Transonic resonance tones in orifice and pipe jets

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ABSTRACT

This paper investigates the flow resonance while the jet is issued out from a nozzle at transonic Mach numbers. In present study the jets emerging out from orifice and pipe nozzles are considered. The jet flow diameter of orifice and pipes is 10 mm, and the length of the pipe is varied in the range of $1 \le L/D \le 6$. The pressure ratio of the jet flow is varied in the range of subsonic to supersonic Mach numbers; however the study predominantly concentrates on transonic regimes. Results indicate that distinct transonic resonance tones occur in the range of transonic Mach numbers (0.95 to 1.01). Unlike screech that occurs during the presence of shock cells, the transonic frequencies slightly increase with Mach number. Moreover numerous multiple non-harmonic frequency tones are observed during this transonic resonance thus indicating the non-linearity in the flow resonance. In case of pipe nozzles, the transonic tones tend to diminish with increase in pipe length and cease to exist beyond a certain length.

Keywords: Transonic resonance; pipe jet; orifice jet; jet noise

1. INTRODUCTION

The richness of the flow physics and engineering application prospects of jet flows have deepened the thirst of researchers to probe deeper to understand their behaviour. Jet flows are studied extensively by numerous researchers to understand the turbulence, instabilities, mixing, entrainment, and so on. Simultaneously, the study on the noise generated from such jet flows are gaining momentum from the past few decades. Since the present work is associated with the acoustics studies from jet flows, most of the introduction and the literature discusses on the noise generated from various jets. It was the pioneering contribution of Lighthill's analytical work [1] in 1952 that elevated flow acoustics as a new research field. Several researchers seem to have been motivated by his work and started validating with their experimental results. The noise from jet flows is broadly classified as turbulent mixing noise and supersonic shock associated

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noise. The former noise is the main noise source in case of subsonic jets. More works are devoted to understand the noise sources from these jets, however there is a lacuna in understanding such noise sources and their origins. In contrast, the noise from supersonic jets seems to be well understood. In case of incorrectly expanded jets *viz*; underexpanded and overexpanded jets, the shock cells constitute the main noise source [2]. Such noise can be characterized as the screech tones and broad band shock associated noise (BBSAN). Screech tones are formed due to the feedback mechanism and lock-on between the upward propagation of acoustic waves and downward propagating hydrodynamic instability waves. Several archival articles extensively describe the screech tones generation, and excellent review articles by Raman [3, 4] helps in understanding such tones better. Broad band shock associated noise is the other noise content generated by the scattering of coherent structures when interacted with shock cells. Interestingly the frequency of BBSAN is observed to increase when nearing to the acoustic source. Thus this BBSAN is referred to have a Doppler shifting effect [5, 6]. In addition to the screech tones and BBSAN, the supersonic jets also emit Mach wave radiation. During the propagation of jet coherent structures at supersonic velocity, they tend to emit intense Mach waves leading to acoustic radiation [6].

In this paper, a special kind of noise from orifice and pipe jets called "transonic resonance" is discussed. This phenomenon occurs at the intermediate range between subsonic and supersonic jet Mach numbers around unity (transonic Mach numbers). At these transonic conditions, the jet flows tries to attain disturbance velocity which is the speed of the sound. In such cases, the flow locks on with the characteristic length of the geometry leading to the resonance and generation of prominent tones. The transonic tonal mechanisms are not clearly understood and not much work is available in the archrival literature. During the flow transition from subsonic to supersonic Mach numbers, there occur numerous complex phenomena which are difficult to understand. Even the operation of aircraft in this regime is considered to be hazardous since the drag force shoots up to higher values [7] and hence prolonged operations over such regimes are avoided. Numerous research works have been carried out on transonic flows. Some relevant literature in general, and on resonance tones from orifice jets, in particular, is discussed below.

Zaman et al. [8] discussed in great detail about the transonic resonance from the convergent divergent nozzles. They have distinguished the characteristics of transonic resonance with that of screech tones that generally occur at higher pressure ratios. They have tested with various configurations of the convergent divergent nozzles such as different throat and exit diameter, varying length of divergent portion of nozzle, varying diverging angle of nozzle and so on. It is also shown both experimentally and computationally that these tones undergo staging behavior depending on the nozzle divergence angle. Hill and Greene [9] showed that the self acoustic oscillations from such jets could lead to improved mixing in the subsonic turbulent jets. They designed a nozzle containing convergent divergent section followed by a constant area section and a step with increased cross sectional area. They named the nozzle as the 'whistler nozzle' [9]. The further work on this type of nozzle was extensively carried out by Husain, Hussain and Hasan [10–12]. Lacombe et. al. [13] investigated the whistling frequency from a sharp edged orifice at very low Mach number of around 0.02. They also found the acoustic velocity during whistling and showed its dependence on Strouhal number and acoustic reflection within the pipe. Karthik et al. [14] investigated the vertex shedding due to excitation tones generated from subsonic flow through pipe connected with orifice. They used the flow visualization methods to resolve the vortex shedding phenomenon from an orifice exit. However most of their work was based on the elliptic cross sectional nozzles and at lower flow velocities. They have discussed the mechanisms of noise generation from whistler nozzle by varying the nozzle configuration. The first noise generation mechanism is by the shear layer impingement, and the other is due to the pipe resonance.

Wong [15] studied the resonance and damping in a convergent divergent nozzle at transonic and underexpanded flow conditions by formulating a model, and validating the results with the experimental and numerical data. Yonamine et al. [16] has discussed transonic tones in a convergent divergent nozzle and shown that the directivity is towards the flow direction. Loh and Zaman [17] numerically investigated the transonic resonance in a convergent divergent nozzles and shown that the unsteadiness in shock oscillations leading to such resonance tones. They identified frequency stages namely stage 1 which is due to one quarter standing wave in the divergent portion of nozzle, and stage 2 which is due to three quarter standing wave.

In summary, it is observed from most of the literature that the excitation tones were generated using subsonic flow through a nozzle to enhance the mixing, turbulence, or combustion capabilities. A very few literature discuss on the noise generated at transonic flow conditions from convergent – divergent nozzles. Thus the objective of the present work is deliberated to analyze the noise generated due to transonic resonance from a round orifice and pipe jets. There are numerous discussions on the noise generated from transonic resonance from convergent – divergent nozzles. However the subject of transonic resonance from orifice jets and pipe jets is scarce in the archival. This lacuna in the literature was the motivation to undertake the present problem.

