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Jet noise reduction by chevrons : A review

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Abstract - *This article presents a review of acoustic characteristics of chevrons in modern bypass Jet engine. Jet noise is still a major concern for civilians and to the environment. Manufactures and research engineers are actively working to provide a viable solution for noise reduction without trade-off fuel efficiency. One such passive method to reduce jet noise is by using either chevrons at the end of nozzle. This review paper discusses various geometries in chevrons and nozzle along with their computational analysis on acoustics. This gives a wider perspective to understand these passive methods and helps researchers to come up with novel solution addresses the earlier implications.*

Key Words: Chevron nozzle, Jet Engine, Aeroacoustics, Bypass , Noise reduction , CFD Analysis, Notched, RANS, Jet Noise, Chevrons

Abbreviations:

BPR: Bypass Ratio , SFN: Separate Flow Nozzle , SPL: Sound Pressure Level, EPNL: Effective Perceived Noise Level, OASPL: Overall Sound Pressure Level, NPR: Nozzle Pressure Level, API: Acoustic Power Index, TKE: Turbulence Kinetic Energy, ANOVA: Analysis of Variance, MDOE: Modern Design of Experiments ,DNS: Direct Numerical Simulation

Nomenclature:

Z: Mach Number,

D_{eq}: Equivalent Diameter,

M_{ij}: Local Mach Number,

$V_{j,mean}$:Mean Jet Velocity,

St: Strouhal Number ,

D_{core} :Core Diameter

1. INTRODUCTION:

Jet engine is a reaction engine, basically every action has equal and opposite reaction .Early Jet engine has to suck a large volume of air into the combustion chamber .Along with fuel-air mixture it becomes a controlled explosion which increases temperature. As a result volume of air intake is increased. This is directed outward through nozzle [1-9]. These jet plumes react with ambient air in the atmosphere. When two different air masses at different flow speed of different temperature causes turbulence or vertices .These vortices generates noise .The difference in flow speed between engine exhaust and ambient air is very large ,So there is huge noise[10-11] .This became a concern for civilians and natural habitats due to its unpleasant screening noise, especially during night. So in late 1960's airplane manufacturers came up with commercial bypass jet engine[12],[14],[52]. In modern jet engines, there is a huge fan in front of engine. This fan uses the energy created by jet exhaust and converts it into kinetic energy. This huge fan operates at relatively less speed than the exhaust. Due to this the bypass air coming from bypass ducts provided mixes up with ambient air. These plumes are uncontrolled but has less noise than earlier jet engine without bypass. These bypass air and ambient air Mixing encapsulates all around the jet exhaust and it reduces the intensity of vortex. This bypass ratio engines had reduced around nearly 30%-40% from earlier jet engines without bypass .Still with bypass jets had substantial noise. Later , NASA came up with Chevrons Many research lab testing and full scale flight tests conducted as part of Quiet technology Demonstrator(QTD) programme have proven that using chevrons to bypass turbojet engines is effective way of passive method to reduce in both subsonic and supersonic flows.[16]

2. JET NOISE :

Three main sources of jet noise are due to aerodynamics, engine and other control systems. Primarily noise from the engine is because of jet plumes getting away of exhaust nozzle [1] .When high speed jet withdraw from the engine has intrinsic shear layer and it swirls up into vortices like ring-shaped .This disintegrates into turbulent plumes mixing with ambient fluid which results as a source of noise[2].Jet noise has been considerably decreased by increases in Bypass ratio in turbofan engines This reduced the velocity gradient[3].Some of passive methods to reduce noise in jet engine are chevrons, notched nozzle, micro tabs, corrugated nozzle, inverted velocity profile[48]. Active methods to reduce noise are water injection, air injection, nitrogen injection. By these methods more or nearly 2-3dB noise has been reduced.[4]

In common, mostly noise arises due to pressure variations in an unsteady flow. Pressure variations occur in an unstable flow to counterbalance momentum variations. "These pressure changes are transmitted to the surrounding fluid and spread outward from the flow since all real fluids are compressible"[5]. The sound that is heard is made up of these pressure waves in the surrounding fluid.[5]

When a jet fluid strikes a background fluid that is stationary or flowing relatively slow, shear among in motion and immobile fluids creates a fluid mechanical transcience that makes the interface to disintegrates into vortices. Then these vortices move subsequent by speed that is between the high and low speed flows in magnitude. It follows the indicated velocity is subsonic or supersonic in compared to exterior flow determines the characteristics of jet noise[6].The high speed exhaust gases are responsible for most of noise, particularly during taking off and landing.[7]

By Lighthills eighth power law[8],

Sound power $\propto$ *jet area× (jet velocity)^2* (1)

3. CHEVRONS:

Chevrons are jagged back edges at tip of nozzle. The triangular shaped cut outs at edge of nozzle reduces jet plumes length by indicating streamwise vortices into shear layer which enhances the mixture. This results in reduced jet noise. Chevrons transform an axisymmetric jet into lobbed jet at close proximity to nozzle, intensifying mixing owing to expanded shear layer perimeter. Subsequently the mid line velocity decay rate arises, the theoretical core length shrinks and the spherical cross sectional of jet changes to disc like shape bounded of a small length of 5D.

The aforementioned effects are amplified by increasing chevron penetration, especially when it occurs in mixing layer's thinner zone. "Chevrons shift the acoustic energy from low frequency to high frequency, which directs beams to greater polar angles where OASPL is improved"[24]. Chevrons emit noise from near field move efficiently toward polar angles greater than or equal to 50°[24]. Chevrons enhance the high frequency SPL at polar angles greater than 40° and decrease the low frequency SPL at all polar angles in distant field. But the corresponding frequency spectrum multiply in SPL at higher frequencies for probe in thin blending layer and at low frequencies for probe on thin blending layer and low frequencies for penetrating thick blending layer, despite the fact that the resultant OASPL for same penetration of chevron petals is above or below invariant irrespective of their location.[24]

3.1Chevron configuration:

"Geometry of chevron nozzle is defined by the parameter such as number of chevrons(N), length of chevron(L), tip angle(β) and penetration angle(α)" [9]

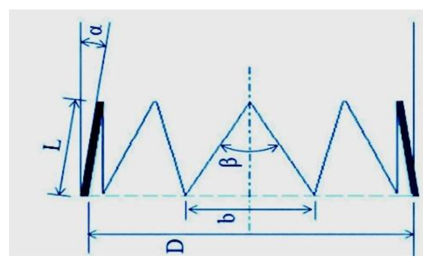

Fig1 [9]

