Simulation of the wedge-shaped vibration-driven robot motion in the viscous fluid forced by different laws of internal mass movement in the package OpenFOAM

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ABOUT VIBRATION-DRIVEN ROBOT (VDR)

Vibration-driven robot (VDR) is a multi-mass propulsion system consisting of a closed shell and movable internal parts. In a resistive medium the motion of the system as a whole is forced by periodic oscillations of internal parts relative to the shell.
Such a principle of movement seems to be expedient for mini and micro-robots (for motion in low-Reynolds-numbers range).

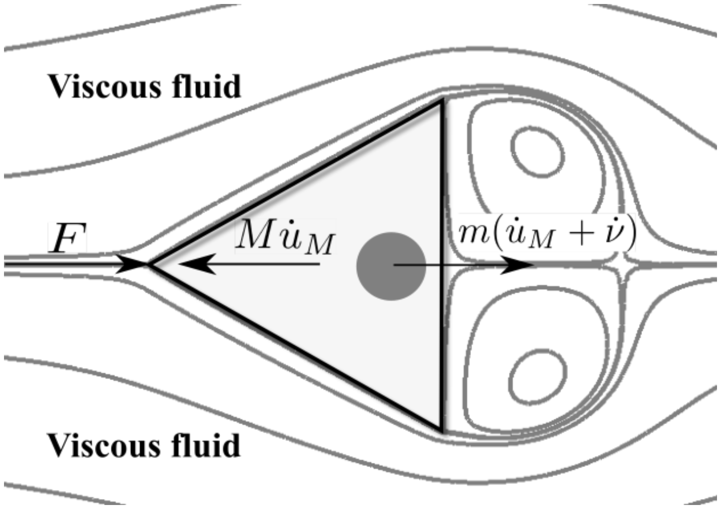

Fig. 1: Motion scheme of two-mass VDR

MATHEMATICAL MODEL

Basic equation of rectilinear motion of the two-mass system:

$$\dot{u}_M = -\mu_2 \dot{\nu} + \mu_1 \frac{R^2}{S} F$$

Governing system of a fluid motion around VDR:

$$\frac{\partial U}{\partial t} + U \cdot \nabla U = -\nabla p + \frac{1}{\mathrm{Re}} \Delta U, \ \nabla \cdot U = 0$$

Forces acting on VDR by a viscous fluid :

$$F_p = \int_S pnds - \int_S \overline{\sigma} \cdot nds,$$

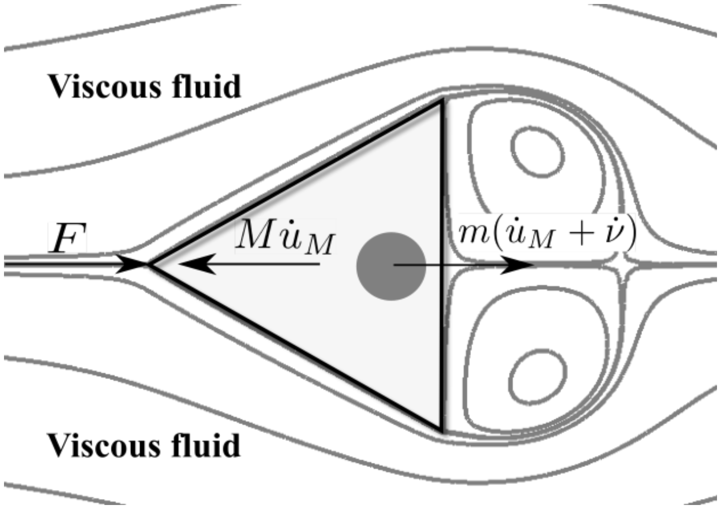

Fig. 1: Motion scheme of two-mass VDR

$\dot{u}_M$ - acceleration of the shell,

$\dot{\nu}$ - acceleration of the internal mass

MATHEMATICAL MODEL

We rewrite governing equations in a moving (non-inertial) coordinate system associated with the shell. To retain the governing system in the basic form, we determine a new pressure as

$$p = \tilde{p} + x\dot{u}_M \,.$$

BC on the surface of VDR:

$$u\,|_c = v\,|_c = 0.$$

BC at infinity:

$$\dot{u}\,|_\infty = \mu_2 \dot{v} - \mu_1 \frac{R^2}{S} F,\ \dot{v}\,|_\infty = 0$$

Correction of forces:

$$F = F_x - \int_S x\dot{u}_M nds.$$

NUMERICAL SOLUTION

Numerical solution is carried in the OpenFOAM software package. For discretization of equations 2nd order scheme is used. The resulting discrete problem solution is based on the PISO method implemented in the icoFoam solver. The next additional steps for updating the BC are defined:

1. The predictor for the acceleration of the moving coordinate system is calculated as

$$\dot{w}_p^j = 2\dot{w}^{j-1} - \dot{w}^{j-2}.$$

2. The boundary conditions at the input and output boundaries are updated

$$\dot{u}_\infty^j = -\dot{w}_p^j + \dot{w}_c^{j-1},\ u_\infty^j = (-2\dot{u}_\infty^j dt + 4u_\infty^{j-1} - u_\infty^{j-2})/3$$

3. The discrete governing system of the fluid motion is solved by the PISO method, the force is calculated.

4. The real acceleration of the system is calculated using the new value of the force:

$$\dot{w}^j = -\mu_2 \dot{v}^j + \mu_1 \frac{R^2}{S} F^j$$

5. The corrector is calculated as

$$\dot{w}_c^j = \dot{w}_p^j - \dot{w}^j.$$

APPROBATION OF THE NUMERICAL MODEL. STEADY FLOW PAST TRIANGULAR CYLINDER.

