Journal of
Engineering and
Applied Sciences

MEDWELL PUBLICATIONS

Effect of Thermal Load on Vibration of Clamped-Clamped Pipe Carrying Fluid

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Key words: Natural frequency, Fluid velocity, Thermal loads, Elastic foundation, Finite element method, ANSYS

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Page No.: 3708-3712
Volume: 15, Issue 23, 2020
ISSN: 1816-949x
Journal of Engineering and Applied Sciences

Abstract: This study aims to show the effect of heat on free vibration of pipe conveying fluid with fixed ends by numerical model. The study depends on the calculation of the first natural frequencies of a hot fluid-conveying pipe. The hot fluid circulating has the flexional motion as that of pipe structure. A numerical modal analysis is realized in the fluid-structure interaction configuration where the equations are discretized with finite element method. Configuration has been done by coupling the two commercial solvers, Fluent software of fluid mechanical (CFD) and ANSYS Workbench code of structure mechanical. The initial approach is based on some research and models. The results are compared with those predicted by semi-analytic method. Results are presented for two cases: clamped-clamped pipe conveying fluid without foundation and with Winkler elastic foundation, for varying values of fluid velocity and thermal effect.

INTRODUCTION

The problem of pipe carrying fluid has very important role in various industrial applications. They are used in manufacturing industries, heating exchangers as nuclear production and hydropower systems. The first study of the dynamic of a pipe with internal fluid is found by Housner[1]. He described the pipeline as a curved path. Free vibration induced by internal fluid flow of a tube is a consequence of fluid flow through the pipes[2]. The effect of internal fluid flow on transverse vibration of a pipe was studied by Paıdoussis and Li[3]. Dahmane[4] have studied the effect of Coriolis force of the internal fluid of pipeline by analytical approach using Galerkin method. By Chellapilla and Simha[5], studied the effect of a Pasternak foundation on the critical velocity of a fluid-conveying pipe. The fundamental frequencies of a pipeline resting on a two-parameter foundation with different boundary conditions were studied by Chellapilla and Simha[6]. Many researchers have studied fluid flow and thermal charges induced free vibration[7-9]. Solution method for the thermally induced vibrations in cantilevered beam structures subjected to step heat input has been presented by Kidawa-Kukla[10]. Qian *et al*.[11] studied the static instability (Buckling) of pinned-pinned pipes conveying fluid under thermal charges, applying the Hamilton’s principle, the equations of motion is derived for the pipe under the effects of linear and non-linear stress-temperature cases. As with the methods used to treat this problem, the Finite Element Method (FEM) has made it possible to simulate the dynamic motion of the fluid coupled with the flexible pipe for arbitrary geometries within the context of a general purpose finite element program[12]. In the same numerical way, Dahmane *et al*.[4], Mouloud *et al*.[13] and Moulouda *et al*.[14] were studied the vibration of a tube under internal flow by calculating the first natural frequencies and critical velocity of fluid with different parameters. Coupling the two commercial solvers, fluent code of fluid mechanical and ANSYS-Workbench code[4], the results were very impressive and satisfactory. We will adopt the same methodology in this research where the hot fluid is considered incompressible and the pipe structure is an elastic body.

MATERIALS AND METHODS

Equation of motion: We consider a straight pipe with a length L, an internal cross-section area A, mass per unit length m_s and a flexural rigidity EI. The mass per unit length of a conveying fluid m_f has an axial velocity U varying with time, referring to a Cartesian coordinate system (Oxyz). The equation derivation is based on Bernoulli-Euler elementary beam theory. The model of system is shown in Fig. 1a and b shows forces on fluid element, Fig. 1c shows forces and pipe element moment.

