

FLOW-ACOUSTIC COUPLING IN T-JUNCTIONS: EFFECT OF T-JUNCTION GEOMETRY

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ABSTRACT

The flow-acoustic coupling mechanism in a T-junction, which combines flows from two branches, forming the “cross-bar” of the T-junction, into one pipe, forming the “stem” of the T-junction, is investigated experimentally. The T-junction has a step pipe expansion at its inlets. The shear layer separating from this step expansion is found to excite intense acoustic resonances over multiple ranges of flow velocity. The excited acoustic mode is confined to the branch pipes and has an acoustic pressure node at the centerline of the T-junction. The length of the expansion section of the T-junction is found to control the frequency of the shear layer oscillation and therefore determines the ranges of reduced flow velocity over which acoustic resonances are excited.

1. INTRODUCTION

The excitation of acoustic resonances by the coupling between an acoustic mode and an unstable separated fluid flow is a well-recognized problem in industrial piping systems. Acoustic resonances can produce unacceptable noise levels as well as excessive pipe vibration.

The present work was motivated by a vibration problem of a steam piping system in a power plant. This piping involved a T-junction combining flows from two branches, forming the “cross-bar” of the “T”, into one pipe, forming the “stem” of the “T”. As shown in Fig. 1(a), this T-junction has an expansion zone to allow matching the two inlet pipes, with a smaller diameter, d , to the outlet pipe, which has a larger diameter, D . In high-pressure steam piping and the natural gas transport industry, similar geometry T-junctions are commonly used to maintain approximately constant flow velocity in various pipe sizes. This paper focuses on the effect of the T-junction geometry on the mechanism causing acoustic resonances in the associated piping system. The expanded portion of the T-junction will be referred to hereafter as the

transition or expansion zone and the pipes upstream of the junction will be referred to as the *branch pipes*, whereas the pipe downstream of the T-junction will be referred to as the *main pipe*. This terminology is consistent with that used in an earlier, related paper by Ziada et al. (2007).

In that earlier study, Ziada et al. (2007) performed an investigation on a simplified T-junction where the transition zone was omitted, and therefore the pipe diameter was constant throughout as shown in Fig. 1(b). In that study, the lowest mode, or the primary mode, of the branch acoustic modes was excited. As illustrated in Fig. 1(c), this mode is confined to the branch pipes and has a pressure node at the centreline of the T-junction.

While this investigation showed that the branch acoustic modes, and in particular the lowest one, are the only modes susceptible to strong excitation by the flow in the T-junction, the produced resonances were rather weak in comparison with those observed in the industrial problem. It is believed that stronger acoustic resonances may be excited by the separated flow at the inlets of the transition zone. This supposition is examined in some detail in the present work.

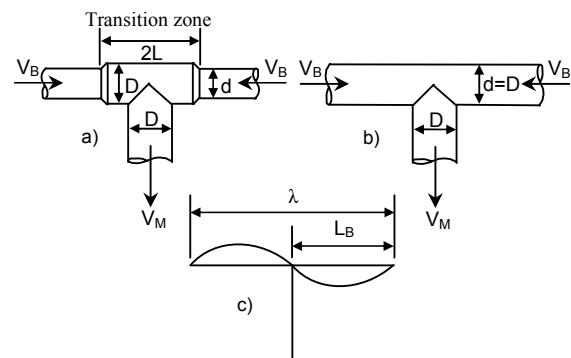


Figure 1: Schematic of various T-junction geometries. a: T-junction with transition zone; b: T-junction without transition zone; c: Primary branch acoustic mode

2. EXPERIMENTAL TECHNIQUES

2.1 Test setup

The cylindrical pipe test setup is shown schematically in Fig. 2. Similar to the piping geometry of the industrial case history, the experimental piping configuration consisted of two co-axial branch pipes connected to a main pipe through the use of a T-junction with a transition zone. This arrangement is conducive to the excitation of the primary mode of the branches which has a pressure node at the centre of the T-junction, Fig. 1(c). The only difference from the previous study reported by Ziada et al (2007) is that the T-junction in the present study allowed the branch pipes to have a different diameter from that of the main pipe. Since numerous T-Junctions were needed for this study, commercial, off-the-shelf PVC piping, T-junctions and expansion joints were used. The piping dimensions were chosen such that the flow velocity in the main pipe is as close as possible to that in the branch pipes. The selected branch pipes had a diameter of $d = 76$ mm (3 inches) and the main pipe diameter was $D = 102$ mm (4 inches). With this arrangement, the flow velocity in branch pipes was only 10% lower than that in the main pipe.

