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Toward Attenuation of Self-sustained Oscillations of a Turbulent Jet through Two Orificies with Same Diameter

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Abstract: The experiments were carried out with various types of attenuators such as volume addition, compliant boundaries and vortex generators. It was observed that the volume addition to the pipe system changed the resonant frequencies of the pipe system and caused some reduction in the amplitudes of pressure fluctuations. The compliant boundaries are made from plastic material while thin vortex generators are made from the manganese based alloy. It was also observed that these had an important effect on the attenuation of flow-induced vibrations in the model pipe system with two orifices.

Key Words: Self-sustained oscillations, attenuation or damping of flow-induced vibrations, turbulent pipe flow.

Aynı Çaplı İki Orifisi Geçen Türbülanslı Bir Jetin Oluşturduğu Titreşimlerin Sönümlenmesi

Özet: Deneyler hacim ilavesi, hareketli saçaklar ve vorteks jeneratörleri gibi çeşitli tip sönümleyicilerle yürütülmüştür. Boru sistemine hacim ilavesinin, rezonans frekanslarının değişmesine (kaymasına) ve çalkantı basıncı genliklerinde ise bir miktar azalmaya neden olduğu gözlenmiştir. İnce plastikten yapılmış hareketli saçakların ve mangan alaşımlı ince levhalardan yapılmış vorteks jeneratörlerinin ise iki orifisli model boru hattında oluşan akış kaynaklı titreşimleri sönümlemede oldukça etki olduğu görülmüştür.

Anahtar Sözcükler : Kendinden uyarımlı titreşimler, akış kaynaklı titreşimlerin zayıflatılması veya sönümlenmesi, türbülanslı boru akımı.

Introduction

Valves, bends, orifices, and fitting elements used for several purposes in pipelines produce vortices in flow medium because of boundary layer separation and consequently, vortical structures take place. Exciting fluid column, vortices may cause oscillations in pipeline and a feed-back mechanism between vortices and fluid column in pipe can occur, thus, as vortex shedding frequency locks on one of the acoustic freqencies of the pipeline, resonance occurs. In this way, vortex shedding frequencies are controlled by acoustic structure of pipeline. These oscillations are called as "Self-sustained Oscillations".

Self-sustained oscillations in pipelines can be attenuated by changing the vortical structures or acoustic structures of pipeline. Flow-induced vibrations in pipelines having valves such as swing check valves, thermostatic radiator valves, safety relief valves and control valves have been investigated in recent studies of Weaver (1978), Ziada et al. (1983), Baldwin and Simmons (1986), Ziada and Buhlman (1989). In all of these studies, the attenuation of flow-induced vibrations has been basically made by changing vortical structure of valves. The acoustic frequency of pipeline might be changed by adjusting the position of valve (Chen and Florijancic, 1975). The attenuation of self-sustained oscillations of a turbulent jet through a cavity (suddenly expansion) on the pipeline was examined previously by using the various attenuator types such as compliant boundaries, vortex generators, slotted boundary and asymmetric boundary, and it was observed that compliant boundaries and vortex generators were the most effective attenuators (Karadoğan and Rockwell, 1983).

The pipe system including two orifices is one of the flow rate measurement methods either flow in low Reynolds numbers (in this study Re=1000-30000

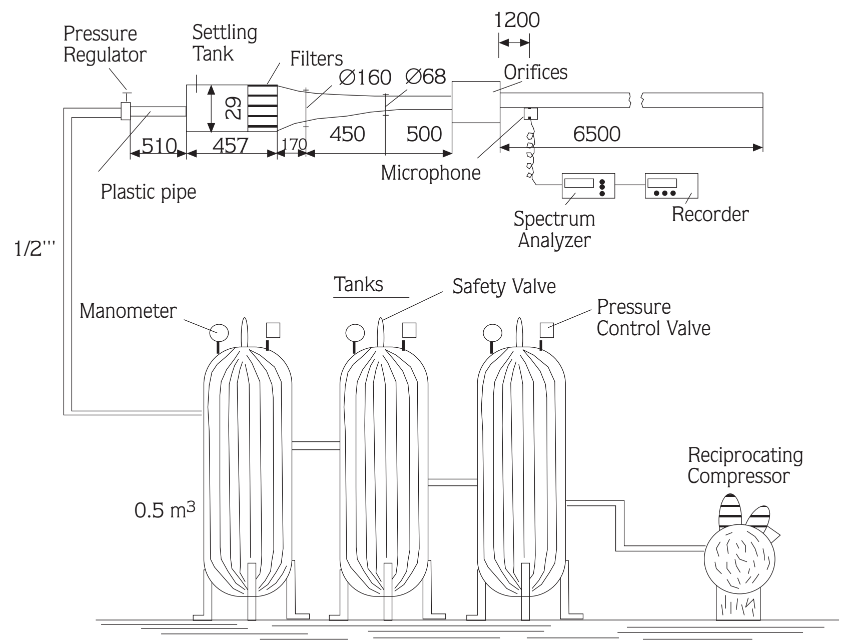

Figure 1. The model pipe system with two orifices having same diameter and experimental measurement set-up (all lengths in mm).