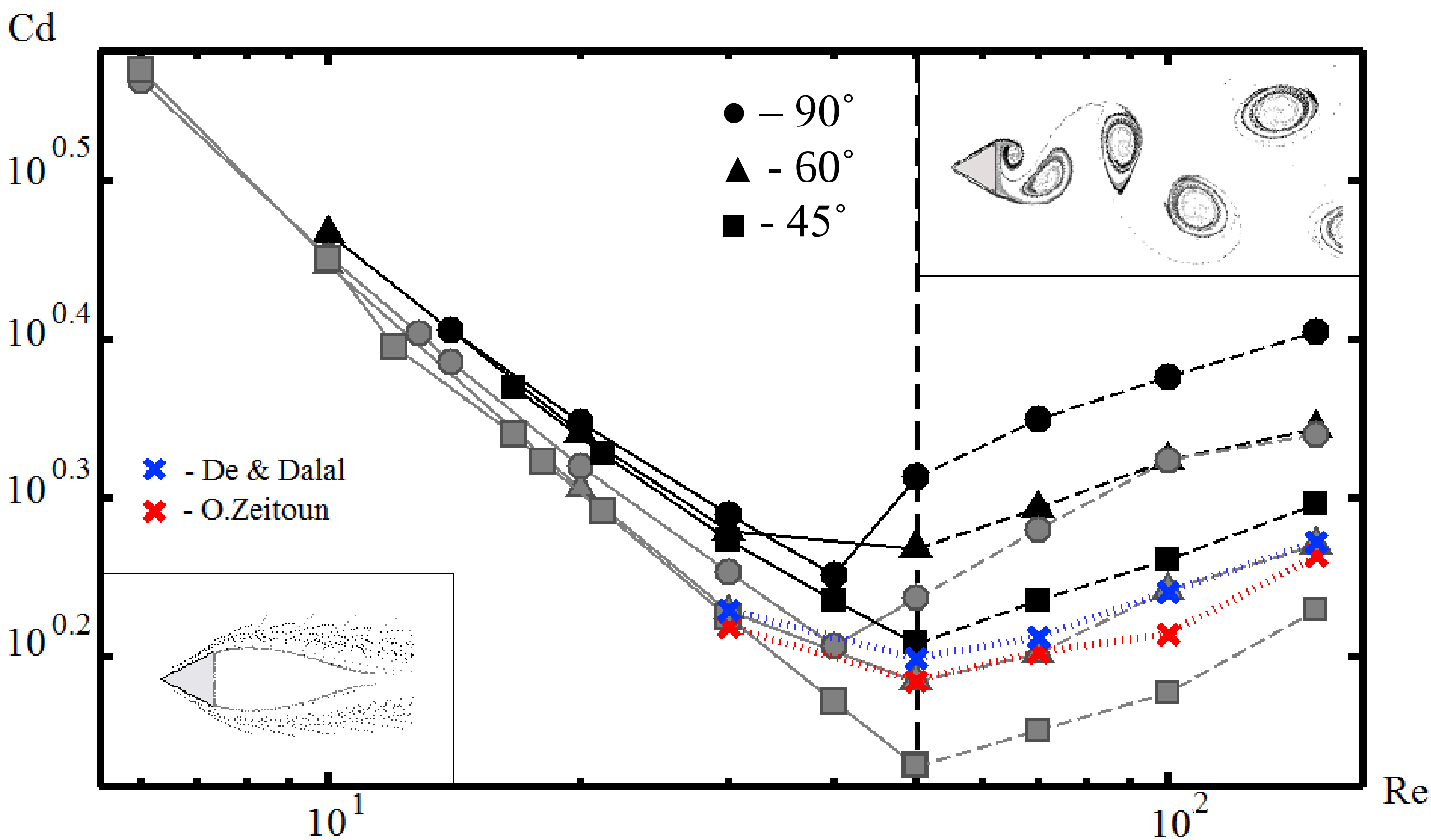

Fig. 2: The drag forces acting on the cylinder. Gray markers – vertex facing flow, black markers – base facing flow.

APPROBATION OF THE NUMERICAL MODEL. OSCILLATORY FLOW PAST TRIANGULAR CYLINDER.

