

Research Article

Numerical Analysis of Flow-Induced Vibration of Heat Exchanger Tube Bundles Based on Fluid-Structure Coupling Dynamics

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According to the needs generated by the industry, there is an urgent need to investigate the flow vibration response law of the elastic tube bundle of heat exchangers subjected to the coupling effect of shell and tube domain at different inlet flow velocities. In this paper, based on the continuity equation, momentum equation, turbulence model, and dynamic grid technology, the vibration response of the elastic tube bundle under the mutual induction of shell and tube fluids is studied by using pressure-velocity solver and two-way fluid-structure coupling (FSC) method. The results show that the monitoring points on the same connection block have the same vibration frequency, while the vibration amplitude is different. Monitoring point A is the most deformed by the impact of fluid in the shell and tube domain. When the inlet velocity($v_{shell} = v_{tube} = 0.15$, 0.4, 0.5 m/s) of shell and tube is low, the amplitude of tube bundle vibration in the Y direction is greater than that in X and Z direction, and the tube bundle produces periodic vibration in the vertical direction. The vibration equilibrium position of the tube bundle along the shell flow direction gradually moves up with the increase of the inlet velocity. The amplitude in the Y-direction of the elastic bundle decreases with the increase of shell-side and tube-side velocity. The relationship between the vibration amplitude in the Y direction and the entrance velocity is a linear function.

1. Introduction

Heat exchangers are widely used in petroleum, chemical industry, machinery, refrigeration, and shipping [1, 2]. Bergles [3] reviewed that the heat transfer enhancement technique was classified into active, passive, and compound. Passive enhanced heat transfer technology can improve the heat transfer coefficient and make the heat exchanger's volume smaller and lower cost [4, 5]. The vibration of the elastic bundle heat exchanger induced by the internal fluid can enhance heat transfer between shell and tube side media at different temperatures and open up a new research direction for passive enhanced heat transfer technology in the heat exchanger [6].

For the research on the vibration of elastic tube bundle heat exchangers, a large number of scholars have carried

out a lot of fruitful work. Dorao and Fernandino [7] found that the vibration response of elastic bundle can improve the heat transfer coefficient, which is three times higher than that of the rigid bundle. Su et al. [8] numerical simulation results show that the heat transfer coefficient of the plane bending elastic tube bundle under vibration conditions is about 2.6 times higher than that under nonvibration conditions. Lai et al. [9] found that vibrating frequency increases monotonously as the void fraction of the two-phase flow increases by conducting a rotated triangular tube array. Tan et al. [10] concluded that low water inlet velocity causes the tube bundle to have a high vibration amplitude based on water tunnel experiments. Akram et al. [11] dealt with analysing the turbulence on flow-induced vibration response of the parallel triangular tube bundle and turbulence strongly affecting the tube bundle's frequency response.

With the rapid development of CFD technology, numerical simulation has gradually become an effective research method and is increasingly used in research. Zheng et al. [12] applied three-dimensional DNS study the fluid elastic instability of a single flexible pipe. Pedro et al. [13] studied a single elastic tube in a rigid tube bundle based on the one-way FSC method and dynamic grid technology. The unsteady flow field of self-oscillation of an equilateral triangular multicolumn array is simulated numerically by using the fluid-structure interaction [14]. The results show that the low-pressure zone formed by string vibration can improve heat transfer. Zhang and Øiseth [15] analyzed the effect of multimode coupling on the fluid elastic instability of tube arrays in a nonuniform flow and figured out conditions under which the multimode coupling effect becomes significant. Longatte et al. [16] proposed a numerical model of fluid-induced vibration using the LAE method. Still, the model could only predict the vibration frequency of the elastic supported rigid tube in crossflow and could not consider turbulence and tube deformation.

