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NUMERICAL STUDY OF COMBINED EFFECT OF FLUID AND THERMAL INDUCED FREE VIBRATION ON PIPE WITH SUPPORTED ENDS

NUMERIČKA STUDIJA KOMBINOVANOG UTICAJA FLUIDA I TOPLOTOM IZAZVANIH SLOBODNIH VIBRACIJA U CEVOVODU SA OSLONCIMA

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Keywords
- fluid and thermal induced vibration
- natural frequency
- thermal loads
- pressure
- elastic foundation
- finite element method

Abstract

The article aims to establish a coupled thermo-hydraulic numerical model for calculating the first natural frequencies and the first critical velocity corresponding to the appearance of buckling in the first mode, known as static instability of a hot fluid-conveying pipe. The circulating hot fluid has flexional motion as that of pipe structure. A dynamic characteristic of a pipe conveying internal fluid undergoes mechanical load due to the inertia effect of fluid, Coriolis effect, fluid kinetic force due to fluid flow velocity, dynamic load due to inertia effect, and thermal load due to hot fluid. A numerical modal analysis is realised in the fluid-structure interaction configuration. One-dimensional beam finite element is used for investigating the dynamic behaviour of the thin pipe, where the beam type has two degrees of freedom per node. According to the approved method, different elementary matrices are extracted, which are included into Matlab®. Results are compared with those predicted by analytical, numerical, and experimental methods. Results are presented for cases: pinned-pinned pipe conveying fluid without foundation; with elastic foundation by Winkler-model; with pressure force, for varying values of fluid velocity and thermal effect. The study shows that increase in temperature negatively affects the stability of the system, as the critical velocity of the fluid decreases regularly and corresponds to the decrease in the frequencies.

Ključne reči
- fluid i toplotno izazvane vibracije
- sopstvene frekvencije
- termičko opterećenje
- pritisak
- elastičan oslonac
- metoda konačnih elemenata

Izvod

Cilj rada je formulisanje spregnutog termohidrauličnog numeričkog modela za proračun prvih sopstvenih frekvencija i prve kritične brzine koje se odnose na pojavu izvijanja u prvom modu, što je poznato kao statička nestabilnost cevovoda sa toplim fluidom. Topli fluid koji protiče se pomera fleksiono kao i cevovodna konstrukcija. Dinamička karakteristika cevi kojom se transportuje fluid podrazumeva: mehaničko opterećenje usled inercije fluida; uticaj Koriolisove sile; kinetičko opterećenje usled brzine kretanja fluida; dinamičko opterećenje usled inercije; i termičko opterećenje usled toplog fluida u cevovodu. Urađena je numerička modalna analiza interakcije fluid-konstrukcija. Primenjen je konačni element jednodimenzionalnog nosača za određivanje dinamičkog ponašanja tanke cevi, gde tip nosača ima dva stepena slobode u čvoru. Shodno datom postupku, dobijene su različite elementarne matrice, koje su unete u Matlab®. Rezultati su upoređeni sa rezultatima dobijenim analitički, numerički i eksperimentalno. Rezultati su predstavljeni za slučajeve: cev za transport fluida sa dva nepokretna oslonca bez podloge; sa elastičnom podlogom po Winkler modelu; sa silom pritiska, za promenljive brzine fluida i sa termičkim uticajem. Istraživanje pokazuje da porast temperature utiče negativno na stabilnost sistema, dok kritična brzina fluida redovno opada i odgovara opadanju frekvencija.

INTRODUCTION

The problem of pipes conveying hot fluid has a very important role in various industrial applications. They are used in heat exchangers as nuclear production, fuel pipes in high duty engines, hydropower systems. Dynamic response of pipe structure conveying fluid with thermal load is very important for safe design and operation. The effect of internal fluid flow on transverse vibration of a pipe is studied by Païdoussis /1/. Fluid flowing through a pipe can impose pressure on the pipe wall which deflects the pipe, leads to fluid induced vibration; this type of force is referred to by the researcher in his first book /2/. Coriolis acceleration effect of the internal fluid is taken into account in /3/. Dahmane et al. /4/ studied the effect of Coriolis force of the internal fluid of pipeline by analytical approach using Galerkin method. Dahmane et al. /5-7/ studied the effect of a Winkler foundation on the critical velocity of a fluid-conveying pipe under different parameters. The fundamental frequencies of a pipe conveying incompressible fluid resting on a two-parameter foundation with different boundary conditions are studied by Chellapilla et al. /8/. This is a research on some of the geometric and physical parameters which have an effect on the vibration of the pipe carrying a fluid. Back to the topic of the thermal effect, many researchers have studied fluid flow and thermal load induced vibration /9-12/. Qian et al. in /13/ studied the instability of simply supported pipes conveying fluid under thermal loads, and by applying Hamilton's principle, the equation of motion is derived for the straight pipe under effects of linear and nonlinear stress-temperature cases. Recently, Zhao et al. analysed the stability of the pipe conveying fluctuant flow under thermal charge, by developing a mathematical model governing a pinned-pinned pipe conveying hot fluid. The problem is developed according to the Hamilton principle. Two partial differential equations describing the lateral and longitudinal vibration are obtained. The frequency response and the relationship between critical thermal rate and the pulsating fluid velocity are obtained /14/. Khoruzhiy et al. /15/ studied the effect of internal pressure on natural frequencies of bending vibrations of a straight pipe with fluid, where the effect of temperature on the natural frequency is not considered. Natural frequencies of bending vibrations of a pipe are computed by finite element method using ANSYS Mechanical®. The first natural frequencies are obtained for the pipe with the fluid depending on the density and internal pressure. In this case, the density of the fluid is taken into account in the equivalent density of the tube material. By the experimental method, Muhsin Jweeg and others in 2016 was able to calculate and analyse the effect of pressure on the first natural frequency and the buckling critical velocities. The results show good agreement between the estimated and analytical critical velocities in case of pinned-pinned ends and clamped-pinned ends of pipe conveying fluid. For clamped-clamped pipes, the accurate estimation requires higher flow rates /16/. Similar to this study, the numerical simulation method adopted by Dahmane et al. /4, 17, 18/ did not neglect the effect of pressure force emanating from the external medium, mainly represented by pressure forces resulting from the pumps, compressors, boilers, and generators, but the studies are not extensive and accurate in this aspect as they do not show the extent of its effect or not. The last study presented is tagged with effect of thermal load on vibration of clamped-clamped pipe carrying fluid, providing new and expanded accounts of a problem of pipes conveying hot fluid. The study shows that thermal loads reduce the natural frequencies of the system, the temperature has an effect on displacement as well as natural frequencies. We have found here that the parameter ΔT has a destabilizing effect, and the elastic foundation Winkler-model increases the system rigidity and consequently, the natural frequencies.

