Flow Acoustic Interaction In A Rectangular T-Junction With Mounted Perforate Using Acoustic Three-Port Measurements

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ABSTRACT

Varying acoustic behaviour of perforates in presence of grazing flow and under acoustic excitation from different directions has been under research since mid-1950s. Empirical and semi-empirical studies have shown differing estimations of the perforate transfer impedance in presence of grazing flow. Studying a perforated plate in a rectangular T-Junction, this study aims to study the perforate from three-incidence directions. Scattering matrix and the acoustic transfer impedance are determined experimentally under the presence of external grazing flow to characterise the perforate and the T-Junction. In accordance with previous research, an oscillating behaviour of amplification and attenuation is observed in the empty T-Junction. Results obtained of the perforate are of a similar nature. Comparing with the rectangular T-junction, the similarity in the flow acoustic nature of a perforate is shown.

1. INTRODUCTION

Research to study the behaviour of a T-Junction in presence of grazing flow has been carried out previously in Ref. [1, 2]. A three-port technique has been defined in the references for the aero-acoustic characterization of the cross section of the T-junction. The advantage being that the technique allows the characterisation of the cross section using excitation from three directions. Studying a perforate in the T-junction is inspired from Ref. [3, 4], where an extra impedance tube has been used as an addition to the two-port technique, i.e., a third duct. Using the three-port technique, the acoustic characterization of the perforate is attempted in Ref. [5, 6]. Characterisation of the acoustic properties is carried out by comparing the normalised transfer impedance and the scattering matrix coefficients. The results from Ref. [6] show a similarity with the trends observed in experiments conducted in a two-port setup [7]. Compared to the results of Ref. [6], the testing conditions are expanded in this study. Similar to Ref. [1, 2], an oscillating behaviour of the incoming sound waves are seen in an empty T-junction. These characteristics are determined under different grazing flow speeds and a Strouhal Number is used as a scaling factor. On observing the results at different flow speeds, it is found that the Strouhal number at which, for an empty T-Junction the resistance is minimum, is a harmonic of the Strouhal number at which the resistance is minimum for a perforated T-

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Junction. This suggests a resemblance in their behaviour, however, no oscillations are seen in case of the perforate, suggesting the proposal of Ref. [6] to be only partially correct.

2. EXPERIMENTAL SETUP AND ACOUSTIC CHARACTERISTICS

The schematic of the three-port setup with and without the perforate in place is as shown in Figure 1. In case of the perforated T-Junction, the perforate is flush mounted at the intersection of the T-Junction. Moreover, the end of duct-3 is sealed to avoid any flow leakage and to obtain a constant flow profile over the perforated section. The intersection is exposed to stepped sine excitation from all three direction in the plane wave frequency range and wave decomposition is carried out to study the sound field in all three ducts.

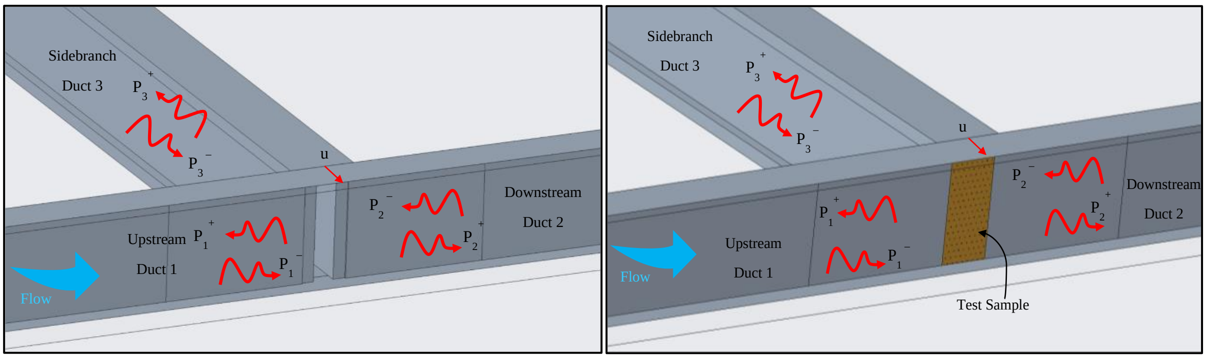

Figure 1 Schematic of the three-port experimental setup [6]; **a)** Empty T-Junction, **b)** Perforate at the intersection of the T-Junction

