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THE ROLE OF CASTELLATIONS ON PIPE JET NOISE

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ABSTRACT

This paper explores jet noise control using castellations at the exit of pipe-jets. Far-field acoustic measurements and schlieren visualizations are performed for two configurations of castellations; namely, two and four counts. The results are compared with that of pipe-jet without castellations. The nozzle pressure ratio range of the study is 1.5 to 4.5. With each configuration, the position and strength of vortices vary causing it to interact in different manners. For pipe with two castellations, the screech is amplified and the overall sound pressure level is higher than the reference jet in most of the nozzle pressure ratios under study. For pipe with four castellations, there is no noise variation in the azimuthal direction, and screech is eliminated at all nozzle pressure ratios.

NOMENCLATURE

C	Castellation number
L	Length of the pipe
NPR	Nozzle Pressure Ratio
OASPL	Overall Sound Pressure Level
d	Diameter of the pipe
g	Arc length of the gap
p	Arc length of the teeth

INTRODUCTION

Noise caused by jet flow has various social and technical implications. Control of the jet noise has been primarily done by two methods namely active and passive methods. Various passive methods have been adopted in the past such as non-circular nozzles, trailing edge modifications such as notches, tabs, vortex generators, splitter plate for mixing enhancement. Passive control by modifying the nozzle lip produce streamwise vortices which helps in the mixing enhancement in shear flows [1]. One such trailing edge modification is castellations at the nozzle exit. These are simple rectangular cut outs at the nozzle lip which increase the effective exit area of the nozzle thereby augmenting the shear layer surface area. Although numerous studies have been carried out on trailing edge modifications, a few representative studies are presented in the following section.

BACKGROUND

Early investigations on trailing edge modified nozzles were carried out by Pannu and Johannesen [2]. They set forth to study the effect of V-shaped notches in a conical nozzle. They pointed out that the trailing edge vortices split into 4 discrete vortices causing it to persist for longer distances. This makes the notches effective in the mitigation of noise as the low speed flow through the notches shield the effective sources of noise in the core flow. Wlezien and Kibens [3] studied the influence of nozzle asymmetry on supersonic jet noise. The indeterminate nozzle models they used were similar to castellated nozzle but with a depth of cut equal to the diameter of the exit. The gap between the tabs released the internal pressure and expanded the flow well before the jet reached the exit. Therefore, the core flow had lesser velocity which did not support screech. This improved mixing and also altered the shock cell system. Following their work, Longmire et al. [4] sought to study the near field characteristics of jet from crown-shaped nozzles under both axially forced and unforced conditions. They suggested a mechanism by which the longitudinal structures arising due to the azimuthal variation of the nozzle, enhance mixing. They also observed an increased level of entrainment in the trough plane of the nozzle exit owing to the pressure difference the external fluid forces itself into the jet core.

A comprehensive detailed study on mixing enhancement by trailing edge modifications of nozzle by the production of stream wise vortices was done by Samimy et al. [5]. One of their study involved the estimation of noise field of an axisymmetric jet perturbed by tabs at different azimuthal locations. They reported that the tabs eliminated the screech noise and 4-tab model worked the best with a drop in total sound pressure level of 6.5 dB compared to the reference model. A reduction of broadband levels of noise over a wide range of frequency spectrum was also observed for the 4-tab case. They pronounced that tabs are inefficient in over expanded flow because, the pressure gradient at the jet exit being adverse does not favor instigation of stream wise vortices. The next step was to know, how the interaction of stream wise vortices influenced the entrainment and acoustic characteristics. This work was done by Rogers and Parekh [6] by generating artificial stream wise vortices using the half delta wing vortex generators in a rectangular jet. In their work they concluded that the sign of the vortex signs placed an important role in determining the way stream wise vortex structures interacted among themselves. It is reported that the co-rotating vortices entrained up to 50% more fluid without increasing noise unlike counter-rotating vortices. Co-rotating vortices reduced the low frequency sound due to mean shear pressure fluctuations by 3 dB and increased the high frequency turbulent mixing noise by 8 dB. Even though counter-rotating vortices showed similar behavior, it was not as effective as co-rotating vortices in reduction of sound.