2. EXPERIMENTAL SETUP AND METHODOLOGY

Figure 1 shows the experimental setup that consists of an anechoic chamber to simulate the free field environment. The anechoic chamber is made of 'V' shaped wedges which is designed in attenuating the noise having the frequency above 630 Hz and is considered as the cutoff frequency of an anechoic chamber. The chamber has the wedge tip to tip dimensions of 2.5 × 2 × 2 m. The settling/plenum chamber is contained within the anechoic chamber where the nozzles can be attached. The settling chamber is provided with progressive fine meshes to attenuate the hydrodynamic turbulence created in the flow. Also the internal surface of the settling chamber is lined with acoustic foam to reduce the acoustic disturbances. The compressed air is provided to the settling chamber by a 150 HP compressor. The compressed air is stored in a tank of 20 m^3 at the required operational pressure and taken to the experimental setup by a 4 inch pipeline. Needle valve is used to control the mass flow rate of the air flow. The end of the settling chamber is provided with a groove where the required pipe nozzles or orifices can be attached. The schematic diagram of the orifice/pipe holder is shown in Fig. 2a which is connected to

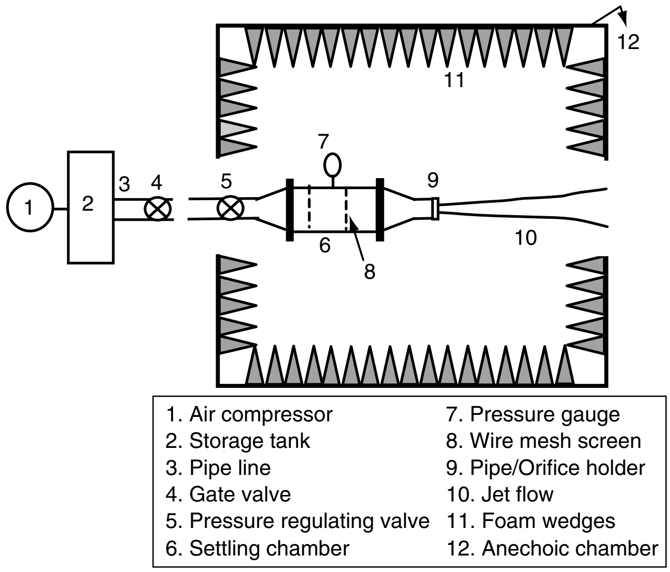

Figure 1: Schematic of the experimental setup.

the settling chamber. A plate having a circular slot is sandwiched with the orifice holders, and the jet is allowed to emerge through this orifice at various pressure ratios. In present study a square edged circular slot of diameter, D = 10 mm is grooved in a circular plate of 2 mm thickness and 73 mm diameter. The pipe nozzles that are used for the study varies in the range of $1 \le L/D \le 6$ where L is the length of the pipe and D is the internal diameter which is same as that of orifice diameter. Six pipes of equally increasing length are chosen, and are attached to the nozzle holder as shown in Fig. 2a.

2.1. Measurements

In present study acoustic measurements are carried out using the microphones using a quarter inch pre-polarized microphones of PCB make (model no. 377A01) having a sensitivity of 4 mV/Pa at 250 Hz. The acquired signal is low-passed at 70 kHz with an analog filter of Krohn-Hite make (model 3364). The signal from the microphone is acquired at the rate of 150 kilo-samples per second digitalized using NI sampling card. The microphones are placed at a distance of 40 D from the jet exit at an angle of 90 degrees (normal to jet flow) and at 135 degrees (upstream of the jet) as shown in Fig. 2b. Piezo-resistive pressure transducer is connected to the setting chamber to record the stagnation pressure data and has an uncertainty of 0.2% of full scale. Error in Mach number is expected to be within 2% . The error in the measurements of noise levels are within the range of ±1 dB since all the experimental conditions such a flow parameters, microphone positions are maintained accurately for complete set of experiments.

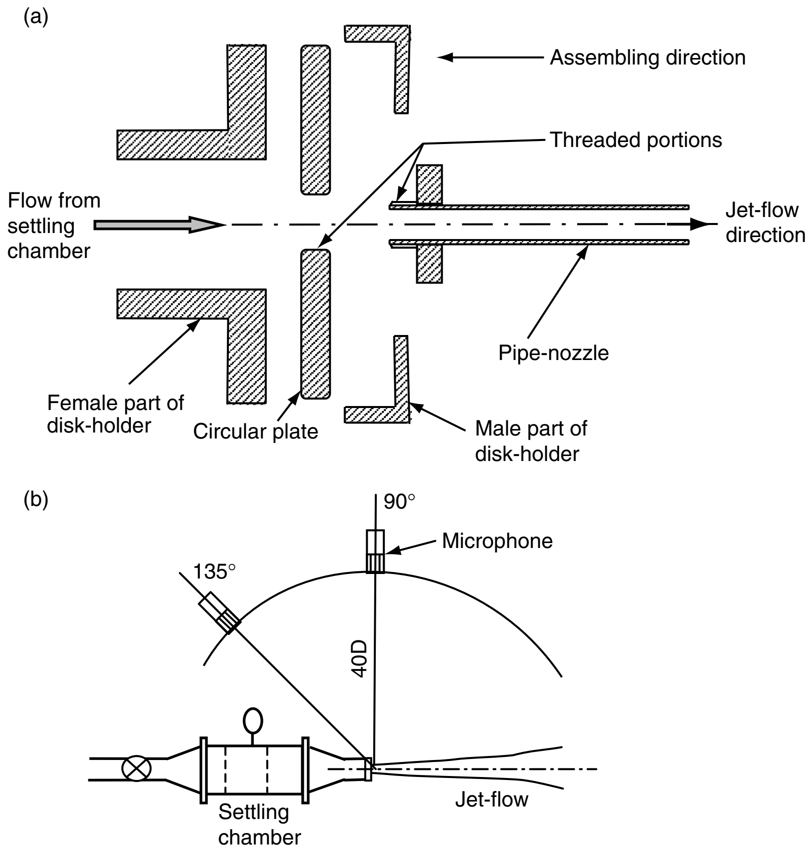

Figure 2: Schematic diagram showing the (a) orifice/pipe nozzle holder (b) Microphone locations.