In the present study, calculation methods are developed for the analysis of stability regions and static instability in pinned-pinned pipe carrying fluid under thermal loads. Numerical modelling of structure-fluid is conducted by finite element method (FEM). We performed several calculations to obtain natural frequencies and critical velocities of fluid under various parameters, taking into account: fluid velocity, mass ratio, thermal load, pressure, and elastic foundation.

EQUATION OF MOTION

We consider a hot fluid element and beam element of length L, an internal cross-section area A, a mass per unit length m_S, and flexural rigidity EI. The mass per unit length of a conveying hot fluid m_f has an axial velocity U varying with time and P is the average pressure, referring to a Cartesian coordinate system (OXY), as shown in Fig. 1.

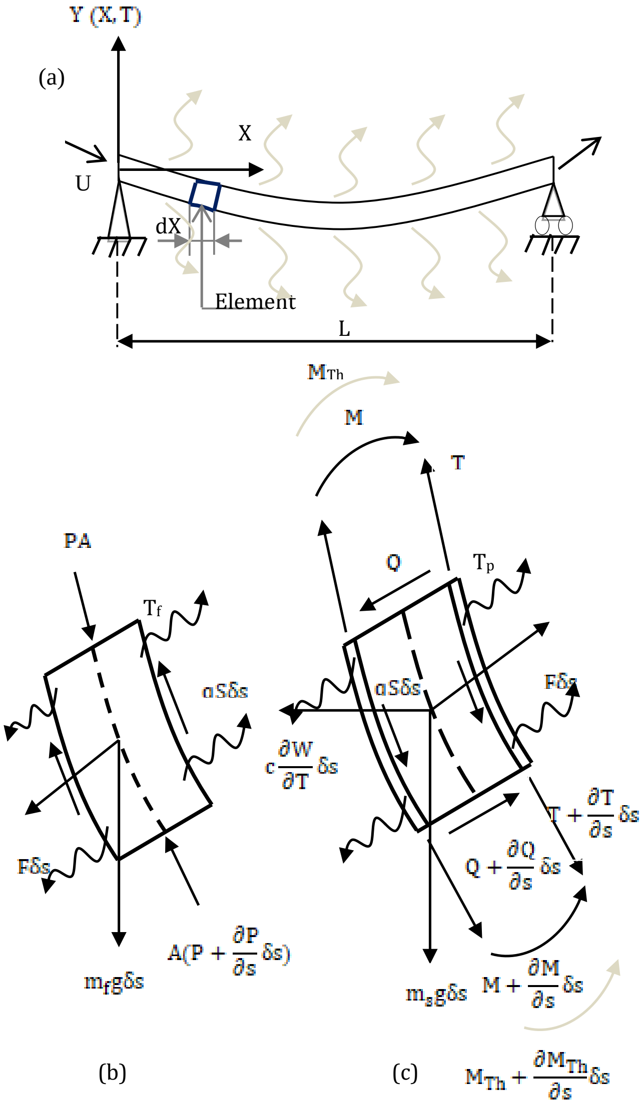


Figure 1. a) Pinned-pinned pipe conveying fluid; b) forces on fluid element; c) forces and moments on beam element δs /2, 18-19/.

Heat flux induced by the internal source is

$$h_1 S_1 (T_{\infty 1} - T_f)\,. \tag{1}$$

Heat transfer from hot fluid to pipe is:

$$\alpha S_2(T_f - T_s) \Big/ \ln\left(\frac{R_2}{R_1}\right). \quad (2)$$

Heat transfer from hot pipe to atmosphere at compressed side is

$$h_2 S_3(T_s - T_{\infty 2}). \quad (3)$$

The thermal moment M_{Th} due to change in rate of heat transfer is $EA\alpha\Delta T \frac{\partial^2 Y}{\partial X}$, /19/.

Where: h_1 is heat transfer coefficient from internal source (fluid); α is coefficient of thermal conductivity (pipe); h_2 is heat transfer coefficient of the external fluid (atmosphere); T_∞ is ambient temperature; T_f is temperature of hot fluid; T_s is temperature of structure (pipe); S_1, S_2, S_3 are the areas corresponding to each heat flow; R_1, R_2 are the inner and outer radius of the tube.

The pipe is assumed as an Euler-Bernoulli beam initially aligned with the X axis and lateral displacement. The equation derivation is based on Bernoulli-Euler elementary beam theory. The model of system is shown in Fig. 1a,

$$EI\frac{\partial^4 Y}{\partial X^4} + (m_f U^2 + PA + E\alpha\Delta TA)\frac{\partial^2 Y}{\partial X^2} + 2m_f U\frac{\partial^2 Y}{\partial X \partial T} + (m_s + m_f)\frac{\partial^2 Y}{\partial T^2} = 0, \quad (4)$$

where: $EI\frac{\partial^4 Y}{\partial X^4}$ is the stiffness term; and the curvature term is $(m_f U^2 + PA + E\alpha\Delta TA)\frac{\partial^2 Y}{\partial X^2}$; the linear elastic stress-temperature coefficient /13/ is defined as $E\alpha\Delta T$; the Coriolis force term is $2m_f U\frac{\partial^2 Y}{\partial X \partial T}$; and $(m_s + m_f)\frac{\partial^2 Y}{\partial T^2}$ is the inertia force term. The non-dimensional parameters /2, 14, 15/ are obtained as: $x\ X/L$; $y = Y/L$; $t = [EI/(m_f + m_s)^{1/2}]T/L^2$; $\beta = m_f/(m_f + m_s)$; $u = UL(m_f/EI)^{1/2}$; $\Omega = (m_f + m_s/EI)^{1/2}\omega L^2$; $k = KL^4/EI$; $\Pi = PAL^2/EI$. The non-dimensional thermal load is $\Gamma = \alpha A\Delta TL^2/I$.

The boundary conditions for our system are,

$$Y\big|_{X=0} = \frac{\partial^2 Y}{\partial X^2}\bigg|_{X=0} = Y\big|_{X=L} = \frac{\partial^2 Y}{\partial X^2}\bigg|_{X=L} = 0. \quad (5)$$

The presence of an internal heat source in a cylindrical shape with small dimensions makes the heat difference negligible, meaning that the exchange is almost floating. In this study the transfer of heat from the fluid to the structure is adopted, accordingly we adopt the following relationship in the research /18/,

$$\Delta T = T_f - T_s. \quad (6)$$

FINITE ELEMENT DISCRETIZATION

Equation (4) is a fourth-order partial differential equation in two independent variables subject to various boundary conditions. It is not easy to get its analytical solution, but we get it through the use of finite element method. The equation of element deflection for straight two-dimensional beam elements could have the form /20/,

$$W(X,T) = \sum_{i=1}^{N} N_i(X) W_i(T). \quad (7)$$

There are two degrees of freedom (DOFs) at a node in a planner beam element. They are deflection in the Y-direction and rotation in X-Y plane /21/. Hence, each beam element has four DOFs.

