EXPERIMENTAL AND STATISTICAL ANALYSIS ON THE NOISE REDUCTION USING CHEVRON NOZZLE IN SUPERSONIC FREE JET

P. KALEESWARAN[1], P. SHANMUGHASUNDARAM[2]

Experimental investigation was carried out for the suppression of noise level in the supersonic free jet with chevron nozzle by varying different Nozzle Pressure Ratios (NPR). Chevrons are incorporated to reduce the supersonic jet noise at the nozzle exit. The noise level was measured using sound level meter. Taguchi and ANOVA techniques were used to find the optimum levels of the parameters and contribution of the parameters on the sound level respectively. The research outcome infers that 14 chevrons at the nozzle exit was found to be more effective in reducing the noise level by 2% compared to the 10 chevrons and without chevron in the supersonic free jet. Mathematical model was developed using multiple linear regression technique.

Keywords: Chevron nozzle, Nozzle Pressure Ratio, Taguchi, ANOVA, multiple linear regression

1. Introduction

Among all noise sources, aircraft noise is considered as the most annoying. People are very much concerned about the quality of their environment that noise is quoted as the first reason of vexation [1].The increasing air traffic in the past has led to the fact that more people were affected by aircraft noise. Meanwhile, the potential of suppressing noise level of current aircraft will be limited in the future after recent developed techniques have been realized in practice [2].The public request for quieter airports lead to develop a stringent legislation based on the compulsory noise monitoring which usually combine information emerging from noise level meters and radars as highlighted by the ISO 20906[3]. Literature review reveal that addition of chevrons to the nozzle reduces the sound pressure level (SPL) radically with substantial reduction in performance. This vorticity leads to increased mixing and reduced jet plume length in the supersonic jet. Still, the level of penetration of the individual

[1] Research Scholar, Karpagam Academy of Higher Education, Coimbatore, India, e-mail: p_kalee@yahoo.co.in
[2] Prof., Dept. of Automobile Engineering Karpagam Academy of Higher Education, Coimbatore, India, e-mail: sunramlec@rediffmail.com

chevrons is typically much less than that for tabbed nozzles and the induced vorticity is weaker. Due to formation of vortices at the tip of chevron decreases the strength of shock formation at the exit of the supersonic nozzle thereby noise level tend to reduce [4].

Tide and Srinivasan [5] investigated the effect of chevron count and penetration on the acoustic characteristics of chevron nozzles. They reported that higher chevrons count with a lower level of penetration yields the maximum noise reduction with various nozzle pressure ratios and careful selection of chevron parameters can help significant noise reduction. Catherine Lavandier et al [6] studied an impact of aircraft sound quality combined with the repetition of aircraft flyovers on annoyance as perceived activity disturbance in a laboratory context. They elucidated the influence of the number of aircraft flyovers is statistically significant at the 5% level and high tonal components have no effect on perceived disturbance. Fan Shi Kong et al [8] studied the application of Chevron nozzle to a supersonic ejector–diffuser system. Chevron nozzle was employed to activate the shear actions between the primary and secondary streams, by means of longitudinal vortices generated from the Chevron. Christophe Bogey and Christophe Bailly [10] studied the importance of specifying appropriate nozzle-exit conditions in jet noise prediction with respect to initial turbulent jets strong additional noise components generated by pairings of coherent vortical structures in the transitional shear layers are in addition observed. Philip J. Morris et al [12] investigated the noise reduction in supersonic jets by altering the configuration and operating conditions of the fluidic inserts. They reported that active noise reduction for both mixing and substantial noise reduction was achieved. The total injected mass flow rate was found to be less than 4% of the core mass flow rate.

Ali Uzun and M. YousuffHussaini [14] examined the simulation of noise generation in near nozzle Region of a Chevron Nozzle Jet with six symmetric chevrons in nozzle design. They observed that the consequent noise generation occurs in the mixing layers of the jet within the first few diameters downstream of the nozzle exit.

Rask et al [16] studied how chevrons modify noise in a supersonic jet with flight effects. They observed that chevrons reduce the shock-cell spacing with minimal effect on the shock-cell strength.

Casalino et al [18] studied the aircraft noise reduction technologies: A bibliographic review The aeroacoustic mechanisms involved in the noise generation from airframe and engine components are presented as a key element of the noise reduction technology. Ching-Wen Kuo et al [19] analysed the acoustic measurements of models of military style supersonic nozzle jets in modern military aircraft jet engines that are designed with variable-geometry nozzles to provide optimal thrust in different operating conditions, depending on the flight envelope [19]. Max Kandula [20] studied the broadband shock noise reduction in turbulent jets by water injection in supersonic jets to the estimation of broadband shock noise reduction and the range of water mass flow rates over which saturation of mixing noise reduction and existence of parasitic noise are manifest.