Cheng et al. [17] proposed a new type of elastic tube bundle, a novel horizontal curved tube to enhance heat transfer based on the above discussion. Ji et al.'s [18] study results show that the velocity of the shell side significantly influences the vibration frequency of stainless steel connection, and the vibration of elastic bundle induced by lowvelocity fluid has a harmonic frequency. The elastic tube bundle was made of copper, and stainless steel was used to connect the tube bundle. Stainless steel connector is not easy to install and easy to corrosion and rust for a long time. When welding copper and stainless steel, it is easy to form virtual welding, which is not conducive to long-term use. Therefore, the use of copper connectors in industrial production is more practical. The vibration response of the improved copper elastic tube bundle heat exchanger under shell-side fluid has not been studied. After the all-copper bundle was installed and fixed, the area of greatest force influenced by the shell process fluid was not revealed. The functional relationship between the tube bundle vibration displacement and the shell fluid velocity has not been established.

Therefore, this work aims to investigate the vibration rules of the whole copper tube bundle using the numerical calculation and experiment method. The research results can be used to guide the strength design of distributed elastic tube bundle heat exchangers and control the amplitude of tube process vibration using shell process flow rate, thereby improving enhanced heat transfer and cleaning the tube process wall fouling.

The main structure of this article is as follows: Section 2 introduces the structure of an all-copper elastic tube bundle heat exchanger. Section 3 presents the numerical approach, including the physical model, governing equations, grid system, boundary conditions, and data reduction. Then, the results and discussion are presented in Section 4, in which the heat transfer performance of the overall planar elastic tube bundle, single tube, local position, and the circumference of tube is discussed; at last, the final conclusions are provided in Section 5.

2. Numerical Simulation

2.1. The Structure of the Heat Transfer Device. The elastic tube bundle heat exchanger uses copper elastic heat transfer elements to replace traditional steel heat transfer elements, which is a specific device that uses flow-induced vibration to achieve passive heat transfer enhancement. An elastic tube bundle heat exchanger can enhance heat transfer by inducing elastic tube bundle vibration with fluid. Still, tube bundle vibration will cause fatigue damage, so the design reasonably of elastic tube bundle structure is essential [19, 20]. In the design of the elastic tube bundle heat exchanger, the fatigue life of the internal tube bundle should be taken into account. Fluid-induced vibration in elastic heat exchangers is a complex fluid-structure interaction problem, and most of the relevant research uses experimental methods with significant limitations. Therefore, the numerical method is applied to study the vibration response of elastic tube bundles in heat exchangers induced by shell-side fluid. And it is of great significance to further strengthen the heat transfer mechanism, optimize elastic bundle structure, and realize vibration control.

Figure 1 shows the geometric structure of the elastic tube bundle heat exchanger and the inside shell-side fluid domain [17]. The medium of shell-side fluid enters from the bottom and outflows from the upper shell-side outlet of the heat exchanger. The medium of tube-side fluid enters from the right side at the bottom and outflows from the bottom of the heat exchanger. There are six-row elastic tube bundles installed vertically on the shell side. As shown in Figure 1 on the right, take a single-row tube bundle as the research object in this paper.

The elastic bundle comprises four pure copper bends with radius R_1 , R_2 , R_3 , R_4 , and two pure copper connectors (*E* and *F*). In the practical application situation of the heat exchanger, the tube-side fluid flows into the port at I and flows out of the port at II. The elastic bundle's inner and outer diameters are d_1 and d_2 , respectively. The copper connecting block's length, width, and height are *l*, *m*, and *n*, respectively. In Figure 1, *Y* refers to the direction of the shell-side fluid. Detailed structural parameters of the elastic tube bundle are shown in Table 1.

2.2. The Mathematical Model. The main research problem in this paper is the elastic tube bundle in the shell, and tube side of different inlet velocities combinations induced vibration characteristics. Therefore, the whole solution domain is divided into the fluid domain (including the shell-side and tube side fluid domains) and the structure domain. The numerical calculation of flow-induced vibration of plane elastic tubes includes fluid and solid field calculations. Based on the ALE theory and motion/deformation grid method, the transient dynamic analysis module of ANSYS Workbench software and the CFD analysis software Fluent are used in this paper to conduct numerical research on the vibration response of elastic tube bundle induced by shell and tube side flow fields at different flow rates.

The geometry of the shell side and tube side fluid domain is shown in Figure 2, and Fluent Meshing software is used to complete discrete grids of the fluid domain. For



FIGURE 1: Schematic diagram of the elastic tube bundle heat exchanger [1].