Therefore, Eq.(7) becomes

$$W(X,T) = N_1(X)W_1(T) + N_2(X)\theta_1(T) + N_3(X)W_2(T) + N_4(X)\theta_2(T), \quad (8)$$

and

$$\theta(X,T) = N_1'(X)W_1(T) + N_2'(X)\theta_1(T) + N_3'(X)W_2(T) + N_4'(X)\theta_2(T). \quad (9)$$

The potential (deformation) energy of the solid and the kinetic energy of the solid and the fluid element allows us to present the different elementary matrices as follows /5, 22-25/:

stiffness matrix

$$[\mathrm{K_s}] = \frac{m_f U^2}{30l}\begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix}, \quad (11)$$

fluid element matrix

$$[\mathrm{K_f}] = \frac{m_f U^2}{30l}\begin{bmatrix} 36 & 3l & -36 & 3l \\ 3l & 4l^2 & -3l & 3l^2 \\ -36 & -3l & 36 & -3l \\ 3l & 3l^2 & -3l & 4l^2 \end{bmatrix}, \quad (12)$$

element mass matrix

$$[\mathrm{M}] = \frac{(m_s + m_f)l}{420}\begin{bmatrix} 156 & 22l & 54 & -13l \\ 22l & 4l^2 & 13l & -3l^2 \\ 54 & 13l & 156 & -22l \\ -13l & -3l^2 & -22l & 4l^2 \end{bmatrix}, \quad (13)$$

fluid damping matrix

$$[\mathrm{C}] = \frac{2m_f U}{30}\begin{bmatrix} -30 & 6l & 30 & -6l \\ -6l & 0 & 6l & -l^2 \\ -30 & -6l & 30 & 6l \\ 6l & l^2 & -6l & 0 \end{bmatrix}, \quad (14)$$

fluid pressure matrix

$$[\mathrm{K_p}] = \frac{PA}{30l}\begin{bmatrix} 36 & 3l & -36 & 3l \\ 3l & 4l^2 & -3l & 3l^2 \\ -36 & -3l & 36 & -3l \\ 3l & 3l^2 & -3l & 4l^2 \end{bmatrix}, \quad (15)$$

element thermal matrix

$$[\mathrm{K_{Th}}] = \frac{E\alpha A\Delta T}{30l}\begin{bmatrix} 36 & 3l & -36 & 3l \\ 3l & 4l^2 & -3l & 3l^2 \\ -36 & -3l & 36 & -3l \\ 3l & 3l^2 & -3l & 4l^2 \end{bmatrix}. \quad (16)$$

Foundation matrix of the system given by /18, 23-25/,

$$[\mathrm{F}]=\frac{Kl}{420}\begin{bmatrix}156 & 22l & 54 & -13l\\ 22l & 4l^2 & 13l & -3l^2\\ 54 & 13l & 156 & -22l\\ -13l & 3l^2 & -22l & 4l^2\end{bmatrix}. \qquad (17)$$

The equation for pipe carrying hot fluid on a Winkler elastic foundation is given as,

$$EI\frac{\partial^4 Y}{\partial X^4}+(m_f U^2+PA+E\alpha A\Delta T)\frac{\partial^2 Y}{\partial X^2}+2m_f U\frac{\partial^2 Y}{\partial X\partial T}+$$
$$+(m_s+m_f)\frac{\partial^2 Y}{\partial T^2}+KY=0\,. \qquad (18)$$

The standard equation of motion in finite element form is

$$[\mathrm{M}]\{\ddot{q}\}+[\mathrm{C}]\{\dot{q}\}+([\mathrm{K}])\{q\}=0\,. \qquad (19)$$

RESOLUTION METHOD

Considering the displacement vector as /5/,

$$\{Q\}=\{E\}\exp(\lambda t)\,. \qquad (20)$$

The governing equation of the system for fluid-structure coupling can be transformed into its state-space,

$$\left\{\begin{bmatrix}0 & \mathrm{I}\\ -\mathrm{M}^{-1}\mathrm{K} & -\mathrm{M}^{-1}\mathrm{C}\end{bmatrix}-\lambda\begin{bmatrix}\mathrm{I} & 0\\ 0 & \mathrm{I}\end{bmatrix}\right\}\begin{bmatrix}\lambda\{E\}\\ \{E\}\end{bmatrix}=\begin{bmatrix}0\\ 0\end{bmatrix}, \qquad (21)$$

where: I is the identity matrix.

The solution of eigen-values problem should be executed to the characteristic matrix of frequency [Ω] /26/, which is equal to

$$[\Omega]\equiv\begin{bmatrix}0 & \mathrm{I}\\ -\mathrm{M}^{-1}\mathrm{K} & -\mathrm{M}^{-1}\mathrm{C}\end{bmatrix}. \qquad (22)$$

The solution of the eigen-value problem gives complex roots /2/. The imaginary part of the roots represents natural frequencies of vibration and the real part represents the rate of decay of vibration. The characteristic equation is solved by using Matlab program. Complex conjugate eigen-values,

$$\lambda^m=\mathrm{Re}^m+j\omega^m\,. \qquad (23)$$

The stability and static instability of the system under consideration is determined by the sign of real part, and the natural frequency values (imaginary part) of the complex eigen-value.

RESULTS AND DISCUSSION

In the current work, results are discussed according to different values of temperature parameter (ΔT), fluid velocity (u), mass ratio (β), elastic foundation (k) and the effect of pressure, calculating the frequency of the first three eigen-modes of pinned-pinned pipe on a Winkler elastic foundation. The results are divided into two main parts. The first part is devoted to evaluating the numerical model by presenting the results and comparing them with previous studies. Part two contains three sections, where results are presented in terms of several parameters. The physical and structural properties of the model are the same as used in studies /5-7/, with the addition of the following thermal property $\alpha = 11\times10^{-6}$ °C^{-1}. As for the properties of the fluid, it corresponds to that which was previously studied, /4, 18/.

Validation of the numerical model

In the first part, the results are presented and compared with previous studies to clarify the effect of thermal loads on buckling of beam and system stability. The preliminary results are for a temperature difference not exceeding 2.5 degrees Celsius, provided that the study is generalized in its second part, over an interval of 12.5 degrees Celsius with 2.5 steps. Results are given in dimensionless values (section 1, below), and dimensional values (section 2, below).

Section 1: The results of this section are presented dimensionless in accordance with many previous studies, the three frequencies variation of the pinned-pinned pipe are presented under fluid flow with little thermal force for different mass ratios, where the temperature difference between the two middles does not exceed 2.5 °C. Through Figs. 2 to 4, in respect, the effect of thermal action on natural frequencies variation of the pipe carrying incompressible fluid is clear. The thermal loads contribute to the buckling phenomenon between the supports, and these appear clearly in the first mode and less severe in the following two modes. This action reduces the stability of the system, resulting in lower natural frequencies, and hence, the critical velocity of the fluid that reaches the point of saturation, which leads to the disappearance of the first mode of transverse vibration. No matter how much we increase the value of β, the results remain somewhat convergent, and this is due to the use of dimensionless values. We have referred to this proposition in another paper /5/.