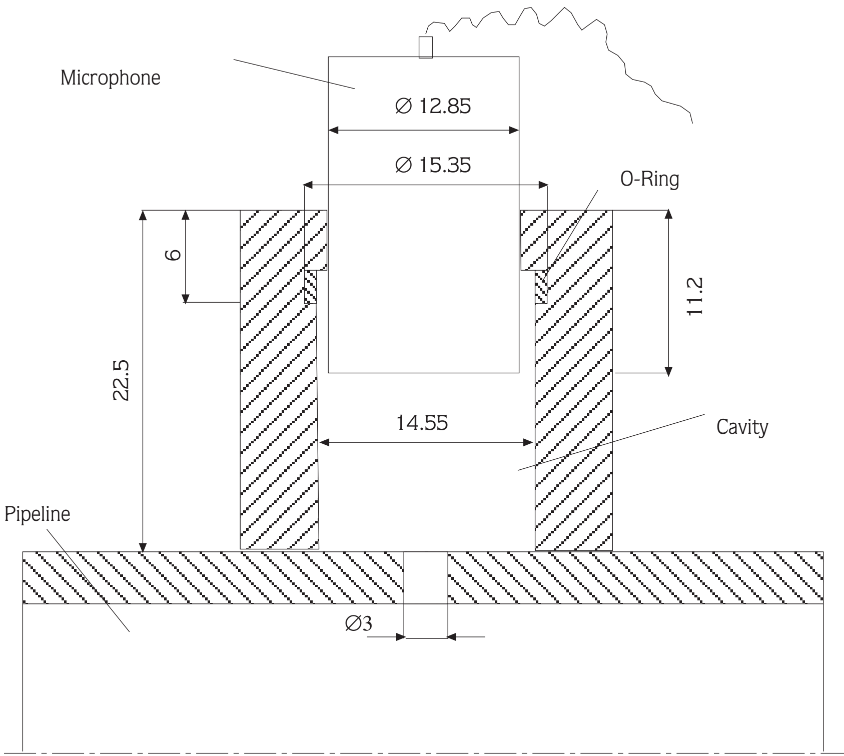

Figure 2. The details of conjuction form of microphone to model pipe system (all lengths in mm).

based on pipe diameter and mean flow velocity on pipe cross-section) or the flow in conditions smaller than fifty mm of pipe diameter, that is, the standard orifice was not used. In this study, the experiments were not carried out by using the geometries of pipe system and orifce plates having flow rate measurement conditions with two orifices given in literature. The objective of this approach is to obtain the oscillations having pressure fluctuations with large amplitude and to assess several concepts regarding the attenuation of these oscillations. The attenuation of self-sustained oscillations induced from the separated turbulent flow through orifices which are often used to measure the flow rate in pipelines is a very important

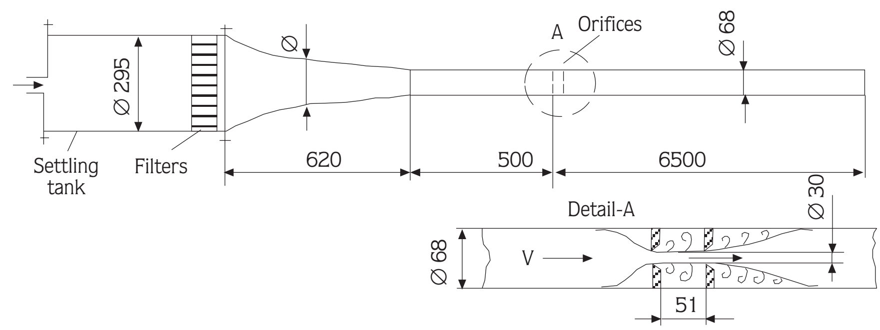

Figure 3. The details of model pipe system with two orifices having same diameter (all lengths in mm).

problem due to the fact that these oscillations can lead to the errors of flow rate measurements in pipelines. Although much effort has been devoted to characterizing the nature of these oscillatory flows, their attenuation deserves indepth consideration comparing with investigations on the nature of oscillatory flows, there have been few investigations related to mitigation of these oscillations at their source, namely the process of flow separation (Weaver, 1978; Ziada et al. 1983; Chen and Florjancic, 1975; Karadoğan and Rockweel, 1983). In this study, those techniques that have been employed will be discussed in the appropriate categories of attenuation. The primary objective of this study is to assess several concepts regarding the attenuation of self-sustained oscillations of turbulent flow through two orificies.

Experimental Set-up

Air used in experiments has been provided from three tanks connected as shown in Figure 1 and having the volumes of 500 liters fed by a reciprocating compressor. Constant flow rate required during measurements was provided by a pressure regulator having 10^4 Pa sensitivity. As shown in Figure 1, when compressor stops, the air filled to the tanks feeds the model pipe system by opening the pressure regulator. Settling tank and filters were used to settle the flow. All measurements were carried out when compressor did not work.