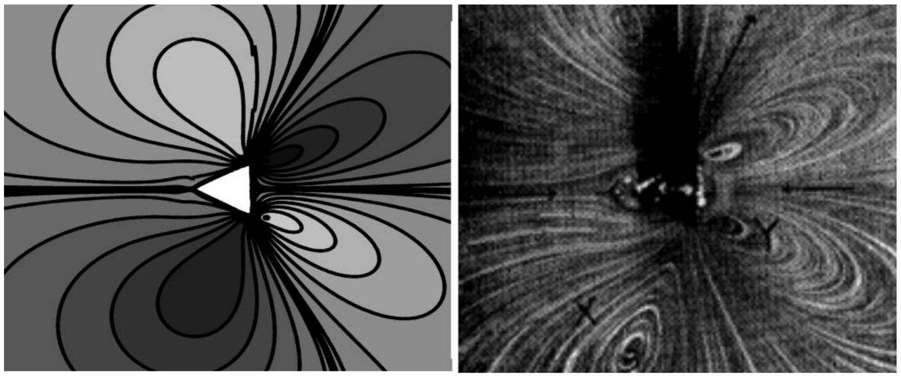

Fig 3a: Average stream function for regime S*. Re = 31,5; KC = 0,35

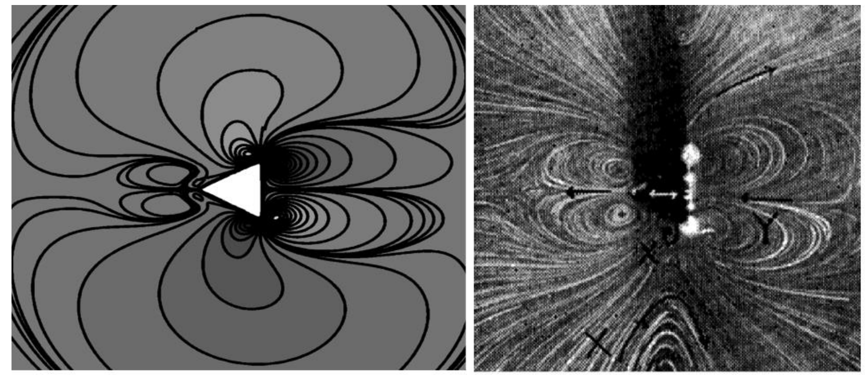

Fig. 3b: Average stream function for regime S. Re = 57.7; KC = 0.64

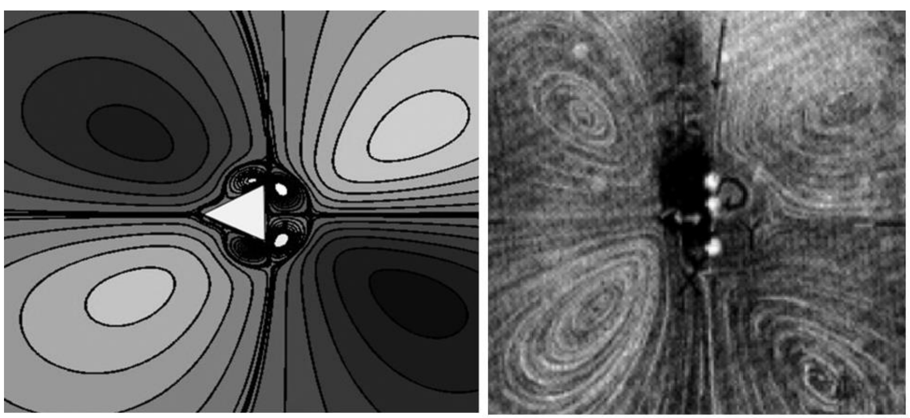

Fig. 3c: Average stream function for regime S. Re = 68.25; KC = 0.727

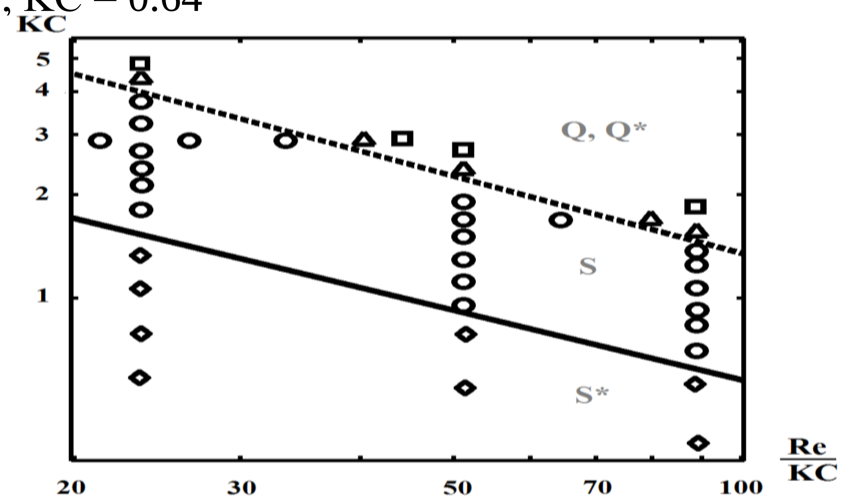

Fig 3d: Map of regimes

VDR MOVEMENT.
INTERNAL MASS MOTION LAWS