Characterization of the T-Junction is done using the transfer impedance (normalised with respect to the characteristic impedance of air) and the scattering matrix (S-Matrix) coefficients. Definitions of these characteristics are following Ref. [2, 6] and as shown in the following equations:

$$\begin{bmatrix} P_{1+} \\ P_{2+} \\ P_{3+} \end{bmatrix} = \begin{bmatrix} \rho_1 & \tau_{2\to1} & \tau_{3\to1} \\ \tau_{1\to2} & \rho_2 & \tau_{3\to2} \\ \tau_{1\to3} & \tau_{2\to3} & \rho_3 \end{bmatrix} \begin{bmatrix} P_{1-} \\ P_{2-} \\ P_{3-} \end{bmatrix}, or\ \mathbf{P}^{+} = \mathbf{S}\mathbf{P}^{-}\ , \quad (1)$$

where $P_{x\pm}$ are decomposed wave pressure amplitudes in duct-x. The subscripts '+' and '-' depict the directions as per Figure 1, ρ and τ describe the reflection and transmission coefficients, respectively, and the subscripts represent the respective ducts.

$$\overline{Z_1} = \frac{(\rho_1+\tau_{1\to2}+1)}{2\tau_{1\to3}} - 1\ , \overline{Z_2} = \frac{(\rho_2+\tau_{2\to1}+1)}{2\tau_{2\to3}} - 1\ , \overline{Z_3} = \frac{1+\rho_3}{1-\rho_3} - \frac{1}{2}\left(\frac{\tau_{3\to1}+\tau_{3\to2}}{1-\rho_3}\right), \quad (2)$$

where $\overline{Z_x}$ is the normalised transfer impedance measured under acoustic excitation from duct- *x*. Given that the acoustic wavelength of the incoming sound waves is significantly greater than the sample thickness, the real part of the transfer impedance, i.e., the resistance ($\Re$) is the important characteristic considered in this study.

The cross-section of each duct is 25mm by 120mm, and the perforated plate has the same dimensions. The porosity of the perforated plate is 2.54%, diameter of the square-edged perforations (*d*) and the plate thickness is 1.2mm. All the measurements were performed at room temperature and in-duct temperature was monitored using calibrated thermocouples. Data acquisition of acoustic pressure signals was carried out at a sampling frequency of 25.6kHz, using flush mounted Brüel and Kjær ¼- inch 4938 type condenser microphones and NI 9234 DAQ modules. Microphone positioning was carried out following the recommendations of Ref. [8] and wave decomposition was carried out using the wave numbers modelled as per Ref. [9]. The flow profile is defined as in Ref. [6], and the bulk velocity is used as input to determine the mean Mach number of the grazing flow in ducts- 1 and 2. Experiments are carried out in the grazing flow speed range of ≈10m/s to ≈60m/s. To have a dimensionless comparison between the characteristics, Strouhal number and Helmholtz number are used as defined in the following equation:

$$St = \frac{2\pi f d_{eq}}{U};\ He = \frac{2\pi f d_{eq}}{c}, \tag{3}$$

where U is the bulk velocity, c is the speed of sound, and d_{eq} is the equivalent diameter. For the perforated T-Junction d_{eq} is the diameter of the perforation and for an empty T-Junction it is calculated by taking the ratio of the area and the perimeter of the rectangular cross-section (d_{eq}= 41.37mm).