The pressure fluctuations were measured using a Mini Type Condenser Microphone of 1/2" (diameter 12.85 mm) as shown in Figures 1 and 2. The position of microphone is constant during the experiments and is at a distance of 1200 mm to the orifices as shown in Figure 1. Main reason of this distance selection is the fact that the signals with large amplitudes were observed at this distance only. Signals taken by microphone were analysed using a Spectrum Analyzer (HP-3582A) and the results were plotted on X-Y/t Recorder. Flow velocities were measured by a vane anemometer (micromuline) having ± 0.015 sensitivity mounted on the pipe axis at the exit of the model pipe system. The frequency specturms of pressure fluctuations were obtained taking 32 samples and using RMS mode. Fundamental Helmholtz frequency of the cavity under microphone in cojuction pipe shown in Figure 2 is approximately 2900 Hz and this value is out of the limits of observed frequency band. Helmholtz frequencies of settling tank could not be observed due to the ratio of the settling tank volume to the volume of model pipe system was 1/1.24 (Canbazoğlu, 1989).

Flow-acoustic Structure Coupling

Vortices form due to boundary layer separation in flow through an orifice. These vortices may couple with acoustic structure of pipelines and flow-acoustic coupling phenomenon can occur. Resonance will occur as vortex shedding frequency locks on acoustic frequency of pipe system with orifice. This state is not desired because of the flow rate measurement errors, noise, energy losses and system destruction as a result of fatigue.

Vortices can be more periodic and more developed when two sharp-edged orifices are located in the pipeline system as shown Figure 3. Orifices are in 30 mm diameter and located 51 mm apart. In this case, flow-acoustic coupling phenomenon, that is, the coupling of vortex and acoustic waves, occurs strongly due to the location of the orifices. A whistling sound was detected during the experiments in which attenuator was not employed.

Attenuation of Flow-induced Vibrations

The equation governing flow-acoustic coupling phenomenon may be writen, as;

$$f_v=nf_a; \qquad (n=1,2,3,...) \qquad (1)$$

where f_v and f_a show vortex shedding frequency and natural acoustic frequency of pipe system in Hz respectively. The attenuation of vibrations can be achived

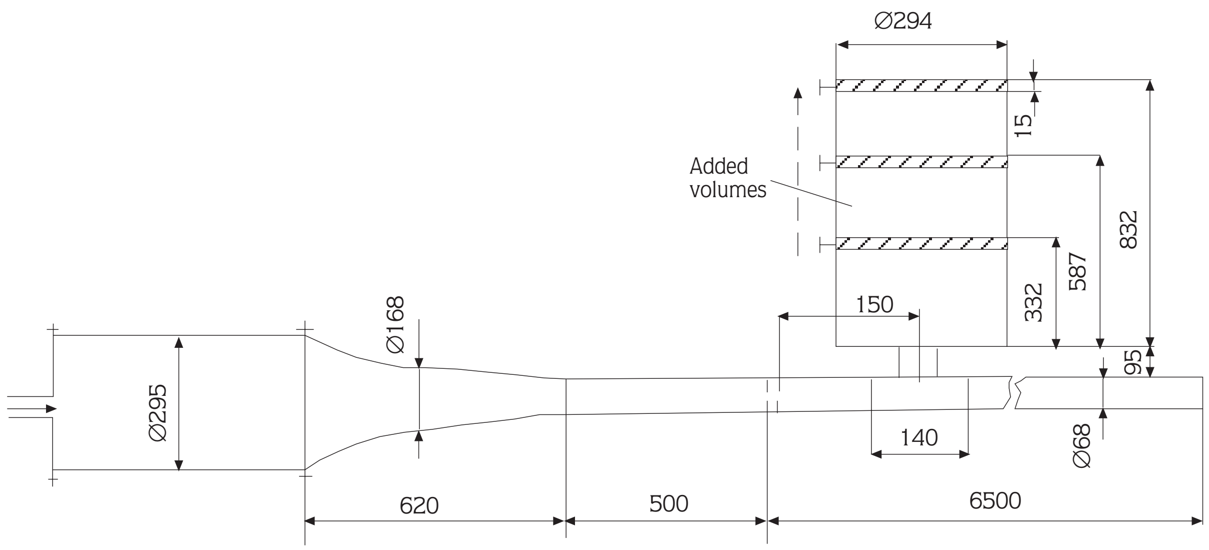

Figure 4. The details of conjuction form of model pipe system with two orifices having added volume (all lengths in milimeters).