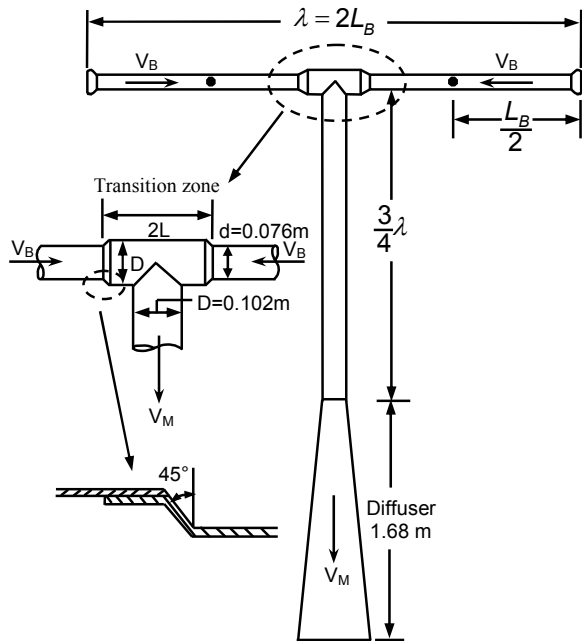


Figure 2: Experimental setup.
 • denotes microphone locations

In order to investigate the effect of the transition zone length on the acoustic resonance mechanism, eight different T-junction geometries were tested. These geometries were characterized by the ratio of *one half* of the transition zone length, L , to the main pipe diameter, D . The ratios selected ranged from $L/D = 1.0$, to $L/D = 5.0$. For the shortest case, $L/D = 1.0$, the total length of the branch pipes including the T-junction, i.e. the length between the two inlets, was initially 2.84 meters. This length, which is equivalent to the wavelength, λ , of the primary acoustic mode as shown in Fig. 1(c), was therefore increased when the length of the transition zone of the T-junction was increased up to a length of 3.66 meters for $L/D = 5.0$.

As shown in the inset of Fig. 2, the inner surface of the pipe expansion at both sides of the T-junction was carefully machined to produce smooth and well defined transition geometry. In addition, the entrances of the branch pipes were fitted with circular contractions to minimize entry losses and produce a smooth, uniform flow, while still maintaining a high pressure reflection coefficient to promote the excitation of acoustic resonances (Selamet et al. 2001). In order to minimize the radiation of acoustic energy into the main pipe, the length of the main pipe was set at $\frac{3}{4}\lambda$, where λ is the wavelength of the primary acoustic mode of the branch pipes, as shown in Fig. 1(c). With this geometry, the acoustic impedance of the main pipe was greatly increased and, as a result, its participation in the primary acoustic mode was precluded. When the length of the transition zone was increased during the tests, thus increasing the wavelength (λ) of the primary acoustic mode, the main pipe length was adjusted to maintain it at $\frac{3}{4}\lambda$.

The flow velocity in the piping system was produced by means of a variable speed centrifugal blower. As shown in Fig. 2, the outlet of the main pipe was connected to the suction side of the blower by means of a diffuser and a flexible duct. This arrangement reduced vibration transmission from the blower to the piping system.

2.2 Measurement technique

To characterize the acoustic response of the piping systems at various flow velocities, measurements of both the flow velocity and the pressure pulsations were performed. As shown in Fig. 2, the locations of pressure measurements were placed at the mid-point of each branch pipe, which

coincide with the antinodes of the primary acoustic mode of the branches. The mean flow was measured by means of a pitot-static probe and the pressure pulsations with the aid of 1/4" condenser microphones type G.R.A.S. The microphones were flush-mounted to the inner pipe wall to prevent interference with the flow field. Before each test, the microphones were calibrated by means of a pistonphone.