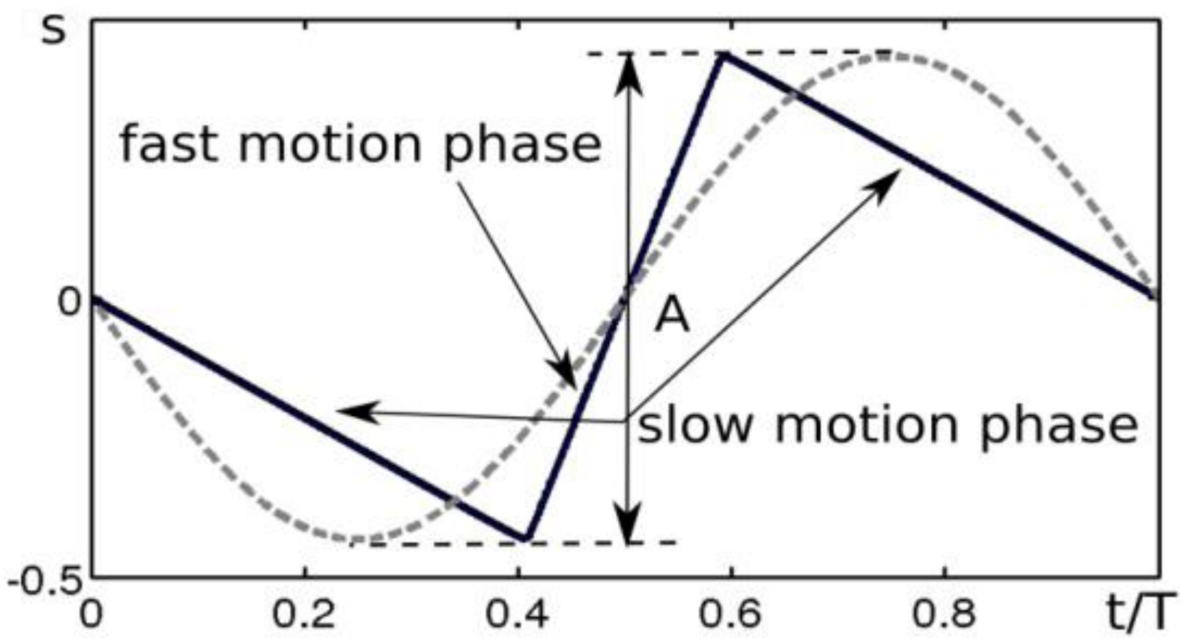

Fig. 4: Harmonic (dashed line) and two-phase* (solid line) laws of the internal mass motion

* Egorov A .G., Zakharova O. S. The energy optimal motion of a vibration driven robot in a resistive medium. J. Appl. Math. Mech. 74 p. 443. 2010

HARMONIC LAW OF THE INTERNAL MASS MOTION. EQUILATERAL TRIANGLE

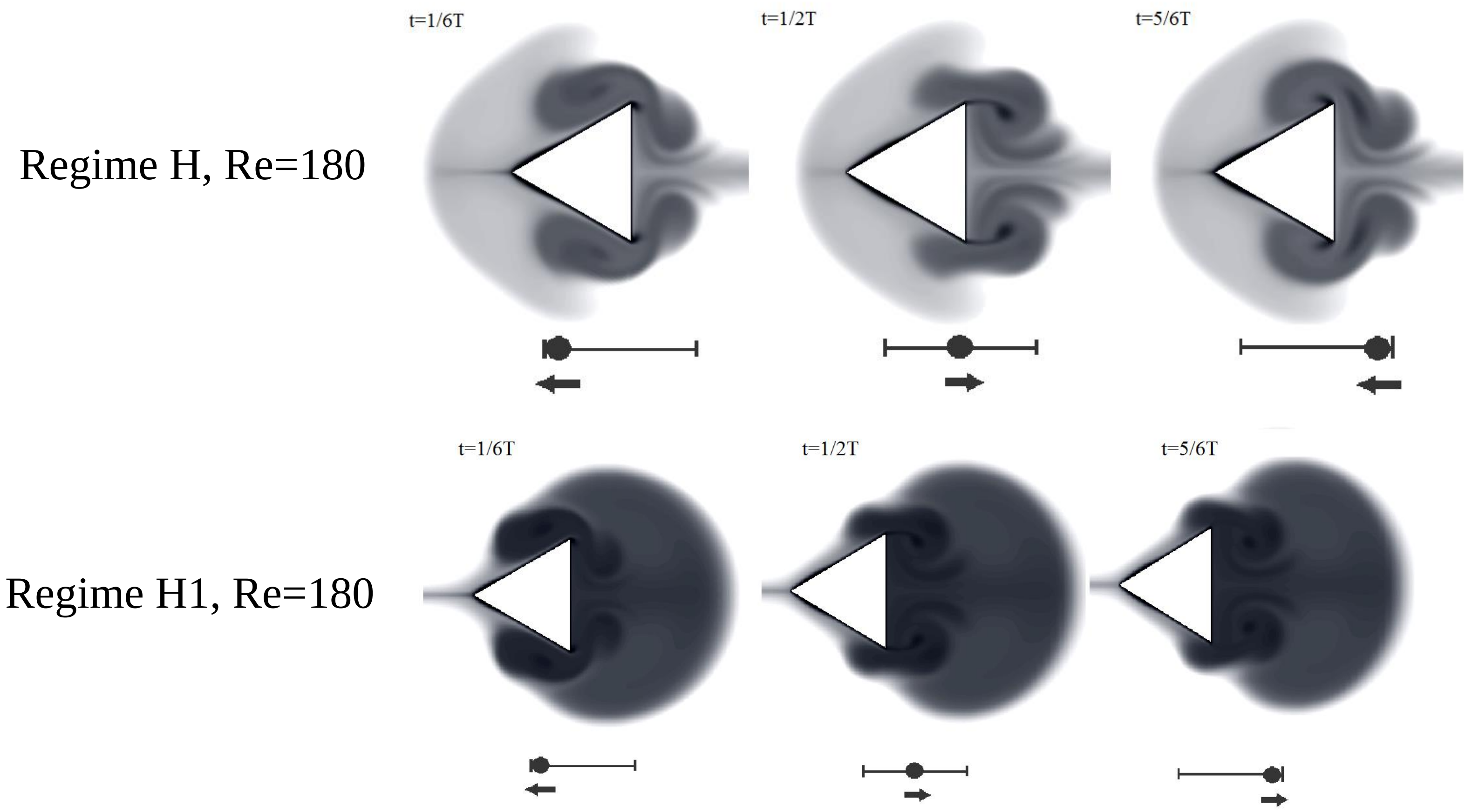

Fig. 5: Flow patterns around vibration-driven robot.