Early research on castellated nozzles for rapid mixing technology was carried out by Miller and Seel [7]. The castellations used in their study had a teeth depth of 1/20th of the diameter of the nozzle exit. The streamwise disturbances produced were found to be effective even after a distance of 5 times the diameter. Thus it helps in rapid mixing. The more the number of castellations, the lesser the effectiveness in mixing due to the mutual interactions between the vortices. They reported that nozzles with 4 and 8 castellations performed better than the others. They also claimed that the castellations destroy the ordered ring vortex structure which would have been generated at the nozzle lip otherwise. The work by Saddington et al. [8] confirmed the previous observations. They did numerical simulation and experimental investigations to study the effect of entrainment and vortical interactions in castellated nozzles. They explained how the profile of the gap whether convergent, divergent or regular, affected the mixing parameters. The constructive interaction between the two counter-rotating vortices generated at the edge of the teeth and gap enhances mixing. The regular castellated nozzles are shown to have 45% increase in non-dimensional mass flow rate over the uncastellated nozzle. One of the recent work on castellations is by André et al. [9]. They used a 24 notch converging nozzle with a depth of notch of 1/10th of the diameter of the jet exit and unequally spaced gap and teeth. The notches were found to eliminate the screech and increase the broadband shock-associated noise. Their key observation was the increase in the number of shock cells downstream, as the screech was eliminated. They claimed that the screech acts as a damper of the shock-cell structure. A mechanism on how notches suppress screech is discussed. The flow through the gap hindered the receptivity of the screech thereby disrupting the feedback loop. A basic understanding of the pipe flow under consideration was given by Jothi and Srinivasan [12]. The pipe chosen for the current study has an L/d of 10. From their work, it can be related that the pipe under study will behave similar to a nozzle because of the increase in the number of instability modes with shear layer thickness. Their findings include, for $NPR < 5$ the acoustic power is tone dominated.

The effect of azimuthal sound variation with the number of castellations is yet to be studied in detail. The aim of the current paper is to study the azimuthal variation of the noise components with the number of castellations in sonic under expanded jet using microphone measurements and schlieren imaging.

EXPERIMENTAL SET UP AND PROCEDURE

JET FACILITY

The experimental set-up is housed in Thermodynamics and Combustion Engineering Laboratory of Indian Institute of Technology, Madras. A two-stage, water-cooled reciprocating air compressor was used to compress the air up to 8 bar gauge pressure. Two storage tanks of 10 m^3 capacity are used to contain the compressed air. The air from the tanks are supplied to the settling chamber inside the anechoic chamber using a 4 inch pipe. The settling chamber is a cylinder of 500 mm length and 380 mm diameter. At the inlet and exit of the chamber, series of meshes are placed to streamline the flow and the inner walls are covered with foam to prevent acoustic reflections inside. It converges to a diameter of 43.5 mm over a length of 100 mm, where the test model is fitted using a mild steel holder. The stagnation pressure in the settling chamber is measured a piezo-resistive transducer (Endevco Model 8510C-100) during the measurements. A bourdon pressure gauge is also used while operating the pressure valve.

ANECHOIC CHAMBER

The acoustic experiments were performed inside the semi-anechoic chamber of size 2.5 m × 2 m × 2 m (wedge tip-to-tip) where the free jet and measurement facility is housed. The walls and roof of the chamber are covered with pyramidal polyurethane foam wedges for free-field environment to avoid reflections and reverberations. The floor of the chamber is covered with carpet, and with foam during experiments. Along various linear paths inside the chamber, the chamber was calibrated using inverse square law. It obeyed the law up to a frequency of 700 Hz which is considered as the cut-off frequency of the chamber. Any frequency below that is not considered for analysis. The temperature and humidity of the chamber was monitored throughout the experiment.

