Nomenclature

$\bar{A}, \bar{A}_x, \bar{A}_y$ - rms amplitudes of tube vibrations in any, longitudinal and transverse directions relative to the direction of an incident flow, m;

$a$ - relative transverse pitch ($s_1/d$), thermal diffusivity, m$^2$/s;

$b$ - relative longitudinal pitch ($s_2/d$);

$b'$ - relative diagonal pitch of the staggered bundle ($s_2'/d$);

$c_D$ - total drag ($P_D/(0.5d\rho \bar{u}^2)$);

$s_f$ - friction drag ($P_f/(0.5d\rho \bar{u}^2)$);

$c_w$ - pressure drag ($P_w/(0.5d\rho \bar{u}^2)$);

$c_x, c_y$ - coefficients of the longitudinal and transverse nonstationary fluid-dynamic forces ($P_x/(0.5d\rho \bar{u}^2)$, ($P_y/(0.5d\rho \bar{u}^2)$);

$d$ - diameter, m;

$e$ - nondimensional displacement of the tubes relative to the symmetric position ($y/(s_1 - d)$);

$\bar{e}$ - relative spacing between the tube bundle and the wall ($h/(s_1 - d)$);

$l$ - tube length, m;

$l_c$ - correlation length, m;

$\Delta l$ - distance between two measurement points, m;

$F$ - force, N;

$f$ - frequency, Hz;

$f_s$ - frequency of vortex shedding, Hz;

$f_n$ - natural frequency of tube vibrations, Hz;
\( h \) - channel height; minimal flow section between the end tube of the bundle and the channel wall, m;

\( m \) - design mass of the tube per unit length \((m_i + m_a + m_f)\), kg/m;

\( m_i, m_a, m_f \) - tube mass, additional fluid mass and fluid mass in the tube, respectively, kg/m;

\( P_D \) - resultant drag force \((P_t + P_w)\), N;

\( P_t, P_w \) - resultant of the frictional forces and resultant of the pressure forces, respectively, N;

\( P_x, P_y \) - longitudinal and transverse stationary fluid-dynamic forces, N;

\( p \) - pressure, Pa;

\( \Delta p \) - pressure drop, Pa;

\( \bar{p} \) - pressure coefficient \((1 - \Delta p / (0.5 \rho \bar{u}^2))\);

\( S_A, S_u \) - spectral density of the tube vibration amplitude and of the flow velocity fluctuations, respectively, s;

\( s_1, s_2 \) - transverse and longitudinal pitches between the bundle tubes, m;

\( s' \) - diagonal pitch of the staggered tube bundle, m;

\( Tu \) - turbulence degree, \( \sqrt{\frac{\bar{u}^2}{\bar{u}}} \)

\( t \) - time, s;

\( \Delta t \) - time interval, s;

\( U_0 \) - velocity of the incident flow, m/s;

\( \bar{u} \) - velocity in the narrow cross section of the bundle \((U_0a/(a - 1))\), m/s;

\( u, v, w \) - components of the flow velocity, m/s;

\( u', v', w' \) - fluctuating components of the flow velocity, m/s;

\( X, Y \) - drag and lift forces, respectively, N;

\( x, y, z \) - Cartesian coordinates, m;

\( \alpha \) - angle of the bundle turn relative to the flow direction, deg.; thermal conductivity, W/(m²K);

\( \beta \) - angle of the tube inclination to the flow direction, deg.;

\( \delta \) - logarithmic decrement;

\( \mu \) - dynamic viscosity, Pa·s;

\( \gamma \) - kinematic viscosity m²/s;

\( \rho \) - fluid density, kg/m³;

\( \sigma \) - stress, N/m²;

\( \phi \) - angle, deg.;

\( \omega \) - angular frequency \((2\pi f)\), 1/s;

\( Pr \) - Prandtl number \((v/\alpha)\);
\( \text{Re} \) - Reynolds number \((\bar{u}d/\gamma)\);

\( \text{Sh} \) - Strouhal number \((f_d/\bar{u})\);

\( \text{Sh}_n \) - nondimensional vibration frequency of the tubes \((f/d/\bar{u})\).

Subscripts:

- \( f, 0 \) - in the undisturbed flow;
- \( w \) - at the wall;
- \( (\cdot) \) - averaging;
- \( (\cdot)' \) - fluctuating components.

The remaining nomenclature is given in the text.