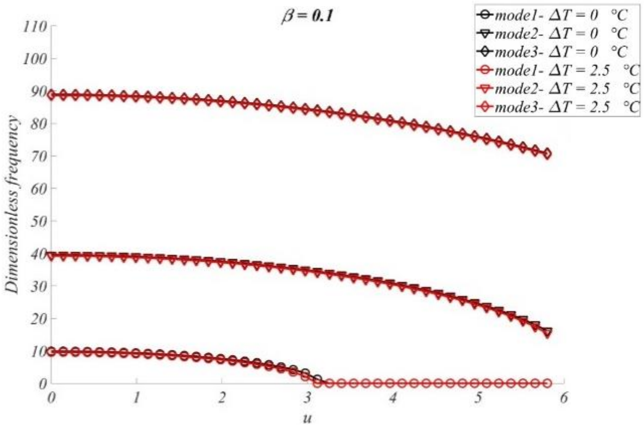


Figure 2. First 3 natural freq. vs. fluid velocity of pinned-pinned pipe for $\beta = 0.1$, without /5/, and with thermal effect (present study).

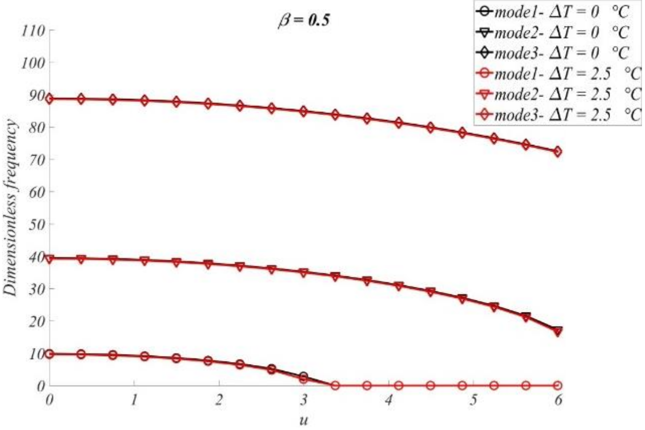


Figure 3. First 3 natural freq. vs. fluid velocity of pinned-pinned pipe for $\beta = 0.5$, without /27/, and with thermal effect (present study).

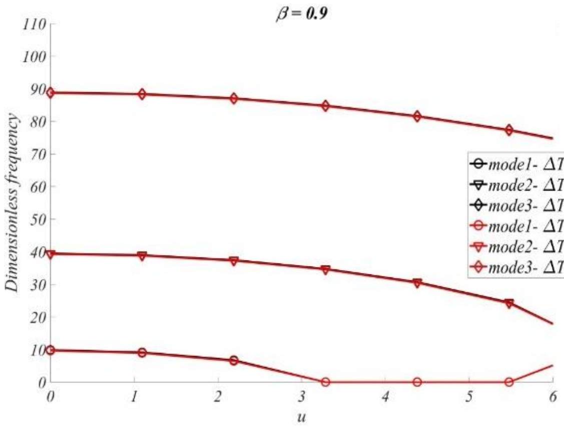


Figure 4. First 3 natural freq. vs. fluid velocity of pinned-pinned pipe for $\beta = 0.9$, without /16/, and with thermal effect (present study).

The effect of thermal loads on the vibration behaviour of the pipe conveying fluid is shown when we study each frequency separately (Fig. 8), where the largest variation is at the level of the first mode, within 2.75 %, while critical velocity decreases by 2.85 %, where it corresponds to the same mode.

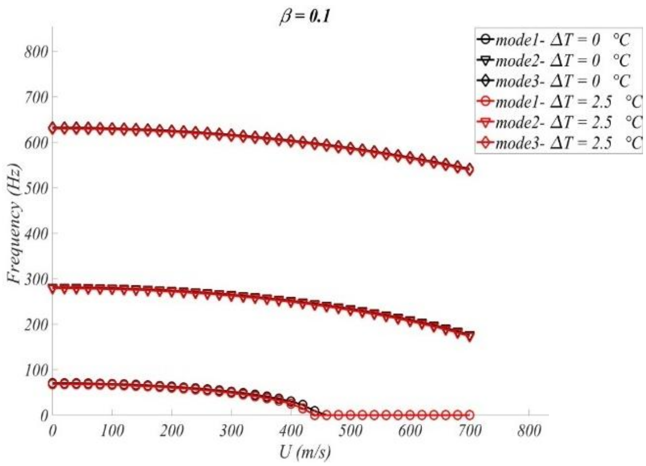


Figure 5. First 3 natural freq. (Hz) vs. fluid velocity of pinned-pinned pipe for $\beta = 0.1$, without ($\Delta T = 0$), and with thermal effect ($\Delta T = 2.5$).

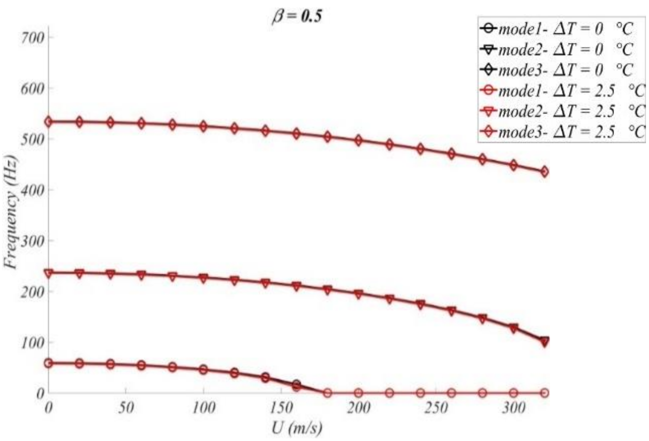


Figure 6. First 3 natural freq. (Hz) vs. fluid velocity of pinned-pinned pipe for $\beta = 0.5$, without ($\Delta T = 0$), and with thermal effect ($\Delta T = 2.5$).

Section 2: Figs. 5 to 7 show the first three modes (Hz) of pipe on simple supports conveying hot fluid for different mass ratios. It appears clear on these figures that the mass ratio influences the first modes and consequently the critical velocity and system stability. Results show the same variation in dimensionless and dimensional values for temperature increment $\Delta T = 2.5$ °C.

