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Experimental and Theoretical Investigation of Combined Effect of Fluid and Thermal Induced Vibration on Vertical Thin Slender Tube

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***Abstract**: The paper presents an experimental and theoretical analysis on the study of dynamic response of a thin slender cantilever pipe conveying air at different pressures and temperature. A dynamic characteristic of a pipe line conveying internal fluid experiences mechanical load due to inertia effect of fluid, coriolis force, fluid rotation kinetic force due to fluid flow velocity, dynamic load due to inertia effect and thermal load due to hot air on the pipe. One dimensional beam finite element is used for investigating the dynamic behavior of the thin slender pipe with appropriate numerical computational method for analysis. The fundamental natural frequency of vibration is correlated with experimental and numerical method.*
Keywords- Fluid and thermal induced vibration, finite element method, natural frequency, slender tube

I Introduction

Thin walled tubes are widely found in various structural engineering applications. Static and dynamic response of pipe structure to fluid load and thermal load is very important for safe design and operation. Fluid flowing through a pipe can impose pressure on the pipe wall which deflects the pipe, leads to fluid induced vibration. Non uniform heat transfer due to difference in convective heat transfer over the surface of the tube leads to thermal induced vibration. Many researchers have studied thermal and fluid induced vibration. Studies have been conducted to assess the relationship between fluid flow velocity, pressure of the fluid and its influence on the free vibration. Among the papers available in the literature, Paidoussis et al. [1] and Rousselet and Herrmann [2] presented a paper on analytical studies to investigate dynamic stability of a slender and long tube conveying fluid. Numerical investigation on the vibration behavior of the pipe conveying fluid was presented by Lin and Tsai [3] and Lee and Oh [4]. Bar-Avi [5] has conducted an experimental and analytical study on the dynamic response of a vertical cantilever pipe conveying fluid which is subjected to sea wave forces. Kuiper and Metrikine [6] investigated dynamic stability of a submerged vertical cantilever pipe. Paidoussis and Semler [7] examined the planar dynamics of a fluid conveying cantilever pipe with a small mass attached at the free end by theoretically and experimentally. Sinha et al. [8] studied the results of a modal experiment on an open ended cantilever pipe conveying fluid and their numerical simulation using finite element method. Zou et al. [9] studied analytically fluid induced vibration of composite natural gas pipelines and investigated the influence of fluid velocity, internal pressure and initial tension on pipeline vibration frequency. Tran et al. [10] analysed the structural intensity pattern of thin isentropic and laminated composite plates which are subjected to thermally induced vibration. Kidawa-Kukla [11] has proved the frequency of the thermally induced beam vibration is a multiple of harmonic motion frequency of the heat source and then resonance can occur in the system. Hong [12] analysed the thermally induced vibration of a thermal sleeve using computational Generalized Differential Quadrature(GDQ) method for calculating the natural frequency, displacement and thermal stresses. Kukla [13] analysed the temperature distribution and transverse vibration of beam induced by using the property of the Green functions. Blandino and Thornton [14] carried out the detailed study of a thermally induced vibration caused by internal heating. From the literature review it is observed that not much work has been reported on the response of structure due to combined loading of thermal, fluid, fluid inertia and structure inertia. Hence the present work focusing on this topic set out the following objectives. To visualize the problem, an experimental and theoretical analysis is contemplated.

(a) An experimental setup is fabricated in the laboratory to simulate fluid as well thermal load for the thin tube.
(b) Experiments were conducted for various fluid temperature and pressure
(c)Observation on the transient and steady state response of thin pipe due to these loads will be analyzed.

(d)Experimental and numerically obtained natural frequency is compared.