MODEL

Brass pipe of inner diameter 10 mm, width 2 mm and length 100 mm is used as the base model for the current study. The inner surface of the pipe is polished by honing process to ensure that the roughness of the surface does not cause significant loss of pressure head due to turbulence inside the pipe. The inlet of the pipe is rounded to allow a smooth entry. The area projected out of the pipe is termed as teeth and the cut out is termed as gap. The arc length of gap and teeth are kept equal. Castellations are machined at the pipe exit using cylindrical milling cutter and pipes of various castellation numbers are fabricated as shown in Fig. 1. To classify the number of teeth and gap in each model castellation number is defined as, $C = \pi * d / (g + p)$. The models used for experimentation are base model without castellation (reference), 2*C* and 4*C* as shown in Fig.1.

Figure 1. Photograph of Base model, 2C model and 4C model. (From left to right)

DATA ACQUISITION

The acoustic data was acquired using quarter-inch free field PCB microphone of model number 377A01 which has a flat frequency response in the range 4 Hz – 70 kHz within ±1 *dB*. The microphones were calibrated using B&K Piston-phone calibrator (Model No. 4228) at sound pressure level of 124 *dB* and frequency of 250 Hz at reference conditions. The open circuit sensitivity of the microphone is 4 mV/Pa at the calibrated frequency. The acoustic data from the microphone was conditioned using a signal conditioner of PCB model 482C. Then it was passed through an analog filter Krohn-Hite model no. 3364 to low pass the signal at a cut-off frequency of 70 kHz. An eight channel-channel simultaneous sampling card from National Instruments (NI-PCI-6143) was used to sample the signal at the rate of 150 kHz for a second. The ADC resolution of the card is 16 bits. The digitized time series data was stored in the computer using LabView and the data was processed using Matlab R2016a.

The microphone is placed at a distance of 40 times the diameter of the pipe, from the jet center to deduce the far field acoustic characteristics. The experiment was carried out for NPR ranging from 1.5 to 4.5 at an emission angle of 90° from the jet axis. The azimuthal measurements were made at the center of the teeth element and gap element for each castellated model.

RESULTS AND DISCUSSION

ACOUSTIC MEASUREMENT

Blow down study was conducted by pressurizing the storage tank to its maximum capacity and opening the valve thereby releasing the flow. Acoustic data was captured for the entire flow time. Figure 2 gives the overall sound pressure level variation for all nozzle pressure ratios during the blow down starting from 4.5 to 1.5. The figure shows this variation for the reference model, 2 and 4 castellated model measured at the mid of teeth and gap. As we can observe, there is a marked rise in the overall sound level of the 2*C* model teeth than the other models. At lower *NPR*s that is in the transonic region, the OASPL of *C*=2 model gap is higher than the base model. Near the teeth element of 2*C* model, the screech is getting amplified which results in higher sound level than the base model whereas the sound level in the gap element of 2*C* is lower than the base model. This shows that the flow asymmetry in the azimuthal direction gives rise to differential sound augmentation and suppression by the teeth and gap at different *NPR*s. Till *NPR* 2.9 the noise characteristics near the teeth element of both 2*C* and 4*C* models are the same. But after that, there is a significant variation in their behavior. There is a visual agreement between the behavior of 2*C* Gap and 4*C* teeth. At further higher NPRs, the 2*C* gap noise characteristics match with 4*C* gap. The spectrum in the regions of coincidence also match as well.