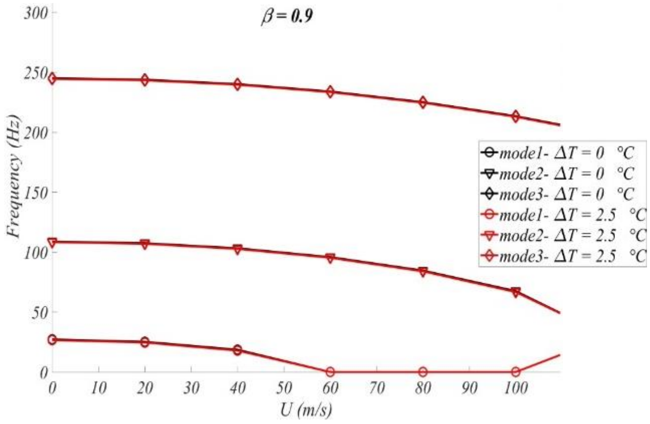


Figure 7. First 3 natural freq. (Hz) vs. fluid velocity of pinned-pinned pipe for $\beta = 0.9$, without ($\Delta T = 0$), and with thermal effect ($\Delta T = 2.5$).

Pipes conveying incompressible fluid under thermal loads

In the general case, the hot fluid-conveying pipe is subjected to various force and parameters that affect its vibration behaviour. In the second part, the numerical results are presented and discussed according to different parameters, as it divides the study.

Section 1: Firstly, we extend the study to an interval of 12.5 °C. Figures 8 to 10 show the first three frequencies in terms of fluid velocity and thermal effect for different values of β. Its k is zero (without foundation), the largest variation in frequency values is equal to 16 % as it corresponds to a change of 15.84 % in the critical velocity with a value of 2.64, see Fig. 8.

Figure 9 shows a slight difference in the results, due to the fact that the thickness of the tube reduces the heat transfer between the two mediums (R1 to R2), while the variation remains the same in the third mode, regardless of the pipe thickness, see Fig. 10.

Section 2: We repeat the same study to an interval of 12.5 °C with the addition of a Winkler elastic foundation to increase the rigidity of the system. Figures 11 to 16 show the first three frequencies in terms of fluid velocity and thermal loads for different values of β and k-elastic foundation. Low frequency values mean that the structure of the system has lost some of its rigidity under the dual effect of fluid and heat transfer, where the changes in frequencies due to the energy are emanating from the fluid and the thermal transfer in its linear behaviour. We remark that the first natural frequency is decreasing gradually for various values of temperature increment (ΔT) and various values of fluid velocity (u). The higher the stiffness value, the higher the frequency value.

Section 3: The pipes carrying incompressible fluid on supported ends are subjected to other forces due to the internal pressure generated mainly by pumps and compressors. The aim of this section is to calculate the natural frequencies and critical buckling velocity in terms of pressure force and Winkler elastic foundation for different mass ration.

Figures 14 and 15 show the variation in the first mode in terms of velocity and effect of fluid for two values of k_0 and β. The pressure force lowers the frequencies and hence the critical velocities, while opposite to that of the elastic foundation. Figures 14 and 15 also show the emergence of the second critical velocity corresponding to the flutter (dynamic instability) /7/, in addition to the above it decreases by increasing β.

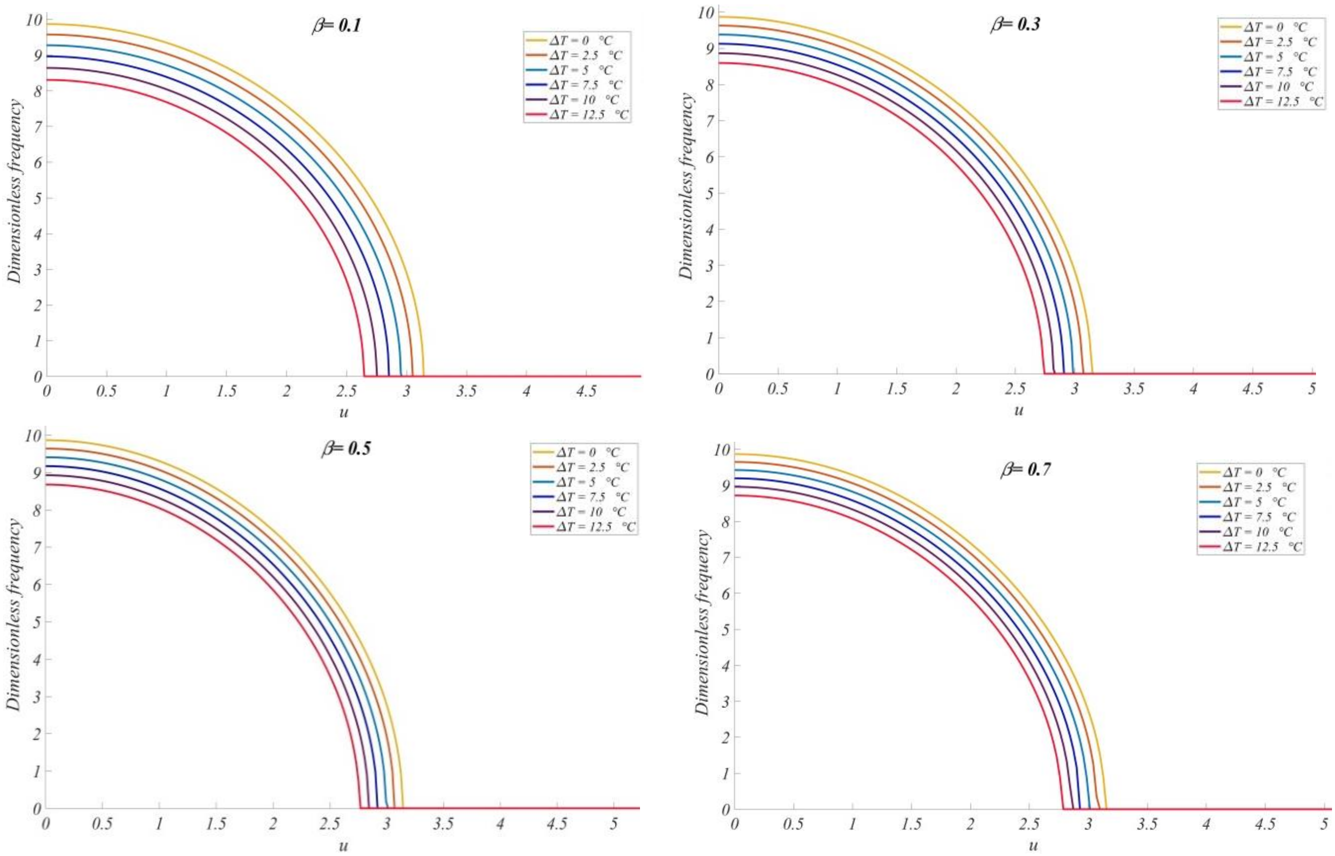


Figure 8. First natural freq. vs. fluid velocity and thermal load of pinned-pinned pipe for different β, without thermal effect (ΔT = 0) /5/.