II Experimental setup

An experimental setup is fabricated in the laboratory to demonstrate the fluid thermal interaction in a thin slender tube. The setup consists of two narrow tubes of diameter 3 mm. The tubes are connected through an orifice assembly. The orifice assembly produces an additional load due to fluid expansion. The orifice size can be changed to obtain different hole diameter. Experiments were conducted for 1 mm and 1.5 mm orifice hole sizes. The one end of the first tube is for the entry of the compressed air. The other end of this tube is connected to another tube through orifice assembly. The other end of the second tube is exposed to atmosphere. These two tube assemblies are in such away that one end is fixed and other end is free with orifice assembly. The setup is mounted inside a test stand. The test stand acts as a means to hold the two ends of the tube as shown in Figure 1. The supply pressure is controlled by the pressure regulator. The air is passed through stainless steel heating box of cylindrical shape of diameter 200 mm and the arrangement is suitable for generating pressurized air at required temperature. The stainless steel heating box contain 200 watt heating coil connected through 220 V, 5 amp AC source with a voltage regulator. The voltage regulator is required to vary the power supply to the heating coil in order to vary the supply air temperature. As the air flows, the heat from the compressed air is lost by conduction through the tube and by convection from the tube surface to atmosphere. A thermocouple was mounted inside the test box to measure the ambient temperature which was recorded by means of digital thermometer. The data acquisition program in LabVIEW through a closed loop controlled the acquisition of displacement data from the test specimen. Due to conveying of compressed air pressurized air, fluid load on the structure and an additional load due to sudden expansion of the air through an orifice is present. The air enters into one chamber of the sudden expansion assembly and flow through an orifice plate having small hole. Thus, flow results in sudden expansion of air and hence additional load at the tube tip. From the second chamber, air exits through the second tube to atmosphere. To obtain the transient and steady state response of the tube, a piezoelectric accelerometer AD1221 N605 with sensitivity 10 mv/g is used. In order to acquire the signals NIPXI 1050 chassis containing NIPXI 4472 DAQ with 24 bit having 8 analog input channels and 2 analog output channel is used as shown in Figure 1. Then, instrument is connected to CPU and monitor to display of the output. The programming was done to acquire response signals through LabVIEW 8.0.

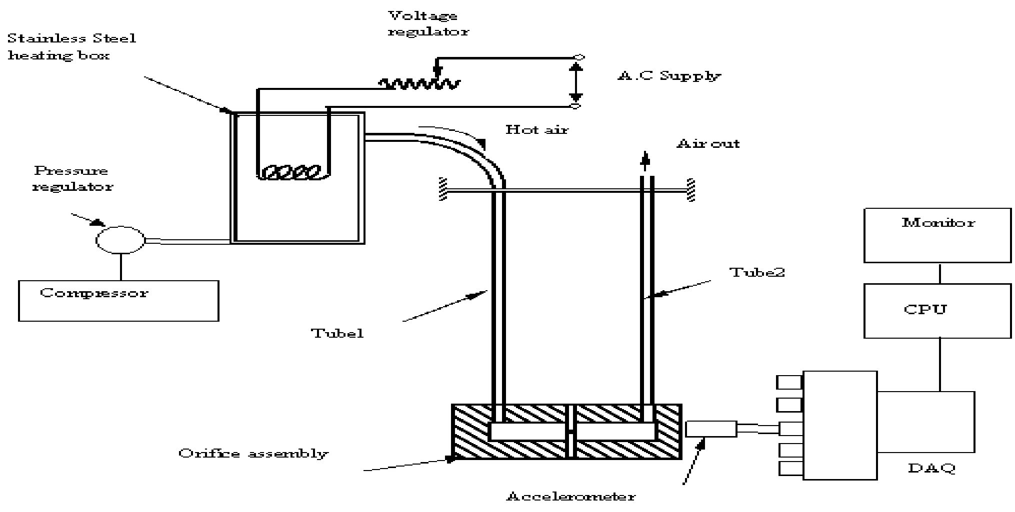

Fig.1. Experimental Setup

III Finite element formulation

Consider a hot fluid element and pipe element with various forces and moments acting on it due to flow of hot fluid through pipe as shown in figure 3 and 4. The fluid element is subjected to pressure forces $\overline{p}$, reaction forces of the pipe on the fluid normal to the fluid element $F\delta s$, and tangential to it is $q_s S\delta s$, associated with the wall-shear stress q_s and gravity force $m_f g\delta s$. The pipe element is subjected to the longitudinal tension T_o , transverse shear force Q_T , bending moment M and damping due to friction with the surrounding fluid as $B\frac{\partial w}{\partial t}$. Heat transfer from hot fluid to pipe is $hA\left(T_f - T_p\right)$, heat transfer from hot pipe to atmosphere at compressed side is $h_1 A\left(T_f - T_p\right)$ and at elongated side is $h_2 A\left(T_f - T_p\right)$, where h is heat transfer coefficient, T_f is temperature of hot fluid, T_p is temperature of pipe and T_∞ is ambient temperature. The thermal moment due to change in rate of heat transfer is M_T . The basic equation of motion conveying fluid [15] can be modified to include the thermal load [14] and hence the governing equation for pipe conveying hot fluid could be derived as:

$$EI\frac{\partial^4 w}{\partial x^4} + \left[m_f U^2 - \bar{T} + \bar{p}A(1-2\nu)\right]\frac{\partial^2 w}{\partial x^2} + 2m_f U\frac{\partial^2 w}{\partial x \partial t} + (m_f + m)\frac{\partial^2 w}{\partial t^2} + E\alpha\Delta T\frac{\partial^2 w}{\partial x^2} = 0, \tag{1}$$

where E is the modulus of elasticity of the pipe, I the area moment of inertia of the pipe, A the fluid flow area of the pipe, ρ the density of fluid, m_f is the fluid mass per unit length, and m is the pipe mass per unit length, U is the flow velocity of fluid $\bar{p}$ is the average pressure, $\bar{T}$ is the applied tension, α is thermal coefficient of expansion of material and T is temperature. The last term, thermal moment $M_T = E\alpha\Delta T\frac{\partial^2 w}{\partial x^2}$ considers deformation due to thermal load (Blandino and Thornton, 2001) which include conduction and convection through the tube. Using the Galerkin's approach for the equation (1), the finite element equation of motion can be obtained as:

$$\left[M^{(e)}\right]\left\{\ddot{w}^{(e)}\right\} + \left[G^{(e)}\right]\left\{\dot{w}^{(e)}\right\} + \left[\left[K_s^{(e)}\right] + \left[K_f^{(e)}\right] + \left[K_t^{(e)}\right] + \left[K_p^{(e)}\right] + \left[K_{th}^{e}\right]\right]\left\{w^{(e)}\right\} = 0, \tag{2}$$

where,

Stiffness matrix

$$\mathbf{K}_s^e = \frac{EI}{l^3}\begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix}$$

Fluid element matrix

$$\mathbf{K}_f^e = \frac{MU^2}{30l}\begin{bmatrix} 36 & 3l & -36 & 3l \\ 3l & 4l^2 & -3l & -l^2 \\ -36 & -3l & 36 & -3l \\ 3l & -l^2 & -3l & 4l^2 \end{bmatrix}$$

Pipe tension matrix

$$\mathbf{K}_t^e = \frac{\bar{T}}{30l}\begin{bmatrix} 36 & 3l & -36 & 3l \\ 3l & 4l^2 & -3l & -l^2 \\ -36 & -3l & 36 & -3l \\ 3l & -l^2 & -3l & 4l^2 \end{bmatrix}$$

Fluid pressure matrix

$$\mathbf{K}_p^e = \frac{\bar{p}A(1-2\upsilon)}{30l}\begin{bmatrix} 36 & 3l & -36 & 3l \\ 3l & 4l^2 & -3l & -l^2 \\ -36 & -3l & 36 & -3l \\ 3l & -l^2 & -3l & 4l^2 \end{bmatrix}$$

Fluid damping matrix

$$\mathbf{G}^e = \frac{MU}{30}\begin{bmatrix} -30 & 6l & 30 & -6l \\ -6l & 0 & 6l & -l^2 \\ -30 & -6l & 30 & 6l \\ 6l & l^2 & -6l & 0 \end{bmatrix}$$

Element mass matrix

$$\mathbf{M}^e = \left(\frac{(M+m)l}{420}\right)\begin{bmatrix} 156 & 22l & 54 & -13l \\ 22l & 4l^2 & 13l & -3l^2 \\ 54 & 13l & 156 & -22l \\ -13l & -3l^2 & -22l & 4l^2 \end{bmatrix}$$

Element thermal matrix

$$\mathbf{K}_{th}^e = \frac{E\alpha\Delta T}{30l}\begin{bmatrix} 36 & 3l & -36 & 3l \\ 3l & 4l^2 & -3l & -l^2 \\ -36 & -3l & 36 & -3l \\ 3l & -l^2 & -3l & 4l^2 \end{bmatrix}$$