The pressure signal from each microphone was acquired by means of a National Instruments PCI-4452, four-channel 16 bit simultaneous sampling input board. A LabView program was used to sample these signals at a frequency of 2048 Hz. Analysis of the phase between the microphone signals was used to identify the acoustic modes associated with various peaks in the pressure spectra.

2.3 Dimensionless parameters

The test results are presented in terms of normalized amplitude of pressure pulsation, P^* , as a function of the reduced velocity, V . Unless otherwise stated, the root mean square amplitude of pressure pulsation, P , is normalized by the dynamic head in the branch pipes as follows:

$$P^* = P / \left(\frac{1}{2} \rho V_B^2 \right) \quad (1)$$

where V_B is the flow velocity in the branch pipes. The reduced velocity, V , is also based on the branch flow velocity, V_B , on the frequency of the lowest acoustic mode of the branches, f , and a characteristic length, ℓ .

$$V = \frac{V_B}{f \ell} \quad (2)$$

Initially, the pipe diameters, D or d , were used to normalize the flow velocity, especially when comparing the present results with those reported for a T-junction without a transition zone (Ziada et al., 2007). Later on, the half length of the transition zone, L , was identified to be the key characteristic length controlling the frequency of flow instability in the T-junction. When this length is used to normalize the flow velocity, the acoustic resonances of different T-junction geometries occurred over the same range of reduced velocity.

3. FLOW-EXCITED ACOUSTIC RESONANCE

For each test case of the T-junction geometries, measurements were taken at a series of progressively increasing flow velocities. Typical pressure spectra with $L/D = 2.5$ are shown in Fig. 3 for a range of flow velocity from $V_M = 6$ m/s to 65 m/s. The lowest acoustic mode of the branches near 110 Hz is seen to be excited over two different velocity ranges. The first resonance is weaker and occurs between 25 m/s and 35 m/s. The second resonance is much stronger and starts near 45 m/s and continues until the maximum capacity of the blower is reached. Note also that the higher modes of the branches are also excited, albeit weakly in comparison with the first mode resonance. The maximum pressure amplitude attained during the first mode resonance in this particular case is about 900 Pa, which is equivalent to 153 dB.

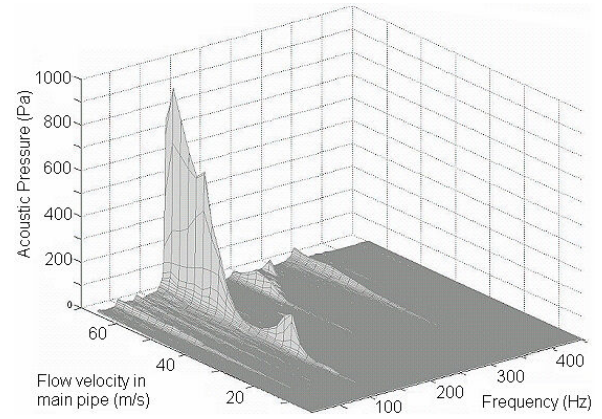


Figure 3: Typical waterfall plot of pressure spectra. $L/D=2.5$

Figure 4 shows a comparison of a typical response of the present piping system ($L/D = 2$) with that reported by Ziada et al. (2007) for a T-junction geometry without the transition zone, such as that shown in Fig. 1(b). This figure shows the amplitude of the normalized acoustic pressure pulsation of the lowest acoustic mode of the branches as a function of the reduced velocity based on the main pipe diameter and flow velocity, V_M / fD . In both cases, the resonance frequency is practically the same, near 110 Hz. The present T-junction geometry is seen to generate much stronger acoustic resonances than in the case of T-junction without transition zone. Similar to the case shown in Fig. 3 for $L/D = 2.5$, the acoustic resonance

occurs over two ranges of flow velocity. Since the main difference between the two cases is the step expansion at the inlets of the T-junction, it is likely that the oscillation of the shear layers separated from the expansion corners at the entrance of the T-junction is the main source of excitation. The effect of changes in the extent of the flow separation region on the pipe acoustic response is investigated by changing the length of the transition zone of the T-Junction.