2.2. Blowdown test facility

Blowdown analyses are carried out in the present study. In this process, the compressed air in storage tank which is at the absolute pressure of 8 bars is open to flow freely through the orifice nozzle or pipe nozzles. The microphones continuously acquire the acoustic data with the variation in the stagnation pressure until the pressure in the storage tank decreases to the lowest value. This test helps in understanding the variation of noise levels with pressure ratio. Pressure ratio is defined as the ratio between the stagnation pressure (P_o) measured in settling chamber to the atmospheric pressure (P_{amb}). Using this pressure ratio (P_o/P_{amb}), the fully expanded jet Mach number (M_j) can be calculated using the following isentropic relation.

$$\frac{P_o}{P_{amb}} = \left(1 + \frac{\gamma - 1}{2} M_j^2\right)^{\gamma/(\gamma-1)} \Rightarrow M_j = \left(\frac{2}{(\gamma - 1)}\left[\left(\frac{P_o}{P_{amb}}\right)^{(\gamma-1)/\gamma} - 1\right]\right)^{0.5} \quad (1)$$

3. RESULTS AND DISCUSSION

The acquired microphone data are processed to obtain the Overall Sound Pressure Levels (OASPL) of the jet flow at two different emissions angles. This is followed by the comparison of transonic resonance tones with that of screech tones in terms of their frequencies and amplitude levels. The transonic tones in pipe jets are analyzed and compared with those of the orifice jet.

3.1. OASPL variation with Mach number

Figure 3 shows the overall sound pressure level variation of jet emerging from orifice nozzle, with the Mach number at two different emissivity angles namely at 90 and 135 degrees respectively. This continuous variation in the OASPL is obtained by performing blowdown test as discussed in the previous section. The noise levels are observed to increase with the Mach numbers. It can also be observed that around the transonic range of Mach number, there occurs an OASPL hump. There is a sudden rise in the noise levels in that range of Mach numbers. This is due to the formation of transonic resonance in this range of Mach numbers. In order to investigate the directionality dependence of the transonic resonance tone, the noise levels are plotted for upstream and normal directional angles of 135 degrees and 90 degrees respectively. During transonic regime, the OASPL sharply increased from 100 dB to 113 dB due to transonic resonance, at 90 degree emission angle. In both the case of directivity angles, almost 10 dB

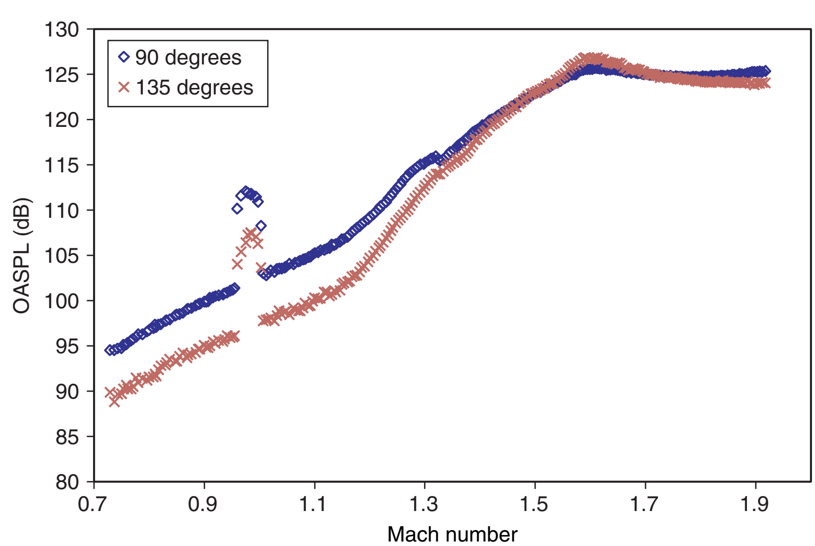

Figure 3: OASPL variation with Mach number at different emissivity angles.

rise is observed due to the transonic resonance. It is observed that the overall sound pressure levels are higher in case of 90 degrees until the Mach number of around 1.4, beyond which the overall noise levels are almost similar. It is noted that beyond the Mach number of 1.4, the shock cell dominates and hence the screech tones are generated. However, it is known from the literature that screech noise is higher in the upstream compared to the normal direction [6].

3.2. Transonic and screech tones

Figure 4 shows the gray scale map indicating the screech and transonic tonal variation with Mach number at emissivity angle of 135 degrees (Fig. 4a) and 90 degrees (Fig. 4b).

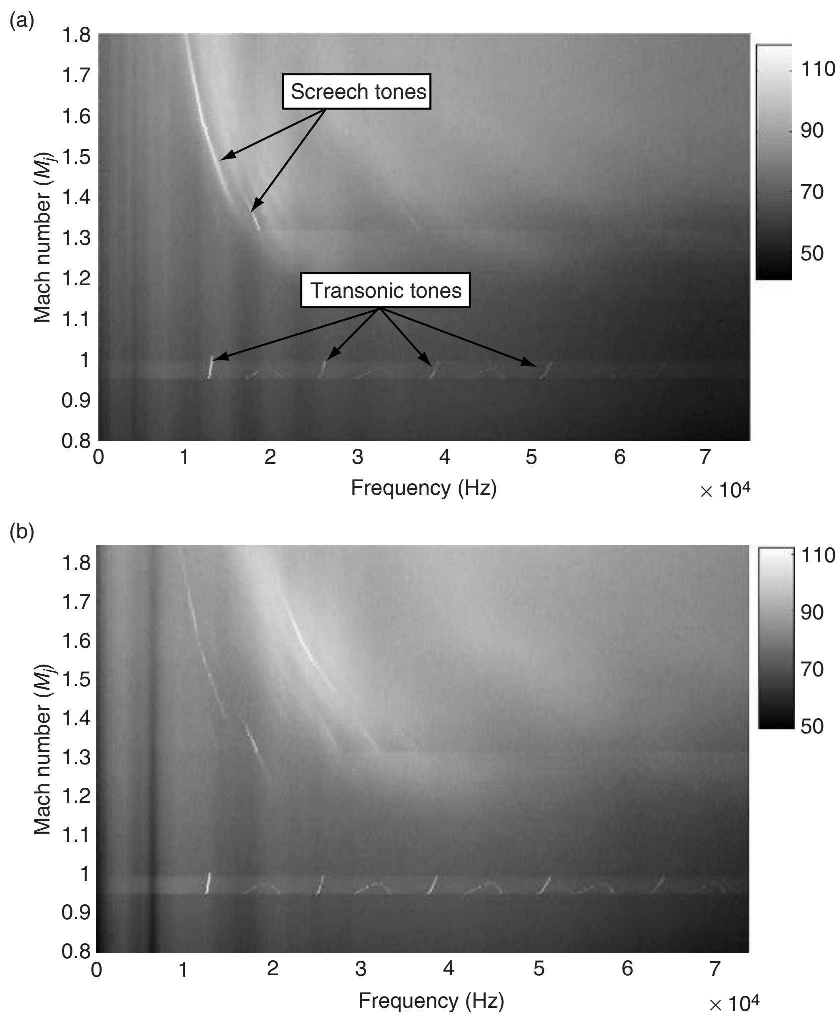

Figure 4: Grey contour map of frequency spectra variation over Mach number showing screech and transonic tones at emission angles of (a) 135 degrees and (b) 90 degrees.