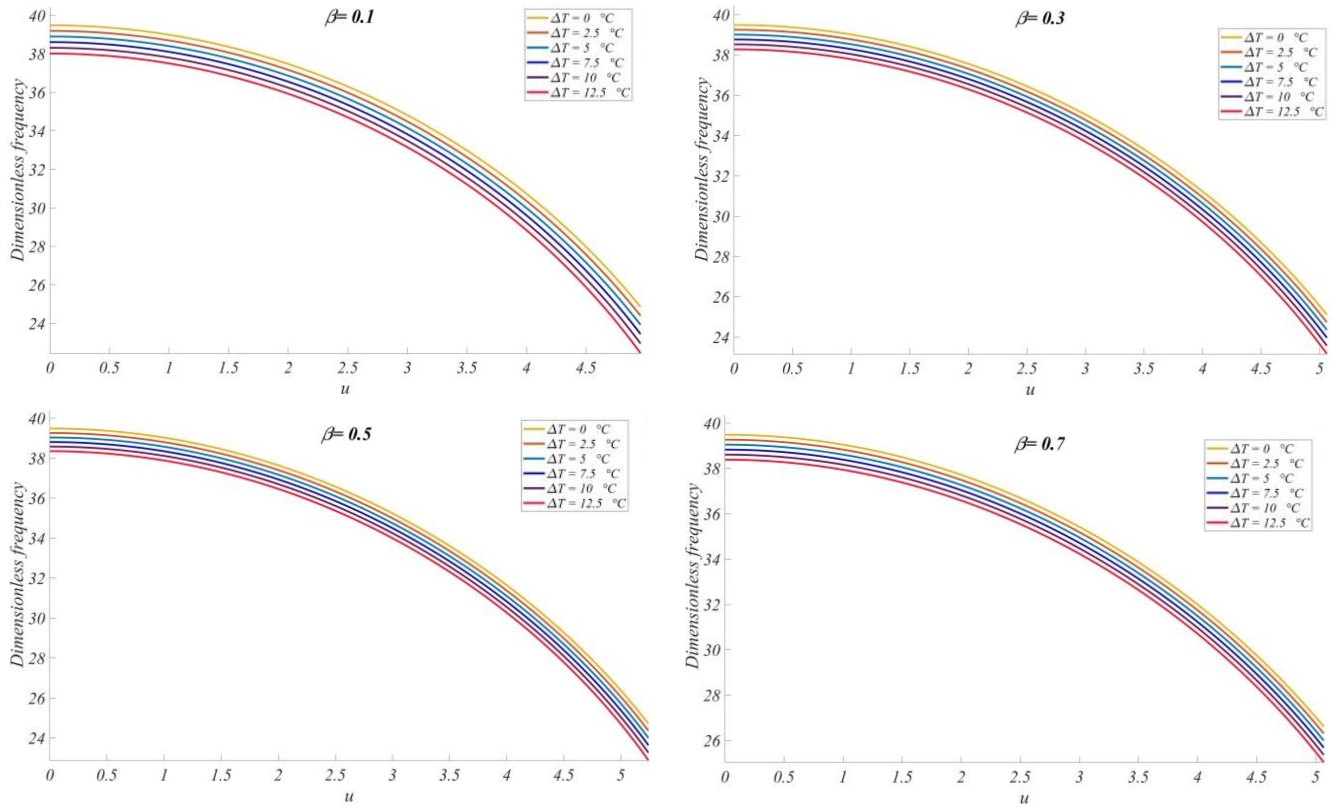


Figure 9. Second natural freq. vs. fluid velocity and thermal load of pinned-pinned pipe for different β, without thermal effect /2/.

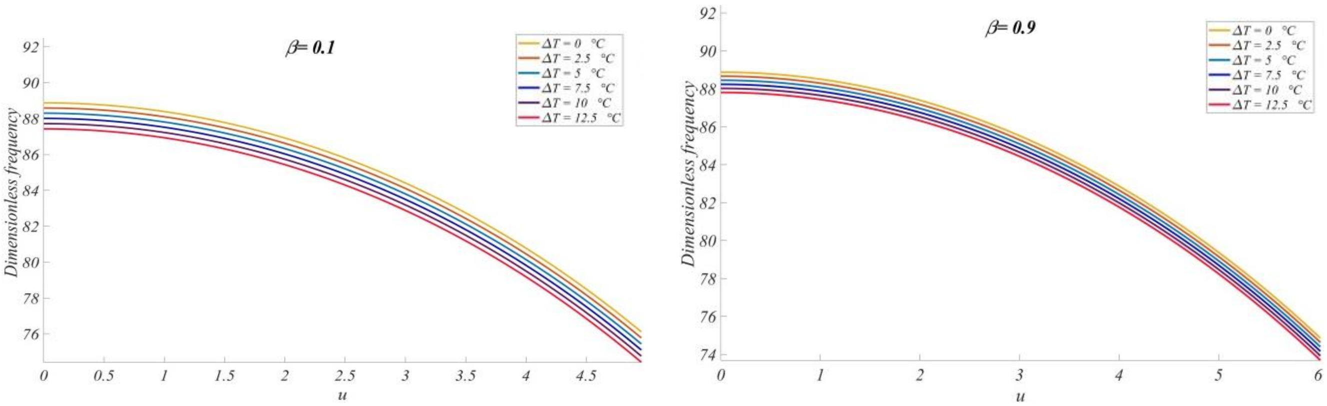


Figure 10. Third natural freq. vs. fluid velocity and thermal load of pinned-pinned pipe for $\beta = 0.1$ and 0.9, without thermal effect /16/.