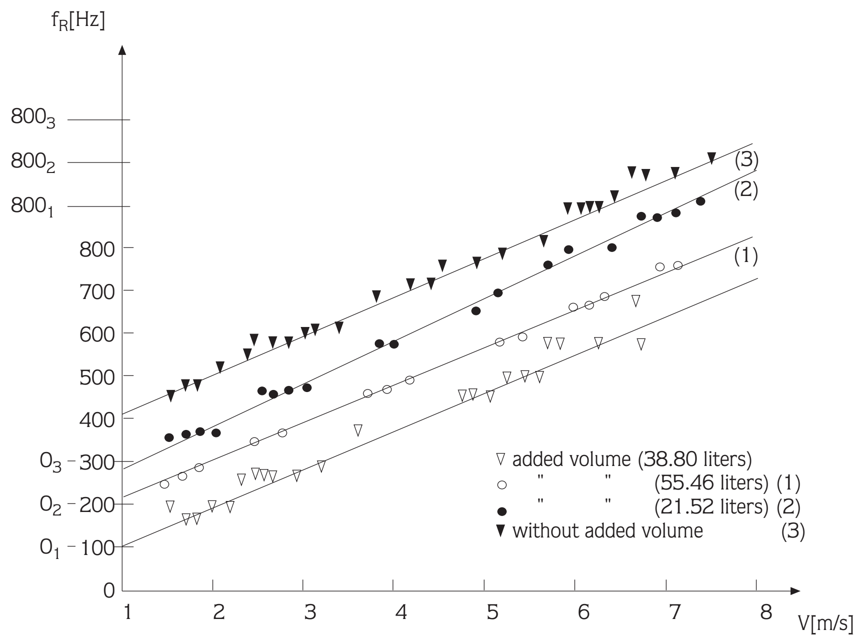

Figure 5. The comparison of variations with mean flow velocity of resonant frequencies for the model pipe systems with two orifices without added volume, and those having the added volumes of 21.52, 38.80 and 55.46 liters.

by changing either vortex shedding frequency or natural acoustic frequency of pipeline as seen from equation (1). However, the most effective way to increase the attenuation of flow-induced vibrations has obtained by changing vortical structures (Ziada et al., 1983; Baldwin and Simmons, 1986; Ziada and Buhlman, 1989; Karadoğan and Rockweel, 1983; Yakut, 1992).

Acoustic frequencies of the model pipe system were obtained experimentally by using both a loudspeaker and an oscillator (Canbazoğlu, 1989).

The Effect of Acoustic Structure of Pipe System

In the model pipe system as shown in Figure 1, acoustic frequencies of system have been changed by mounting pipes having three different volumes vertically. The volumes added to the pipe system are 21.52, 38.80 and 55.46 liters. The volume of model pipe system excluding settling tank and contraction parts is the 31.42 liters. The model pipe system with added volume is shown in Figure 4 (Yakut, 1992). The volume of settling tank is 3.2 liters approximately.

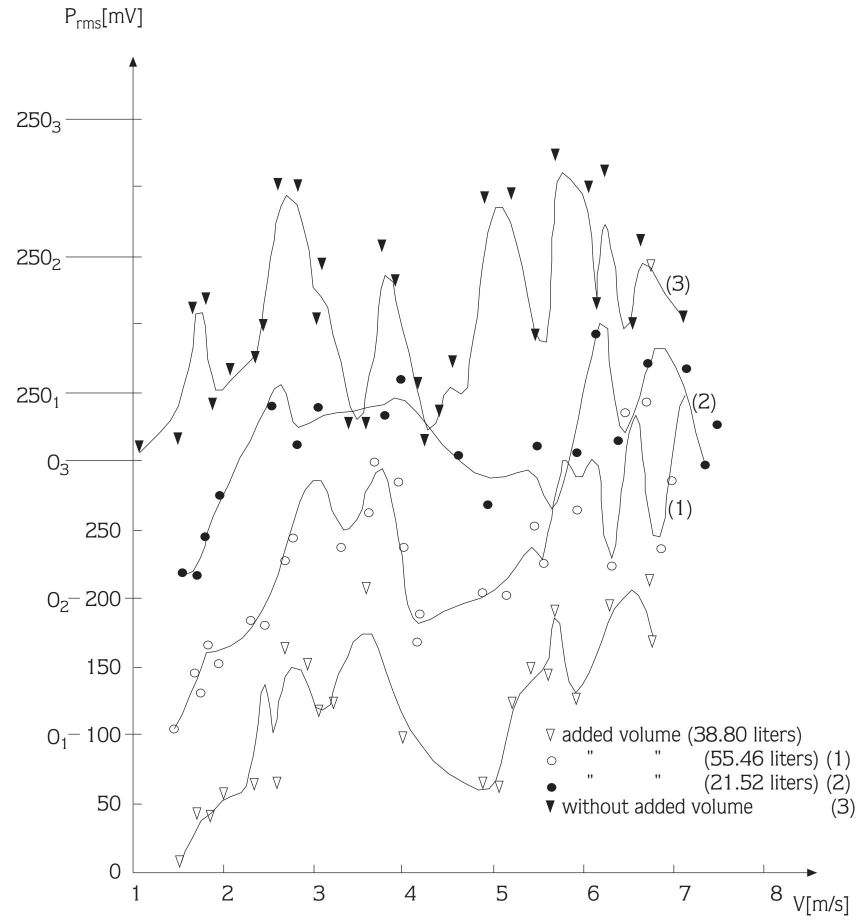

Figure 6. The comparison of variations with mean velocity of relative amplitude of pressure fluctuations in resonance states for the model pipe systems with two orifices without added volume and those having the added volumes of 21.52, 38.80 and 55.46 liters.

