Movement Of The Flexible Thread System In The Viscous Fluid Stream

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***Abstract*—In this paper the movement perfectly flexible thread in a viscous liquid.Elastic deformation assocaited with the thread tension or compression, are not counted. We assume that the thread of the wetting liquid and the conditions of adhesion. The fluid motion is described by the Navier-Stokes equation (Radiant approximation for low Reynolds numbers). A closed system of equations with the boundary conditions.**

Keywords—Flexible thread, Reynolds number, Navier-Stokes equations, elastic deformation, tension force.

The paper considers the motion of a flexible filament system in a viscous fluid flow (Fig. 1)

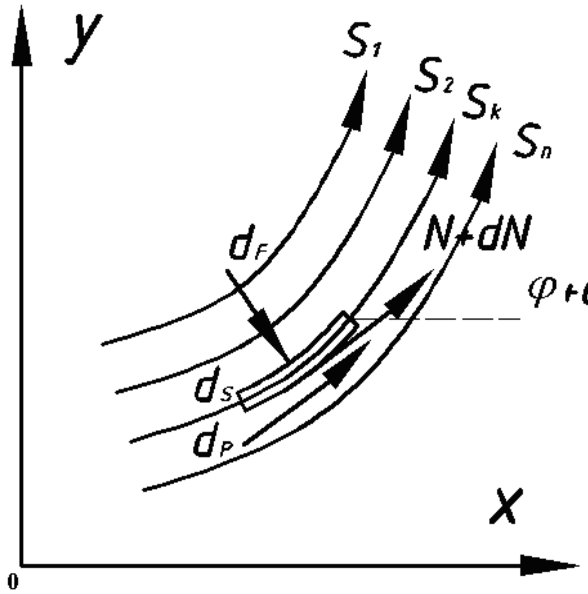
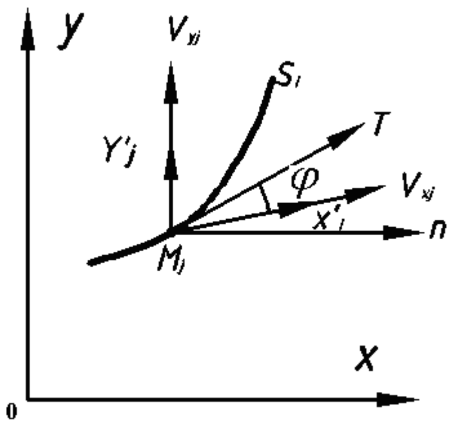


Fig. 1



The problem under consideration reduces to solving a two-dimensional problem. We consider an ideally flexible thread in the flow of a viscous fluid (Fig. 1). Since such a system does not have a resistance to bending, the only internal force is the tension force. The forces of inertia and gravity are negligibly small in comparison with the axial tension. It is assumed that each thread (j = 1,2 . N) in the zone of a viscous liquid does not come into contact with other threads. From the side of the deformable viscous liquid, the frictional force due to the velocity field acts on it.

The velocity field in the liquid is not violated. Elastic deformations associated with tension or compression of the filament are not taken into account. There are no sections of large (or infinite) curvature on the filament. The flow of a liquid is laminar and isothermal. The axis of the filament remains in the plane of fluid motion.

Write the equation of equilibrium. In the Cartesian XOU, the yarn coordinate system in the parameters of the pure shape is described by the functions x (s), y (s), where s is the coordinate counted along the filament axis. The axis of the filament lies in the plane XOY. The friction force acts on the thread element of length ds on the liquid side, the projection of which on the normal is dF, and on the tangent - dP (Fig. 1a). The angle between the horizontal direction, which we take as the direction of the x axis, and the tangent to the axis of the filament, is denoted by φ. Then the equilibrium equations have the form:

$$\sum x = 0 : (N_j + dN_j)\cos(\varphi + d\varphi) - N_j \cos\varphi + dF_j \sin(\varphi + d\varphi/2) + dP_j \cos(\varphi + d\varphi/2) = 0$$

$$\sum y = 0 : (N_j + dN_j)\sin(\varphi + d\varphi) - N_j \sin\varphi + dP_j \sin\left(\varphi + \frac{d\varphi}{2}\right) - dF_j \cos(\varphi + d\varphi/2) = 0$$

N_j - taking into account the relations:

$$\cos(\varphi + d\varphi) = \cos\varphi - d\varphi \sin\varphi + ...$$

$$\sin(\varphi + d\varphi) = \sin\varphi + d\varphi \cos\varphi + ...$$

and neglecting infinitesimals above the first order, we obtain the equations:

$$d\left(N_j^{x'}\right) + y'dF_j + x'dP_j = 0 \quad (1)$$

$$d\left(N_j y'\right) + y'dP - x'dF_j = 0 \quad (2)$$

Taking into account the relations $\sin\varphi = dy/ds = y'$; $\cos\varphi = dx/ds = x`$, here and below, the prime denotes the derivative of S.