Brighter color in this gray scale map indicates higher noise levels and the darker one represents the lower noise level values. The white streaks in the Mach number range of 1.3 to 1.8 indicate the screech tones. Moreover at Mach number around the transonic conditions of 0.95 to 1, a white streak is noticed which are recognized as the transonic tones. It is well understood that screech is due to the feedback phenomenon happening between the hydrodynamics and acoustics waves. However, the transonic tones generation phenomenon is still unclear. It is suspected that at transonic conditions (0.95 to 1) the oscillation of shock waves exactly at the orifice mouth is leading to such transonic tones. Such tones are observed by Zaman et al. [8] where they investigated for the various convergent – divergent nozzles. Careful investigation stipulates that the screech frequency decreases with increase in Mach number or nozzle pressure ratio [3]. Figure 4a shows the dominance of the fundamental screech tone, and the first harmonic is much quieter. However in case of 90 degrees (Fig. 4b) the first harmonic of the screech tones is clearly observed to be dominant compared to the fundamental tone [3, 4]. Unlike screech tones, the transonic tone frequencies are observed to slightly increase with the increase in the Mach number. This aspect will be discussed in much detail in the forthcoming sections. The transonic tonal amplitude is almost similar at both the emission angles. The transonic tones are accompanied by their harmonics. At 135 degrees, three harmonics are observed apart from the fundamental transonic tone, while at 90 degrees, four harmonics are distinctly seen. In between the fundamental and harmonics of these transonic tones, there is an occurrence of intermediate complex tones, and are discussed in the following section. Figure 5 shows the waterfall spectra of the transonic tones with Mach number. Analyses of Fig. 5 reveal that the transonic tones get initiated at around a jet Mach number of 0.95 and vanish at 1.01. This characteristic is unlike the screech tone formation. During the screech initiation, the

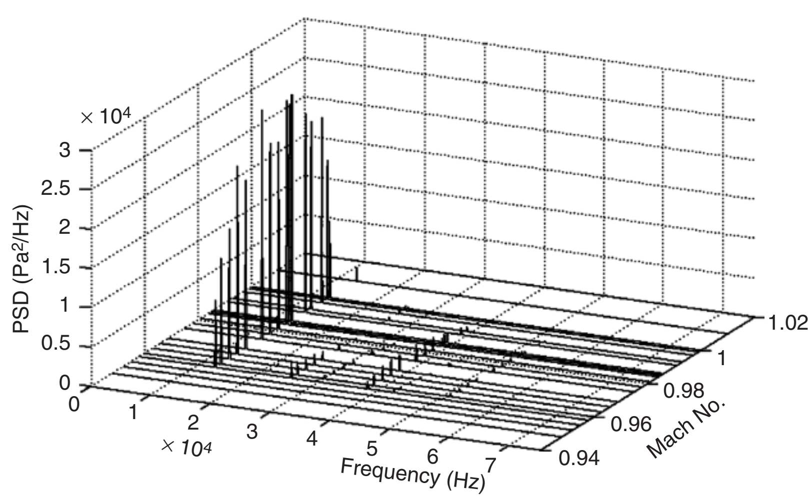

Figure 5: Waterfall spectra showing transonic tones of orifice nozzle jet.

tonal amplitude gradually increases, attains a maximum value and ceases gradually with Mach number. However in case of transonic tones, sudden jumps occur across the operating Mach number range.

The evolution of transonic tones with Mach number is shown in Fig. 6 in the form of successive spectra for jet noise data procured at 90° emission angle. At Mach number of 0.955 no tones are observed (Fig. 6a). However immediately at succeeding Mach number of 0.958, several transonic resonance tones have emerged (Fig. 6b). These transonic tones at this Mach number can be distinguished in two types; namely harmonic tones and non-harmonic or non-linear tones. A fundamental and four harmonics frequencies that are observed at Mach number of 0.958 in Fig. 6b are given in Table 1. In addition to harmonic tones, numerous intermediate non-linear resonance tones are also seen. These intermediate tones may be due to the non-linear effects associated with the flow resonance at transonic conditions. If carefully observed from Fig. 6b for jet Mach number of 0.958, it is interesting to note that these intermediate non-linear tones are formed at frequencies of $f_o + \Delta f_o / 3$, $f_o + 2\Delta f_o / 3$ where f_o is the fundamental transonic resonance frequency of an orifice jet, and Δf_o is the difference between the harmonic frequencies. These above mentioned non-linear frequencies values at Mach number of 0.958 are tabulated in Table 1. With increase in the Mach numbers, these two intermediate non-linear tones merge together [Fig. 6(b–e)] to form a single intermediate non-linear tone at frequency value of $f_o + \Delta f_o / 2$ at jet Mach number of 0.981 (Fig. 6e). The fundamental and harmonic along with non-linear frequency at this Mach number are tabulated in Table 2. The estimated non-linear frequencies using above relations is within ±100 Hz. At Mach number of 0.993 these intermediate non-linear tones completely fade out and only transonic tones are seen along with their harmonics (Fig. 6g). In summary it is concluded that the transonic tones initiate because of non-linear flow resonance effects, and slowly evolve to linear acoustic conditions as described in Fig. 6 (b–g). These linear acoustic transonic harmonic tones diminishes with further increase in jet Mach number as seen in Fig. 6(g–i) resulting in only one fundamental tone. This is because at this higher Mach number, shock waves will try to move out of the orifice mouth leading to the suppression of the resonance tones.