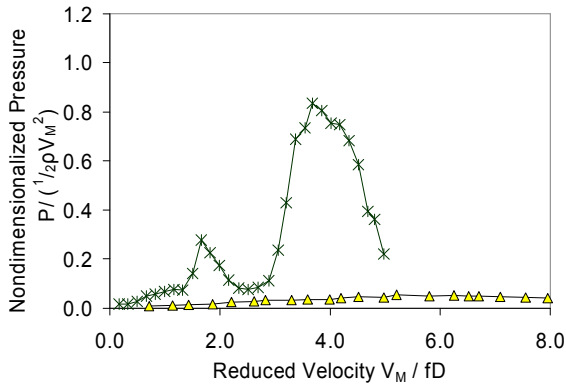


Figure 4: Comparison of typical responses for T-junctions with and without a transition zone.
 * , T-junction with transition zone, $L/D = 2$;
 \blacktriangle , T-junction without transition zone.

The response of the lowest acoustic mode of the branches is depicted in Fig. 5 for all tested cases of transition zone length. In this figure, the reduced velocity is based on the branch pipe diameter, d , and the flow velocity in the branch pipes, V_B , is used to normalize the pressure amplitude.

These parameters, i.e. d and V_B , were initially used to normalize the test results because they were originally thought to be most relevant for the instability of the jet issuing from the branch pipes and expanding into the transition zone. For the sake of clarity, the results of the eight test cases are detailed in two separate figures. Note that, the results for $L/D = 2.0$ are presented in both figures to facilitate easy comparisons between the results of all cases. The acoustic resonance peaks of various T-junction geometries are seen to occur over different ranges of reduced velocity, which indicates that the diameter of the branch pipe, d , is not the key characteristic length associated with the flow instability inside the T-junction. Similar conclusions can be drawn regarding the main pipe diameter, D , or the height of the expansion step at the entrance of the transition zone, $(D - d)/2$, see

Fig 1(a). Since these parameters are constant for all tested geometries, they also will produce a wide scatter in the acoustic resonance data similar to that observed in Fig. 5. It follows that neither D nor $(D-d)/2$ can be regarded as the key length scale which determines the excitation frequency generated by the flow instability in the T-junction.

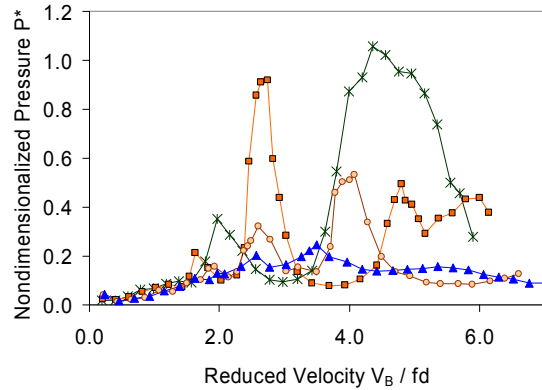
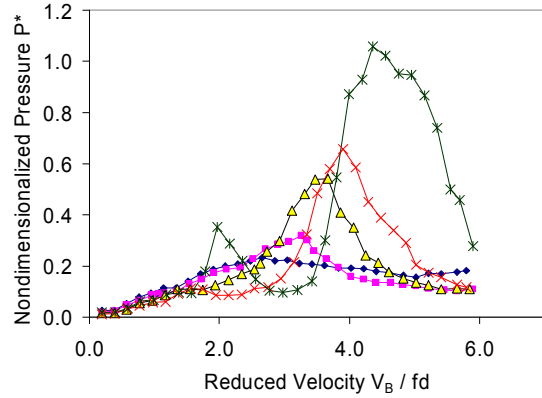


Figure 5: Normalized acoustic pressure of the primary mode as a function of reduced velocity, based on the branch pipe diameter d .
 \blacklozenge , $L/D = 1.0$; \blacksquare , 1.25; \blacktriangle , 1.5; \times , 1.75; \ast , 2.0; \blacksquare , 2.5; \circ , 3.75; \blacktriangleleft , 5.0.