Linear pipe-dynamic equations on a Winkler elastic foundation have been derived in the previous work[2, 15] as follows:

$$EI\frac{\partial^4 y}{\partial x^4}+m_f U^2\frac{\partial^2 y}{\partial x^2}+2m_f U\frac{\partial^2 y}{\partial x\partial t}+\left(m_s+m_f\right)\frac{\partial^2 y}{\partial t^2}+ky=0 \quad (1)$$

The boundary conditions for our system are:

$$y_{x=0}=\frac{\partial y}{\partial x}_{x=0}=y_{x=1}=\frac{\partial y}{\partial x}_{x=1}=0 \quad (2)$$

Thermal load term: The interest of the present study is the dynamic of pipes conveying fluid under thermal loads. The thermal charges consider linear[11]. A uniform temperature increment ΔT is applied to the system. The equation of motion for a fluid-conveying pipe (1) can be modified to include the thermal load-linear:

$$\begin{aligned}&EI\frac{\partial^4 y}{\partial x^4}+m_f U^2\frac{\partial^2 y}{\partial x^2}+2m_f U\frac{\partial^2 y}{\partial x\partial t}+\\&\left(m_s+m_f\right)\frac{\partial^2 y}{\partial t^2}+ky+E\alpha\Delta T\frac{\partial^2 y}{\partial x^2}=0\end{aligned} \quad (3)$$

Where:

- EI ($\partial^4y/\partial x^4$) = Stiffness term
- (m_fU^2) $\partial^2y/\partial x^2$ = Curvature term
- $2m_f$U ($\partial^4y/\partial x\partial t$) = Coriolis force term
- ($m_s + m_f$) $\partial^2y/\partial t^2$ = Inertia force term
- EαΔT ($\partial^2y/\partial x^2$) = Considers deformation due to thermal load which include conduction and convection through the tube where α is thermal coefficient of expansion of material and T is temperature

And:

$$\Delta T = T_f - T_p \quad (4)$$

Where:

T_f-T_p = Represent the heat transfer from hot fluid to pipe (Fig. 1)

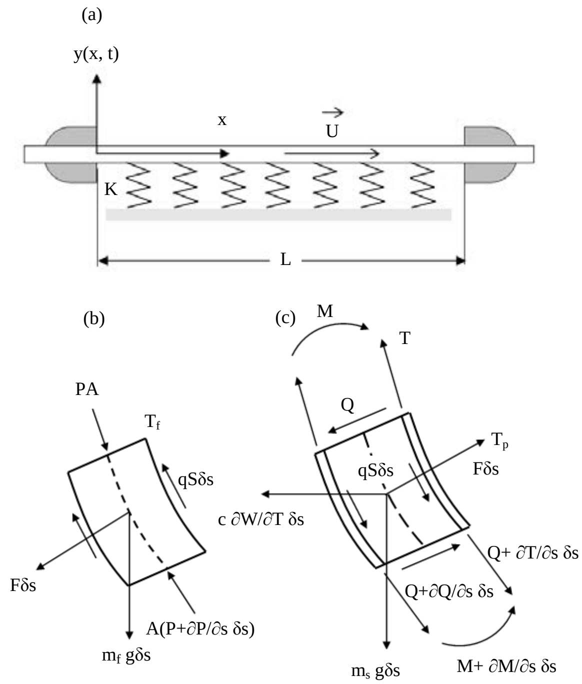

Fig. 1(a-c): (a) Clamped-clamped pipe conveying uid, (b) forces on fluid element and (c) forces and moments on pipe element δs[2, 16]

The non-dimensional parameters[2, 13, 15, 16], we obtain:

$$x=X/L, y=Y/L, t=\left(EI/\left(m_f+m_s\right)^{1/2}\right)T/L^2, \beta=m_f\left(m_f+m_s\right),$$

$$u=UL\left(m_f/EI\right)^{1/2}, \Omega=\left(\frac{m_f+m_s}{EI}\right)^{1/2}\omega L^2$$

The dimension less Winkler elastic foundation[4, 6] is $\gamma = kL^4/EI$.

RESULTS AND DISCUSSION

In this current research, results will be discussed for various values of fluid velocity and temperature parameter, calculating the first natural frequencies of clamped-clamed pipe on an elastic foundation with one low values where γ is 0.01. So, we load the stresses caused by the thermal forces and pressure of the fluid onto the structure (pipe) and then calculated the first natural frequencies, using the same methodology used in the aforementioned research[4]. This is what we see in Fig. 2-4 accompanying each operation.