HARMONIC LAW OF THE INTERNAL MASS MOTION. SYMMETRY BREAKING

Regime H2, Re=240

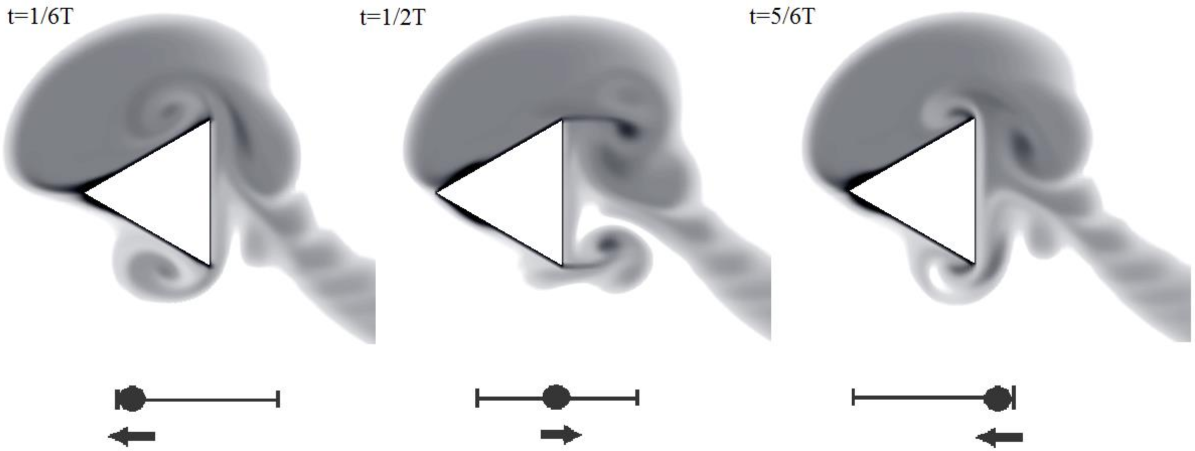

Fig. 6: Flow patterns around vibration-driven robot.

TWO-PHASE LAW OF THE INTERNAL MASS MOTION. EQUILATERAL TRIANGLE

Regime T, Re=180

Regime T2, Re=240

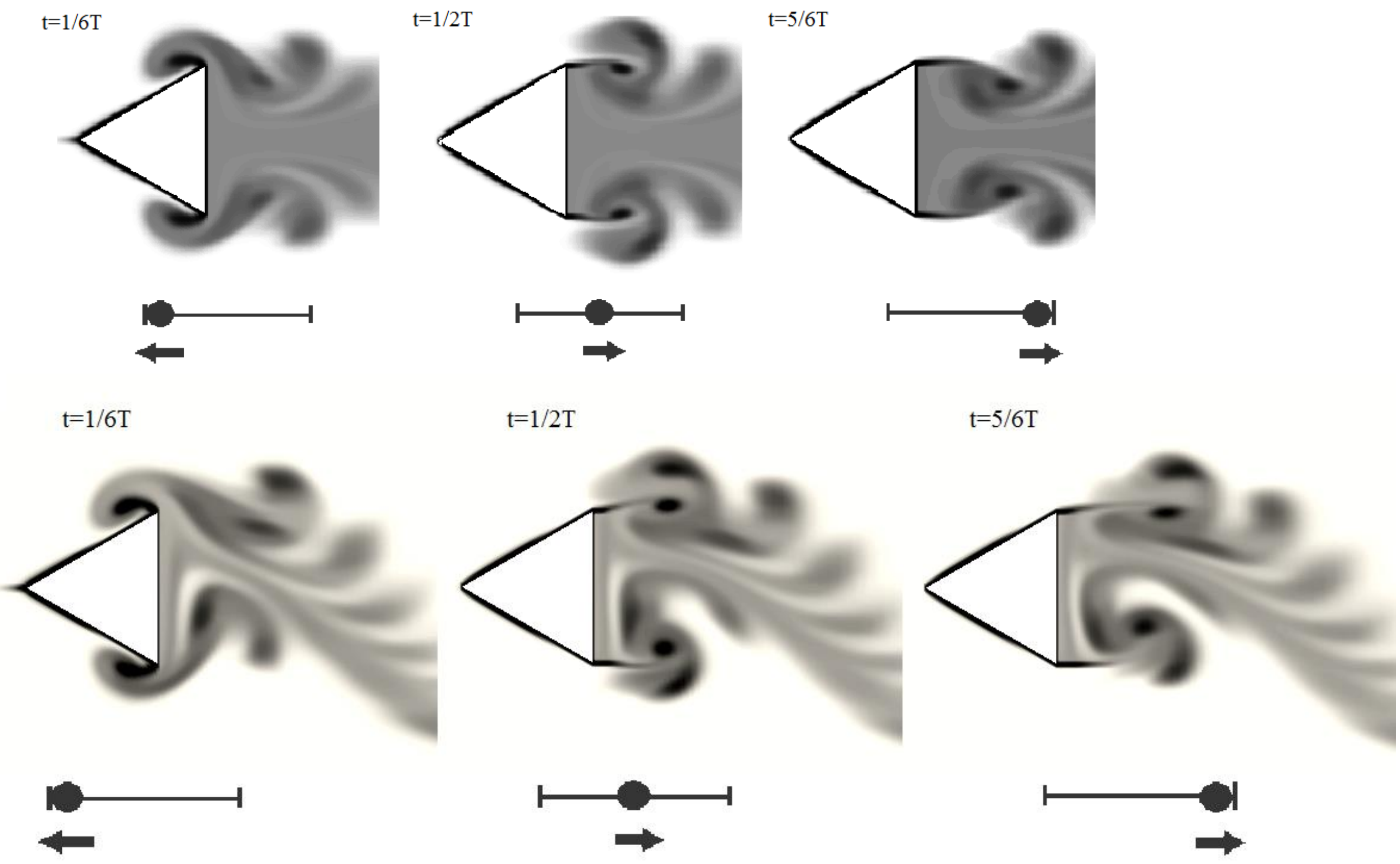

Fig. 7: Flow patterns around vibration-driven robot.