The results of all cases presented in Fig. 5 are re-plotted in Fig. 6 in which the flow velocity is normalized by the half-length of the transition zone, L , instead of the pipe diameter. In this figure also, the results for all T-junction geometries are presented in two separate figures. Note that although the maximum flow velocity is approximately constant in all cases, the range of the reduced velocity ($V = V_B / L$) becomes smaller as the length scale L is increased. This causes the range of the data points in Fig. 6 to become narrower for the cases with longer transition zone.

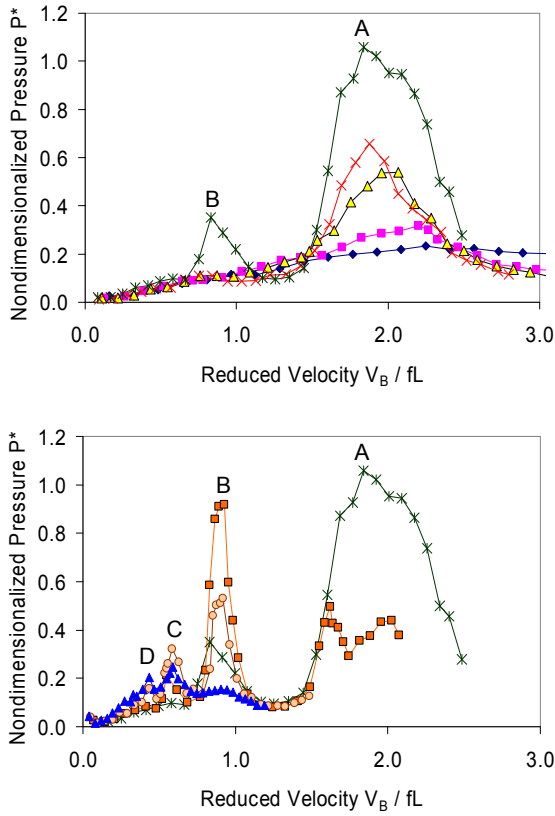


Figure 6: Normalized acoustic pressure of the primary mode as a function of reduced velocity, based on half the transition zone length, L .

◆, $L/D = 1.0$; ■, 1.25 ; ▲, 1.5 ; ×, 1.75 ;
 * , 2.0 ; □, 2.5 ; ◻, 3.75 ; ▲, 5.0 .

As can be seen in Fig. 6, using L as the characteristic length scale of the flow oscillation reveals the remarkably organized nature of the flow mechanism which excites acoustic resonances of the branches. The resonance peaks of all cases occur over well defined ranges of reduced velocity. As the transition length increases, a resonance peak starts to appear near a reduced velocity of 2. This main resonance peak, referred to as resonance “A” in Fig.6, reaches its strongest amplitude at $L/D = 2$. At the same time, a second resonance peak “B” starts to appear near a reduced velocity of 0.9. This second peak gains in strength, while the first peak becomes weaker as the transition length is further increased. This trend continues as the transition length is increased, i.e. new resonance peaks start to appear at lower reduced velocities, e.g. peaks “C” and “D” in Fig. 6, while those at higher reduced velocities become weaker. All these resonance peaks occur at well defined ranges of reduced

velocity, which are centered near the reduced velocities of 1.82, 0.89, 0.58 & 0.43. As the Strouhal number is simply the inverse of the reduced velocity, the resonance peaks occur at Strouhal numbers of approximately 0.55, 1.13, 1.73 & 2.33. These values are remarkably similar to the Strouhal numbers reported in the literature for acoustic resonance of cavities exposed to grazing flow. For example, Ziada et al. (2003) reported Strouhal numbers of 0.54, 1.12 & 1.7 for the acoustic resonance of confined shallow cavities. Rockwell et al. (2003) also reported similar Strouhal numbers for an axisymmetric shallow cavity in a pipe, except the lowest value (0.54) which was not observed in their experiments. Flow visualization studies reported in the literature, e.g. Ziada et al. (2003), have shown these Strouhal numbers to be related to the instability mode of the shear layer which excites the resonance. Additional work on a two-dimensional T-junction with rectangular ducts and published elsewhere, Ziada et al. (2008), confirmed that the measured Strouhal numbers for the T-junction correspond to the formation of different numbers of vortices along the half length of the transition section. Once this analogy between the present case and flow over shallow cavities is established, the relevance of the length scale L becomes clear.