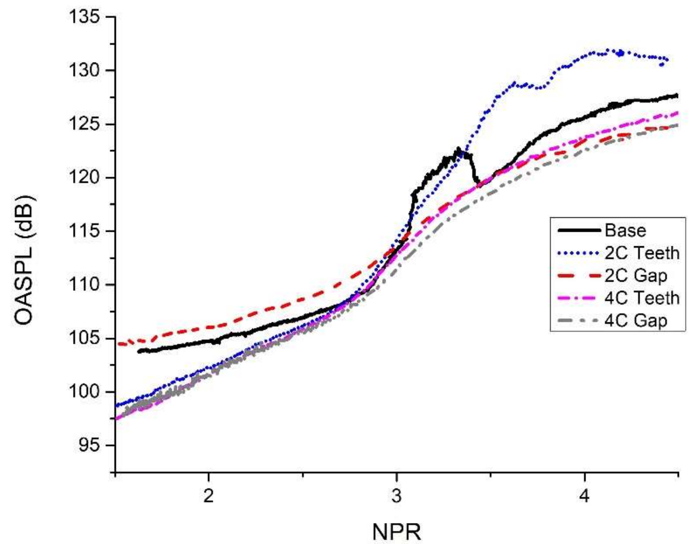

Figure 2. *OASPL* variation with *NPR* for Base, 2*C* and 4*C* models.

The spectral comparison of base model with 2*C* model at two azimuthal positions namely mid-teeth and mid-gap at a *NPR* of 3.6 is given in Fig.3. The figure shows that the screech and harmonic are getting amplified more than the base model which causes the increase in *OASPL* of the 2*C* model. There is a marked reduction of *SPL* by 20 dB in the mid-gap plane from the mid-teeth plane. This reduces further with increase in *NPR* and goes up to a difference of 24 dB. A shift in the screech frequency can be observed from the base model which denotes the change in mode of oscillation of instability waves.

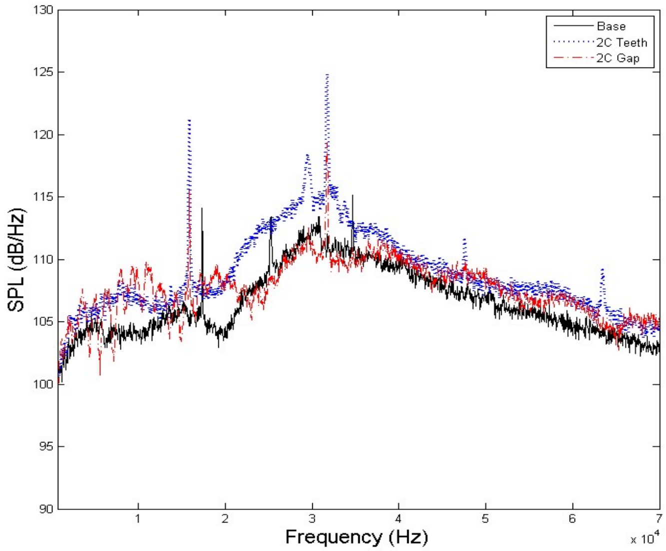

Figure 3. Spectral comparison of 2*C* model with base at *NPR*=3.6

From Powell et al. [11], we can infer that the change in screech frequency at a given NPR is probably because there is a mode change occurring from base model to 2*C* model. We can get a clearer picture of this by looking at Fig. 4. Further understanding can be attained with modal analysis which is beyond the scope of this paper.

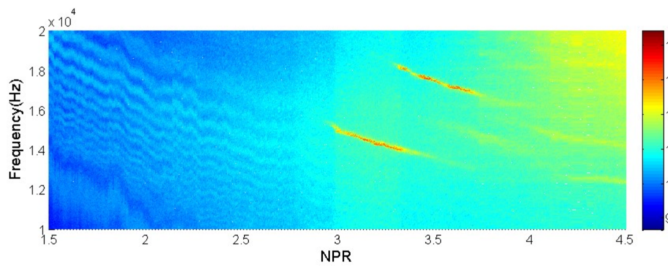

Figure 4a. Spectral color map of Base model

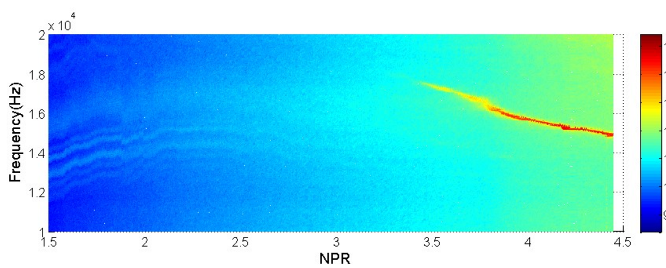

Figure 4b. Spectral color map of 2*C* model

Figure 4 gives the spectral color map of base model and 2*C* model plotted against the nozzle pressure ratio. The color bar indicates the sound pressure level in dB/Hz. It is seen that the change in mode of oscillation occurs at the *NPR* of 3.6. The increase in the amplitude of screech in case of 2*C* model more than the base model can be seen in Fig. 4. After a *NPR* of 3.7 we can observe the screech cessation in case of base model, whereas screech persists to exist in 2*C* model.