Figure 7 shows the time series at different transonic Mach numbers ranging from 0.955 to 0.993. It is evident from Fig. 7a that the acoustic pressure amplitude at 0.955 is the lowest indicating the absence of any tonal events. Fig. 7b&c depict the events at regular time intervals at Mach number of 0.969 and 0.978. Moreover each cycle of time series is engulfed with the several other events leading to the non-linear tones as observed in the frequency spectra in Fig. 6(c–f). Figure 7d shows the time series at Mach number of 0.993 where only the transonic resonance fundamental tone is present without the non-linear tones.

3.3. Tonal frequency and amplitude

Figure 8 shows the frequency and corresponding sound pressure levels variation of transonic and screech tones with Mach number. Figure 8 is shown in different zones of Mach number where the different tones are dominant. At around Mach number

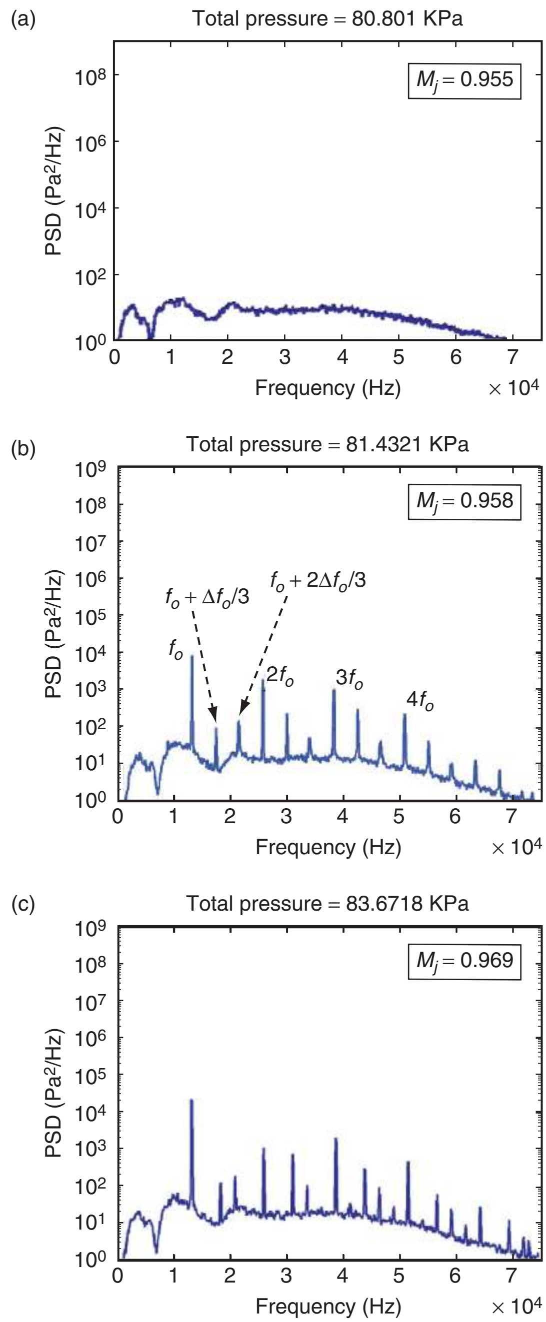

Figure 6: (*Continued*)

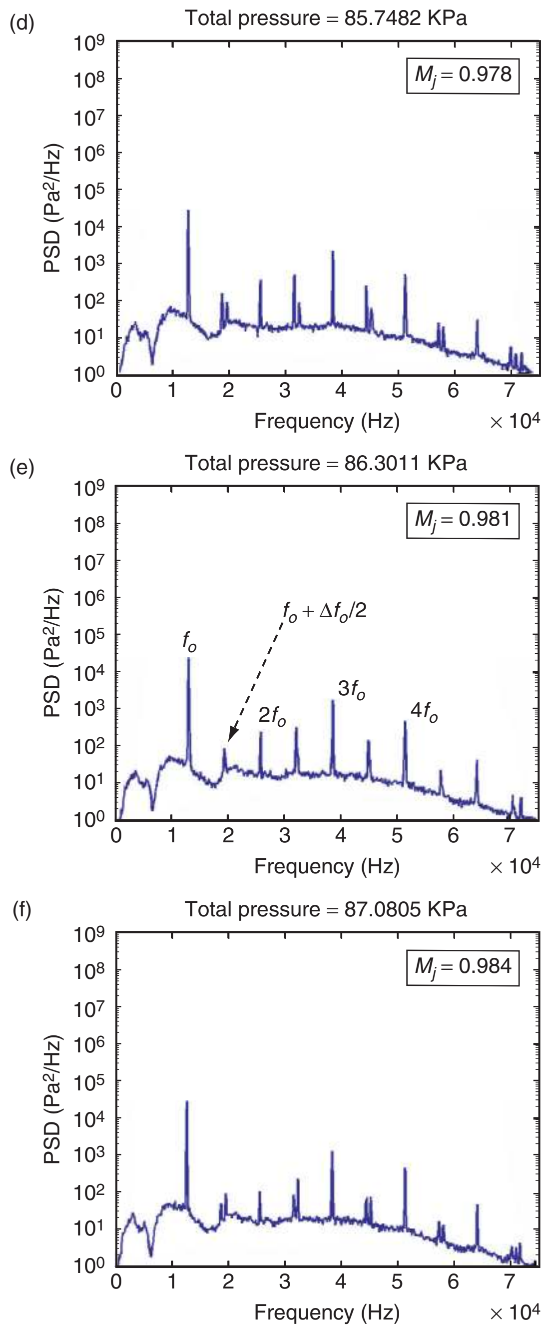

Figure 6: (*Continued*)