Base of the single chevron(b) can be computed by[9]

$$b=\pi\times(D/N) \quad (2)$$

$$\tan(\beta/2)= b/(2L) \quad (3)$$

By combining (2) and (3),

$$(L/D)\times(\tan(\beta/2)\times N)= \pi/2 \quad (4)$$

Nozzle length that is influenced by nozzle exhaust diameter[9]

$$L' =4.25\times D \quad (5)$$

Height of chevron is [5]

$$H=b/2 \quad (6)$$

These formulae implies that chevron length is reliant on chevron count and tip angle. Chevron arrangement can be shown as "N×βy". From eqn(4),it is understood that L/D is primarily depend on chevron count and tip angle. This relation provides an insight that these fundamental variables determines the geometry of chevron are interrelated and that it is impossible to change one variable without also affecting the others. Therefore extremely considerable consideration goes into selecting chevron configurations so that the impact of each individual parameter can be determined.[9]

3.2 Role of chevrons in Jet noise reduction:

One effective technique for minimising jet noise is chevron which improves the mixing of fan ,core and ambient streams more quickly than traditional nozzle without affecting efficiency [9], [10].The triangular cut out placed along the nozzle's trailing edge cause streamwise vortices to form in shear layer, increasing mixing and shortening the duration of jet plume. As a result the chevrons effectively boost mixing while lowering overall jet noise. The chevrons increase the noise when there is too much mixing. The benefits of noise reduction are not experienced if it is insufficient. The nozzle reduces less frequency mixing noise from highly turbulent flows by allowing the core and bypass flows to mix[10]. With baseline nozzles, the azimuthal component makes up the majority of vorticity in shear layer. Such vorticity gather into distinct ring shaped structures. These structures undergoes distortion while spreading downstream causing intense turbulence to develop. Contrarily the streamwise vortex are segment of continuous flow and possess a time average phenomenon. The effluent boundary layer is the primary origin of vorticity within the nozzle. Simply said, the chevrons disperse come of it at expense of azimuthal component. This often leads to decrease in turbulent intensities with reduction in noise. Heavy mixing on the other hand will raise levels ,so optimum mixing is to be employed[15].

3.3Variable Geometry Chevron:

This concept provides chevron alignment with flow for the cruising period of jets, which is most important for fuel economy, and allows for fan chevron penetration at take-off, in which SPL reduction is must important. Shape memory flexures were included into the chevron in variable geometry chevron design. Shape memory alloys have unique phenomenon to change shape at a specific temperature. During take-off the chevron nozzle shape is different, then during cruise they can have aerodynamically effective shape[11][54]. Even though chevrons are said to have only attenuated a jet engine exhaust noise by roughly 2 to 3dB at low polar angles, its still an effective OASPL attenuation.[12]

4. EXPERIMENTAL STUDIES FOR JET NOISE REDUCTION BY CHEVRONS:

Naseem H. Saiyed et al conducted acoustics tests at NASA Glenn Research centre. Three different configuration of chevron was chosen and compared to baseline nozzle(3BB SFN).[13]

(B for Baseline; C for Chevrons; T for tabs; I for inward; A for alternate)

Table1 [13]

Chevron Placement	Number of Chevrons	Configuration
Chevron in Core Nozzle	12	$3C_{12}B$, $3I_{12}B$, $3A_{12}B$
Chevron in fan Nozzle	12	$3BC_{24}$
Chevron in Fan And Core Nozzle Simultaneously	24	$3T_{24}T_{48}$, $3T_{48}T_{48}$, $3T_{48}C_{24}$, $3I_{12}C_{24}$, $3A_{12}C_{24}$, $3T_{24}C_{24}$

Table 2 [13]

3BB	Baseline	Baseline	Baseline
$3A_{12}C_{24}$	3.52	-	0.49
$3C_{12}B$	1.38	1.3	0.55
$3I_{12}B$	2.29	2.1	0.32
$3T_{48}C_{24}$	2.58	-	0.51
$3BT_{48}$	1.22	1.0	0.57
$3T_{48}B$	2.29	2.0	0.77
$3T_{24}B$	2.73	2.3	0.99
$3T_{24}T_{48}$	2.56	2.0	1.14
$3T_{48}T_{48}$	2.77	-	1.10
$3A_{12}B$	2.59	-	0.34
$3BC_{24}$	-0.16	-0.1	0.55
$3T_{24}C_{24}$	3.16	-	0.43
$3I_{12}C_{24}$	2.82	2.7	0.06

a)Chevrons in core nozzle: The difference in EPNL is because 3I12B SFN penetration the boundary layer and 3C12 SFN remains inline with core streamline.
b)Chevrons in fan nozzle: 3BC24 SFN was 0.2EPNL dB louder than 3BB

c*)"Core Chevrons with Fan Chevrons simultaneously*"[13]***:* With 3I12C24 configuration reduction of 2.7EPNl dB is seen at Z=1.07 and remains uniform beyond high thrusts. Simultaneously adding of chevrons in core and fan resulted in additional reduction of 0.6EPNdB compared to 3I12B. 3I12C24 results in overall reduction of 2.7dB compared to 3BB SFN. At low frequencies, the resulted noise reduction are promising but at higher frequencies there is an excess noise which is undesirable .When used as fan nozzle instead of core nozzle both chevrons were found ineffective.[13]

James Bridges et al 2004, studied ten models of chevrons with varied chevron counts, penetrated length and chevron symmetricity to find relationship between chevron geometric flow characteristic and far field noise. The hot condition and cold condition have been tested at Mach number 0.9. The study implied that chevron's length was not influencing either flow or sound. In particular for low chevron counts, chevron penetration raises high frequency noise and decreases lower frequency. Number of chevrons is a significant factor with excellent lower frequencies reduction that is accomplished with more chevron count without severe higher frequency penalty while the asymmetry of the chevrons affected. The study also demonstrated that even though the hot jet distinguish structurally from cold jet, overall chevron parameter were same. The most important factor in noise creation in chevrons is velocity gradient[14], [15].

$$\Gamma = (\partial r/\partial s) \quad (7)$$

Γ - vortex strength parameter

Four major parameters on which comparisons were made:

C1 : Constant N; Varying length

C2 : Constant N; Varying length

C3 : Constant strength; Varying N

C4 : Constant N; Varying symmetry, strength

Table 3 [14]

Chevron Configuration	Model
C1	SMC000, SMC005, SMC001, SMC006
C2	SMC000, SMC006, SMC007
C3	SMC000, SMC002, SMC004, SMC001, SMC003
C4	SMC000, SMC003, SMC010

In SMC001 and SMC006, the frequency decrease at 150° is same as high frequency rise at 90°, which is 3-5dB above circular jet(SMC000). SMC005 was insignificantly distinguishable from round jet(SMC000). The noise of cold jet increases more at broadside angle and decreases more at rear angle than hot jets.

