Locomotion of the fish-like foil under own effort

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ABSTRACT

Self-locomotion of the fish-like foil is simulated by the mesh-free method of viscous vortex domains (VVD). The foil consists of three rigid sections connected by the spring hinges. The forcing periodic moment is applied between first and second sections imitating the muscular effort of the fish. The hinge between the second and third sections is elastic and passive. The task is solved as coupled flow-structure interaction.

Keywords: Flow-structure interaction, vortex method, VVD, flapping foil, elastic connections, Navier-Stokes equations

1. INTRODUCTION

To understand the bionic wings flow mechanism will be helpful to design high performance underwater vehicles and new conception aircrafts. Investigations of flapping wing thrust performance were carried out in a number of experimental and theoretical works (see, for example, [1-12]),

In most of theoretical works on this topic, the law of body motion in a constant incoming flow is set. The forces resulting from the movement are investigated. However, this formulation of the problem differs from the real situation, where the speed in a quasi-stationary motion is the result of applied efforts, the average horizontal hydrodynamic force is zero, and the vertical component balances the force of gravity if the density of the body exceeds the density of the medium. In addition, the speed of the body is not constant. To study such movement it is necessary to solve the flow-structure problem coupled motion. An effective method for solving such problems in a two-dimensional formulation based on the mesh-free method of viscous vortex domains (VVD) [13] was developed in [14, 15]. The method allows calculating the coupled motion of fluid and body systems with elastic connections.

2. METHODOLOGY

The model of a fish is represented by a foil consisting of three sections, which are connected by hinges (see fig. 1). The moment of force is applied between the first and second sections by harmonic law, resulting in the bending of the fish body. This simulates the muscular effort of a fish. The second hinge is elastic and passive. Its torque obeys the Hooke's law. The angles between the sections are determined by the dynamics equations. At the initial moment the fish begins bending in resting medium. This leads to the forward movement.

2.1 General governing equations

Fluid flow is described by the Navier–Stokes equations which are written for the vorticity ω in the form

$$\begin{aligned} &\frac{\partial \omega}{\partial t} = \nabla(\mathbf{u}\omega), \quad \mathbf{u} = \mathbf{V} + \mathbf{V}_d, \quad \mathbf{V}_d = -\nu\frac{\nabla\omega}{\omega}, \\ &\boldsymbol{\omega} = \omega\mathbf{e}_z = \nabla\times\mathbf{V}, \end{aligned} \tag{1}$$

where $\mathbf{V}$ is fluid velocity, $\mathbf{V}_d$ is so called diffusion velocity [16], ν is kinematic viscosity. The no-slip condition is imposed on the foil surfaces.

The fish-like foil is composed of three sections connected by elastic hinges. The contour of each section consists of circular arcs and straight line segments tangent to the arcs (see fig.1).

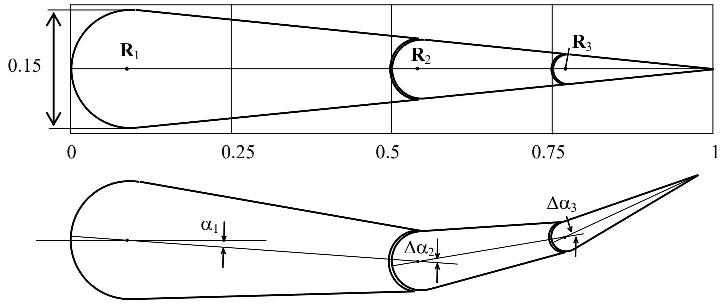

Fig.1 The fish-like model

The position of each section is described by the coordinates of the point $\mathbf{R}_i$, (i = 1,2,3) called the section axis and by the rotation angle α_i relative to the horizontal. The point $\mathbf{R}_i$, (i = 2,3) is connected with $\mathbf{R}_{i-1}$ and α_{i-1} as following

$$\mathbf{R}_i = \mathbf{R}_{i-1} + a_{i-1}\begin{pmatrix}\cos\alpha_{i-1}\\ \sin\alpha_{i-1}\end{pmatrix}, \quad a_{i-1} = \left|\mathbf{R}_i - \mathbf{R}_{i-1}\right| = const \tag{2}$$

The movement of the ith section is composed of the axis velocity $\mathbf{u}_i = \dot{\mathbf{R}}_i$ and the angular velocity $\Omega_i = \dot{\alpha}_i$. An arbitrary point $\mathbf{r}$ of the ith section moves at the velocity

$$\dot{\mathbf{r}} = \mathbf{U}_i + \mathbf{\Omega}_i \times \left(\mathbf{r} - \mathbf{R}_i\right) \tag{3}$$