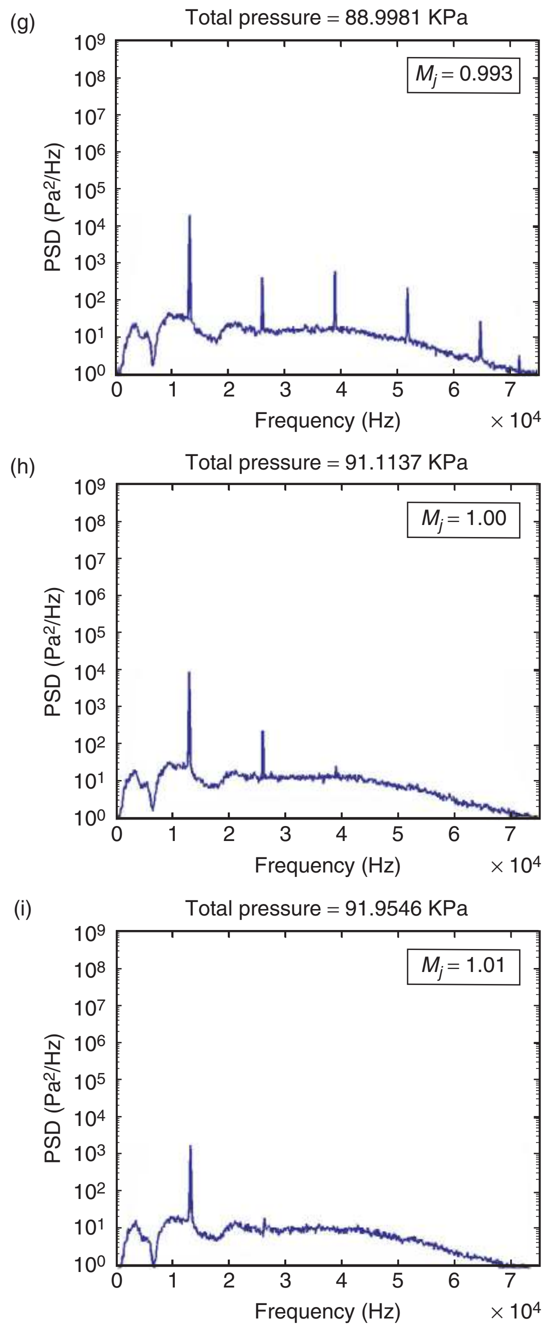

Figure 6: Frequency spectra showing the evolution of transonic tones with Mach numbers.

Table 1. Frequency values of transonic resonance tones at Mach number of 0.958.

Mach number	Fundamental frequency (Hz)	Harmonic frequency (Hz)				Non-linear frequency (Hz)	
	f_o	$2f_o$	$3f_o$	$4f_o$	$5f_o$	$f_{oL1} = f_o + \Delta f_o/3$	$f_{oL2} = f_o + 2\Delta f_o/3$
0.958	12732.7	25391.2	38123	50781.5	63513.2	17049.8	21074.2

Table 2. Frequency values of transonic resonance tones at Mach number of 0.981.

Mach number	Fundamental frequency (Hz)	Harmonic frequency (Hz)				Non-linear frequency (Hz)
	f_o	$2f_o$	$3f_o$	$4f_o$	$5f_o$	$f_{oL1} = f_o + \Delta f_o/2$
0.981	12879.1	25830.3	38708.3	51659.5	64537.6	19318.1

range of 0.9 to 1.1, the transonic tones are dominant as observed. It is evident from this figure that the transonic resonance frequency increases with the Mach number. However the increase is seen to the maximum of 500 Hz. It is noted that these tones ceases to exist beyond the threshold minima and maxima Mach numbers. As explained in the earlier section, these tones may be due to the resonance of the shock waves at the nozzle throat leading to the tonal noise at this particular flow condition. Prior to the Mach number of 0.9, the flow is in subsonic range and such resonances are not seen. Above Mach number 1 the shock waves are persuaded to move out of the nozzle thus ceasing the resonating condition. From around Mach number of 1.01 to 1.3, no such tonal contents are observed in the spectra. After Mach number of 1.3, there forms the different mode of screech tones whose frequency gradually decreases with the Mach number. Screech characteristics are well understood phenomenon and numerous articles are dedicated on it. Transonic resonance tones are in contrast with screech tones where the former's frequency increases with Mach number. The explanation for this behavior of transonic tones may be complex and the authors are not clear. However similar observations were made by Zaman et al. [8] even in the case of convergent divergent nozzles. They tested with different variety of nozzles of different throat and exit diameters, and in different test setups. They showed that different nozzles showed different tonal frequency values ranging from the Mach number of 0.6 to 1.4. Figure 8 also shows the different modes in screech tones which has not formed in transonic tones. On comparing the tonal sound pressure levels of transonic and screech tones, the former is less by around 15 dB maximum. Thus transonic tones are not much intense and hence may not sustain beyond the threshold Mach number as in screech phenomenon. Moreover the transonic tonal noise is similar in all emissions directions unlike the screech noise which is dominant in the upstream (see Fig. 4).

Figure 9a shows the variation of fundamental and its harmonics transonic tonal frequency with Mach number. The resonance tones up to fourth harmonic are observed