Viswanathan [21] observed the characteristics of the shock noise component of jet noise is generated by the interaction of the downstream convecting coherent structures of the jet flow with the shock cells in the jet plume. Vorobyov et al [22] studied the problem of intensity reduction of acoustic fields generated by gas-dynamic jets of motors of the rocket-launch vehicles at launch suppression of acoustic fields by water injection. It was determined that injection angle of 600 has greater effectiveness to reduce pressure pulsation levels.

In this article, it was observed that 14 chevrons at the nozzle exit was found to be more effective in reducing the noise level by 2% compared to the 10 chevrons and without chevron in the supersonic free jet.

2. Experimentation

In this experiment,a supersonic free jet test rig is established with 15hp air compressor and air tank capacity of $5m^3$. The schematic of experimental setup is shown in the Fig.1.Air is brought to the settling chamber through 1.5cm pipe line. A control valve was used for controlling the stagnation pressure at the settling chamber. The settling chamber is also provided with three wire mesh of progressive order for reducing initial turbulence level. CD nozzle was designed to produce supersonic flow at the exit. Blow down test was performed in CD-nozzle to establish supersonic flow. The Fig.1 (a), (b) and (c) shown is the experimental set of supersonic free jet of CD-nozzle with 14 chevrons, 10 chevrons and without chevron which is connected to the exit of supersonic free jet. Sound level meter was placed at 30cm away from the nozzle exit to measure the sound level for the various pressure conditions.

Supersonic nozzle contour is provided with and without chevrons at the downstream flow. To reduce the sound pressure level two schemes (10Nos. and 14Nos.) of chevrons predict the variation in jet velocity and pressure. The features of triangular serrations in the nozzles along the trailing edge, which encourage stream wise vorticity into the shear layer.

Figure1. Experimental set up

3. Results and Discussion

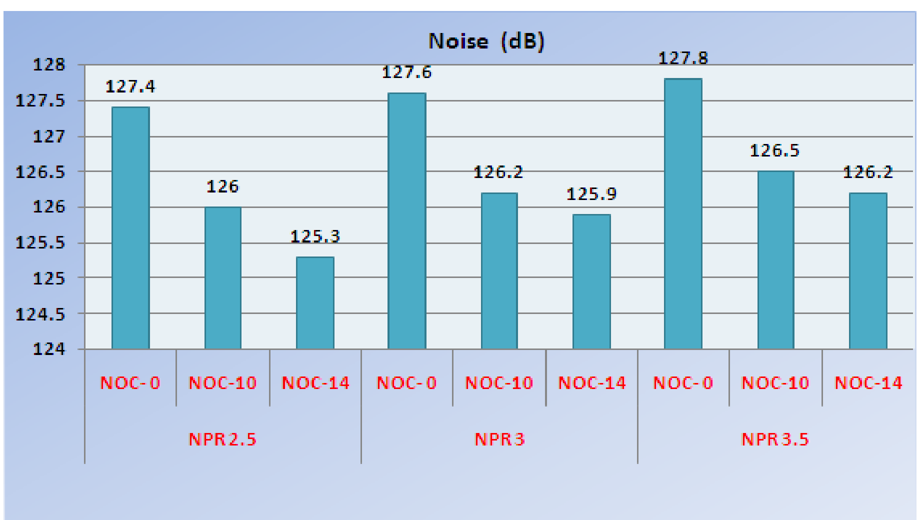

Figure 2 Effect of nozzle pressure ratio (NPR) and No. of Chevrons (NOC) on noise level

The effect of nozzle pressure ratio and No. of Chevrons on noise level is shown in Fig.2. The results were plotted for three different nozzle pressure ratios(2.5, 3,and 3.5) and No. of chevrons (0, 10, and 14) at the exit of the CD-nozzle. It was observed that when the pressure ratio increases, noise level tend to increase irrespective of chevrons used. On the other hand, noise level tends to decreases as the No. of chevrons increases at the exit of the nozzle.

When the nozzle pressure ratio was decreased from 3.5 to 2.5, noise level decreased from 126.2dB to 125.3dB for 14 chevrons.The results indicate that there is 2% reduction in noiselevel by incorporating 14 chevrons. The results appreciable when compared to other existing design [5]where noise level reducedby 1% at the tested pressure conditions.