Resonant frequency on the frequency spectrums recorded by a spectrum analyzer of the relative pressure fluctuations measured with microphone is dominant frequency on the frequency spectrums, that is, this frequency is the frequency of the relative pressure fluctuation having the largest amplitude. It is estimated that the order of maximum relative error doing on mesurement of resonant frequencies is ±3-4% appoximately. Resonant frequency is either fundamental natural acoustic frequency or its harmonics. The comparison of variations of resonant frequencies measured by the spectrum analyzer is shown in Figure 5 as a function of mean flow velocity for the model pipe systems without added volume, and those having the added volumes of 21.52, 38.80 and 55.46 liters. The lines on Figure 5 were obtained by the least squares method. In order to provide clearity in the figure, the curves of resonant frequencies have been shifted relative to each other. Therefore, 0_1, 0_2 and 0_3 origin points have existed in different points in the Figure 5. Variation of mean flow velocity with resonant frequency is approximately linear. From Figure 5, it can be observed that acoustic structure of pipe system have controlled the vortex shedding frequencies and resonant frequencies have been shifted because of that volume addition to the model pipe sytem will change the natural acoustic frequencies of pipe system. In this case, a feed-back mechanism is established between the vortices shedding from orifices and the fluid column oscillating in pipe system.

Figure 6 shows the comparison of the variations of mean flow velocity with relative amplitude of pressure fluctuations in resonance states for the model pipe systems with two orifices without added volume, and those having the added volumes of 21.52, 38.80 and 55.46 liters. In order to provide clearity in the figure, the curves of pressure fluctuations have been shifted relative to each other. Therefore, 0_1, 0_2 and 0_3 origin points have existed in different points in the Figure 6. It can be seen that the relative amplitudes of pressure fluctuations have been generally decreased by added volume in the model pipe system. It is observed from Figure 6 that the vibrations having large amplitudes are observed in higher mean flow velocities by adding volumes to the system hence changing its natural acoustic frequencies.

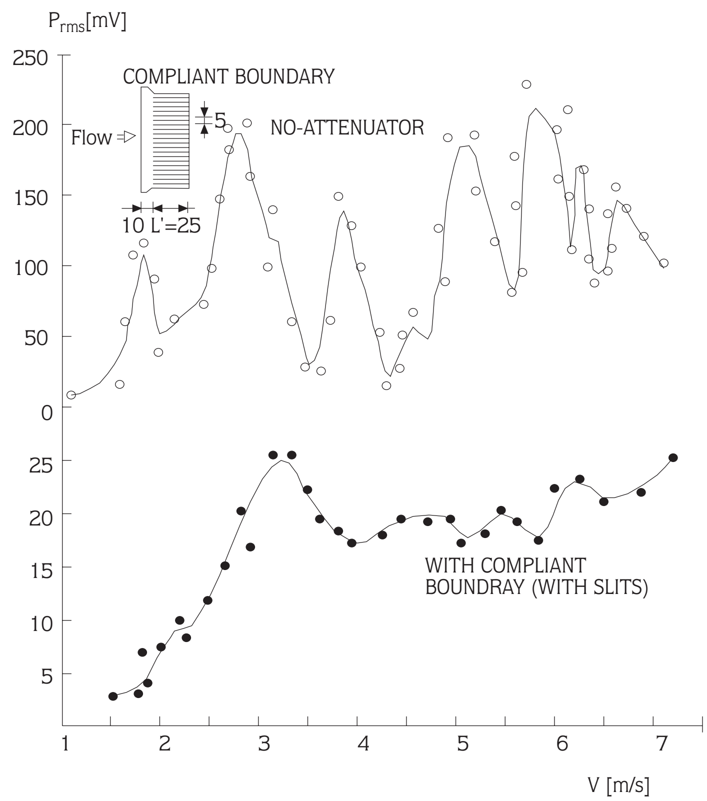

Figure 7. The comparison of variations with mean velocity of relative amplitude of pressure fluctuations in resonance states in the model pipe systems one without compliant boundaries and the other having compliant boundaries of 25 mm length (all lengths in mm).

Effect of Vortical Structure

It is known that the structure of vortices has an important effect on the attenuation flow-induced vibrations in pipelines. For this reason, the boundary layer separation should be prevented. Compliant boundaries and vortex generators may prevent boundary layer separation (Karadoğan and Rockwell, 1983). In the present study, compliant boundaries and vortex generators were mounted circumferencially around the first orifice.

It was assumed that the jet flow through the orifice was fully turbulent, and the mean flow velocity distribution was well-fitted by the equation (2), (Rockwell and Naudascher, 1986);

$$\frac{u}{U} = 1 + \tanh\left(\frac{r}{2R}\right) \qquad (2)$$

where u, U and R show flow velocity at radial distance r, maximum velocity in the cross-section and the radius of orifice respectively.