MAIN CHARACTERISTICS OF THE MOTION. EQUILATERAL TRIANGLE

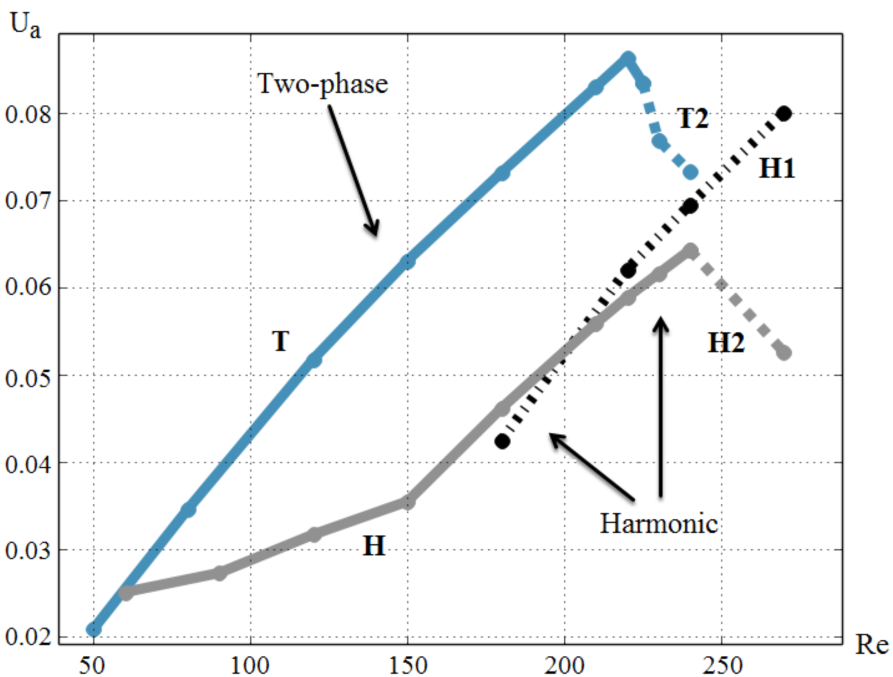

Fig.8a: Average velocity of movement ($\boldsymbol{U_a} = \langle \boldsymbol{U} \rangle$)

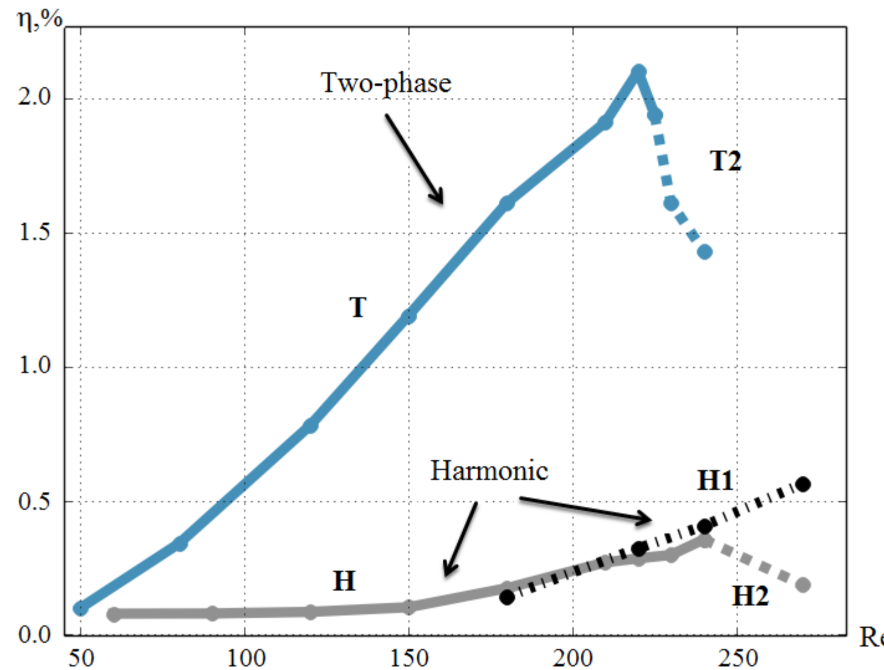

Fig. 8b: Efficiency of movement ($\eta = \frac{N_0}{N_{vbr}}$).