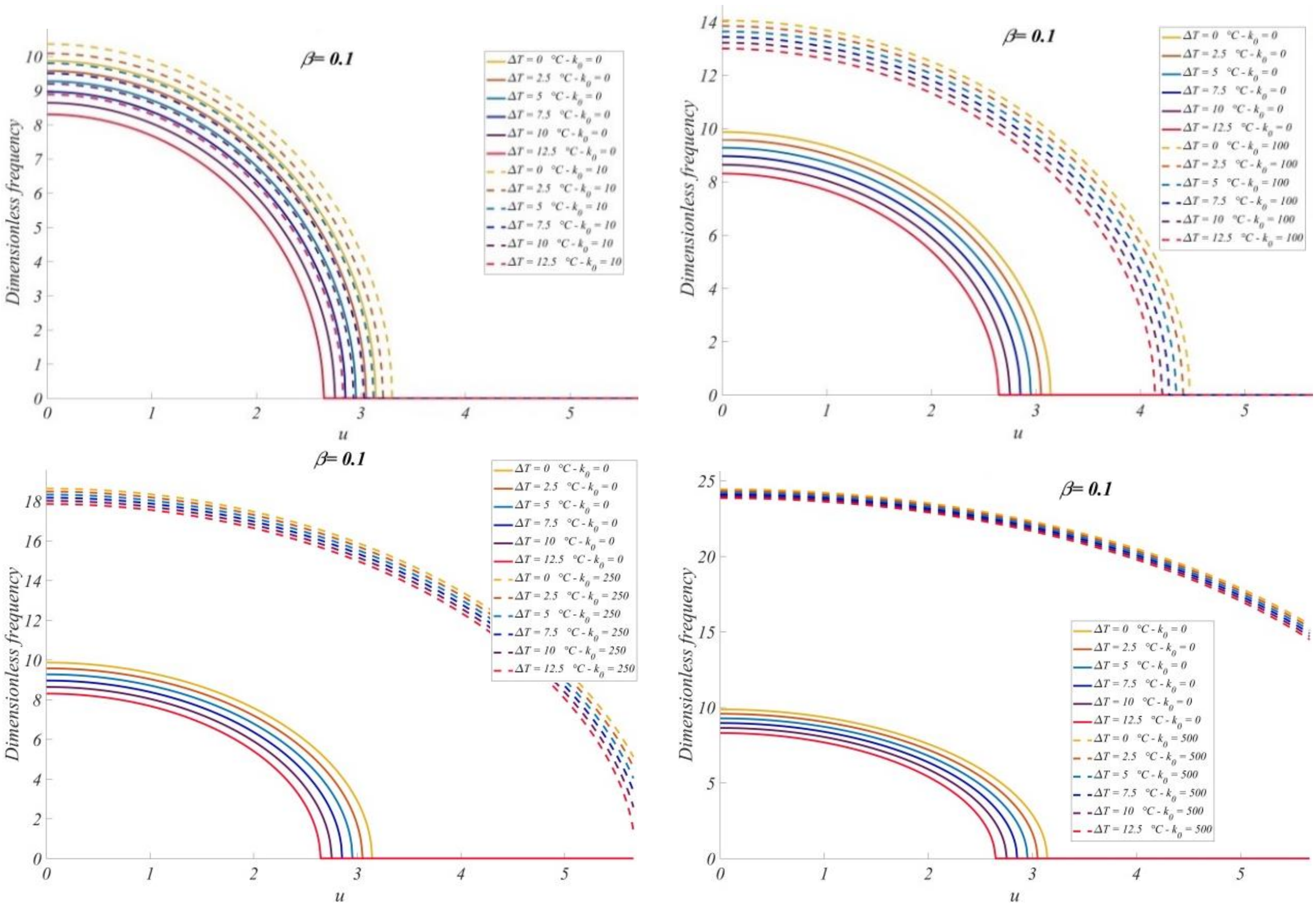
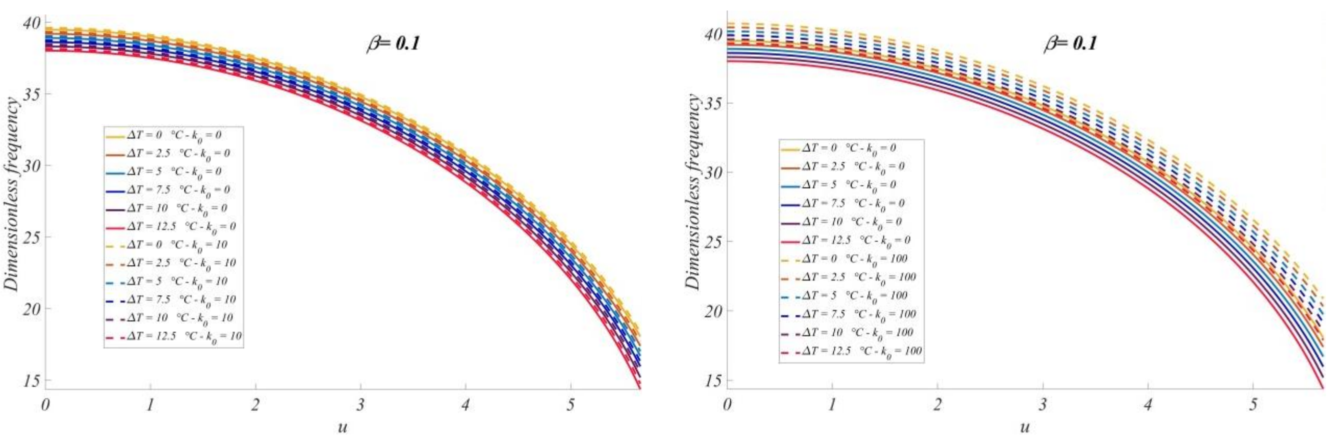


Figure 11. First natural freq. vs. fluid velocity and thermal load of pinned-pinned pipe for different Winkler elastic foundation, $\beta = 0.1$.



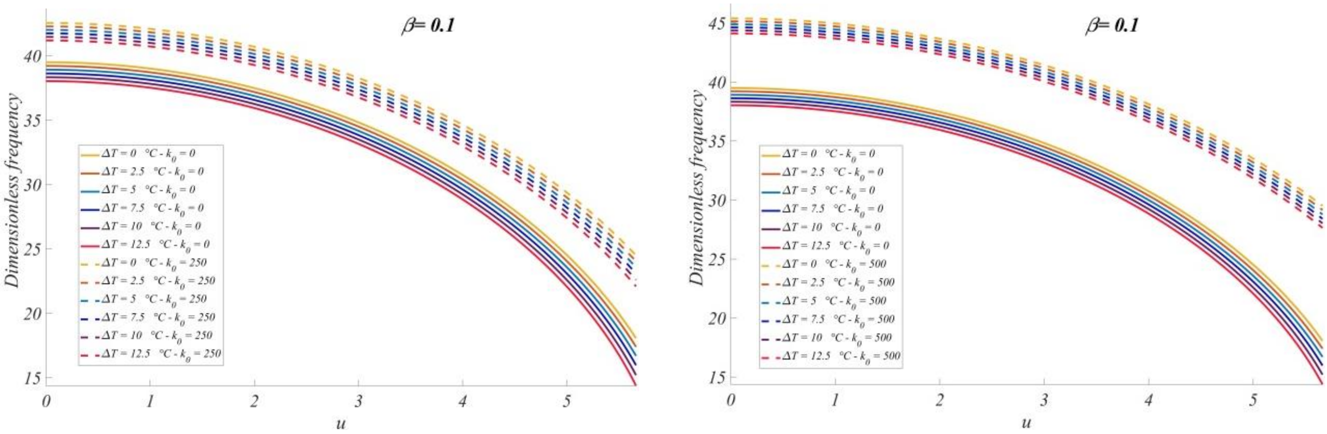


Figure 12. Second natural freq. vs. fluid velocity and thermal load of pinned-pinned pipe for different Winkler elastic foundation, $\beta = 0.1$.