If we use the conditions of inextensibility of the axis of the filament, then we obtain the following differential equation:

$$(x')^2 + (y')^2 = 1 \; . \quad (3)$$

We differentiate (3) by s:

$$x''x' + y''y' = 0 \; . \quad (4)$$

We multiply equation (1) by x′, and equations (2) - on y′, adding them together with (3) and (4) we have

$$dN + dP = 0 \quad (5)$$

Similarly, multiplying equation (1) by y′, (2) by x, and subtracting the equalities obtained taking into account relation (3), (4), we obtain the second equation of equilibrium

$$F' - Ny''/x' = 0 \quad (6)$$

Equations (5) and (6) describe the velocities of a liquid and a filament.

Consider the components of the frictional force. We assume that the thread is wetted with a liquid and the adhesion conditions are fulfilled. The maximum radius of curvature is much larger than the diameter of the filament. A boundary layer forms near the surface of the moving filament. Because of the linearity of the Navier-Stokes equations (the inertial approximation for small Reynolds numbers), the motions in the boundary layer can be regarded as the imposition of two motions: transverse and longitudinal flow around the filament. We note that for the non-Newtonian fluid the superposition principle of flows is not satisfied. In the case of a transverse flow past a filament (in an infinite cylindrical form), the friction force is determined by Lamb's formula [1].

$$dF = B_n \Delta V_n dS \quad (7)$$

where $B_n = 4\pi\mu/\ln(7.4\,\mathrm{Re})$; $\mathrm{Re} = \langle V \rangle d\rho/\mu$ - Reynolds number; μ - Fluid viscosity; d- Thread diameter; ρ - Fluid density; ΔV_n - Relative velocity of transverse flow; $\langle V \rangle$ - Characteristic velocity.

In the formula (7) the coefficient B_n takes into account the influence of the diameter of the thread. In a wide range of Reynolds numbers, it varies insignificantly (with increasing Re от 10^{-8} before 10^{-3} coefficient $B_и$ increases by 2.3 times). Therefore, the value B_n is assumed to be constant, corresponding to the characteristic flow velocity of the filament by the liquid.

With the mixing of systems filled with fibers (filaments), the flow of fluid around the individual fiber is topographically limited by the hydrodynamic influence of neighboring fibers. Therefore, in the first approximation, we consider a filament axially moving in a cylindrical tube filled with a viscous liquid (axisymmetric flow of Poette). Radius of the conditional tube <r> is determined by the average distance between the fibers and is related to their volume concentration <c> ratio [2] $\langle r \rangle = d/(2.1\sqrt{\langle c \rangle})$ (d – thread diameter), <c>=0.05÷0.30). In this case, the axial frictional force acting on the surface of the filament is given by [1]

$$dP = A_\tau \Delta V_\tau dS \quad (8)$$

where,

$$A_\tau = \pi d\mu / [\langle r \rangle lu(2\langle r \rangle / d)] = 21\pi\mu / lu(0.952\sqrt{\langle r \rangle}$$

;

ΔV_τ - the relative velocity of longitudinal flow around the filament by a liquid. Formulas (7) and (8) correctly reflect the linear dependence of the frictional force on the velocity under laminar flow. The stationary field of fluid velocity is characterized by components $\vec{v} = v_x \vec{i} + v_y \vec{i}\left([i = j]\right) = 1$, single points for the point M (arbitrary orthogonal vectors) of the point of the thread $v_x = \dot{x} = dx/dt, v_y = \dot{y} = dy/dt$.

The forces of viscous friction are due to some lag of the filament from the moving surrounding fluid. For

example, in the direction of the X axis, the fluid velocity v_x exceeds the thread speed $\dot{x}$, this is the magnitude $v_x - \dot{x}$. Projecting these velocities to the tangent and normal to the axis of the filament, for relative velocities we obtain expressions:

$$\Delta v_n = (v_x - \dot{x})\sin\varphi - (v_y - \dot{y})\cos\varphi,$$
$$\Delta v_\tau = (v_x - \dot{x})\cos\varphi + (v_y - \dot{y})\sin\varphi.$$

The dot denotes the derivatives with respect to t. As in (1), replacing trigonometric functions by the quantities $\dot{x}, \dot{y}$, we have

$$\begin{aligned}\Delta v_n &= (v_x - \dot{x})\dot{y} - (v_y - \dot{y})\dot{x} = 0,\\ \Delta v_\tau &= (v_x - \dot{x})\dot{x} + (v_y - \dot{y})\dot{y} = 0.\end{aligned} \quad (9)$$

Considering together (3), (5) - (9), we obtain a system of equations describing the nonstationary deformation of a flexible filament:

$$\begin{aligned}&w' + A_\tau\left[(v_x - \dot{x})x` + (v_y - \dot{y})y'\right] = 0\\ &Bn\left[(v_x - \dot{x})y' + (v_y - \dot{y})x'\right] - Ny''/x' = 0\end{aligned} \quad (10)$$

$$(x')^2 + (y')^2 = 1$$

Equations (10) must be supplemented by initial and boundary conditions:

$$t = 0 \quad x = x_0(s),\; y = y_0(s),\; N = 0$$

$$t > 0 \quad s = t_l \quad N = 0;\; y'' = 0$$

where t_l- length of thread; x_o (s), y_0(s)- Parametric description of the initial form of the thread. We take the sample S from the middle of the thread: to the right - the positive direction, to the left - the negative one (Fig. 1).

Literature

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