Turbulent mixing noise is the dominant component of jet noise in the mixing region, which is defined as the region of high turbulence that results as the potential core velocity begins to decay. This phenomenon was initially explained by Balsa [9]. It was reported that the minimum noise level was a direct consequence of the reduction in turbulence intensity in the inner-to-outer stream mixing layer as the outer flow velocity was increased. Further increases in outer flow velocity cause the outer-to-ambient stream mixing layer turbulence to produce the dominant noise.

The noise evidences are accomplished in chevron nozzles are more obvious in the range of nozzle pressure, where the baseline circular nozzle screeches. The chevron nozzles studied in this analysis are free from screech.

3.1. Taguchi and ANOVA analysis

Taguchi's technique can be used to find the optimum levels of the parameters which have an influence on the quality characteristics of the process. An L_9 orthogonal array wasused for the present investigation. The notation 3^2implies that 2 factors, each at 3 levels. In this study, “smaller is better” S/N ratio was used to predict the optimum levels of parameters because lower noise levelwas preferred.

Mathematical equation of the S/N ratio for “smaller is better” can be expressed in the equation (i).

$$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum_{i}\frac{1}{Y_i^2}\right) \quad (1)$$

Where, Y is the observed data and n is the number of observations.

The selected factors and the corresponding levels are presented in Table 3. Accordingly, nine tests were carried out and each test was performed twice in order to minimize the errors. Moreover, the test results were analyzed using

Analysis of Variance (ANOVA) to evaluate the influence of the factors on the performance measure.

Table 1

***Factors* and levels**

Level	Nozzle Pressure Ratio (A)	No. of Chevrons (B)
I	2.5	0
II	3	10
III	3.5	14

Table 2

Measured values and S/N ratios

Test No	Nozzle Pressure Ratio (A)	No. of Chevrons (B) dB	Noise level (dB)	
			Measured Values	S/N ratios
1	2.5	0	127.4	-42.1034
2	2.5	10	126	-42.0074
3	2.5	14	125.3	-42.9590
4	3	0	127.6	-42.1170
5	3	10	126.2	-42.0212
6	3	14	125.9	-42.0005
7	3.5	0	127.8	-42.1306
8	3.5	10	126.5	-42.0418
9	3.5	14	126.2	-42.0212

Results of S/N Ratio

Tests were conducted as per the L9 orthogonal array and the corresponding values and S/N ratios for the noise level are presented in Table 2.The S/N ratio for each parameter level is calculated by averaging the S/N ratios at the corresponding level. The parameter with the highest S/N ratio gives minimum noise level. From the response diagram of S/N ratio (Fig.3), it was found that the optimum parameter levels were Nozzle Pressure Ratio (2.5) and No. of Chevrons (14) in reducing the noise level.

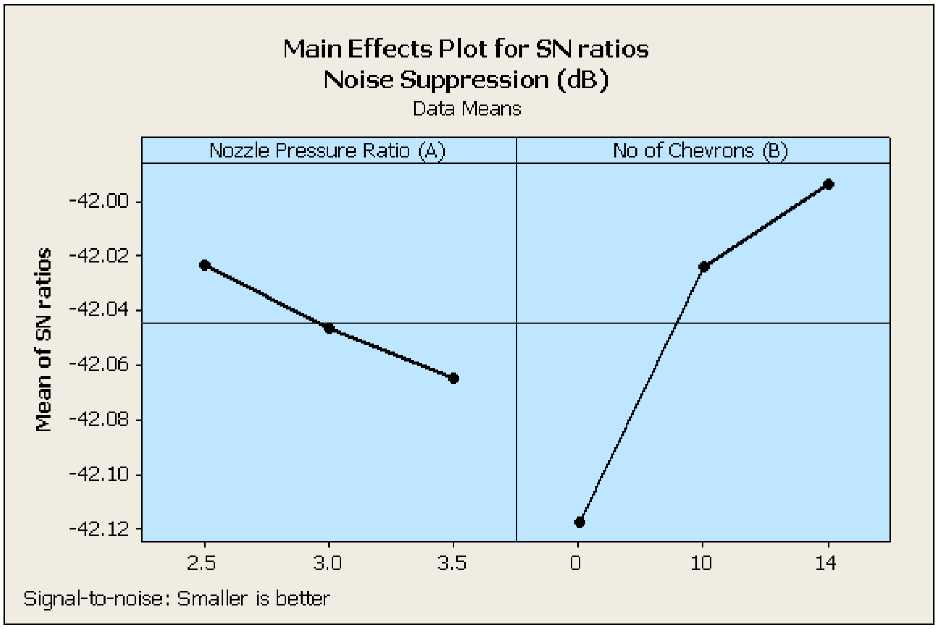

Fig. 3: Response diagram of S/N ratio

Results ofANOVA

The analysis of variance was employed to find the statistically significant parameters and the contribution of these parameters on the noise level. ANOVA was performed with the help of the software package MINITAB15 for a level of significance of 5%. Measured values and Signal to Noise ratios (S/N) are presented in table 2.