Callendar et al conducted experimental studies on impact of chevron-nozzle on near-field aeroacoustics for a isolated flowing exhaust system. Penetrating level of chevron was varied to understand the impacts of certain parameters in near-field aeroacoustics. Two chevron nozzles with eight chevron lobes were studied to understand the level of penetration. One nozzle penetration level was modest. Based on magnitude of boundary layer thickness, other nozzle has around two times compared to nominal level[16]. It was found that nozzle penetration was more significant than chevron lobe count for near field reduction in noise.[[7],[16]

Table 4 Nozzle Geometry Summary [16]

Nozzle	**No. of Chevrons**	**Penetration**
Baseline	0	Baseline
12LP	12	Nominal
8LP	8	Nominal
8HP	8	Increased

Ps tide et al, investigated the novel possibility of using sinusoidal chevron profile and also the effect of asymmetry in chevrons[7]

$$SPL= 10log_{10}(P_{rms}/P_{ref}^2) \quad (8)$$

$$OASPL = 10\ log_{10}\sum_{f1}^{fn}(P_{rms}^2\ /P_{ref}^2\ ) \quad (9)$$

The NPR used for the experiments ranged from 1.5 to 5.0. “Analysis was done on acoustic properties such as OASPL, spectrum, directiveness, acoustics power and broad band noise”[7]. The findings show that noise reduction is significantly influenced by both chevron asymmetry and chevron lobe profile. For both of the tested symmetric chevron nozzles(Chev6-0 and Chev6-sine), the OASPL is reduced by about 2.5dB. “Due to the impact of smooth chevron lobe shape, the sinusoidal chevron nozzle(Chev6-sine) exhibits improved noise reduction for all emission angles at higher levels of NPR”[7]. Due to the lower dispersion of vorticity inside the axial vortex, the shock cell length is also shortest for Chev-6 nozzle.

Table 5 Geometric details of Nozzles[7],[18]

Nozzle ID	Chevron Count	Penetration angle (degree)	Chevron Length (mm)	Penetration Depth (mm)	Exit diameter (mm)
Baseline	0	0	0	0	16.0
Chevron4-0	4	0	10.88	0	16.0
Chevron4-5	4	5	10.88	0.97	14.06
Chevron4-10	4	10	10.88	0.97	12.06
Chevron6-0	6	0	7.25	0	16.0
Chevron6-5	6	5	7.25	0.65	14.70
Chevron6-10	6	10	7.25	1.31	13.38
Chevron8-0	8	0	5.44	0	16.0
Chevron8-5	8	5	5.44	0.48	15.04
Chevron8-10	8	10	5.44	0.98	14.04
Baseline	0	-	-	-	16.0
Chevron6-0	6	-	7.25	0	16.0
Chev6-Sine	6	-	7.25	0	16.0
Che6-Asym	6	-	7.25&10.88	0	16.0

For Chev6-Asym asymmetric nozzle, a moderate drop in OASPL of 1dB is seen along the larger isosceles triangular side and significant reduce of 4.5dB is seen throughout smaller equilateral triangular side.[7], [17]

K. Srinivasan et al conducted experiments with number of chevrons and penetration as parameter at various nozzle pressure ratios. The findings show that for less and medium nozzle pressure ratio, the highest noise reduction is produced by a large chevron count with low level penetration.[18]

The 6 and 8 lobed chevron nozzle provide around 2dB and 4dB reductions in noise but the 4-lobed chevron nozzle only decreases noise by 1dB. The chevron nozzle with 8 lobes and 0° tapering offers greatest noise reduction of every evaluated geometries.

At low values of NPR, chevrons with 4 lobed and tapering angles of 5° and 10° generate greater noise in comparison to baseline nozzle. The chevron nozzle sometimes more noise than the baseline nozzle at higher penetration levels because the mixing becomes more aggressive as penetration angle increases. The chevron nozzle with deeper penetrated nevertheless exhibit improved noise reduction for all mission angle of larger levels of NPR. It can be concluded that at low pressure ratios, chevron count is the most important criterion for noise reduction whereas at high NPR ,chevron penetration is very important. As number of Chevrons and penetration increase the shock cell length was observed to decrease. It was also noted that regardless of NPR, the forward angles for entire chevron designs are noisier than the aft angles. It was found that for all chevron nozzles, acoustic efficiency is less than 1%. 8-lobed chevron nozzle with 0° taper have the lowest acoustic efficiency. Four lobed chevron nozzle has highest API among all tested configurations whereas eight lobed chevron nozzle has least API.[18]

R.H. Schlinler et al conducted experiments to examine OASPL, directivity patterns, far field spectra of baseline round CD nozzle with 3’’ diameter nozzle exit diameter and chevron nozzle with 6 chevron count of 3” diameter with 1° angle of penetration was tested. Under conditions with Mach number = 1.5, Stagnation temperature ratio ranging from T_r= 0.75 to 2 . At frequencies above Strouhal peak, slender penetration chevron were found to have lesser noise level of around 2dB in aft quadrants. At 90° and forward angles wideband noise level increased. The main advantage of chevron geometry was at under expanded operating conditions lowering intensity of screech tone.