The elastic modulus of pipe is (E = 201 GPa), pipe length is (L = 1 m), fluid density is (m_f = 1000 kg m^{-3}), pipe density is (m_s = 7850 kg m^{-3}), the Poisson's ratio is 0.26, pipe thickness for mass ratio β = 0.1 and β = 0.6

Fig. 2: Represents the distribution of the constraints of pressure charge plus on the level of the interface of pipe: imported charge

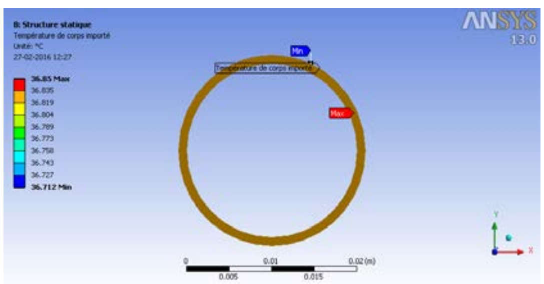

Fig. 3: Represents the distribution of the temperature on the level of the interface of clamped-clamped pipe conveying hot fluid

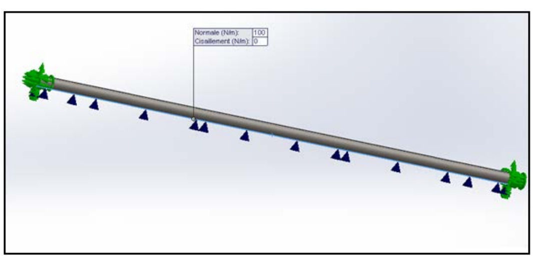

Fig. 4: Representation of the system with an elastic foundation (Winkler-model)

and the outer diameter of the pipe is (0.03 m). Figure 5 shows that the dimensionless results obtained numerically are similar to those obtained by the semi-analytical approach so-called DTM[11]. The biggest change in the range of 1% is very acceptable where mass ratio is 0.1. It is preferable to use a dimensioning to see the effect of fluid velocity and thermal load on first natural frequencies developments.

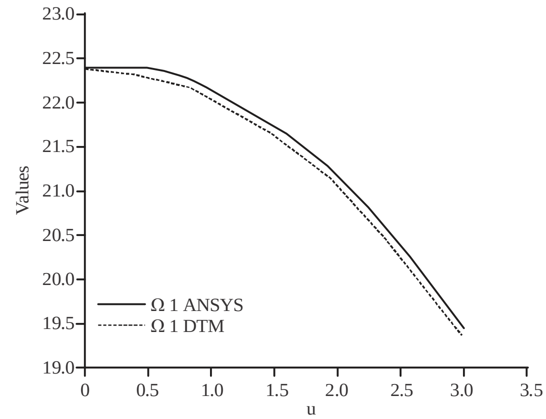

Fig. 5: The first natural frequency of clamped-clamped pipe conveying fluid, $\beta = 0.1$

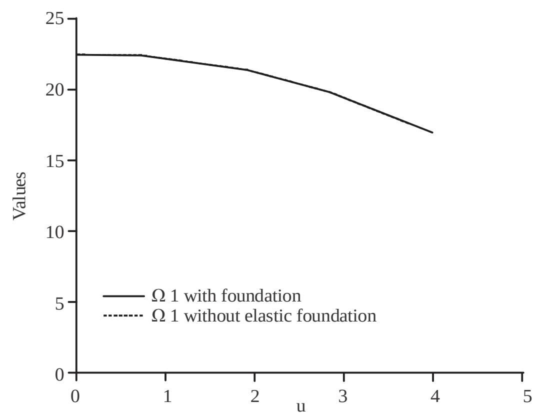

Fig. 6: Effect of elastic foundation on the first natural frequency of the clamped-clamped pipe, γ = 0.01 and β = 0.6

Figure 6 shows effect of Winkler elastic foundation on the first natural frequency of the clamped-clamped pipe carrying fluid where $\gamma = 0.01$ and $\beta = 0.6$.