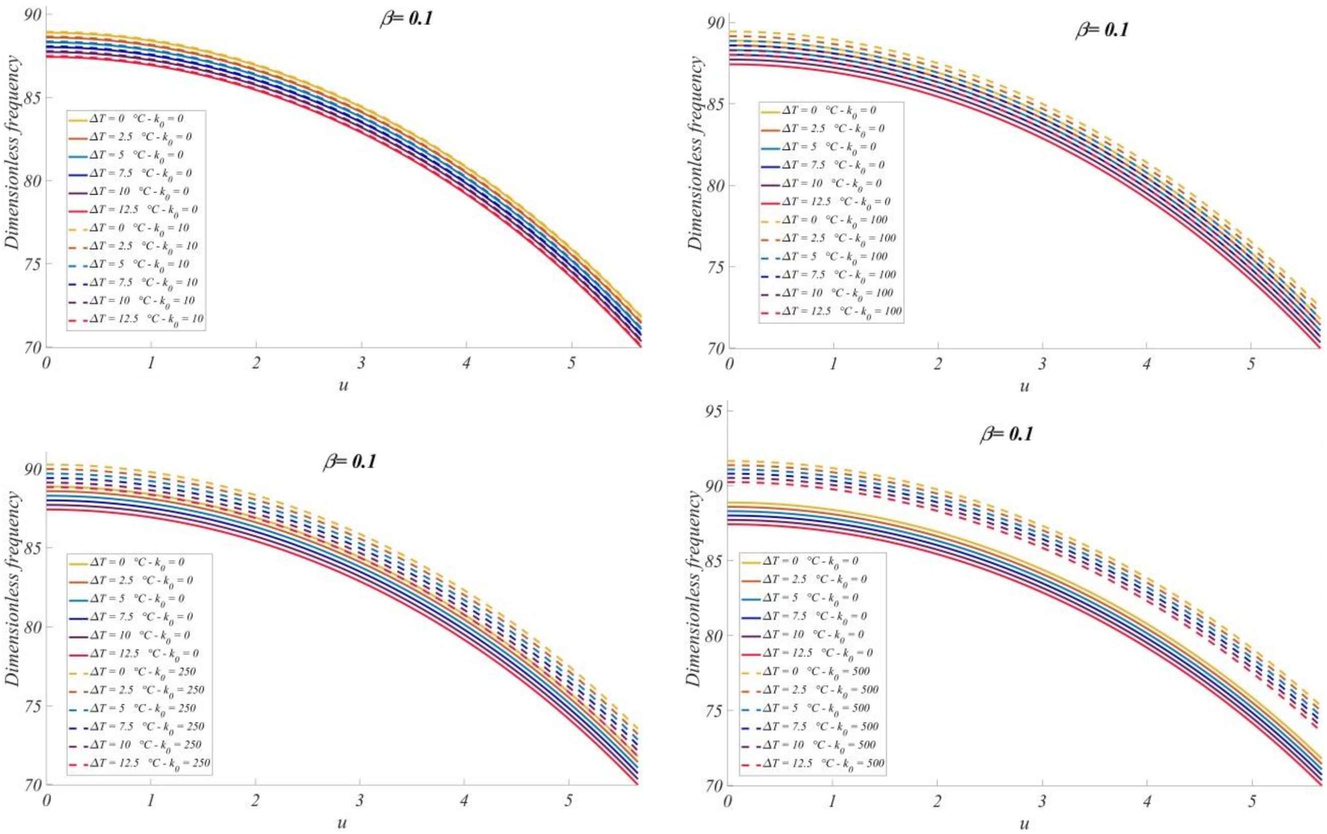


Figure 13. Third natural freq. vs. fluid velocity and thermal load of pinned-pinned pipe for different Winkler elastic foundation, $\beta = 0.1$.

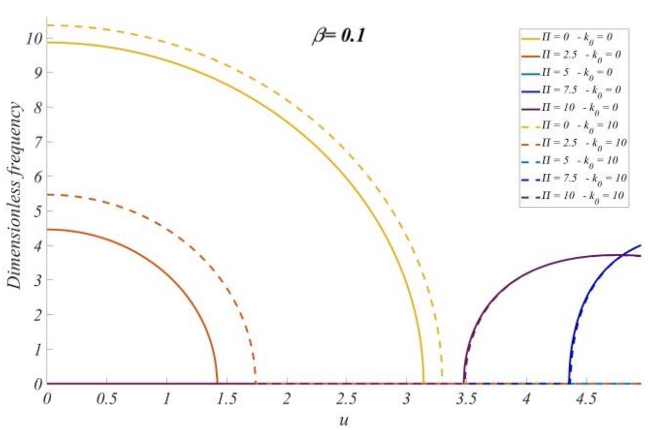


Figure 14. First natural freq. vs. fluid velocity and pressure effect of pinned-pinned pipe for different Winkler elastic foundation, $\beta = 0.1$.

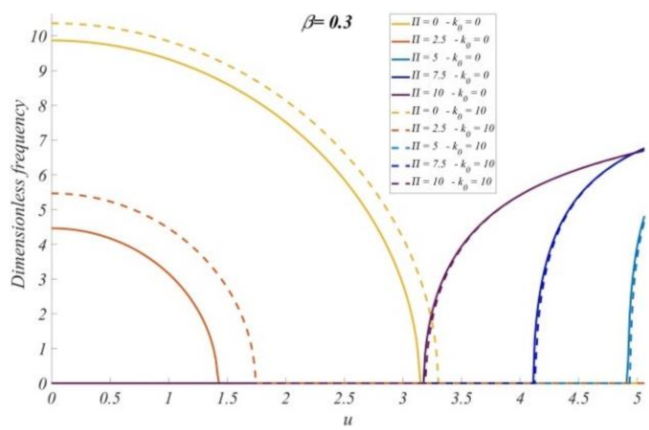


Figure 15. First natural freq. vs. fluid velocity and pressure effect of pinned-pinned pipe for different Winkler elastic foundation, $\beta = 0.3$.

CONCLUSIONS

The current work is a contribution to the study of the free vibration of pipes conveying fluid under thermal loads, by studying the fluid and thermal effect on the first vibration modes of pinned-pinned tube in terms of several variables. The system is hydrodynamic, taking into account the unidirectional fluid-structure interaction. The first three natural frequencies and critical fluid velocities are obtained and compared with results reported previously; results are very satisfactory for a slight difference temperature. The stability region and system instability develops with increasing ΔT, as the natural frequencies and critical velocities decrease with this. Elastic foundation increases system stability under the same conditions. The results are summarized below:
- natural frequencies and critical velocity of the system depend on the physical properties,
- the flow velocity reduces natural frequencies of the system,
- thermal loads reduce natural frequencies of the system,
- combined effect of fluid and thermal destabilizes the system,
- the Winkler elastic foundation increases system rigidity and consequently the critical velocity of fluid,
- the elastic foundation type-Winkler has a stabilizing effect on the system,
- pressure load has a destabilizing effect on the system.

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