Wavelength of the developing instability wave of the jet (λ_v) may be approximately calculated from the equantion (3) given for jet forming at a sudden expansion section in pipeline by Davies (1981) as;

$$\lambda_v = \frac{U_v}{f_v} \approx \frac{0.63V}{f_v} \qquad (3)$$

where U_v, V and f_v show the propogation velocity of instability (vortex) wave, mean flow velocity and vortex shedding frequency respectively. It was also observed in the present study that the lengths of compliant boundaries which were cut from highly flexible thin plastic material should be at least one-third wavelength of the developing instability wave of the jet, as defined by Karadoğan and Rockwell (1983). The maximum value of wavelength of the developing instability wave of the jet calculated by the equation (3) is 4.2 mm. The lengths of compliant boundaries are approximately 6 and 11 times of wavelength of the developing instability wave of the jet. The comparison of pressure fluctuations for pipe system without the added volume shown in Figure 3, and the results of experiments carried out with compliant boundaries having 25 mm and 45 mm lengths (L′) were shown in Figures 7 and 8. Their thicknesses are very thin (0.040 mm) due to the fact that compliant boundaries must be considerably thin not to disturb the boundary layer. It is evident that the relative amplitudes of pressure fluctuations were attenuated in the order of 90 percent.

Compliant boundaries reduce to correlation between vortices shedding from orifice and because of this reason, vortices cannot be organized sufficiently.

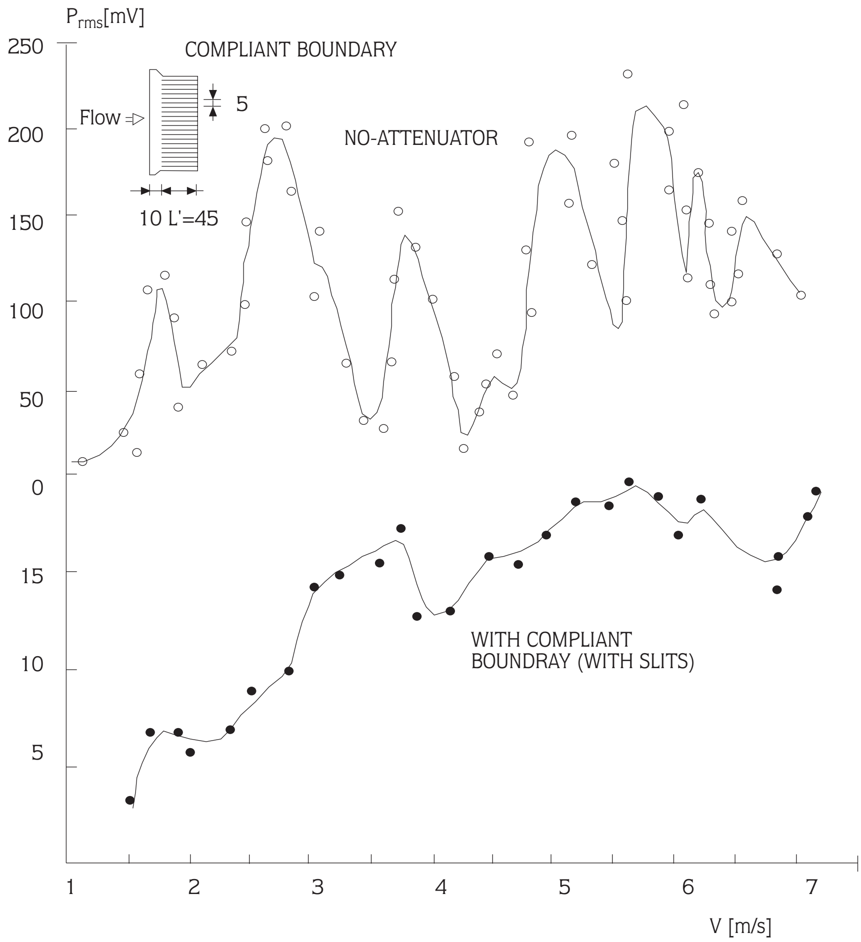

Figure 8. The comparison of variations with mean velocity of relative amplitude of pressure fluctuations in resonance states in the model pipe systems one without compliant boundaries and the other having compliant boundaries of 45 mm length (all lengths in milimeters).

In respect of the compliant boundary configuration, this mechanism involves decreasing the rigidity of the separation edge and mitigating the conversion process (most effective at a rigid trailing edge) between disturbances incident upon the edge and vorticity fluctuations in the shear layer. If the compliant boundary has streamwise slits, the mechanism of azimuthal dephasing can also be expected to play a significant role.

Another attenuator type used to atenuate the flow-acoustic coupling in pipelines is vortex generators. The principle of vortex generators involves production of streamwise vorticity, having a vector orientation orthogonal to the mean vorticity of the seperating boundary layer, thereby destroying the spanwise or azimuthal coherence of the primary vortices. Vortex generators having either the same angle, or alternating angle, of incidence with respect to the mean flow were found to be equally effective (Karadoğan and Rockwell, 1983). It is observed that the height of the generators manufactured from thin sheets of 0.040 mm should be (at least) two momentum thickness of separating boundary layer (θ_0), their angle of incidence at least 30 degrees, and their pitch no more than one-sixth the jet circumference, as defined by Karadoğan and Rockwell (1983).