Table 3

ANOVA analysis for noise suppression

Source	**DoF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Pc%**
Nozzle Pressure Ratio (A)	2	0.5422	0.5422	0.2711	12.84	0.018	9.15
No of Chevrons (B)	2	5.2956	5.2956	2.6478	125.42	0.000	89.4
Error	4	0.0844	0.0844	0.0211			1.42
Total	8	5.9222					

DoF- Degrees of Freedom Seq.SS- Sequential sums of squares; Pc-Percentage of contribution.

In this analysis, p-value is helpful to test the association of each parameter on the outcome. When the P-value is less than 0.05, then the parameter can be considered as statistically highly significant. The last column of the Table3.shows the percentage contribution (Pc %) which indicates the influence of the parameters on the noise suppression. It was observed that the No. of Chevron (89.4 %) was the major contributing factor followed by Nozzle Pressure Ratio (9.15%).

4.1.1. Multiple linear regression model

Multiple linear regression equations were done to establish the correlation among the parameters on the response.
The regression equation developed for Noise measurement in Decibel

$$Noise\ (dB) = 126 + 0.600(A) - 0.130(B), \tag{2}$$

Where A-nozzle Pressure Ratio and B-No. of Chevrons

It was observed from the Eq. (2) that the coefficient associated with nozzle pressure ratio (A) is positive whereas coefficient associated with No. of chevrons is negative. It infers that the noise level decreases with decreasing nozzle pressure ratio and noise decreases with increase in No. of Chevrons (B).

4. Confirmation Test

The confirmation tests were performed to predict the noise level at the constant Nozzle Pressure Ratio of 2 and the two different chevron counts of 8 and 12. The results are given in the Fig. 4.The testing values for the noise level and calculated values from the regression equations are nearly same with least error (± 2%).

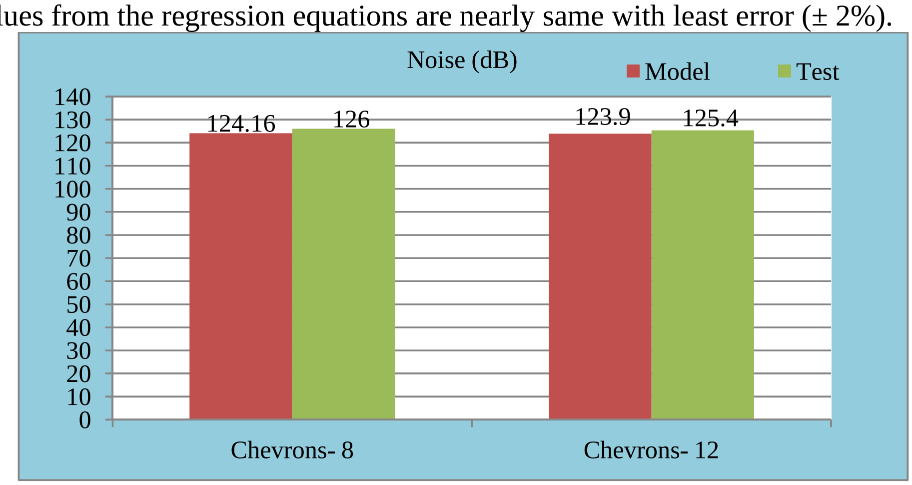

Fig.4 Result of confirmation experiment and their comparison with regression model

The regression equations can be used to predict the noise level to the acceptable level of accuracy within the observed range.

5. Conclusions

Experiments were conducted on chevron nozzles for different nozzle pressure ratio, with 10 chevrons and 14 chevrons. It was observed that 14chevron with nozzle pressure ratio (2.5) was found to be optimum value in obtaining noise reduction.

It was noted that 2% of noise reduction was observed by employing 14 chevrons at the pressure value of 3.5 compared to 10 chevrons and without chevron in the supersonic nozzle.

The results apparently show that the nozzle with maximum number of chevron provides encouraging passive method for noise suppression. No. of chevrons was the dominant factor followed by nozzle pressure ratio within the observed range.

R E F E R E N C E S

[1] *B. Barbot, C. Lavandier* , Perceptual representation of aircraft sounds , Applied Acoustics, **Vol. 69**, 2008, pp. 1003–1016.

[2] *Martin Schütte, Uwe Müller, Stephan Sandrock*, Perceived quality features of aircraft sounds: An analysis of the measurement characteristics of a newly created semantic differential, Applied Acoustics, **Vol. 70**, 2009, pp. 903–914.