Therefore a less penetration chevron design may helpful instances requiring the moderation of screech tone.[19]

Strouhal number, St

$$St = (f\times D_{eq}/V_{j,mean}) \quad (10)$$

O. Rask 2011 et al studied how chevrons modifies noise in jets with consequent flight effect. The study reveals that chevron in any case reduces the shock cell spacings, as seen by static pressure tests, which accounted for the rise in frequency for the aeroacoustic results. Near the nozzle exit, the chevrons raised turbulence levels ($X/D_{eq}=2$) but they had little or no impact on spatial changes in static pressure[20]. In case of Chevron, large peak amplitude of shock-associated noise was caused by high turbulence levels,

$$\sqrt{(TKE)}/(V_{exit}) = \sqrt{(u^2+v^2)}/V_{exit} \quad (11)$$

u – axially varying velocity

v is radially varying velocity

The inner shear layer weakened with increasing secondary flow, which in turn reduced mixing noise and downstream level. Regardless of the secondary flow Mach number, the chevrons always lowered the mixing noise.[20]

Far field observations at aft angles showed that mixing noise was reduced as secondary flow was increased. The inner shear layer had the highest values for secondary flows at the downstream ($X/D_{eq}=8$) according to flow field results. Separate flow chevron pylon based nozzles are to experimental analysis for purpose of reducing jet noise under take off conditions by Jing Yu. The testing results show that pylon reduces noise at low frequencies. The addition of a pylon diminishes the noise reduction uses of chevron nozzles as compared to chevron nozzle without pylon. The results implies that pylon-chevron combined has less influence on directiveness of Overall Sound Pressure Level .[21]

4.1Varying Nozzle Pressure Ratio:

Kaleeswaran in 2016, conducted experiments to suppress noise level of supersonic jet with chevron nozzle of by varying NPR. Three configuration of nozzle was chosen for experiment, nozzle with 10 chevrons, 14 chevrons and baseline nozzle.

Regression equation for noise measurement,

$$Noise(dB) = 126+0.600(A)-0.130(B) \quad (12)$$

Where A- NPR

B – No. of chevrons

This equation implies that noise level drop with lower NPR and with increase in no. of chevrons. It was found that regardless of number of chevrons used, noise levels tend to rise as pressure ratio rises. And also when number of chevron increases at nozzle exit the noise level tend to drop. Noise levels for 14 chevrons decreases from 126.2dB to 125.3dB when the NPR was reduced from 3.5 to 2.5. As a result of adding 14 chevrons , 2% reduction in noise level was observed when NPR 3.5 [22].

Taguchi and Anova techniques were used in this experiment to determine parameters.

Mathematical equation from S/N ratio

$$S/N = -10 \log(1/n \, \Sigma \, 1/Y_i^{\,2}) \text{ ----}(11)$$

Y - observed data

n – no. of observations

Table 6 Measured values and S/N ratio[22]

Nozzle Pressure Ratio	No of Chevrons	Measured Noise Level(dB)	S/N ratio
2.5	**0**	**127**	**-42.1034**
2.5	**10**	**126**	**-42.0074**
2.5	**14**	**125.3**	**-42.9590**
3	**0**	**127.6**	**-42.1170**
3	**10**	**126.2**	**-42.0212**
3	**14**	**125.9**	**-42.0005**
3.5	**0**	**127.8**	**-42.1306**
3.5	**10**	**126.5**	**-42.0418**
3.5	**14**	**126.2**	**-42.0212**

The configuration that has lowest noise level highest S/N ratio. It is found from this study that nozzle with 14 chevrons and NPR 2.5 has high S/N ratio and it is appreciable noise reduction characteristics. This gives an overall idea that in noise suppression ,number of chevrons was dominant factor followed by NPR within 3.5 to 2.5.

Leopoldo P. Bastos et al conducted experiments to study jet surface contact coupled with chevron nozzle causes far-field noise. The experiment uses SMC000(without chevron) and SMC006(with chevron) which was initially experimented by Bridges[2],[22] .It was found that noise levels for weakly integrated designs increased with surface length and decreased with radial location. The far-field observation was at radial extent of 2.33[22] .On other hand, the acoustic advantages of chevrons were insignificant for highly integrated jet configurations and raised noise levels at medium and at all structural valued.[23]

S.R. Nikam et al investigated acoustic parameters of chevron nozzle at M=0.8.Chevrons cause lobe sheared layer across the notched area , increases jet's surface area especially in short distance from nozzle which shortens the possible core length and improves mixing. As penetration increases closer to nozzle lip this impact becomes more pronounced in thinner mixing layer[24].Nikam suggests a more simpler method for finding peak of centreline velocity decay rate which is the primary noise source. On compared to simple baseline nozzle , total noise level measured alongside jet edges are greater at near distant downstream of chevrons but decrease at far distant downstream. The tendency is seen to be reversed at high frequencies, even if they continue to subdue the lower frequency noise. Additionally at high frequencies with increasing penetration for shallow polar angles as regards jet axis but at larger polar angles.[24]

Acoustic and hydrodynamic noise are two components that made up noise that is computed in near-field at the jet edges. When compared to acoustic component the hydrodynamic component is found to be reduced by chevrons.[24],[51]

For a given length and penetration individual chevron petal creates a set of two streamwise vortex, hence an rise in petal count increase the overall strength of streamwise vortices. On the other hand, too many chevrons petals would reduce the size of chevron which is influenced by boundary layer's viscous effect. Eight chevrons petals were chosen of those CH-3 is found to be more efficient than 12 petal nozzle. After the potential core has ended, the degree of centreline velocity decay increases quickly with axial distance, attaining its peak near the inflection point and then decreases more slowly . The region of extremum strain, which is abducted to be the source of extreme turbulence and the main source of noise it is where the centreline velocity decay rate peaks.[24] CH 1-3 found to be effective in increased centreline velocity and reduced core length. In contrast to chevron nozzles, the base nozzle exhibits significant noise level starting at X/D= 4 near the jet edges and moving towards the nozzle's penetration increases[24].