Parameters	Symbol	Value
Distance of shell-side	Н	140 mm
Copper density	$ ho_c$	8900 kg/m3
Elastic modulus of copper	E_c	1.29 GPa
Poisson ration of copper	μ_c	0.33
Tube bend radiuses	R_1, R_2, R_3, R_4	(70, 90, 110, 130) mm
Connect block E	(l, m, n)	(80, 20, 20) mm
Connect block F	(l, m, n)	(40, 20, 20) mm
Position angle of connect block F	β	45°
Inner diameter of the tube	d_1	8 mm
Outer diameter of the tube	d_2	10 mm
Inner diameter of the inlet and outlet tube	d_3	32 mm
Outer diameter of the inlet and outlet tube	d_4	36 mm
Location of the inlet tube I	(X_1, Z_1)	(85, 85) mm
Location of the inlet tube II	(X_2, Z_2)	(22, 50) mm

TABLE 1: The structure and value of planar elastic tube bundles in the present work.

easy convergence, tetrahedral meshes are used in the fluid domain [21]. The single-row tube bundle is the solid field, using structured grids to realize discretization in ICEM CFD, as shown in Figure 3. The contact between the outer surface of a plane elastic tube bundle and the fluid domain is named the FSCI.



FIGURE 2: Grid distribution of each fluid domain.



FIGURE 3: Schematic diagram of two-way FSC calculation.

In the present work, one of the models has been tested for grid independence to find the optimal number of elements that can provide an optimal solution to the problem. Having the optimal number of grids also results in a reduction in simulation time. The grid convergence test was performed for model 1 with a blowing ratio of 1. The test was carried out by changing the mesh size by body size operation of the components and comparing the results of the adjacent wall temperature of the turbine blade.

Two-way FSC or multifield simulation is a concrete application of ALE theory. CFD analysis software Fluent calculated the shell and tube side fluids. The transient dynamics analysis module of ANSYS Workbench software was used to calculate the force on the tube. FSCI accomplishes data transfer between the fluid domain and the solid domain. The fluid-structure coupling solution is solved sequentially and independently in each time step by using the weak coupling method. When fluid-structure interaction is calculated, the outer surface of the tube-side fluid domain and the inner surface of the shell-side fluid domain is set as fluid-structure interaction surface, respectively. In the structure part, the inner and outer surfaces of the elastic tube bundle are set as FSCI, corresponding to the outer surface of the pipe side fluid domain and the inner surface of the shell side fluid domain, respectively.

Two-way FSC calculation data transmission is a twoway street, namely, inside each computing time step of fluid-domain calculation data is passed to solid motion equation to calculate; then, solid motion equation of the calculation results and data will be given back to the fluid-domain motion equation to calculate. Because twoway FSC calculation considers the tube between fluid and solid structure influences each other, the final calculation results are more consistent with the actual situation than those obtained by unidirectional fluid-structure coupling. As shown in Figure 3 is the schematic diagram of two-way FSC calculation.

The iterative calculation process of fluid-structure interaction is as follows:

(1) Set the total time *T* and the subtime step of FSC computation in the system coupling module

- (2) In the fluid domain, calculate the pressure distribution of the two coupling surfaces (outer surface of the shell-side fluid domain and inner surface of the shell-side fluid domain) by using the Fluent software. The CFD solver transmits the obtained pressure value to the structure domain through the system coupling module
- (3) The transient dynamic module takes the pressure as mentioned above as the initial conditions for dynamic analysis to obtain the displacement of the coupling surface of the structural domain
- (4) System coupling inputs the calculated displacement as the initial boundary condition of the fluid domain into Fluent, updating the grids of the fluid domain due to deformation of the structure domain
- (5) System coupling automatically judges whether the calculation time reaches the coupling time. If it does not, the calculation will continue alternately and iteratively until the set coupling time is reached
- (6) Two-way fluid-structure coupling calculation is completed, and the calculated data in the fluid domain and structural domain are analyzed, respectively

The abovementioned calculation process can be represented by the flowchart shown in Figure 4.