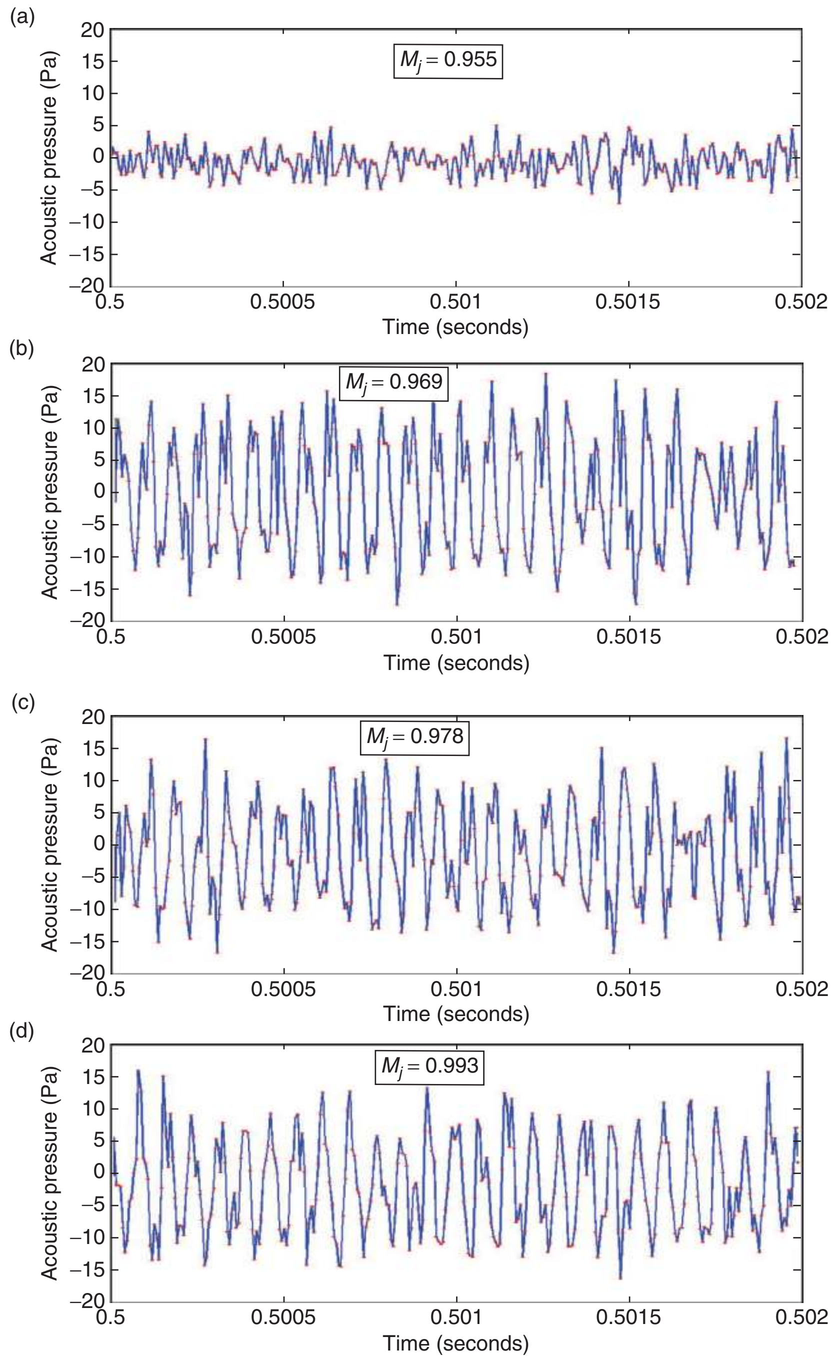

Figure 7: Time series showing the evolution of transonic tones with Mach numbers.

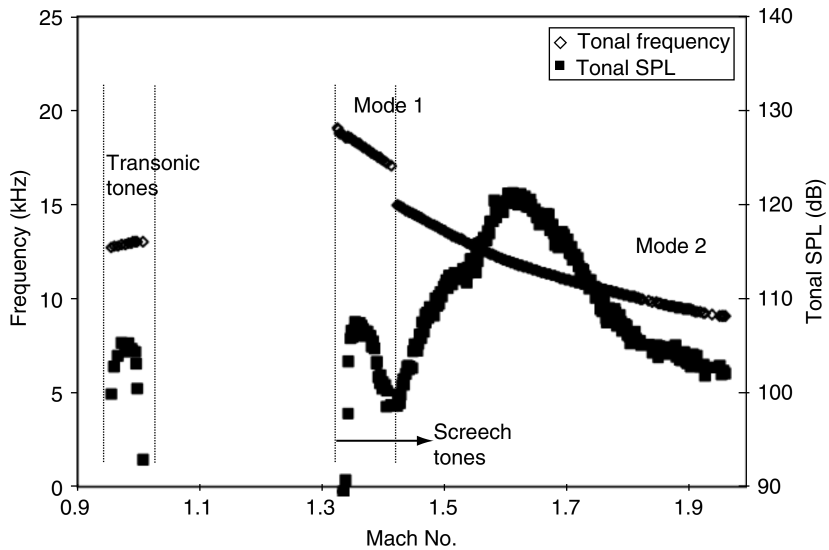

Figure 8: Variation of transonic and screech tonal frequencies, and its SPL with Mach number.

from the figure. Although the increase in transonic resonance frequency values with Mach number is less, about 500 Hz, this is not clearly observed in Fig. 9a. Figure 9b shows the amplitude of the transonic resonance tones. The fundamental tone has the highest amplitude as expected. Interestingly it is observed that the tonal amplitude of fundamental tone and its harmonics increases with Mach number and shows a decreasing trend thereafter. This aspect is quite similar to that of the screech tones. However cessation of these transonic tones is immediate and sudden as seen in Fig. 9b.

3.4. Effect of transonic resonance on pipe jets

Figure 10 shows the OASPL variation with Mach number for various pipe jets. Six pipe nozzles are considered whose length varies in the range of $1 \le L/D \le 6$, where D is the internal diameter and L is the length of the pipe. The Mach number is varied from subsonic range to supersonic range and OASPL of these pipe jets are estimated. At around Mach number of 0.8 to 1, pipe jets from $L/D = 1$ and 3 produces a small OASPL hump indicating the presence of transonic resonance tones (Fig. 10). However importantly at higher length of pipe nozzles ($\ge L/D = 3$), the transonic resonance tones are not observed. This may be because increasing the pipe length helps in the development of the internal boundary layer. This will lead to the increase in the initial shear layer thickness of the jet issuing from pipe nozzles. There are possibilities that flow inside the pipe nozzle is in the subsonic zone. Hence the shock waves are not generated thus leading to the cessation of the transonic resonance for larger L/D nozzles. In case of higher jet Mach numbers, say above 1.25, the screech tones starts dominating in all the pipe jets.