[3] *Marco Tarabini, Giovanni Moschioni, Cesar Asensio, Davide Bianchi, BortolinoSaggin*, Unattended acoustic events classification at the vicinity of airports, Applied Acoustics, **Vol. 84**, 2014,pp. 91–98.

[4] *Bridges J, Brown CA*, Parametric testing of chevrons on single flow hot jets, AIAA Journal, 2004-2824.

[5] *P.S. Tide, K. Srinivasan*, Effect of chevron count and penetration on the acoustic characteristics of chevron nozzles, Applied Acoustics, **Vol.71**, 2010, pp. 201–220.

[6] *Catherine Lavandier , Benoit Barbot , Jonathan Terroir , Martin Schuette,* Impact of aircraft sound quality combined with the repetition of aircraft flyovers on annoyance as perceived activity disturbance in a laboratory context, Applied Acoustics, **Vol. 72**, 2011, pp. 169–176.

[7] *Ma Li, Lu Lipeng, Fang Jian, Wang Qiuhui*, A study on turbulence transportation and modification of Spalart–Allmaras model for shock-wave/turbulent boundary layer interaction flow, Chinese Journal of Aeronautics, 2014.

[8] *Fan Shi Kong, Heuy Dong Kim, Yingzi Jin and Toshiaki Setoguchi*, Application of Chevron nozzle to a supersonic ejector–diffuser system, Procedia Engineering, **Vol. 56**, 2013, pp. 193 –200.

[9] *Balsa, T. F,* The Far Field of High Frequency Convected Singularities in Sheared Flows, with an Application to Jet-Noise Prediction, Journal of Fluid Mechanics, **Vol. 74**, No. 2, March 1976, pp. 193–208.

[10] *Christophe Bogey, Christophe Bailly,* on the importance of specifying appropriate nozzle-exit conditions in jet noise prediction, Procedia Engineering, 2010,pp. 38–43.

[11] *Christopher K.W. Tam, Nikolai N. Pastouchenko, Robert H. Schlinker*, Noise source distribution in supersonic jets, Journal of Sound and Vibration, **Vol.291**, 2006, pp. 192–201.

[12] *Philip J. Morris, Dennis K. McLaughlin, Ching-Wen Kuo*, Noise reduction in supersonic jets by nozzle fluidic inserts, Journal of Sound and Vibration, 2013.

[13] *Stephen Powell, Andra So bester, Phillip Joseph*, Fan broadband noise shielding for over-wing engines, Journal of Sound and Vibration, 2012.

[14] *Ali Uzun and M. YousuffHussaini*, Simulation of Noise Generation in Near Nozzle Region of a Chevron Nozzle Jet, AIAA Journal, **Vol. 47**, No. 8, 2009.

[15] *H. K. Tanna*, An Experimental Part II: Shock Study Of Jet Noise Associated Noise, Journal of Sound and Vibration ,**Vol.**50, No.3, 1977,pp. 429-444.

[16]*O. Rask, J. Kastner, and E. Gutmark*, Understanding How Chevrons Modify Noise in a Supersonic Jet with Flight Effects, AIAA Journal,**Vol. 49**, No. 8, 2011.

[17] *Junhui Liu, K. Kailasanath, and Ravi Ramamurti*, Large-Eddy Simulations of a Supersonic Jet and Its Near-Field Acoustic Properties, AIAA Journal, **Vol. 47**, No. 8, 2009.

[18] *D. Casalino, F. Diozzi, R. Sannino, A. Paonessa*, Aircraft noise reduction technologies: A bibliographic review, Aerospace Science and Technology, **Vol.12**, 2008.

[19] *Ching-Wen Kuo , Jeremy Veltin , Dennis K. McLaughlin*, Acoustic measurements of models of military style supersonic nozzle jets, Chinese Journal of Aeronautics, **Vol. 27**, 2014.

[20] *Max Kandula*, Broadband shock noise reduction in turbulent jets by water injection, Applied Acoustics, **Vol.70**, 2009, pp. 1009–1014.

[21] *K.Viswanathan, M. B. Alkislar, and M. J. Czech*, Characteristics of the Shock Noise Component of Jet Noise, AIAA Journal **Vol. 48**, No. 1, 2010.

[22] *A.M.Vorobyovn, T.O.Abdurashidov, V.L.Bakulev, A.B.But, A.B.Kuznetsov, A.T.Makaveev*, Problem of intensity reduction of acoustic fields generated by gas-dynamic jets of motors of the rocket-launch vehicles at launch, ActaAstronautica, **Vol.109**, 2015, pp. 264–268.