Assemble the element matrices of stiffness, damping, and mass matrices and represent in a state space form (Zou et.al, 2005) as:

$$[\mathbf{\Theta}]\left\{\dot{\xi}\right\} - [\mathbf{\Psi}]\{\xi\} = 0, \tag{3}$$

where

$$[\theta] = \begin{bmatrix} [K] & 0 \\ 0 & [-M] \end{bmatrix}, \quad [\psi] = \begin{bmatrix} 0 & [K] \\ [K] & [G] \end{bmatrix}, \quad [K] = \left[\left[K_s^e\right] + \left[K_f^e\right] + \left[K_t^e\right] + \left[K_p^e\right] + \left[K_{th}^e\right]\right].$$

Eigenvalues are computed using matlab for the equation (3)

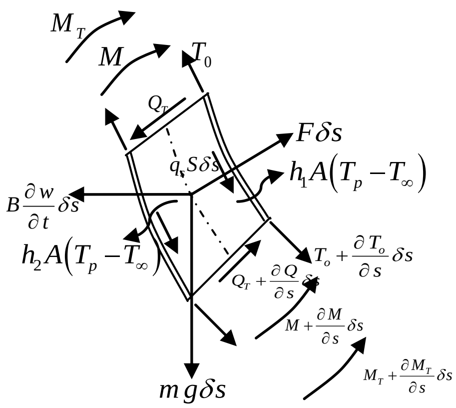

Fig.2 Hot fluid element

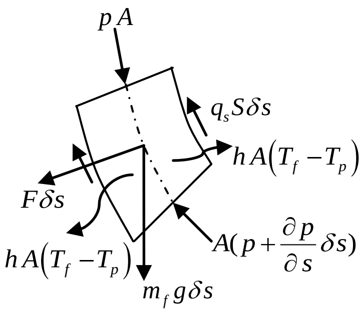

Fig.3 Pipe element

IV Result and discussion

Figures 4 and 5 indicate the transient response of the tube and fundamental natural frequency at supply air pressure of 2 bar and at ambient temperature 31^0C. Experiments were repeated for 1 bar, 3 bar, 4 bar and 5 bar with temperature of air being 58^0 C and 78^0C. Table 1 shows the experimental displacement of the tube for various pressures and temperature. Table 2 shows the experimental and theoretical fundamental frequencies of the pipe conveying hot air with various pressures and temperature. From the response analysis it is observed that displacement varies from 22.2 mm to 25.3 mm as the pressure increases from 2 bar to 5 bar at ambient temperature of air flowing internally. When the temperature of the air being conveyed through the tube is at 78^0C and 1 bar pressure the displacement of the tube various from 22.2 mm to 24.0 mm. The frequency of vibration for a tube of 800mm length increases from 2.614 Hz to 6.217 Hz for an increase in pressure from 1 bar to 5 bar. Similarly frequency of vibration varies from 2.614 Hz to 6.317 Hz for an increase in air temperature from ambient to 78^0C. This shows that as the pressure increases the response becomes more oscillatory and takes more time to attain steady state. Frequency of tube increases with pressure and it decreases with temperature. This may be due to the internal pressure of air being translated into a tensile load along the pipe, hence the natural frequency increases. With the hot air being conveyed, there would likely be the softening effect that can cause the frequency to decrease.

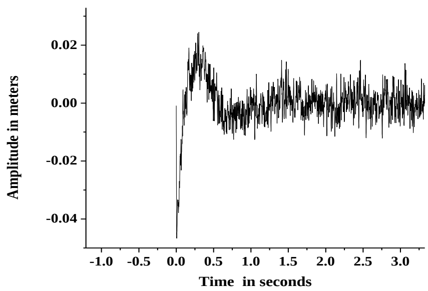

Fig.4 Time response

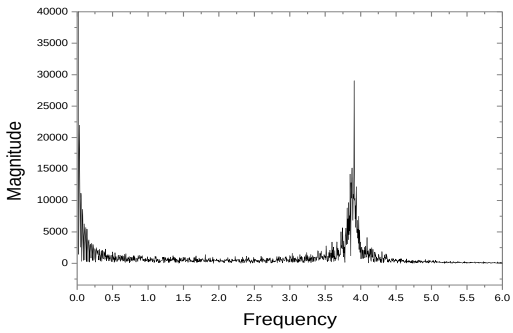

Fig. 5 Frequency response

Table 1 Experimental Displacement of tube for various pressures and temperature

Pressure in bar	Ambient temperature (31^oC)	58^0C	78^0C
1	22.2	23.1	24.0
2	23.1	24.0	24.7
3	23.8	24.7	25.4
4	24.5	25.6	26.2
5	25.3	26.5	27.1