Each section is acted upon by hydrodynamic forces $\mathbf{F}_H$ and moments $\mathbf{M}_H$, as well as forces and moments $\mathbf{F}_h$ and $\mathbf{M}_h$ in the hinges. We suppose that the friction in the hinges is missing, and the moment of elastic coupling is directly proportional to the deviation angle from the equilibrium position $\mathbf{M}_{h,i} = -k_i\Delta\alpha_i$, where ki is spring constant. In addition, a moment of force $\mathbf{M}_f$ is applied in the second hinge simulating the muscular efforts of the fish. The dynamic equations of the sections are:

$$\begin{aligned}
&m_1\dot{\mathbf{U}}_{m,1} = \mathbf{F}_{H,1} - \mathbf{F}_{h,2},;\\
&m_2\dot{\mathbf{U}}_{m,2} = \mathbf{F}_{H,2} + \mathbf{F}_{h,2} - \mathbf{F}_{h,3};\\
&m_3\dot{\mathbf{U}}_{m,3} = \mathbf{F}_{H,3} + \mathbf{F}_{h,3};\\
&I_1\dot{\mathbf{\Omega}}_1 = \mathbf{M}_{H,1} - \mathbf{M}_f - \mathbf{M}_{h,2} - (\mathbf{R}_2 - \mathbf{R}_1)\times\mathbf{F}_{h,2} - m_1\dot{\mathbf{U}}_1 \times \left(\mathbf{r}_{m,1} - \mathbf{R}_1\right);\\
&I_2\dot{\mathbf{\Omega}}_2 = \mathbf{M}_{H,2} + \mathbf{M}_f + \mathbf{M}_{h,2} - \mathbf{M}_{h,3} - (\mathbf{R}_3 - \mathbf{R}_2)\times\mathbf{F}_{h,3} - m_2\dot{\mathbf{U}}_2 \times \left(\mathbf{r}_{m,2} - \mathbf{R}_2\right);\\
&I_3\dot{\mathbf{\Omega}}_3 = \mathbf{M}_{H,3} + \mathbf{M}_{h,3} - m_3\dot{\mathbf{U}}_3 \times \left(\mathbf{r}_{m,3} - \mathbf{R}_3\right).
\end{aligned} \tag{4}$$

Here I_i, $\mathbf{r}_{m,i}$, $\mathbf{U}_{m,i}$ are moment of inertia, coordinates and velocity of the center of mass of i-th section respectively. The hydrodynamic forces and moments of forces consist of pressure and friction components $\mathbf{F}_p$, $\mathbf{M}_p$ and $\mathbf{F}_w$, $\mathbf{M}_w$. The pressure forces acting on the contour between points A and B can be written as the following

$$\mathbf{F}_p = \int_A^B p\mathbf{n}\,\mathrm{d}l = \mathbf{e}_z \times \int_A^B p\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}l}\mathrm{d}l = \mathbf{e}_z \times \left(p_B\mathbf{r}_B - p_A\mathbf{r}_A\right) - \mathbf{e}_z \times \int_A^B \frac{\mathrm{d}p}{\mathrm{d}l}\mathbf{r}\,\mathrm{d}l$$

$$\mathbf{M}_p = \int_A^B p\left(\mathbf{r}-\mathbf{R}_i\right)\times\mathbf{n}\,\mathrm{d}l = \mathbf{e}_z\int_A^B p\left(\mathbf{r}-\mathbf{R}_i\right)\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}l}\mathrm{d}l = \tag{5}$$

$$= \frac{\mathbf{e}_z}{2}\left(p_B\left(\mathbf{r}_B-\mathbf{R}_i\right)^2 - p_A\left(\mathbf{r}_A-\mathbf{R}_i\right)^2\right) - \frac{\mathbf{e}_z}{2}\int_A^B \frac{\mathrm{d}p}{\mathrm{d}l}\left(\mathbf{r}-\mathbf{R}_i\right)^2\mathrm{d}l$$

The pressure difference $p_B - p_A$ is

$$p_B - p_A = \int_A^B \frac{\partial p}{\partial l}\mathrm{d}l \tag{6}$$

Equations (5) – (6) make it possible to express forces and moments acting on the sections as integral of the function $\partial p/\partial l$ over its contour. The partial derivative along the contour $\partial p/\partial l$ is expressed from the Navier-Stokes equation

$$\frac{\partial p}{\partial l} = \mathbf{e}_l\nabla p = -\rho\left(\mathbf{e}_l\cdot\dot{\mathbf{V}}_c - \left(\mathbf{n}\cdot\mathbf{V}_d\right)\omega\right), \tag{7}$$

where $\dot{\mathbf{V}}_c$ is the fluid acceleration at the body surface. Due to the no-slip condition it is equal to the acceleration of the surface. The term $\left(\mathbf{n}\cdot\mathbf{V}_d\right)\omega$ is the vortex flux density from the surface.