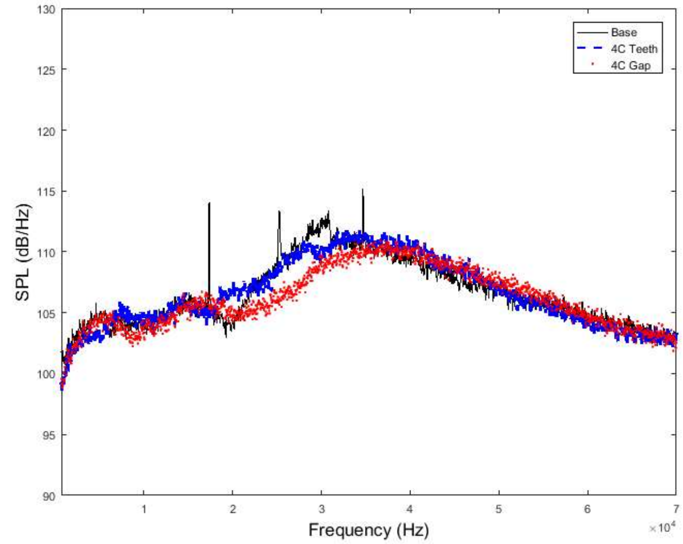

Figure 5. Spectral comparison of 4*C* model with base at *NPR*=3.6

The spectral comparison of 4*C* model with base for the *NPR* of 3.6 is given in Fig. 5. We can find that the screech is completely eliminated by 4*C* model and the spectrum does not vary azimuthally.

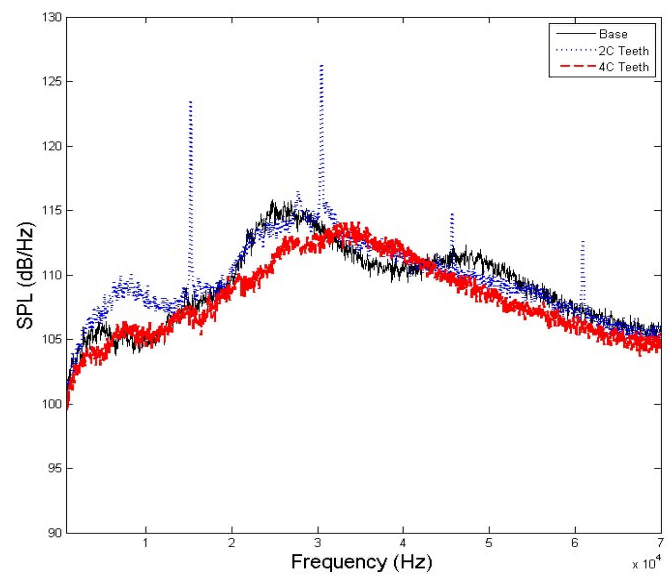

Figure 6. Spectral comparison of 2*C* model mid-teeth and 4*C* model mid-teeth with base at *NPR*=4.2