In near field, chevron nozzle is louder than baseline nozzle due to creation of lobe in jet through notches. Calender et al found such a change in peak noise zone near the nozzle's exit for chevron nozzles with dual steam flow. OASPL grows closer to nozzle outlet as penetration power of streamwise vortices increases with number of chevron petals. Chevron geometry has little effect or near field low frequency noise radiation pattern for dual stream flows.[16]

Table7 [25]

Name	Penetration (°)	Length (inch)	Count	Location
PC 2	16	0.625	8	Primary (Free stream)
PC 4	16	0.625	8	Primary (Buffer)
BC 5	10	1.000	6	Buffer
PC 7	16/ -16	0.625	8	Primary (Buffer)
PC 8	22	0.850	16	Primary (free stream)

Under different test settings the far field spectra for jets have shown that largest noise level occured in a restricted region of Strouhal frequency from roughly St=0.18 to 0.23 which is connected to major noise source along θ =30° [17],[55]. "Noise from jet flow in far field is dependent on nozzle diameter, jet velocity, distance from nozzle, polar angle, temperature of jet, atmospheric absorption coefficient etc"[24].

$$OSAPL= OASPL_{ref} -10\log(D_{ref}/D)^2 + 10\log(r_{ref}/r)^2 - 10\log(u_{ref}/u)^2 \quad (13)$$

n vary from 7 to 8 at θ =90° and 8.5 to 9.9 at θ =30°

It can be noted that polar locations between 90° and 70° have considerably greater noise levels coming from chevron nozzles. The fine scale structures that are developing in mixing are principally responsible for noise that radiates to these polar points. From 60° to 40° the difference in noise level becomes negligible as we approach downstream near the jet axis. It's alluring to observe OASPL suddenly drops by roughly 1.5dB from the chevron nozzles at θ =30°, which are closer to jet and where noise from large scale structures growing downstream of potential core makes up majority of noise.[24]

Table8 [25]

Configuration	OASPL Benefit@90°	Thrust Penalty
240	3.0	4.7%
245	3.0	5.4%
270	3.5	4.5%
080	2.6	5.0%

Table9[25]

Parameter	Low Level	High level	Centre
Penetration (Primary °)	10	22	16
Penetration (Buffer °)	10	22	16
Length(inch)	0.400	0.850	0.625
Nomenclature	P10B10L40	P22B22L85	P16B16L63

Brian et al conducted experimental testing and CFD modelling of shield chevron nozzles, in side flight conditions with several chevrons attachment configurations, a tri streamed inverted velocity profile nozzle simulation has been performed. A jet noise determining method was used to predict far-field noise for each resultant flow field. When compared to chevron that don't alternate ,chevron that alternate into primary stream and tertiary buffer stream exhibit a significant reduction in low frequency noise but has comparatively insignificant high frequency and thrust penalty. A three parameter matrix chevrons of alternating penetration with varied primary stream was created using MDOE approach. By MDOE result, 240 chevron reduced OASPL by 3dB with 4.7% thrust penalty. P10B22L40 chevron with 3.6%thrust penalty offers OASPL reduction of around 3dB. "The numerical findings computed an OASPL benefit to thrust loss ratio of 0.82, whereas the linear model anticipated an OASPL benefit to thrust loss ratio of 0.91,sharing that MDOE model is not applicable outside of parameter space".[25]

Saravanan et al investigated blending properties in subsonic and sonic jets are affected by a chevron with tab fixed at outlet of coflowing principal nozzle. In the experiment jet with Mach equals to 0.6 and 0.8 were used. For each of these jet Mach number decay was estimated using the coflow base line nozzle, chevron nozzle and tab-chevron nozzle. The potential core length of baseline coflow nozzle has been measured to be X/D=6.8. The possible core length is reduced for nozzles with tabbed chevrons nearly X/D ratio equals to 5.8 and X/D ratio equals to 0.8 respectively with 88.23% decay in core length at Mach number=0.6 .

In comparison to chevron nozzle with baseline nozzle it was discovered that the tab-chevron was successful in cutting the possible core length around 88.23%. The radial profile demonstrated that tab-chevron blending enhancement was efficient on compared to chevron-nozzle blending enhancement.[58]

Tabel 10[58]

M=0.8

Model	X/D=5 P(pa)	X/D= 5 SPL(dB)	X/D= 7 P(pa)	X/D= 7 SPL(dB)
Plain- Plain	54025	188.64	52924	1188.45
Chevron-Chevron	51840	188.27	44058	186.86
Chevron with tab Chevron	27102	182.64	22056	180.85

By splitting the jets into two, it is clearly seen how the mixing is improved by core reduction. This technique pushes tabbed chevron vortices away from jet axis, generating an off centred peak profile. The tab-chevron nozzle accelerates the spread of jet and promotes greater blending in transfer zone and sheared layer.[58].

Grigori cican et al experimental study on micro turbojet engine acoustics. In the testing two additional nozzles with chevrons were examined and assessed in addition to baseline nozzle. The first type of nozzle is anticipated to have 8 triangular chevrons with penetrating angle of I=0° and length of L=10% from equivalent diameter. The secondary type nozzle's core length and penetrating angle were kept same and the chevron counts was instead increased to 16. Four distinct speed regimes have been used to test the micro turbojet engine. "By measuring the fuel flow the temperature in front of the turbine, the intake air flow, the compression ratio, the propulsion force and temperature before the compressor the engine performance were kept track off".[26]

Additionally throughout the testing, vibrations in both the axial and radial directions were measured indicating that engine was operating normally while chevron nozzles were being tested. It was determined that employing chevron nozzle does not reduce noise at low regimes, however using them at low regimes results in a general noise reduction of 2-3Db [26]. When it comes to engine performance altering the nozzle by chevron by reducing chevron results in decrease in propulsion force particularly for nozzle with 16 chevrons. Engine traction force losses were from 4% to 6% for regime 3 and from 4% to 6% for other regime. Compared to N=8 the losses were somewhat larger for arrangement with N=16. At the highest regime there was a 6%-7% drop in fuel usage. [26]

5.SIMULATION AND NUMERICAL INVESTIGATION TO REDUCE JET NOISE BY CHEVRONS:

5.1 Computational fluid dynamics(CFD):

Using CFD there are at least three well known ways to simulate turbulent fluid flow and associated acoustic field. [27]–[29]The first is known as Direct Numerical Simulation(DNS) in which the resolution of computational grid is made fine enough to able to solve all motion scales, however the application of DNS is still not practical for high Reynolds number because the grid requirement could make the computational cost unworkable.[30], [31][32], [33]

Large Eddy Simulation is name of second type of simulation(LES). LES is computationally less taxing than DNS and offers a highly promising foundation for formulating methods for predicting jet noise. The ability to immediately acquire the SPL as portion of almost fully resolved energy spectrum is significant benefit of LES. This type of modelling, according to Birch et al [33] is still not applicable to chevron nozzle. The calculations of tiny turbulence vortices and the significant velocity gradient at initial boundary layer and near field are as present the greatest challenges.