For calculating the friction stress the following formula was used [17]

$$\mathbf{F}_w = -\nu\rho_f\int_{C_i}\mathbf{n}\times\boldsymbol{\omega}\,\mathrm{d}l,$$

$$\mathbf{M}_w = -\nu\rho_f\left(4\boldsymbol{\Omega}_i S_i + \int_{C_i}\left(\mathbf{r}-\mathbf{R}_i\right)\times\left(\mathbf{n}\times\boldsymbol{\omega}\right)\mathrm{d}l\right)$$

2.2 Numerical method

The equation of the vorticity evolution (1) is solved here by the fully Lagrangian method of Viscous Vortex Domains (VVD) [13] which is the improved kind of the Diffusion Velocity method [16]. As well as in [16], the vortex region of the flow is presented by the set of vortex “particles” (domains). The domains move at the velocity $\mathbf{u} = \mathbf{V} + \mathbf{V}_d$. The circulation of each domain are not varied. The main advantage of the VVD method is its more accurate way of calculating the diffusion velocity near the surfaces. New vortex domains are generated near the nodes of the body contour at each time step. The values of the new domains circulation γ_i^{new} must provide the boundary conditions. These conditions are written as the linear equations relative to these values. It was shown in [17] that the value $\left(\mathbf{n}\cdot\mathbf{V}_d\right)\omega$ is the vortex flux density from the surface. For *k*-th segment of the surface contour it can be approximated as the following

$$\left(\mathbf{n}\cdot\mathbf{V}_d\right)\omega = \frac{\gamma_k^{new}}{\Delta l_k\Delta t},$$

This equality leads to the expressions of the hydrodynamic forces and moments of force (5) via unknown values γ_k^{new}. As a result equations (4) together with boundary conditions equations and equalities (2) form a closed system of linear equations for all unknown quantities γ_k^{new}, $\mathbf{u}_i$ Ω_i [18]. Solution of this system satisfies the boundary conditions and the dynamic equations of the body simultaneously.

3. NUMERICAL RESULTS

The moment of force imitating the muscular efforts of the fish was set as $\mathbf{M}_f = \mathbf{M}_{f0} \sin(2\pi ft)$. The task was solved in the dimensionless variables. All linear dimensions are related to the length of the foil L, time is $t = \bar{t} / f$, velocity is $V = \bar{V} L f$ moments of force per unit span $M = \bar{M} \rho_f L^4 f^2$, where ρ_f is fluid density, $\mathrm{Re} = L^2 f / \nu$, $k = \bar{k} \rho_f L^4 f^2$, the body density $\rho = \bar{\rho} \rho_f$.

A vortex pattern obtained at $\bar{\mathbf{M}}_{f0} = 5.5$, $\mathrm{Re} = 1000$, $\bar{k}_2 = 13.4$, $\bar{k}_3 = 3.33$ is depicted in fig.2. Blue and red points depict clock-wise and counter clock-wise vortex domains. As can be seen from the figure, the vortex street is not reversive, since the motion is close to quasi-stationary. Average dimensionless velocity $\bar{U} = 0.96$.

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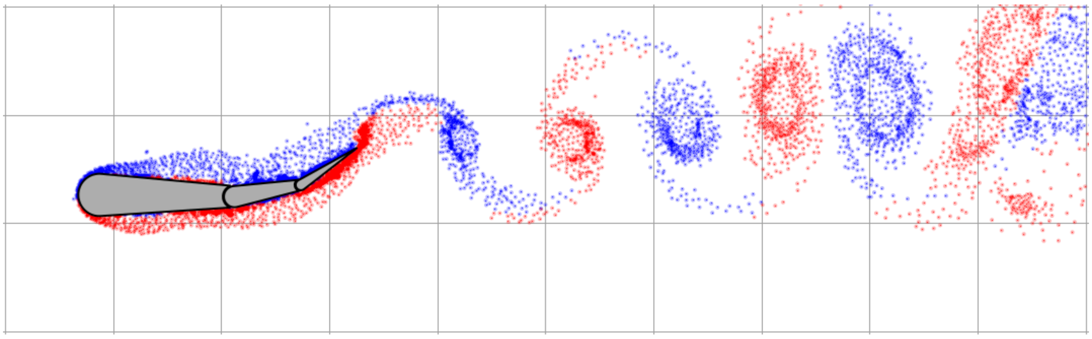

Figure 2 The vortex pattern around the self-moved fish-like foil

Dependency of the quasi-stationary velocity on the spring constant between the second and third sections $\bar{k}_3$ at different dimensionless amplitude of the forcing moment is presented in fig.4 at Re = 1078, and $\bar{k}_2 = 0.06$. One can see that the dependencies are not monotonical, that is, in each case there is an optimal value of $\bar{k}_3$.