The spectral comparison of base with 2*C* teeth and 4*C* teeth for an *NPR* of 4.2 is given in Fig. 6. The figure implies the existence of screech in case of 2*C* teeth position even after the cessation of screech in base model. Also the spectra of 4*C* teeth and base are comparable with 4*C* having lesser *OASPL* value than base. The spectra of the gap profile is similar for both the models. The screech augmentation in 2*C* may be due to the positioning of the vortex pairs in the pipe exit such that it gives rise to strong feedback loop resulting in higher screech amplitude. The pair of counter-rotating vortices generated at the pipe exit is anticipated to position themselves at the mid of the teeth and gap. As the fluid is pushed through the gap, the vortices formed at each edge move closer to each other in the downstream [8]. At lower *NPR*s the mass flow rate of the fluid coming through the gap is less, hence the counter-rotating vortices interact at the mid of the gap leading to increase in high frequency turbulent noise. At higher *NPR*s as the counter-rotating vortices move away they are positioned at the mid of the teeth. The counter-rotating vortices are not effective in reducing the low frequency noise as much as co-rotating vortices [6]. Hence the mean shear pressure fluctuations form a strong feedback loop thereby resulting in augmentation of sound. In 4 castellated pipe jet the positioning of the vortices are ideal for it to cancel the effects and obstruct the receptivity in that process. This results in the elimination of screech and increase in broadband shock associated noise [9].

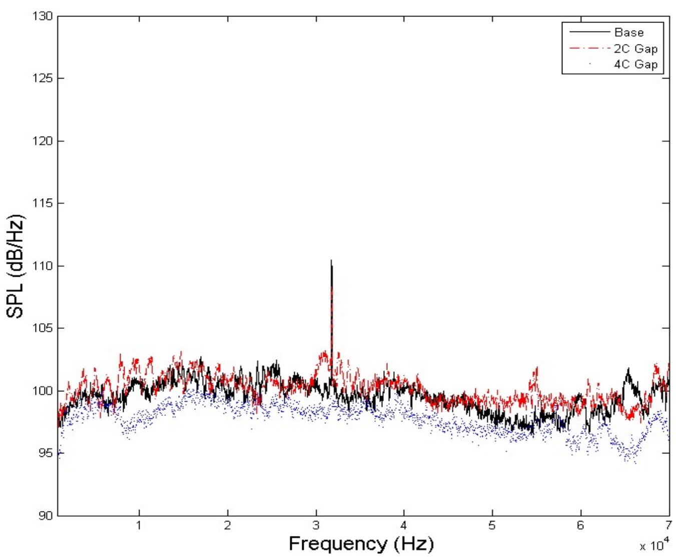

Figure 7. Spectral comparison of 2*C* model mid-gap and 4*C* model mid-gap with base at *NPR*=2

At *NPR* lesser than 2.9, the overall sound pressure level of 2*C* gap is the highest among the measured. This can be explained as the gap profile of 2*C* model pushes out more fluid which results in the increase of overall turbulent mixing noise. The spectral comparison of gap profile of 2*C* and 4*C* model for an *NPR* of 2 is given in Fig.7. From the Fig.7 a transonic tone can be observed for base and 2*C* gap whereas 4*C* gap is void of the tone and has lesser sound pressure level.

FLOW VISUALIZATION

In order to have better understanding of the flow, schlieren imaging was performed using High speed CMOS (Complementary Metal-Oxide Semiconductor) camera Mikrotron of Model no. MC1302. In-line schlieren arrangement was set up. The castellated pipes were kept at two orientations and the images were obtained at the teeth plane and gap plane, because of the azimuthal asymmetry of the flow structure. The pipes were positioned such that along the line of imaging it remains symmetric. Figure 8 gives the orientation of imaging plane of the castellated pipes. The centerline represents the imaging plane.