MAIN CHARACTERISTICS OF THE MOTION. SHAPE OPTIMIZATION

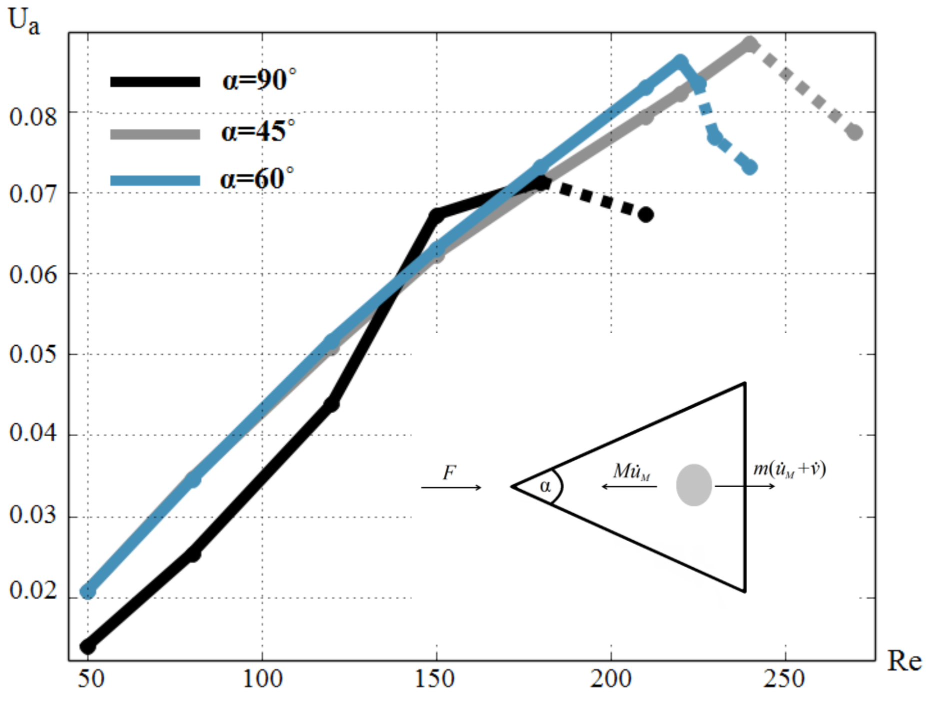

Fig.9a: Average velocity of movement ($\boldsymbol{U_a} = \langle \boldsymbol{U} \rangle$)

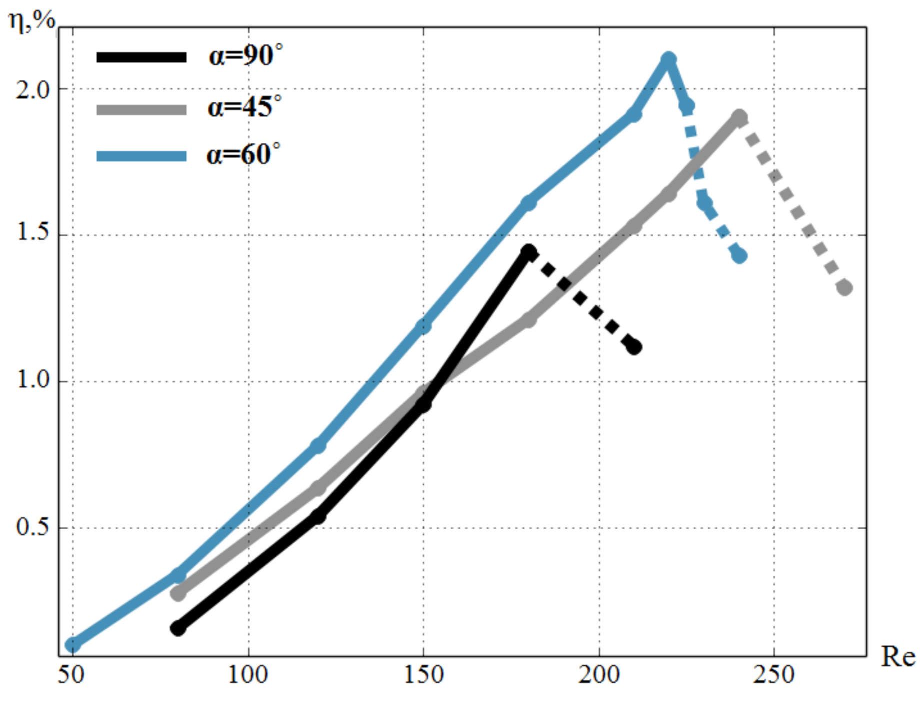

Fig. 9b: Efficiency of movement ($\eta = \frac{N_0}{N_{vbr}}$).

HYDRODYNAMIC FORCES APPROXIMATION

Forces acting on the shell of VDR can be approximately represented in the form:

$$F\left[u(t)\right] = C_D |u| u + C_m \frac{du}{dt}, \quad C_D = \begin{cases} C_{d+}, & u > 0 \\ C_{d-}, & u < 0 \end{cases}$$

We use this approximation to eliminate drag component from the full force calculated numerically:

$$L(C_{d+}, C_{d-}, C_m) = \sqrt{\sum_{i=1}^{N} \left(F[u(t_i)] - F_i^{\text{num}} \right)^2} \xrightarrow[C_{d+}, C_{d-}, C_m]{} \min$$

$$\left\langle F\left[u(t)\right] \right\rangle = \left\langle C_d |u| u \right\rangle \approx 0$$