All results that follow will be displayed in tabular form. Table 1 and 2 show the two first natural frequencies values of pipe supported with fixed-fixed supports conditions respectively with forced convection effect, here elastic foundation is zero ($\gamma = 0$). We remark that the two first natural frequencies are decreasing slowly for various values of temperature parameter (ΔT) and various values of fluid velocity, the biggest change happens simultaneously with the biggest velocity U = 5.15 m sec^{-1} and the greatest thermal difference ΔT = 17°C. With an elastic foundation where $\gamma = 0.01$, the results are presented in Table 3 and 4 for hot fluid of clamped-clamped pipe. The effect of the elastic foundation is apparent on the variation of two first eigen-modes. For the fluid velocity U = 0 m s^{-1} (no-flow), the difference in the first natural frequency is 1 Hz. We find that the heat parameter and flow velocity lead to a

Table 1: The first natural frequency (Hz) of a fluid-conveying pipe with fixed ends for various values of U and ΔT without Winkler elastic foundation

ΔT	U = 0.0 (m sec^{-1})	U = 0.1 (m sec^{-1})	U = 5.15 (m sec^{-1})
0	131.78	131.78	131.78
1	131.44	131.43	131.42
2	131.09	131.07	131.06
4	130.39	130.35	130.34
7	129.34	129.27	129.24
12	127.57	127.43	127.39
17	125.76	125.57	125.51

Table 2: The second natural frequency (Hz) of a fluid-conveying pipe with fixed ends for various values of U and ΔT without Winkler elastic foundation

ΔT	U = 0.0 (m sec^{-1})	U = 0.1 (m sec^{-1})	U = 5.15 (m sec^{-1})
0	361.56	361.56	361.56
1	361.09	361.07	361.07
2	360.62	360.59	360.58
4	359.68	359.62	359.61
7	358.27	358.17	358.13
12	355.90	355.72	355.67
17	353.51	353.26	353.18

Table 3: The first natural frequency (Hz) of a fluid-conveying pipe with fixed ends for various values of U and ΔT with Winkler elastic foundation where $\gamma = 0.01$

ΔT	U = 0.0 (m sec^{-1})	U = 25.79 (m sec^{-1})
0	132.78	132.61
1	132.45	132.25
2	131.99	131.89
4	131.29	131.17
7	130.24	130.07
12	128.47	128.22
17	126.77	126.34

Table 4: The second natural frequency (Hz) of a fluid-conveying pipe with fixed ends for various values of U and ΔT with Winkler elastic foundation where $\gamma = 0.01$

ΔT	U = 0.0 (m sec^{-1})	U = 25.79 (m sec^{-1})
0	362.98	361.11
1	362.50	360.59
2	362.04	360.05
4	361.10	359.08
7	359.69	357.60
12	362.98	361.11
17	362.50	360.59

decrease in the frequency on the same pattern with the above. For an equal field ΔT = 17°C which is the largest studied value, the change does not exceed 4.963 where U = 25.79 m sec^{-1}.

CONCLUSION

The present research is a contribution to the study of pipes under hot fluid vibration where structure is hydrodynamic. Several examples were processed to determine the influence of the fluid velocity, thermal loads and elastic foundation by Winkler-type on natural frequencies. From the obtained results, the following conclusions can be observed:

- The frequencies of the system hot fluid-structure depend on the physical properties
- The fluid flow velocity reduces the natural frequencies of the pipe conveying fluid
- The thermal loads reduce the natural frequencies of our system
- The values of natural frequencies in clamped-clamped supported pipe on an elastic foundation depend on geometrical properties
- Temperature has an effect on displacement as well as natural frequencies, we found here that the parameter ΔT has a destabilizing effect
- The elastic foundation Winkler-model increases the system rigidity and consequently the natural frequencies

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