Because the vortices that develop in the shear layer grow and travel along just half of the total length of the transition zone, the life cycle of a vortex is strongly related to half the length of the transition zone (L). When the time required by a vortex to travel half the length of the transition zone is equal to the period of the acoustic oscillation, acoustic resonance is excited by the first shear layer mode. This *first shear layer mode* resonance is thought to occur in Fig. 6 near $V = 1.82$, or at a Strouhal number of $St = 0.55$, and to have the highest resonance amplitude. When this required time is doubled, the acoustic resonance is then excited by the *second shear layer mode*, seen in Fig. 6 near $V = 0.89$ (or $St = 1.13$). For cases with transition zones larger than $L/D = 2.0$, the resonance is excited also by the *third shear layer mode* near a reduced velocity of $V = 0.58$ (or $St = 1.73$), and the time for one vortex to travel half the length of transition zone is equal to 3 times the acoustic oscillation period. A smaller resonance peak can also be seen near $V = 0.43$, which may correspond to the *fourth shear layer mode*. It is clear that this description of unsteady flow structure

during resonance is crudely simplified because the formed vortices are in fact vortex rings extending along the circumference of the transition zone. In addition, these vortex rings are convected along a very complex, three dimensional flow within the T-junction. However, the very orderly acoustic response depicted in Fig. 6 suggests that the global (or integrated) effect of the flow dynamics over the oscillation cycle is similar to the above description.

Returning to Fig. 6, it is seen that as the length of the transition zone is increased the pressure pulsation levels also increase up to the case with $L/D = 2.0$, at which point the pulsation amplitude begins to decline, but the second resonance near $V = 0.9$ becomes stronger. From a practical point of view, this figure can be used by practicing engineers to select the length of the transition zone to avoid the acoustic resonance altogether or alleviate its intensity. A suitable length L is obviously dependent on the relevant resonance frequency and the design range of flow velocity. For example, a short transition zone of $L/D \approx 1$ dampens the resonance substantially over the whole tested range of reduced velocity ($V = 5$). On the other hand, a relatively long transition zone, $L/D > 5$, can be used to decrease the reduced velocity in order to avoid strong pressure pulsations in the branches and also to reduce the flow losses in the T-junction.

4. CONCLUSIONS

An experimental study has been performed to investigate flow-acoustic coupling in a T-junction which combines the flow from two branches into a main pipe. It is shown that strong acoustic resonances can be excited if the T-junction has a transition (or expansion) zone. The lowest acoustic mode of the branches was the only mode excited during the tests, sometimes over several ranges of flow velocity. This mode is confined to the branches and has a wavelength equal to the combined length of the branches, and therefore it possesses a pressure node at the T-junction centreline. The acoustic resonance of all cases with a transition zone is far more intense than that produced by piping systems utilizing a T-junction without a transition zone. The acoustic pulsation observed for the case with $L/D = 2.0$ exceeds the dynamic head of the mean flow. Since visco-thermal acoustic attenuation is lower in larger size and/or pressurized piping systems, higher levels of

acoustic pressure are expected to occur in industrial applications.

The occurrence of acoustic resonance depends on the time required by the vortices formed in the shear layers to travel from the T-junction inlet to its outlet. An acoustic resonance is excited when this travel time approximates integer multiples of the acoustic resonance period, which is the inverse of the acoustic resonance frequency. For this reason, the acoustic resonance of the branches is excited over multiple ranges of flow velocity. These resonance ranges are controlled by the length of the T-junction transition zone. Using the half length of the transition zone as the characteristic length scale to normalize the flow velocity results in well defined ranges of reduced velocity over which the acoustic resonance is excited in all tested cases, regardless of the transition zone length.

The results of this study, such as those presented in Fig. 6, provide practicing engineers with a means to avoid the occurrence of acoustic resonance or alleviate its intensity. This figure can be used to select a suitable length of the transition zone based on an estimate of the acoustic resonance frequency and the projected range of flow velocity.

5. REFERENCES

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