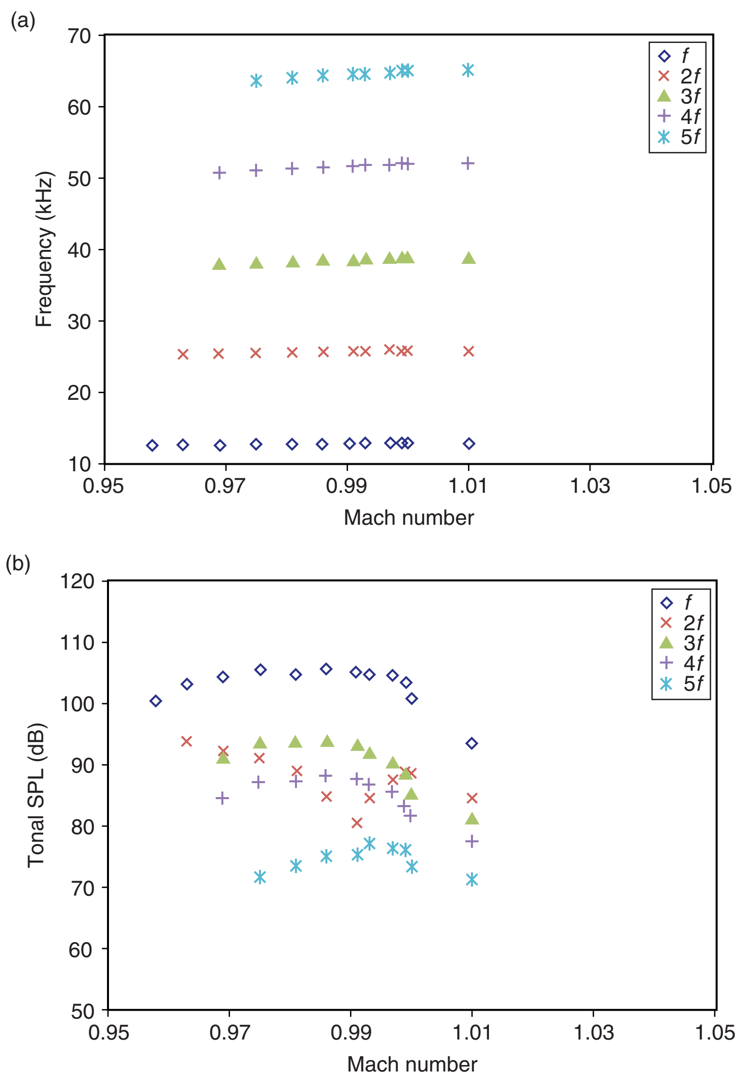

Figure 9: The variation of (a) transonic tonal frequency and its harmonics and (b) transonic tonal sound pressure level with jet Mach number.

Figure 11 shows the waterfall plot of transonic resonance tones variation with Mach number for L/D = 1 and L/D = 3 pipe jets. In case of L/D = 1 pipe jet, the tones are dominant in the Mach number range of 0.95 to 1 while for L/D = 3 pipe jet the tones are dominant at around Mach number of 0.8 to 0.9. Interestingly it is observed that in comparison to the transonic tones of orifice nozzle jet (Fig. 5) the transonic resonance frequency of pipe jets are lower. The reason may be the change in the characteristic length in case of pipe nozzles leading to the lowering of the transonic frequency. Moreover, it is observed that the transonic tonal amplitudes of jets from pipe nozzles are lower by almost one order of magnitude compared to that of an orifice jet. This may be due to the increase in the shear layer thickness of the jet flow that suppresses the shock wave resonance.

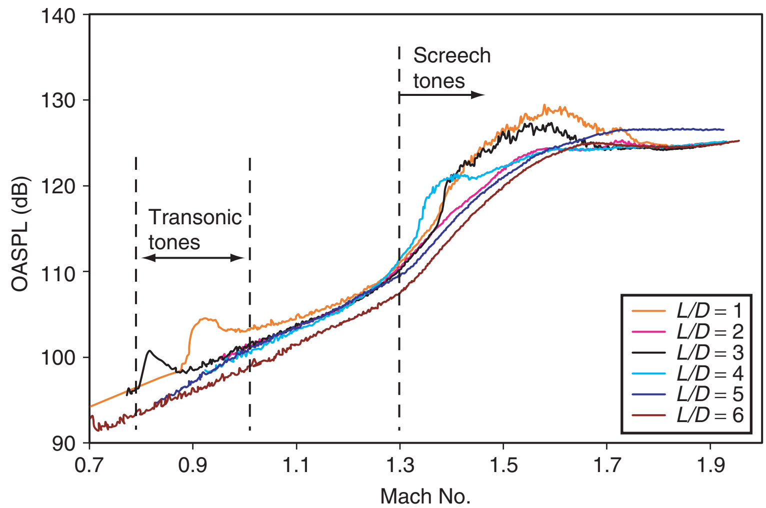

Figure 10: The OASPL variation with Mach number for different pipe jets.

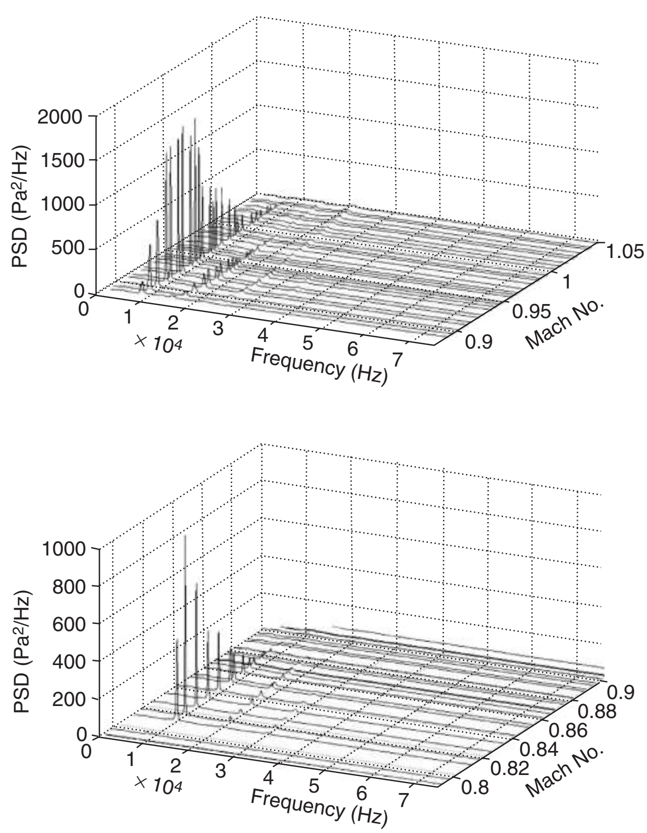

Figure 11: Waterfall spectra showing the transonic resonance tonal frequency variation with Mach number for (a) $L/D = 1$ and (b) $L/D = 3$ pipe jets.

4. CONCLUSION

This paper investigates the peculiar and interesting tones that occur at transonic regimes of jet flows emerging from orifice and pipe nozzles. As the jet Mach number at nozzle exit approaches unity, significant tones are observed. The fundamental and harmonic frequencies of these transonic tones appear to increase with the jet Mach number which is contrasting to the behavior of the screech tones where the screech frequency lowers with increase in Mach number. In addition, numerous non-harmonic multiple tones are also formed during transonic resonance. These are conjectured to be the non-linear tones due to the non-linear behavior in the flow at transonic conditions. These intermediate non-linear tones are initially formed at frequencies of $f_o + \Delta f_o/3$, $f_o + 2\Delta f_o/3$. These tones combine together with increase in Mach number to form a new tone at frequency of $f_o + \Delta f_o/2$ after which this non-linear tones completely cease. In summary it is observed that the transonic tones initiate with non-linear effects and slowly evolve to linear flow conditions, and vanish with further increase of Mach number.

The transonic resonance tones are also seen to form in the case of pipe jets. The results evidently show that the transonic resonance tones seem to be diminishing with increase in length of the pipe nozzle, and at higher pipe length, no transonic resonance tones exist.

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