The maximum momentum thickness calculated from velocity distribution defined by equation (2) is approximately 0.16 mm. The heights of vortex generators used in experiments are 2 and 3 mm. That is, the ratios of the heights of vortex generators to the maximum momentum thickness is approximately 13 and 19. Their incidence angles are 31 and 45 degress, and their pitch is one-twelfth the jet circumference. All of these values agree with the results of Karadoğan and Rockwell (1983). In the conditions mentioned above, the effect of vortex generators used for attenuation of flow-induced vibrations in model pipe system with two orifices was observed. The results of the experiments are shown in Figures 9 and 10. The relative amplitudes of pressure fluctuations were reduced

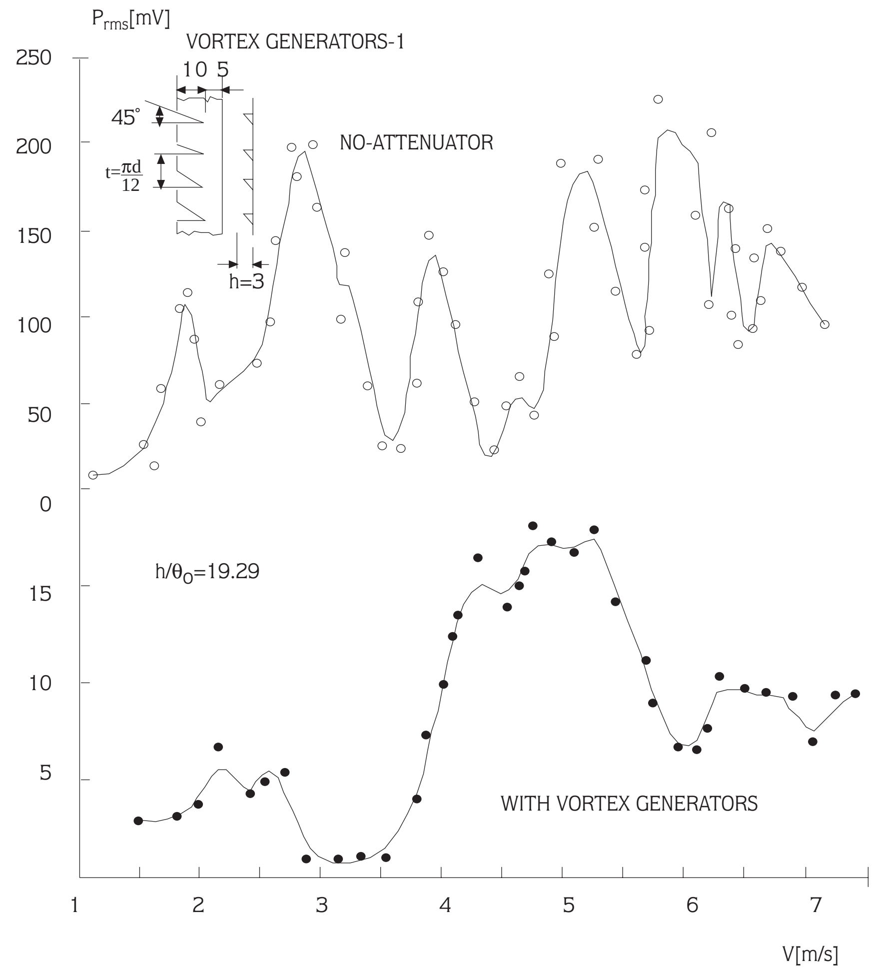

Figure 9. The comparison of variations with mean velocity of relative amplitude of pressure fluctuations in resonance states in the model pipe systems one without vortex generators and the other vortex generators having the same angle (all lengths in milimeteres).

to very small orders as 94 percent. Vortex generators having alternating angle of incidence with respect to the mean flow were found to be more effective becase of that the correlation between vortices shedding from orifices was reduced.

Conclusions

Of the various categories of attenuators such as the volume addition to the model pipe system, the using of vortex generators and compliant boundaries on the circumference of orifices, the most effective are the using of vortex generators and compliant boundaries:

(a) Vortex generators having either the same angle, or alternating angle, of incidence with respect to the mean flow were found to be equally effective. The height of the generators should be (at least) two momentum thickness of the separating boundary layer of jet at orifice exit, their angle of incidence at least 30 degrees, and their pitch no more than one-sixth the jet circumference. It was seen that vortex generators having alternating angle was much more effective than those having same angle in the attenuation of oscillations.

(b) Compliant boundaries involving highly flexible extensions of the jet orifice exit are most effective when slitted in the streamwise direction. The length of these boundaries should be at least one-third wavelength of the developing instability wave of the jet.

(c) Although the maximum relative amplitudes of pressure fluctuations have reduced in order of 90 percent in the model pipe system with orifice having compliant boundaries, they have reduced in the order of 94 percent in the model pipe system with orifice having vortex generators of alternating angle. Therefore, it can be said that vortex generators have some more attenuation effect than compliant boundaries.