Karabasov et al[34]proposed that changes in characteristics of nozzle boundary layer, such as momentum thickness and intensity of velocity fluctuations, significantly alter the whole mixing process and the radiated sound field. Due to these problems the Reynolds number of jet is limited since it significantly affects the necessary good resolution. This method's computational cost also still quite high. LES and Reynolds averaged Naviers-Stokes(RANS) models are used to create hybrid simulations. Such a method is utilised as an alternative to standard LES simulations to enable the simulation of jets with greater Reynolds number at a substantially lower computing cost. Hybrid simulations often use LES in remaining portions of the solution domain and RANS calculations close to wall region with a mesh size of up to 12.5 million elements[35]. The third option is RANS simulation. Tide and Babu[53]used the Ffowcs-Williams and Hawkings approach to assess the acoustic noise and RANS simulations with Shear Stress Transfer(SST) turbulence model.[53],[33],[36].

Engel et al proposed to predict acoustic noise of chevron nozzle with RANS-based method, with two nozzle configuration SMC001 and SMC006 initially investigated by Bridges and Brown[14] and numerical data of that configurations proposed by[[37],[38],[39]]. The team also studied the potential of LRT method to predict the far field noise by taking the data from RANS technique as input. In this study , a hybrid technique was utilised in which RANS turbulence model was used to assess sound waves to observer at a distance[35]. The Lighthill Ray Tracing(LRT) approach which Silva et al[40] devised is the noise prediction technique that was employed in this study. By combining the Ray-Tracing theory with source model based on Lighthills acoustic analogy [8], this technique takes into account sound refraction. To get mean flow data required for noise prediction,, the approach uses RANS simulation. The LRT approach uses RANS simulation. The LRT has benefit of being computationally inexpensive and suitable for the conceptual design of new nozzle configuration. Considering the finding in this study it is reasonable to say that RANS based techniques represent a potent numerical approach for simulating high speed jets[35]

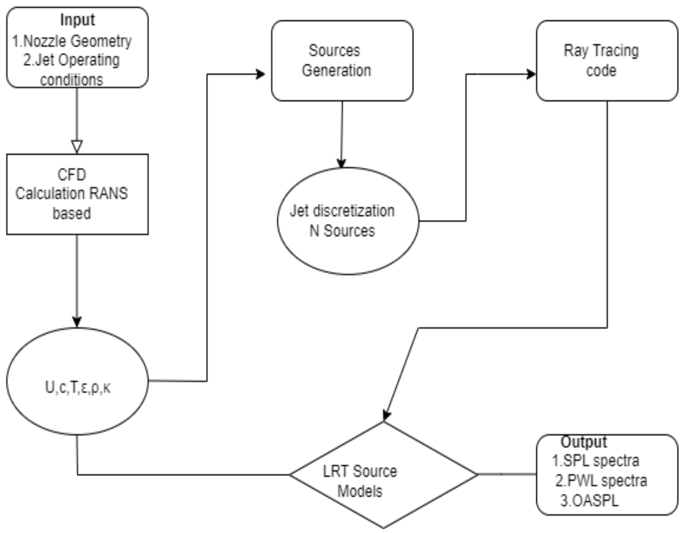

Fig2 [35]

Burak et al using numerical models and experimentation convergent divergent chevron nozzle's flow field and far-field acoustic studies had been conducted. This was carried out for three forward flight Mach values M= 0.1, 0.3 and 0.8. A secondary nozzle was employed in the experiment to create a confluent flow state in a still environment. The flying condition was a real ambient condition in numerical forecast. The near nozzle area flow field models and experimental results match up quite well. After 3Dj the numerical predictions begin to diverge from experiment downstream of nozzle exit. This appears to be result of divergent breakdown of vortical structure between the LES and experiment. It is anticipated that the spacing of shock cell constructions would vary since there is gap between the numerical predictions and observations[27]. But even when distance between shock cells is increased, the LES is able to accurately forecast the majority of current flow properties. On comparing chevron and round nozzle, same noise source are present in both cases. The notable difference in chevron is the screech tone is significantly decreased and broadband shock related noise peaks are moved to slightly higher frequencies with noise reduction of about 3-4dB.Click or tap here to enter text.[28], [38]

Depuru Mohan et al investigated the numerical analysis of jet-noise produced by chevron and circular jet. The 4th order space time velocity cross correlation computed using a large eddy simulation flow field, are used to describe the acoustic sources. The axial, radial and azimuthal cross correlations are shown to be reasonably well fitted by Gaussian functions. The ratio of axial to radial and azimuthal length scales is three to four. "Up to six jet diameter downstream for chevron jet, the cross correlation scales change with azimuthal angle after that they become axisymmetric like these for round jet"[34]. "The axial velocity's fourth order space time cross correlation R1111 is primary source component and R2222, R3333, R1212, R1313 and R2323 cross correlations where 1,2 and 3 stand for axial, radial and azimuthal directions, make significant contributions as well"[34]. When compared to jet which has cross correlations that are generally constant for first 10 jet diameters, the chevron jet exhibits rapid axial distance decline. Within two jet diameter of jet exit the chevron jet amplifies for both R2222 and R3333 cross correlations. A large eddy simulation velocity fields cross correlations. The data and forecasts for far field noise are in very good agreement [41].The chevron nozzle greatly lowers the far field noise at low frequencies by 5-6dB at 30° and 2-3dB at 90° to jet axis. The chevron nozzles does however marginally amplify high frequency noise. It was discovered that at 30° from jet axis, the R1212 and R1313 cross correlations have the biggest contribution to jet noise and at 90° from the jet axis while the R2323 cross correlation has largest contribution. Repeating the Reynolds averaged Navier Stokes computations with several turbulence models reveals that noise forecast is essentially unaffected by turbulence model. [42]

5.1.1Aerodynamics:

Turbulence Intensity

$$I = u'_{rms} / \bar{u} \qquad (14)$$

Where $\bar{u}$- mean axial velocity

u'_{rms} - root mean square of fluctuations axial velocity

The breakdown of jet potential core may be to cause peak turbulence intensity. The peak turbulence intensity of chevron jet is located three to four jet diameters earlier that of the round jet due to its shorter potential core. This shows that the turbulence strength in jet near field is increased by chevrons.[42]

Streamwise vorticity :(ω)

$$\omega_x = (\partial \upsilon / \partial z - \partial \varpi / \partial y) \qquad (15)$$

Where υ - mean radial velocity, ϖ - mean azimuthal velocity

Spreading rate(S):

$$S = dr_{½} / dx \qquad (16)$$

Where $r_{½}$ - radial distance at which mean velocity falls to half of centreline velocity

The spreading rate increases downstream of tip until it is affected by flow through neighbouring chevron tips. Following that the spreading rate reduces till four jet diameters downstream of chevron tip before gradually changing to linear characteristic. Both the round and chevron jets spread linearly with axial distance with spreading rate of 0.11 beyond six jet diameter from nozzle outlet.[42]

5.2 Noise sources:

5.2.1.Cross Correlations:

These correlations have same length and time scales and are shaped like Gaussian Functions. Strong convection in axial direction is the cause of change in peak of cross correlation for axial separation with increasing radial distance the cross correlations rapidly decays. There is a noticeable variance in cross correlations with azimuthal angle because of presence of chevrons creates angular fluctuations in jet flow. Since there is no significant convection in radial and azimuthal direction cross correlation of these separation don't peak shift.

