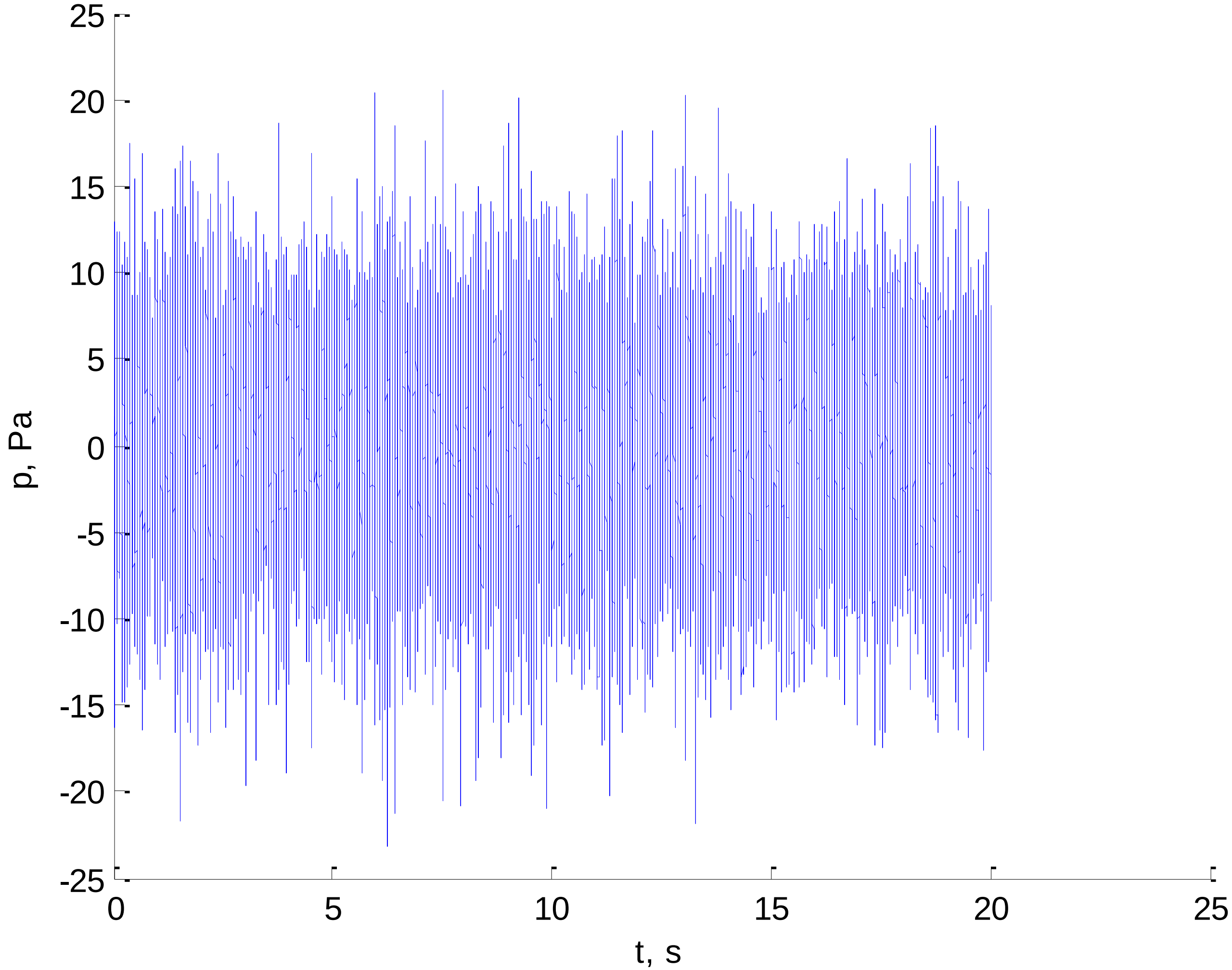
Amount of flow noise



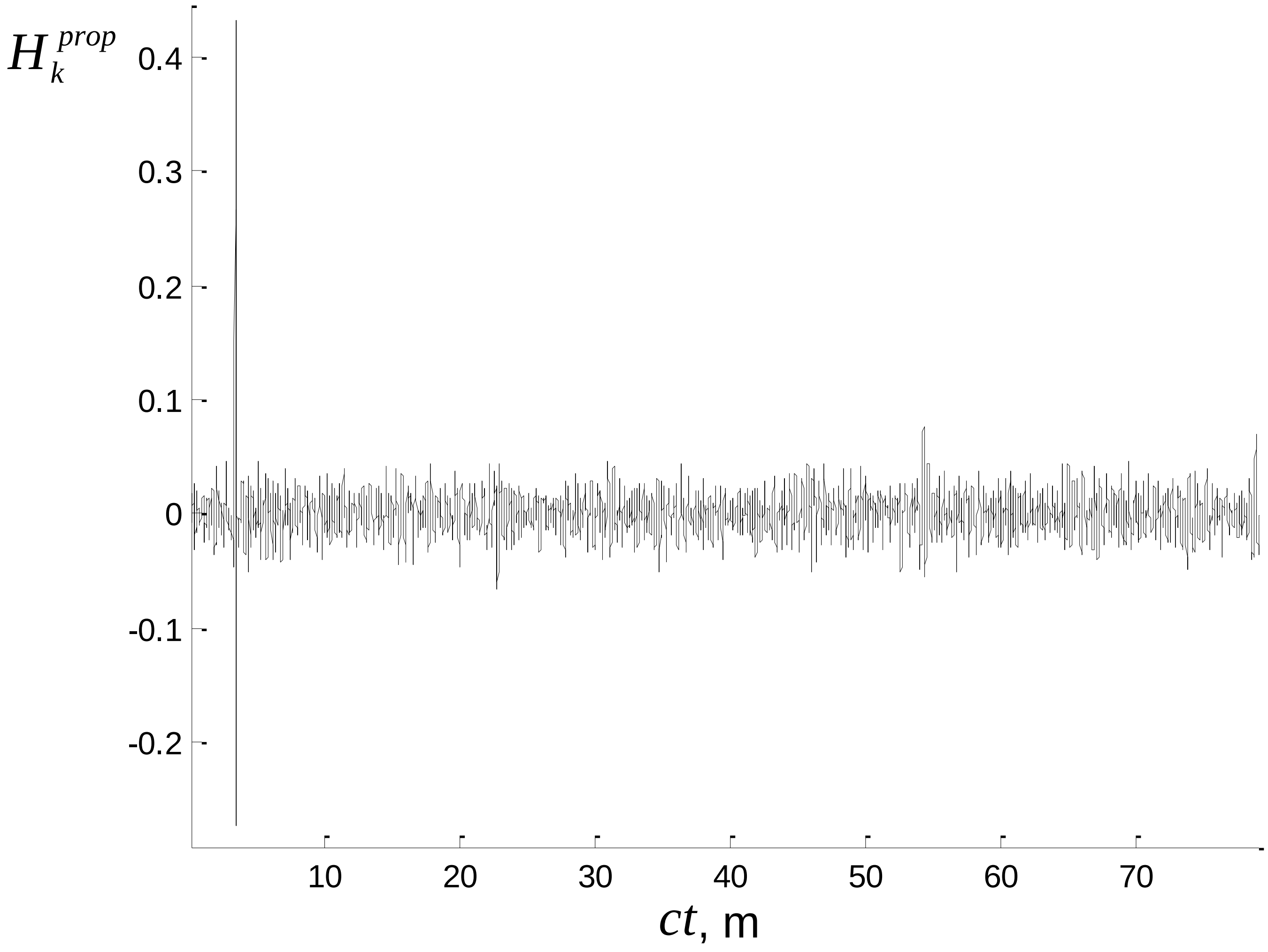
Raw signal without flow



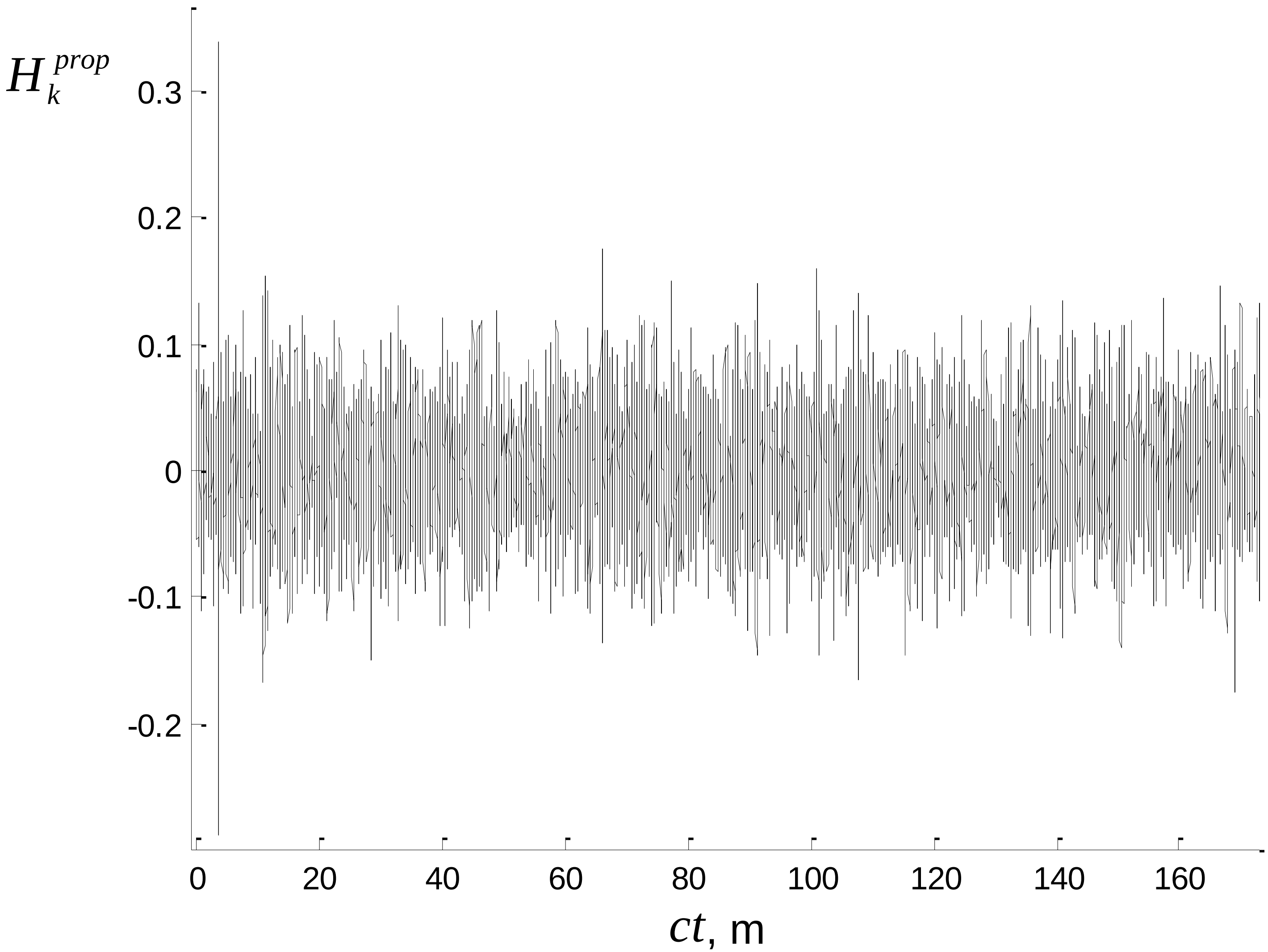
Raw signal at flow velocity V = 20 m/s



Raw signal at flow velocity V = 80 m/s



Impulse response at flow velocity V = 60 m/s



Impulse response at flow velocity V = 80 m/s

Conclusions

1. MLS-method can be used for air flow exploration.

2. Air flow doesn't affect acoustical signal if it propagates perpendicularly to the flow.

3. Acoustical signal drifts and focusing if it has non-zero longitudinal projection on the flow.

4. Numerical results disagree with experiment for flow with big velocity. We suppose that this discrepancy can be overcome if pulsation of the flow will be taken into account.

5. Resulting signal is very noisy due to the flow, but correlation processing allows recovering of the impulse response.