(d) It was seen that the variation of its acoustic

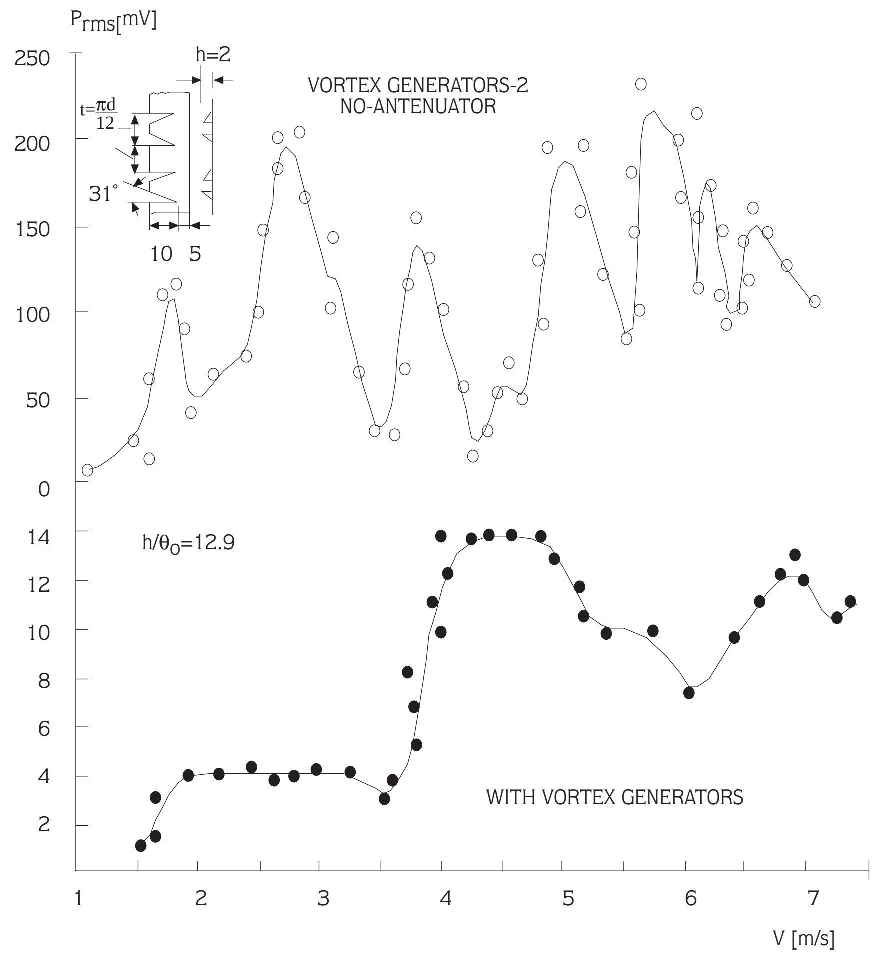

Figure 10. The comparison of variations with mean velocity of relative amplitude of pressure fluctuations in resonance states in the model pipe systems one without vortex generators and the other vortex generators having the alternating angle (all lengths in milimeters).

frequency by adding volume to the model pipe system for attenuation of oscillations was less effective with respect to the changing of vortical structure of orifice by attenuators such as vortex generators and compliant boundaries. But in this case, vibrations occur at a higher mode, that is, the peak amplitude of oscillation may shift to a higher value of the mean flow velocity. However, the comparison of results regarding with changing of vortical structure of orifice and the variation of acoustic structure of pipe system by adding volume to model pipe system is not true due to the fact that the compliant boundaries and vortex generators are at the exit of the first orifice although the added volume is further from the exit of the second orifice.

Consequently, it is the most effective solution to change vortical structure to attenuate self-sustained oscillations in pipelines. For this purpose, vortex generators and compliant boundaries can be used in pipelines with orifice. Vortex generators having alternating angle are most effective with respect to the compliant boundaries.

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Nomenclature

d	:	The diameter of sharp-edged orifice (=2R)
D	:	Diameter of the model pipe system
f_a	:	Natural acoustic frequency of the model pipeline
f_v	:	Vortex shedding frequency
f_R	:	Resonant frequency
h	:	The height of the vortex generators
L'	:	The length of compliant boundaries
P_{rms}	:	The root mean square value of the relative amplitude of pressure fluctuations
r	:	Radial distance from pipe axis
R	:	The radius of sharp-edged orifice
t	:	The pitch of vortex generators (=πd/12)
u	:	Flow velocity in the boundary layer of turbulent jet
U	:	Maximum flow velocity in the cross-section of jet
V	:	The mean flow velocity in the model pipe system
δ_0	:	Thickness of the boundary layer of jet at separation
θ_0	:	Boundary layer momentum thickness of jet at separation

$$\theta_0=\int_0^{\delta_0}\left(1-\frac{u}{U}\right)\frac{u}{U}\frac{r}{R}dr$$

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