3. Governing Equations

3.1. Fluid Dynamic Equations. The medium in the fluid domain is incompressible Newtonian fluid in the study, including mass conservation equation and momentum conservation equation, can be expressed as follows [22]:

Mass conservation equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0.$$
(1)

Momentum equation N - S equation across the three directions x, y, and z is shown as follows:

X-direction:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right).$$
(2)

Y-direction:

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right).$$
(3)



FIGURE 4: The schematic diagram of the fluid-structure calculation process.

Z-direction:

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right).$$
(4)

Considering the shell-side fluid is in-compressible water and the turbulence caused by the vibration of the elastic tube bundle, Fluent's default RNG $k - \varepsilon$ model was selected to express the turbulence [23].

The turbulent kinetic energy equation:

$$\frac{dk}{dt} = \frac{1}{\rho} \frac{\partial}{\partial x} \left[\left(\mu_1 + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x} \right] + \frac{\mu_t}{\rho} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \frac{\partial y}{\partial y} - \varepsilon.$$
(5)

Turbulent kinetic energy dissipation rate equation:

$$\frac{d\varepsilon}{dt} = \frac{1}{\rho} \frac{\partial}{\partial y} \left[\left(\frac{u_t}{\sigma_{\varepsilon}} + u_1 \right) \frac{\partial \varepsilon}{\partial y} \right] + \frac{C_{\varepsilon 1} u_t \varepsilon}{\rho k} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \frac{\partial u}{\partial y} - C_{\varepsilon 2} \frac{\varepsilon^2}{k}.$$
(6)

TABLE 2: Boundary type and parameters of the simulation.

Parameters	Value	Boundary type
Media of fluid domain	Water	Internal domain
Flow temperature, T (K)	340	Internal domain
$v_{\text{shell}} = v_{\text{tube}} \ (\text{m/s})$	0.15/0.4/0.5/0.9	Velocity-inlet
P _{shell} (Pa)	0	Pressure-outlet
FSIC	SC	Wall
Connect block E	Copper	Earth traction
Connect block F	Copper	Earth traction
Tube of structure domain	Copper	Earth traction

TABLE 3: The result of grid independence.

Number of grids	Calculation time(hour)	Results	
		A (mm)	f (Hz)
231985	47	0.00933	19.95
394657	50	0.00933	19.95
648135	73.5	0.00932	19.95

TABLE 4: Natural frequencies of the elastic tube bundle.

Order	Natural frequency	Modal category
1	22.15	Vertical
2	33.28	Vertical
3	49.25	Horizontal
4	52.31	Vertical
5	52.38	Horizontal
6	84.99	Horizontal

The turbulence viscosity μ_t can be written as follows:

$$\mu_t = \frac{\rho C_\mu k^2}{\varepsilon}.$$
 (7)

The model constants have the following values: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_{\mu} = 0.09$, $\sigma_{k} = 1$, and $\sigma_{\varepsilon} = 1.3$.

3.2. FSC Dynamic Equations. The forces of the fluid domain and the structural domain on the coupling surface are in real-time equilibrium during calculation, and the finite element governs equation of the fluid-structure coupling system is obtained as follows [24]:

$$M_f \ddot{P}_e + C_f \dot{P}_e + K_f p_e + \rho R^T \ddot{u}_e = 0.$$
(8)

The structure's global governing equation is established using the Hamilton principle. Considering the effect of the fluid domain, the structural mechanics equation of the elastomer after discretization in the fluid domain is as follows:

$$M_p \ddot{u}_e + C_p \dot{u}_e + K_p u_e = F_P + F_f.$$
(9)

According to Eqs. (8) and (9), a discrete finite element equation describing the fluid-structure interaction problem can be obtained as follows:

$$\begin{bmatrix} M_{P} & 0\\ \omega R^{T} & M_{f} \end{bmatrix} \begin{Bmatrix} \ddot{u}_{e}\\ \ddot{P}_{e} \end{Bmatrix} + \begin{bmatrix} C_{P} & 0\\ 0 & C_{f} \end{Bmatrix} \begin{Bmatrix} \dot{u}_{e}\\ \dot{P}_{e} \end{Bmatrix} + \begin{bmatrix} K_{P} & 0\\ 0 & K_{f} \end{Bmatrix} \begin{Bmatrix} u_{e}\\ P_{e} \end{Bmatrix} = \begin{Bmatrix} F_{P} + F_{f}\\ 0 \end{Bmatrix}.$$
(10)