Table 2 Experimental and theoretical natural frequency for various temperature and pressure

Pressure in bar	Fundamental natural frequency (Hz)					
	Experimental results			Theoretical results		
	Ambient temperature 31^0C	Inlet temperature of the air 58^0C	Inlet temperature of the air 78^0C	Ambient temperature 31^0C	Inlet temperature of the air 58^0C	Inlet temperature of the air 78^0C
1	2.614	2.481	2.134	2.511	2.428	2.156
2	3.834	3.356	3.224	3.656	3.512	3.236
3	4.291	3.935	3.434	4.412	3.921	3.351
4	5.811	4.365	3.564	5.122	4.421	3.641
5	6.317	5.823	4.458	6.516	5.974	4.259

V Conclusions

Table 2 shows the concluding remarks obtained experimentally and theoretically on the fundamental frequencies of the pipe conveying hot air. It is observed that the frequency of vibration increases with the increase in pressure and decreases with increase in temperature. The increase in pressure increases the velocity of the fluid flow and reduces the damping effect. Temperature has an effect on displacement as well as frequency, since thermal contraction and expansion increases due to high heat transfer rate at high velocity. As the temperature of the fluid increases, the frequency decreases due to softening effect of tube.

REFERENCES

[1] Paidoussis M.P.,Luu T.P. and Laithier B.E., Dynamics of finite length tubular beam conveying fluid, *Journal of Sound and Vibration*, 106, 1986, 311-331.

[2] Rouselt J. and Herrmann G., Dynamics behavior of continuous cantilever pipe conveying fluid near the critical velocity, *Journal of Applied Mechanics*, *48*, 1981, 943-947.

[3] Yih-Hwang Lin and Yau-Kun Tsai, Nonlinear vibration of thimoshenko pipes conveying fluid, *Journal of Solids and Structures*, *34*, 1997,2945-296.

[4] Usik Lee and Hyuckjin Oh, , The spectral element model for pipelines conveying internal steady flow, Journal of Engineering Structures, *25*, 2003, 1045-1055.

[5] Patrick Bar-Avi, , Dynamic response of risers conveying fluid, *Journal of Offshore Mechanics and Arctic Engineering*, 122, 2000,188-193.

[6] Kuiper G.L. and Metrikine A.V., Experimental investigation of dynamic stability of a cantilever pipe aspirating fluid, *Journal of Fluids and Structures*, *24*, 2008, 541-558.

[7] Paidoussis M.P. and Semler C., Non-linear dynamics of a fluid conveying cantilever pipe with a small mass attached at the free end, *International Journal of Non-linear Mechanics*, *33*,1998, 15-32.

[8] Sinha J.K., Singh S. and Rama Rao A., Finite element simulation of dynamic behavior of an open ended cantilever pipe conveying fluid, *Journal of Sound and Vibration*, *240(1)*, 2001, 189-194.

[9] Zou G.P.,Cheraghi N.,and Taheri F., Fluid induced vibration of composite natural gas pipelines, *Journal of Solids and Structures*, *42*, 2005, 1253-1268.

[10] Tran T.Q.N, Lee H.P. and Lim S.S. , Structural intensity analysis of thin laminated composite plate subjected thermally induced vibration, *Journal of Composite Structure*, *78*, 2007, 70-83.

[11] Kidawa-Kukla , Vibration of a beam induced by harmonic motion of a heat source, *Journals of Sounds and Vibration*, *205(2)*, 1997, 213-222.

[12] Hong C. C., Liao H. W., Lee L. T., Ke J. B. and Jane K. C.**,** Thermally induced vibration of a thermal sleeve with the GDQ method, *International Journal of Mechanical Sciences*, *47*, 2005, 1789–1806.

[13] Kidawa-Kukla J. , Application of green function to the problem of thermally induced vibration of a beam, *Journal of Sound and Vibration*, *262*, 2003, 865-878.

[14 Blandino J. R and Thornton E. A. , Thermally induced vibration of an internally heated beam, *Journals of vibration and acoustics*, *123*, 2001, 67-74.

[15] PaidoussisM.P., *Fluid-Structure interactions* (Academic press, California,USA, 1998).