3. RESULTS

3.1 No Flow Results

The resistance and magnitude of the S-Matrix coefficients are as shown in Figure 2. As mentioned in Ref. [2], on shifting the origin of an empty T-junction, the near field effects of an empty T-junction are compensated till Helmholtz number (*He*) of unity, as seen in Figure *2*-a. The Helmholtz number is defined as per Equation (3). Hence the magnitude transmission coefficients across all three ducts overlap each other, and the calculated resistance is observed to be zero. In case of the perforate, the reflection coefficient of the main duct, as well as the coefficients describing the transmission in-/out the sidebranch overlap each other, suggesting a symmetry around the duct-3 axis. Moreover, as shown in Ref. [5], the resistance of the perforated plate matches with an analytical model proposed in Ref. [10].

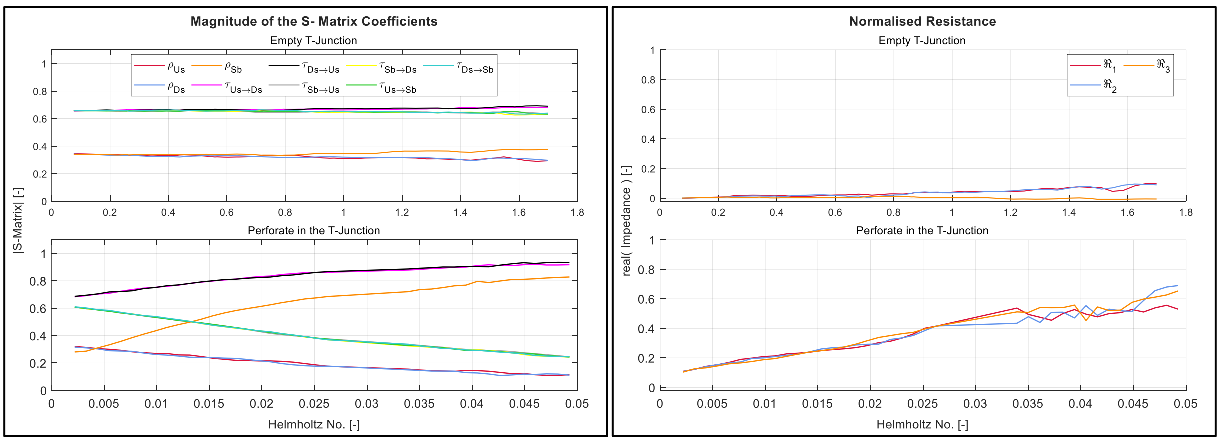

Figure 2 Characteristics of Empty T-junction and the perforate in absence of grazing flow; **a)** Magnitude of the S-Matrix coefficients, **b)** Normalised Resistance

3.2 Empty T-Junction under Grazing Flow Results

Figure 3 shows the resistance of an empty T-Junction observed at different flow speeds compared against the Strouhal number. The oscillating behaviour of amplification ($\Re < 0$) and reduction ($\Re > 0$) can be clearly seen with minima and maxima at Strouhal numbers multiple of ≈ 3.5. The results match that of Ref. [1, 11]. In spite of performing the experiments in the same test rig as Ref. [1], as a different definition of d_{eq} is used, the minima are observed at different Strouhal numbers.

In the case of resistance calculated using an acoustic excitation against the flow direction ($\Re_2$), an opposite behavior is seen in comparison to excitation in the flow direction ($\Re_{1,3}$), although an amplification of incoming sound waves is not observed. Moreover, the resistance calculated under excitation from duct-3 ($\Re_3$) is close to the average of $\Re_1$ and $\Re_2$. A possible reason of these observations is that the leading edge of the T-Junction located in duct-1 is responsible for sound generation, as also predicted in Ref. [1, 2].