Because the coupling between the fluid and the solid domain only happens at the FSI interface, so the displacement and physical quantity are equal, and equation expression is as follows:

$$v_{fn} = v_f n_f = -v_s n_s = v_{sn},\tag{11}$$

$$\tau_{fn} = \tau_{sn},\tag{12}$$

$$x_f = x_s. \tag{13}$$

3.3. Initial and Boundary Conditions. This paper studies the influence of shell-side fluid velocity on tube bundle vibration. Tube side fluid and tube bundle fluid are set at the same temperature to avoid the impact of temperature factors on the properties of tube bundle material. Assume that there is no slip between the liquid and shell surfaces, the velocity component on the interface boundaries with solid elements is considered zero. The incompressible fluid (water) enters the shell-side and tube-side of the elastic heat exchanger with the same temperature and velocity. In the simulation, the inlet velocity profile of the heat exchanger was assumed to be uniform parallel flow.

Moreover, constant pressure (0 Pa) is considered at the outlet sections of the shell-side and tube side. During this simulation, the governing equations and boundary conditions together strictly constitute a complete mathematical description of a physical problem. The finite-volume-based solver and SIMPLE algorithm solved the pressure-velocity coupling problem with the first-order upwind scheme in commercial Fluent. The mentioned specific parameters of boundary conditions and physical parameters are presented in Table 2.

3.4. Grid Independence and Numerical Analysis Equipment. In order to ensure the stability and accuracy of numerical results, it is necessary to conduct grid-independent experiments. Therefore, taking the inlet velocity of the tube-side and the shell-side as 0.5 m/s, the experimental calculation of the vibration amplitude and frequency of monitor point D is carried out. Three sets of grid density on the numerical results are shown in Table 3.

In view of saving computer resources and calculating energy consumption and accuracy, a system with 394657 grids was selected to study the flow-induced vibration of planar elastic tube bundles in this work. Numerical analysis of elastic bundle vibration response is carried out on a workstation with parallel computing capability. HP Z840



FIGURE 5: The total vibration deformation with the coupling calculation time.

workstation having hardware specification of Intel(R) Xeon (R) CPU (E2680@ 2.4 GHz, 14 CPUs), 64 GB of RAM, and 4 GB of graphical memory (NVIDIA Quadro K2200) was used to carry out the analysis. In order to get more accurate simulation results, after several simulation preliminary calculations, the time step and continuity residual that were set to 0.001 s and 0.0001 were selected in the simulation, respectively.

4. Results and Analysis

4.1. Tube Bundle Modal Analysis. Natural frequency and mode were analyzed and conducted for elastic tube bundle using the modal module of ANSYS Workbench. It is beneficial to investigate the influence of shell flow velocity on formation characteristics induced by fluid through modal analysis. The first six orders of natural frequencies and mode shapes of single row elastic bundle are shown in Table 4. The vibration modes of the elastic bundle can be divided into vertical and horizontal vibration [25]. Orders 1, 2, and 4 modes are vertical vibration, and the natural frequencies are 22.15 Hz, 33.28 Hz, and 52.31 Hz, respectively. Orders 3, 5, and 6 mode are vertical vibration, and the corresponding vibration frequency is 49.5 Hz, 52.38 Hz, and 84.99 Hz, respectively. Vertical vibration is the vibration perpendicular to the plane of the elastic tube bundle. Horizontal vibration is the vibration parallel to the plane of the elastic tube bundle [2].