5.2.2.Length Scale: [42]

Length Scales are lowest at chevron roots and highest at chevron tips.

$l_{lip} / l_{slant} / l_{root}$

This relationship holds up to six jet diameters from nozzle exit.

Chevrons significantly diminish the dominating acoustic source (R1111 cross correlations) compared to round jet, by 50-60%. Depuru Mohan using RANS and LES identified the major noise source correlations. RANS based modelling approach very well predicts OASPL at high angles to jet axis and reasonably good at low angles to the jet axis. It was found that influence of anisotropy of length scales or far field noise predictions is roughly 3dB. Small variations in proportionality constants have no effect on forecasts of far field noise.[42]

Uzun 2009 et al conducted numerical simulation studies, the local radial length scale and its eddy turnover frequency are nearly equivalent to local direction length scale and its eddy turnover frequency, at middle of chevron jet mixing layer. This is thought to be a result of greater shear layer mixing brought on axial vorticity generated by chevron.[30]

Xia et al 2011, conducted numerical simulations for chevron at an isothermal high subsonic flow condition compared with standard method(Ffowcs Williams Hawking(FWH)) based on LES data and new method RANS simulation method. The high frequency cut-off limit of precise sound prediction is proven to be extended by the novel acoustic approach when compared to traditional FWH integral based on LES data. Utilizing experimental data up to frequencies as high as St 8 and St 6 at 90deg and 30deg respectively. However the low frequency discrepancies are observed to be relatively larger than LES+FWH approach .[31]

Max Strouhal number which grid supports is calculated by,

$$St_{g,max} = (2 / N_{\lambda} (\Delta s / R_J)) * ((1/M_J)(\sqrt{T_\infty} / T_J)) \qquad (17)$$

Where, N_{λ} –minimum number of grid spacing

M_J – Jet exit Mach number

T_∞ / T_J ratio of ambient temperature to jet exit temperature

$\Delta S/R_J$ relevant grid spacing non-dimensionalised by nozzle exit radius

Nitin et al conducted a study on how to use the immersed boundary method(IBM) which the authors[44,45] have implemented in a high order finite difference discretization based LES algorithm, to analyse the flow field and noise signature of real world complicated nozzle designs. With fair amount of processing power and use of wall modelling simulations at an experimental scale high Reynolds number may be performed without sacrificing the downstream domain's size or length of acoustic record. The findings of this study show that at least for initial turbulent jet shear layers, the change in far field noise levels brought about by nozzle geometry alterations is comparatively insensitive to the turbulence in shear layer. This is a noteworthy finding since it implies that turbulent inflow to nozzles need not perfectly match an experimental configuration in order to anticipate the geometry alteration on far field noise. This is due to the use of LES/CAA approach to analyse new nozzle design.[43]–[45]

J. Devipriya et al conducted computational studies on chevron nozzle with 1mm wedge thickness and chevron with 2mm wedge thickness.[46]In all subsonic Mach number, it was found that the chevron with 2mm wedge was more effective at reducing possible core length and deforming the jet structure with about 67% of uncontrolled jet[46]

Table 11[46]

Specification	Dimension
Length	30mm
Inlet diameter	30mm
Exit diameter	16mm
Chevron length	5.44mm
Wedge	3.08mm

Kanmaniraja et al proposed chevrons with sharp, flat, round and U-type edges. The authors felt challenging to select different types of chevrons for parametric experiments since there was no fixed correlation between chevron shape and jet noise. Result show that the chevrons with round edge is optimum design for noise reduction on order of 6dB [47]. A simulation of near nozzle area of a moderate Reynolds number cold jet flow exhaust from a chevron nozzle was described by Uzun et.al[27]. Symmetric chevrons with 5° penetration angle was used to simulate flow exhaust from a chevron nozzle was used to simulate flow through them. A high order accurate multi block, large eddy simulation algorithm with about 100 million grid points computed both the flow inside the chevron nozzle and free jet flow outside at same time[48]. The simulation accurately shown the noise production that results from the higher shear layer mixing caused by chevrons, for first few diameters downstream of nozzle exit. The peak region of spectrum was accurately plotted but prediction in high frequency region was poor[37]

In order to further investigate complex chevron nozzle flows, Shur et al analysed noise reduction methods like chevron nozzle, bevelled nozzle and dual nozzles. The simulations were run with a goal accuracy of 2-3db for both directing and spectrum with grid size of 2-4 million nodes.Sadanandan et al conducted simulations and analysis at stagnation temperature 286.44K and pressure=178200Pa.A sinusoidal M-lobed chevron nozzle produces 1.6 decibel less noise than a baseline nozzle and 0.93dB less noise than a chevron symmetric nozzle. This study shows that it had no impact on performance of nozzle.