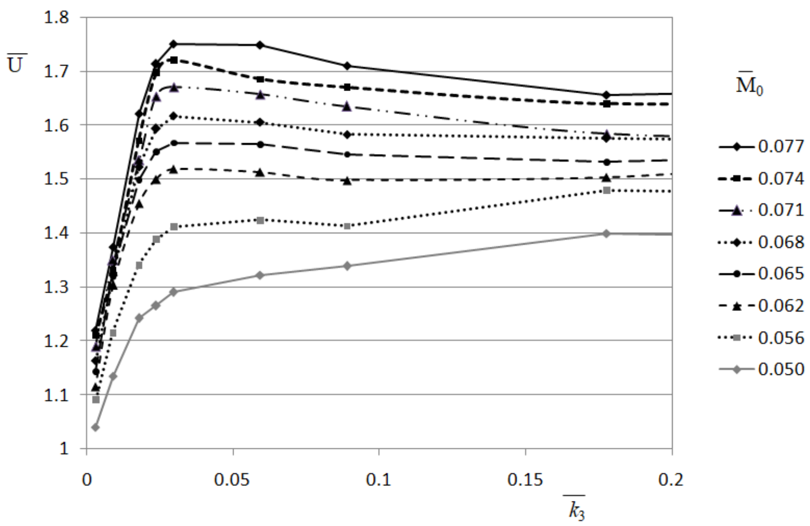

Figure 3. Dependency of the quasi-stationary velocity on the spring constant between the second and third sections at different amplitude of the forcing moment. Re = 1078, $\bar{k}_2 = 0.06$

Dependence of the quasi-stationary velocity on the dimensionless amplitude of the forcing moment at different spring constant between the second and third sections $\bar{k}_3$ is presented in fig.4 at Re = 1078, and $\bar{k}_2 = 0.06$.

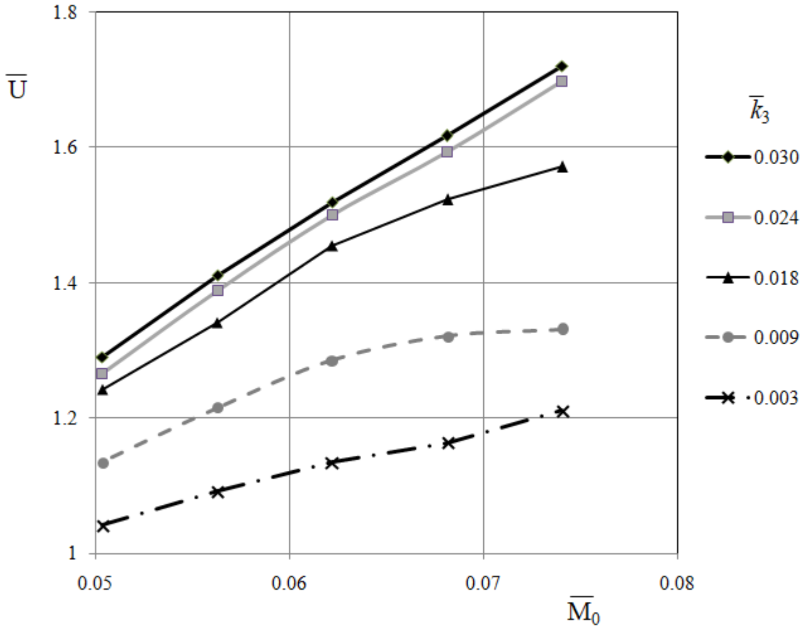

Figure 4. Dependence of the quasi-stationary velocity on the amplitude of the forcing moment at different spring constant between the second and third sections. Re = 1078, $\bar{k}_2 = 0.06$

4. CONCLUSIONS

The methodology of modeling body self-locomotion is presented. A method is applied for modeling the calculations performed by the developed method have shown its effectiveness. The dependency of the obtained quasi-stationary velocity on the recovery coefficient is investigated. It is shown that very low spring constant of the hinge is not optimal as well as very high one.

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