4.2. Numerical Simulation of FSC

4.2.1. Total Vibration Deformation. In order to investigate the effect of fluid velocity on the vibration response of elastic

tube bundle in both shell and tube course fields, the vibration characteristics of the elastic tube bundle induced by combining two fluid fields under different flow velocity conditions are studied. Where the shell and tube fluids have equal flow velocities ($v_{\text{shell}} = v_{\text{tube}}$), the fluid medium is water. The total deformation ζ of the elastic tube bundle as a whole with time t for different flow velocities (0.15, 0.4, 0.5, and 0.9 m/s) is shown in Figure 5. From Figure 5, it can be seen that the vibration can be achieved under the combination of two fields of fluid induced by the elastic tube bundle shell and tube course during the calculation period, and the total vibration deformation decreases with the increase of calculation time. Then, with the increase of calculation time, the total vibration deformation gradually tends to a periodic stable change [3]. This indicates that the computation time of the two-way fluid-solid coupling solution is reasonable. An interesting regulation was also found that the total vibration deformation value of the tube bundle becomes smaller as the flow rate increases.

4.2.2. Vibration Response Analysis in Each Direction. From the total vibration deformation curve of the tube bundle in Figure 5, it can be found that the elastic tube bundle is periodically vibrating after 0.7 s, induced by the combination of two fields of fluid in the shell and tube domain. Therefore, this paper selected and plotted the vibration displacement curves in the *X*, *Y*, and *Z* directions for each monitoring point in coupling calculation time within 0.7-1.1 s, as shown in Figure 6.

The curve of vibration displacement of monitoring point A, B, C, D in the *X*, *Y*, and *Z*-direction with coupling



FIGURE 6: Continued.



FIGURE 6: The vibration displacement under different inlet velocities.



FIGURE 7: The total vibration deformation of $v_{\text{shell}} = v_{\text{tube}} = 0.5 \text{ m/s}.$



FIGURE 8: The vibration displacement of monitor point A.

calculation time under different inlet velocity ($v_{\text{shell}} = v_{\text{tube}} = 0.1 \text{ m/s}$, 0.4 m/s, 0.5, 0.9 m/s) is plotted in Figures 6(a)–6(d). The following conclusions can be obtained from

Figure 6: first, on the same connector, each measurement point has the same vibration period, and the closer the monitoring point to the center of the circle, the lower the balance position of the vibration. Second, connection block E vibrates 1/4 cycle earlier than connection block F because the overall mass of connection block E is smaller than that of connection block F, which is more likely to vibrate first by the impact of water. Third, the vibration balance position of the monitoring points on the two connection blocks increases as the shell and tube inlet velocity becomes higher. Most importantly, the inlet velocity is 0.1, 0.4, and 0.5 m/s; vibration amplitude of each monitor point in the Y-direction is higher than that in X, Z-direction, tube bundle vibration is vertical vibration. At the inlet velocity of 0.9 m/s, the vibration amplitude of the tube bundle in the X-direction is slightly larger than that in the Y and Z-direction, but the vibration amplitude is smaller at high-speed flow. Therefore, based on the above conclusions, only the vibration characteristics of the elastic tube bundle in the y-direction are investigated in the next study of this paper.

The tube bundle's total vibration deformation distribution contour at the inlet velocity $v_{shell} = v_{tube} = 0.5$ m/s is as shown in Figure 7. It can be found that monitoring point A has the largest deformation (this law is applicable in the other three flow velocities, limited to the article's length again). Therefore, the vibration displacement variation law



FIGURE 9: The vibration amplitude in Y-direction under different water inlet velocities.

of monitoring point A in the Y-direction at different inlet velocities was studied, as shown in Figure 8. The vibration displacement is distributed in the negative direction of Y due to the earth's gravity. From the vibration curve, it can be found that as the coupling calculation is carried out, the displacement change of monitoring point A gradually becomes smaller and finally shows periodic vibration with different amplitudes. It was also found that the lower the inlet velocity, the greater the amplitude of vibration after stabilization.

The above interesting regularity was obtained by studying the vibration displacement in the Y-direction of the elastic tube bundle monitoring point A at different inlet velocities. In order to investigate the vibration law of each monitor point in the Y-direction under different inlet velocities by the coupling effect of shell and tube fluid, the fast Fourier transform is used to convert the displacement in the time domain to that in the frequency domain. An interesting phenomenon not mentioned in the previous literatures as shown in Figure 9 is the variation of vibration amplitudes (A) in the Y-direction of the monitor points with the different water inlet velocities. As can be seen from Figure 9, when the inlet velocities gradually become larger, the amplitude of the vibration of each monitoring point in the Y-direction in this study decreases as the inlet flow velocity increases. Moreover, the numerical simulation result experimental values are almost consistent. In other words, this is a good indication that the numerical model and theory used are in agreement with the experimental results. Additionally, the fitting results show the relationship between the vibration amplitude and the inlet velocity as a linear function. Moreover, for inlet velocities of 0.15, 0.4, and 0.5 m/s, the closer the monitoring point on the same connector is to the circle's center, the smaller the vibration amplitude.