Rajashree et al added corrugated plates next to convergent nozzle's exit which also contains chevrons at its trailing edge. The angle of corrugated plates is adjusted after evaluating nozzle settings in order to reduce noise emission with minimal thrust loss. According to this study, using a nozzle with corrugated plate at 115° reduces noise. When compared to other four types of nozzle the corrugated plate nozzle at 115° increases the mixing rate of fluid flow from output of nozzle with ambient air[49].Pranav M et al conducted studies on five nozzle configuration and found M-shaped lobe with sinusoidal curve is most efficient in noise reduction[50]M shaped sinusoidal lobe produce nearly 20db less than baseline nozzle.[50]

Table 12[50]

Configuration	Acoustic Power Level	Sound Pressure Level
Baseline	89	99.99
Chevron with V-shaped	74.2	85.19
Chevron nozzle with Sinusoidal serration	69	79.99
M-lobed chevron	74.11	85.10
M-lobed chevron with sinusoidal serration	67.5	78.49

Parth Parmar et al, studies concluded as number of chevrons increase acoustic power level decrease. The nozzle type Triangular chevron nozzle with number of chevrons=10 has least acoustic power [51]–[57]

Table 13 [51]

Nozzle type	No.of Chevrons	Acoustic Power	Mach number	Nozzle Pressure Ratio(NPR)
Baseline nozzle	0	119	1.21	15.06
Triangular Chevron Nozzle	6	123	1.86	11.68
Triangular Chevron nozzle	8	116	1.97	11.69
Triangular Chevron Nozzle	10	115	2.03	11.38
Pallet Chevron Nozzle	8	116	2.19	12.94
Inverse Pallet Chevron Nozzle	8	132	2.62	13.15

Irfan nazir et al[9] conducted acoustic analysis on N8 chevron nozzle with varying the tip angle in range of 20° to 110°. It is clear from acoustic analysis of chevron nozzle that as tip angle increases, acoustic power level decreases. Although N8-108 model exhibits strongest noise suppression and has only 100.45dB acoustic power, it should be noted that this sound is detected at a larger surface area than that of other models, leading to more pressure taking into account all relevant variables It is determined that efficient model in the N8 configuration either be N8β88.8 or N8β101.6

Table 14 [9]

Configuration	Acoustic Power level(dB)	β In (deg)
Baseline	109.4	0
N8β60	109	60
N8β76.3	76.3	108.6
N8β88.8	88.8	104
N8β101.6	101	101.6
N8β108	100.4	108

Boundary conditions:Temperature=300K,Inlet Pressure=170023.34Pa,Outlet Pressure=28441.92Pa

6. CONCLUSION:

Various Noise reduction methodologies of Jet engine are under research. Chevron nozzle was one among such methodologies which found to be impressive with its noise reduction capabilities. Even though it is promising still it affects the overall thrust performance of engine. So recent research are focussed towards reducing noise without affecting the engine performance. Researcher's findings suggest that performance of chevron nozzles is not determined by penetration, length or number of chevrons. However the chevron nozzle's aero acoustics performance is determined by net strength of the streamwise vortices it generates. Therefore it appears that a thorough knowledge of the altered flow field and nearby acoustic field that are responsible for noise reduction caused by chevrons under subsonic conditions is still lacking, and further systematic investigations are needed to understand the underlying processes.

The bulging of shear layer closer to nozzle exit is exacerbated by early penetration into weaker mixing layer. Stronger streamwise vortices that produce quick mixing and higher centreline velocity decay are indications of enhanced shear layer bulging. The location of dominant noise source determined acoustic measurement of location of maximum decay rate of centreline velocity by time decay technique. Depending on their design chevrons are found to efficiently move the noise source towards the nozzle exit. Therefore dominating noise directed towards lower polar angles in the distant field can be minimised at price of increasing level towards higher polar angles by moving noise source closer the nozzle exit. Chevron may reduce the hydrodynamic component of near field pressure at region of dominating noise, according to a decomposition of hydrodynamic and acoustic pressure in near field using decay law. Notched nozzle along with chevrons are also found to excellent in noise reduction. In earlier design and research it is found that chevron nozzle found to reduce noise to a max of 3-5dB.Along with chevron and notched nozzle studies reveal that bypass engine water or nitrogen injection techniques also substantially reduce jet noise up to 6dB.

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Nozzle	Noise Sources Location by various Methods(X/D)		Measured OASPL in plane above noise source		Estimated acoustic pressure on line a-b(dB)	Estimated hydrodynamic pressure on a-b(dB)	Ratio of hydrodynamic pressure to near field pressure on a-b
	Centre line velocity decay rate=$(du/dx)_{max}$	Time delay technique(Hileman and Samimmy,2001)	On a-b	On c-d			
Base	8	9.7	126.88	114.32	122	119.5	0.43
CH-1	8	9.7	126.18	113.6	121.56	118.5	0.41
CH-2	6	7.9	124.8	113.27	121.24	115.36	0.33
CH-3	6	7.9	125.95	113.78	122	117.13	0.36
CH-1-3	5	6	125.97	114.18	123.12	114.89	0.28

Table 15 [25]

Configuration	Corresponding Author	Test Condition	Remarks
Chevron	Bridges et al	D=51mm,M=0.9,N=4,5,6,10 p= -0.005 to 3.681mm L=14 to 32mm	Each chevron petal generates a counter rotate the vortex pair in the direction of the current at low speed of mixing layer. Reduce OASPL at 30° and increase at 90° is almost equal amplitude from 2 to 5dB.
	Rajashree et al	M_{in} =0.5, M_{out} =0.3, M_{exit} =2.6,T_{in} =286 °C,T_{out} =166° C	
	Birch et al	Dual Flow, BPR=5, D_{core} =16mm.M=0.97	
	Munday et al	D=72.85mm,M=1.22 to 1.71,N=12,L=15.24mm	
	Callendar et al	Plug Nozzle D=54.53mm,M=0.98,N=8,12	
	Tide et al	D=16mm, M=0.5 to 1.7,N=4,6,8,L=5.44 to 10.88mm	
	Schlinker et al	D=76.2mm, M=1.5,N=6	
	Alkishar et al	D=69.85mm, M=0.9,N=9,L=9.42mm,p=2.14mm	
Chevron Tab combine	Sayed et al	D_{core} =92.87mm, M=0.8, D_{fan} =154.1mm,N_T=12,24 N=12,24	Chevron offers both on core nozzle with cap and coaxial jet nozzle noise reduction up to 5dB with 4.9%thrust loss
Chevron in presence of pylon	He and Xu	Dual flow(Plug), BPR=5.5,D_{core} =25.28mm,M=0.78,D_{fan} =43.78mm	The pylon creates an asymmetry of the jet. It affects the benefit of chevron in noise reduction at lower frequencies
	Thomas and Kinzie	Dual Flow(Plug), BPR=5,8 D_{core} =128mm	
Chevron -Microjet combine	Alkistar	D=69.85mm,M=0.9,N=18,d=0.6mm	Combined use resulted in around 1.5dBto 2dB reduction in OASPL

Table 16 [25]