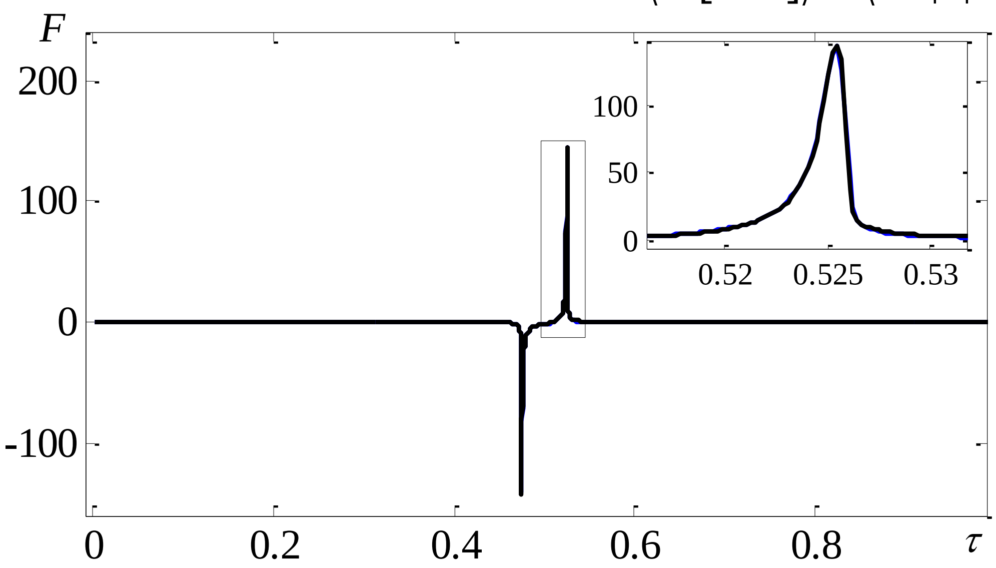

Fig. 10: Comparison of the full force and its approximation.

DRAG COEFFICIENT

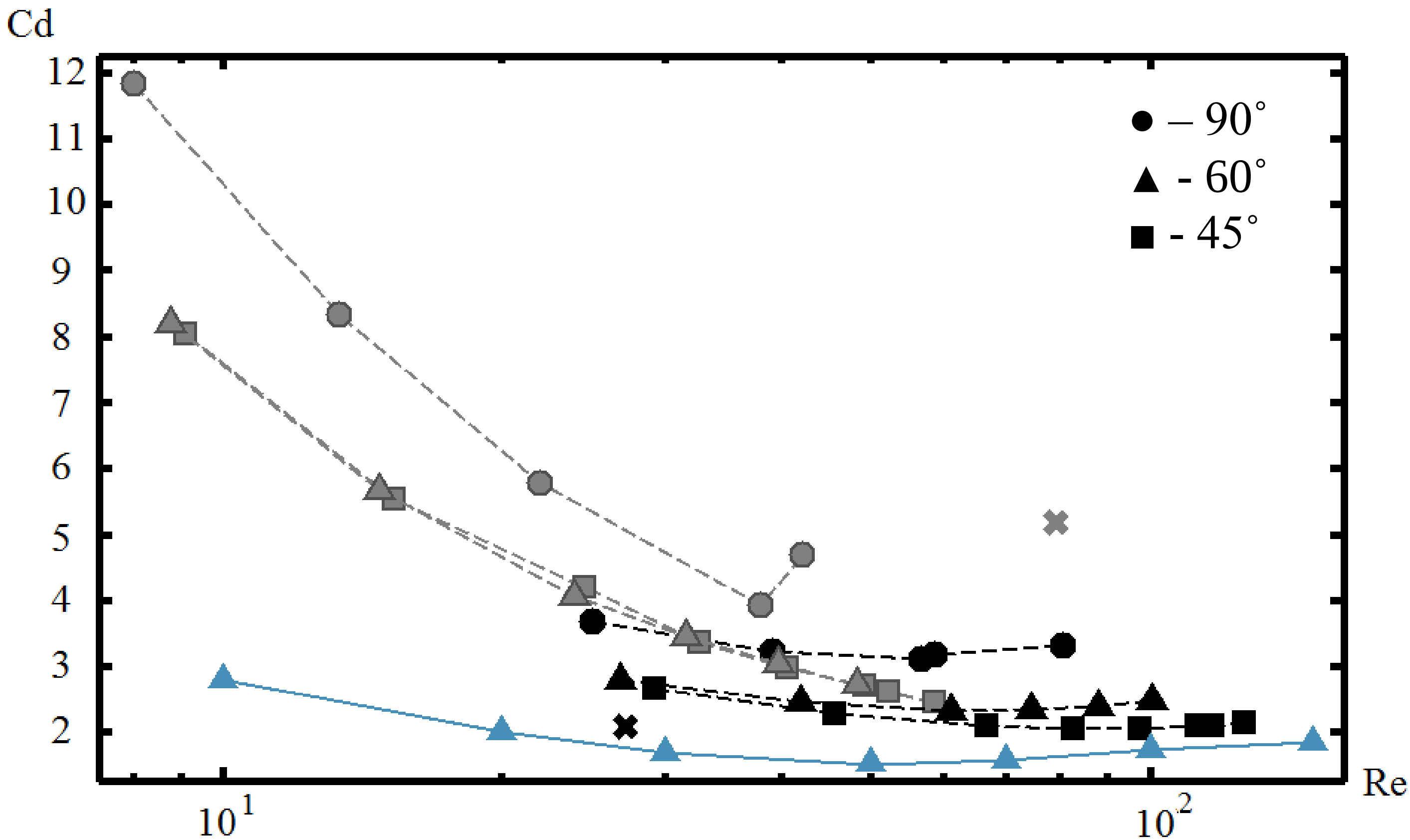

Fig. 11: Drag force coefficients. Gray markers– Cd+, black markers – Cd-. Blue line – Cd for steady flow past equilateral triangular cylinder.

Thank you for attention

Работа выполнена при поддержке грантов РНФ 15-19-10039 и РФФИ 16-31-00462 (мол_а). Численная модель движения виброробота в жидкости разработана при финансовой поддержке гранта РНФ 15-19-10039 в Нижегородском государственном университете.