5. Conclusions

Based on the two-way fluid-structure coupling method, the vibration response of elastic tube bundle induced by the shell-side and tube-side fluid at different inlet velocities is studied. The conclusions are as follows:

- (1) When the tube bundle is in the process of uniform vibration, the vibration deformation of monitoring point A is the largest, and the vibration displacement of monitoring point A becomes smaller with the increase of inlet velocity
- (2) The vibration frequency of the monitoring points on the same connection block is the same, and the vibration amplitude of the monitoring points on different connection blocks is different. The closer the monitoring points on the same connecting block are to the center of circle, the lower the equilibrium position of the vibration and the smaller the amplitude of the vibration
- (3) The inlet velocity is 0.1, 0.4, and 0.5 m/s, vibration amplitude of each monitor point in the *Y*-direction is higher than that in *X* and *Z*-direction, and tube bundle vibration is vertical vibration. And the amplitude of the elastic bundle decreases with the increase of shell-side and tube-side velocity. The relationship between the vibration amplitude in the *Y* direction and the entrance velocity is a linear function

Abbreviations

DNS:	Direct numerical simulation
FSC:	Fluid-structure coupling
ALE:	Arbitrary Lagrange Eulerian
CFD:	Computational fluid dynamics
FSCI:	Fluid-structure coupling interface
RNG:	Renormalization group
SIMPLE:	Semi-implicit method for pressure linked
	equations
SC:	System coupling.
Nomenc	lature
<i>B</i> :	Dimensionless heat source length
C_p :	Specific heat, J. kg ⁻¹ . K ⁻¹
<i>g</i> :	Gravitational acceleration, m.s ⁻²
<i>k</i> :	Thermal conductivity, W.m ⁻¹ . K ⁻¹
Nu:	Local Nusselt number along the heat source
ρ :	Fluid density
<i>v</i> :	Flow rate speed
$v_{\rm shell}$:	Inlet velocity of shell-side fluid
v_{tube} :	Inlet velocity of tube-side fluid
u:	Flow rate speed in the <i>x</i> -direction
<i>v</i> :	Flow rate speed in the y-direction
<i>w</i> :	Flow rate speed in the z-direction
P:	Pressure
μ:	Kinematic viscosity
t:	Time
<i>k</i> :	Turbulent kinetic energy
μ_1 :	Viscosity of laminar flow
μ_{i} :	Viscosity of turbulent flow
<i>E</i> :	Turbulent kinetic energy dissipation rate
$C_{s1}, C_{s2}, 0$	C _u : Constants of turbulent model
σ_{l}, σ_{s}	Prandtl number
M:	Mass matrix
C:	Damping matrix
<i>K</i> :	Stiffness matrix
F_{p} :	Structure internal force
F_{f} :	Force of fluid acting on the structure
ω:	Correction factor
R^T .	The coupling moment matrix on FSCI
ν _ε :	Normal velocity of the fluid on FSCI
v:	Normal velocity of the structure on FSCI
τ_{fn} :	Normal stress of the fluid on FSCI
$\tau_{}$:	Normal stress of the structure on FSCI
x_f :	Vibration displacement of fluid on FSCI
<i>x</i> .:	Vibration displacement of structure on FSC
$\dot{P_{\text{shall}}}$:	Outlet pressure of shell side
A:	Vibration amplitude
ζ:	Vibration displacement
R^2 :	Goodness of fit

Data Availability

Research data is only presented in this manuscript article.

Disclosure

A preprint has previously been published [26].

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Research data is only presented in this manuscript article.

Authors' Contributions

Lei Chen and Hongxin Zhang contributed equally to this article, and both are the first authors of this paper, hereby states.

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