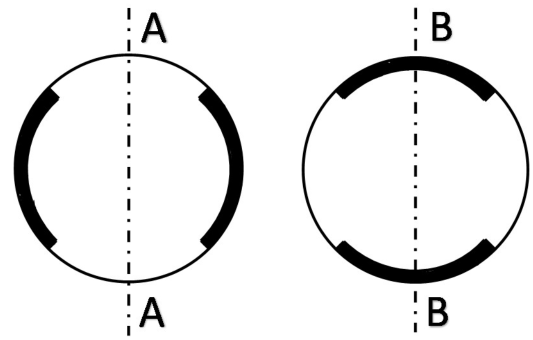

Figure 8a. Gap plane (A-A) and Teeth plane (B-B) of 2*C* model

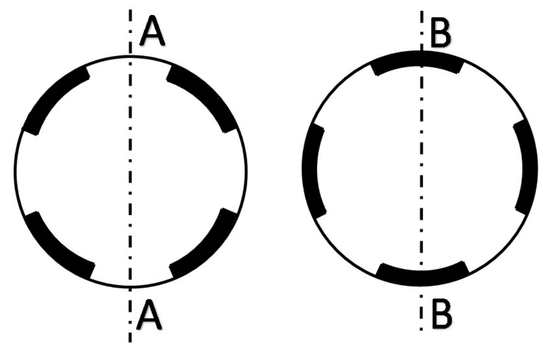

Figure 8b. Gap plane (A-A) and Teeth plane (B-B) of 4*C* model

Figure 9 shows the schlieren images of base pipe flow, 2*C*, 4*C* model flow captured at a *NPR* of 3.6. In Figs. 9b and 9c, A-A represents the gap plane and B-B represents the teeth plane. The schlieren images obtained are in accordance to the results of Saddington et al. [10]. The shortening of shock cell has been observed in castellated pipe jets as seen in Figs. 9b and 9c. The overall potential core length remains unchanged for all the tested models.

From the Fig. 9b, the asymmetry in the teeth plane and gap plane is clearly visible. The jet expansion in the gap plane is prominent in both the castellated pipe jets. The shock cell structure of base pipe flow and 4*C* teeth flow are similar but the number of shock cells in 4*C* model is higher. From the acoustic results, we know that at *NPR*=3.6 screech is completely eliminated in 4*C* pipe. Hence there is increase in broadband shock associated noise which can be attributed due to the increase in the number of shock cells more than the base jet [9]. The acoustic spectra gave us insight about the different mode of oscillation of base pipe and 2*C* model which is explainable from the Figs. 9a and 9b. The shock cell structure of 2*C* and base model are completely different. The last shock cell of the 2*C* jet is diffused which proves that as the strength of the screech is higher, the shock cells are dampened. Also it is inferable from the images that the screech generation in base model and 2*C* is by different means which is yet to be explored. The schlieren images at other *NPR*s show a similar trend as well.

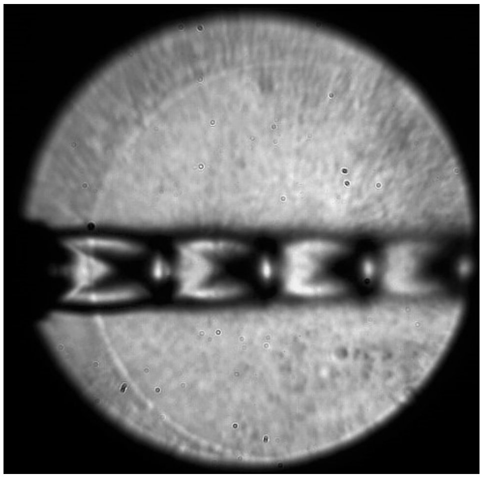

Figure 9a. Schlieren image for base pipe at *NPR*=3.6

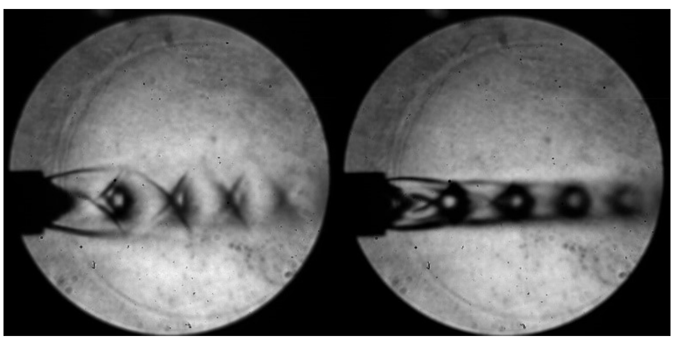

Figure 9b. Schlieren image of 2*C* pipe at *NPR*=3.6 Gap plane (Left) and Teeth Plane (Right)