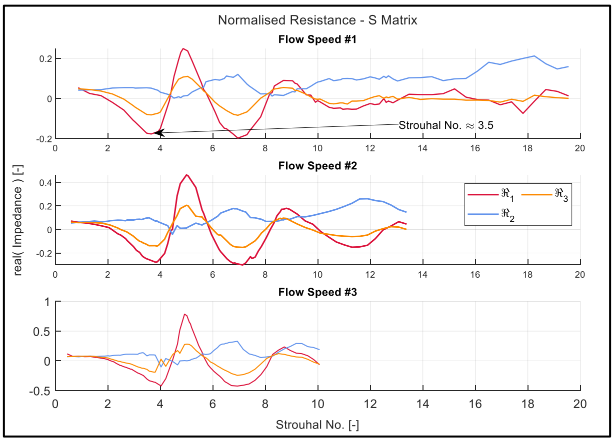

Figure 3 Normalised Resistance of empty T-Junction at different flow speeds

3.3 Perforate in the T-Junction under Grazing Flow Results

On fixing the perforate at the intersection of the T-junction, measurements were carried out in presence of grazing flow and the results are as shown in Figure 4. From the S-Matrix coefficients the change in the behaviour of the transmission coefficients can be clearly marked to a particular Strouhal number. The particular Strouhal number also defines the minimum resistance observed at different flow speeds. The Strouhal number of interest is ≈ 0.7.

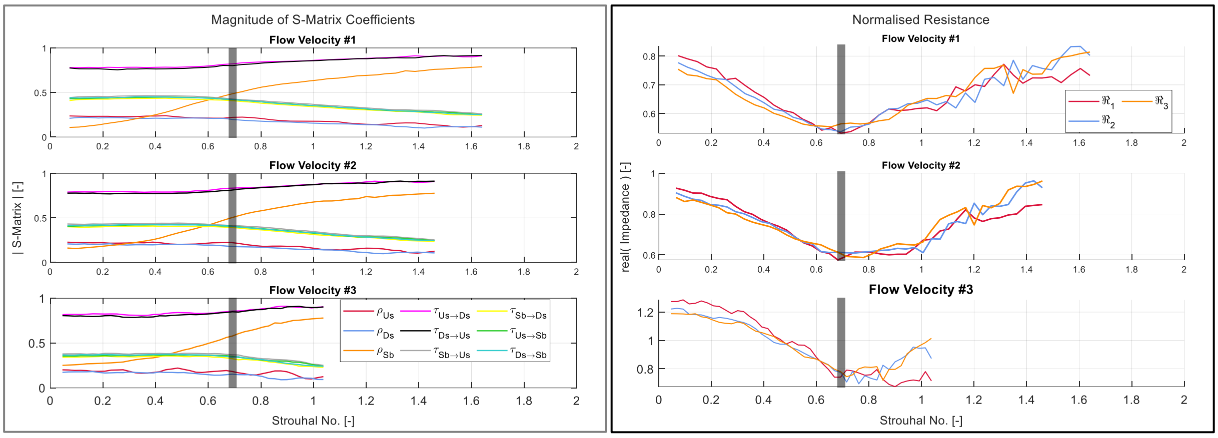

Figure 4 Perforated T-Junction acoustic characteristics at different flow speeds a) Magnitude of the S-Matrix coefficients, b) Normalised Resistance

On observing the resistance of an empty T-junction and the perforate, the Strouhal number at which maximum amplification is observed in the empty T-junction (St ≈ 3.5) is the fifth multiple of the one observed in the case of the perforate. Similar results were proposed in Ref. [6], and based on them it was inferred that the behaviour of the perforate and the empty T-junction is analogous. However, an oscillation is not observed in case of the perforate, suggesting the inference to be only partially correct.

Observing the perforate resistance, for Strouhal numbers greater than 0.7, it is proportional to the frequency, thus following the behaviour of the resistance calculated in absence of grazing flow. This Strouhal number thus indicates a limit, before and after which the nature of the resistance is governed by different factors, dividing the behaviour of the resistance into two regions.

4. SUMMARY AND FUTURE WORKS

Three-port measurements are used to study the aero-acoustic properties of an empty T-junction and a perforate placed in the T-junction. Scattering Matrix coefficients and normalized transfer impedance are studied in the presence of grazing flow. Based on the results, a similarity between an empty T-junction and a perforate placed in a T-junction is shown. Moreover, a Strouhal number based limit is defined for the behaviour of the resistance calculated under grazing flow. Characterisation of the resistance before and after the limit is planned in the future works.

5. ACKNOWLEDGEMENTS

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