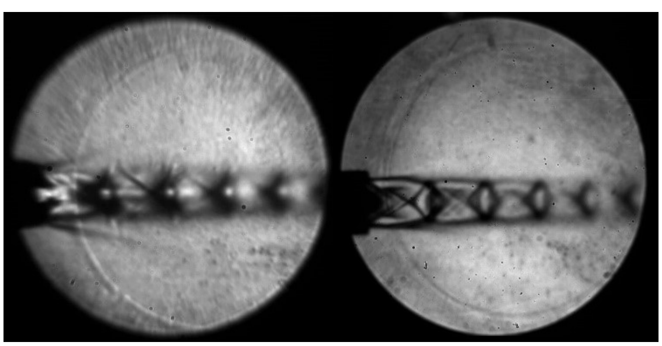

Figure 9c. Schlieren image of 4*C* pipe at *NPR*=3.6 Gap plane (Left) and Teeth Plane (Right)

CONCLUSION

Pipe jets with two castellations have higher screech associated noise than the base pipe flow at *NPR*s above 2.9. The screech tones continue to exist in *2C* jets even after screech ceases in base jet. The amplified screech and harmonic tones are likely due to the interaction of streamwise vortices and strengthening of the feedback loop. Hence, they are unsuitable in terms of noise mitigation. The castellations cause the *SPL* to vary azhimuthally and bring about a difference of 24 dB in teeth and gap plane. Pipes with four castellations have reduced overall sound pressure level than the base pipe jet for all *NPR*s tested and do not vary azhimuthally.

REFERENCES

1. Knowles, K., and A. J. Saddington. "A review of jet mixing enhancement for aircraft propulsion applications." Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 220.2 (2006): 103-127.
2. Pannu, S.S., and Johannesen, N. H., “The Structure of Jets from Notched Nozzles,” Journal of Fluid Mechanics, Vol. 74, 1976, pp. 515–528.
3. Wlezien, R. W, and V. Kibens. "Influence of nozzle asymmetry on supersonic jets." AIAA journal 26.1 (1988): 27-33.
4. Longmire,E. K., Eaton, J. K., and Elkins, C. J., “Control of Jet Structure by Crown Shaped Nozzles,” AIAA Journal, Vol. 30, No. 2, 1992, pp. 505–512.
5. Samimy, M., Zaman, K.B.M.Q., and Reeder, M.F., 1993, "Effect of tabs on the flow and noise field of an axisymmetric jet," AIAA J., Vol. 31, 609-619.
6. C. B. Rogers and D. E. Parekh (1994), "Mixing Enhancement by and Noise Characteristics of Streamwise Vortices in an Air Jet", AIAA Journal, 32(3), March, pp 464-471.
7. Miller, P., & Seel, M. (1991). The application of high pressure ejectors to reaction control systems. The Aeronautical Journal (1968), 95(949), 297-312. doi:10.1017/S0001924000024180
8. Saddington, A. J., N. J. Lawson, and K. Knowles. "Numerical predictions and experiments on supersonic jet mixing from castellated nozzles." ICAS 2002 Congress, UK. 2002.
9. Benoît André, Thomas Castelain, and Christophe Bailly. "Broadband Shock-Associated Noise in Screeching and Non-Screeching Underexpanded Supersonic Jets", AIAA Journal, Vol. 51, No. 3 (2013), pp. 665-673.
10. A. J. Saddington, K. Knowles and R. Y. T. Wong (2001), "Numerical Modelling of Mixing in Jets from Castellated Nozzles", RAeS Aerodynamics Research Conference, London, April 9-10. [ISBN 1-86768- 167-3]
11. Powell Alan, Yoshikuni Umeda, and Ryuji Ishii. "Observations of the oscillation modes of choked circular jets." The Journal of the Acoustical Society of America 92.5 (1992): 2823-2836.
12. Jothi, T. J. S., and K. Srinivasan. "Role of initial conditions on noise from underexpanded pipe jets." Physics of Fluids 21.6 (2009): 066103.