Acoustic Power Prediction of High BPR Turbofan Engine with Chevron Nozzle during Take-off and Landing

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Abstract

Aircraft noise is a major cause of noise pollution around the vicinity of an airport. Jet noise from engines is a common condition, which has considerable impact on overall sound levels. Adding chevron pattern at the fan nozzle is one of the noise reduction enhancements found in current turbofan engine design features. This paper aims to study the power level of sound created in jet shear from the combination of ambient stream, fan and exhaust gas. Computational fluid dynamic modelling of a high bypass turbofan engine with a round shape and chevron nozzle were carried out during take-off and landing conditions. It was found that during take-off, the acoustic power level of the engine without a chevron nozzle was 105.95 dB, while the chevron nozzle was capable of reducing the sound level to 43.57 dB. During landing, the sound level of the round shape and chevron nozzle model were 145.77 dB and 47.51 dB, respectively. The turbulent intensity area at the fan cowling nozzle, where the ambient air stream and bypassed air from the fan mixed together, produced the highest sound power level. Therefore, slower aircraft speed during final approach produced a higher noise level than during take-off due to higher turbulent intensity and larger jet shear area around the high bypass fan cowling nozzle. The chevron pattern nozzle was capable of reducing turbulent intensity, which in turn reduced the acoustic power level.

Keywords: Acoustic power level, Turbofan, CFD, Aircraft noise, High bypass ratio

1. Introduction

Aircraft noise during take-off and landing is the leading cause of noise pollution at many airports around the world, especially in urban areas [1]. Noise from aircraft operations is a complex problem when compared to other noise sources as well as aircraft noise prediction method, which accounts for airframe, high lift systems, propeller and propulsive [2]. Recent evidence suggests that the aircraft noise is associated with gas turbine engines, particularly from high bypass ratio (BPR) turbofan engines [3]. The present high BPR of turbofan engines is between ranges of 10-12 BPR [4].

Since high bypass turbofan engines are designed for optimum fuel efficiency, many airlines utilized aircraft equipped with high BPR turbofan engines. High BPR turbofan engines have been subjected to
continuous improvement predominantly to produce higher thrust with lower noise. Rolls-Royce is the only engine manufacturer to use a three-spool engine design allowing the power from the intermediate spool to deliver a lower thrust at idle during the flight until landing, which helps reduce fuel consumption [5].

It has previously been observed that noise from turbofan engines can be reduced by using jet noise reduction techniques, which involve the installation of acoustic liners such as zero-splice intake liner, bypass duct liner and core duct liner [6]. Studies of aeroacoustics research show that the addition of the chevron pattern at the nozzle can reduce sound pressure levels [7, 8].

The numerical prediction had been made to obtain turbulence quantities as well as acoustic quantities reasonably well for both round and chevron nozzles [9]. The mixing of air stream with air from the fan exit at different temperatures and velocity results in turbulence, which in turn increases noise. It has been found from the CFD analysis for acoustic performance evaluation of different shapes of chevron that managing the mixing area couple with a proper chevron pattern could reduce the sound pressure level [10].

Factors found to be influencing in patterning and geometry of chevron that can reduce noise and turbulence to a considerable degree have been explored in several studies [11]. Experimental testing of the chevron nozzle in subsonic flow was performed and found that each chevron reduced the shear velocity behind it, which results in noise reduction [12]. An investigation of different lengths and widths of chevron was extensively carried out at the supersonic flow. It was found that the shorter the length of the chevron, the less impact there was on noise reduction when compared with the longer one. Nevertheless, it is noteworthy that the noise reduction is significantly better than without a chevron pattern [13].

A high BPR dual-stream jet in a scaled model was also tested. It is now well established from a variety of studies, that a chevron nozzle could reduce the overall noise. The number of chevron teeth might also affect noise reduction capability [14]. The observation of flow characteristics to produce jet noise was done using a simulation of turbulent jet noise, resulting in the thickness nozzle boundary layer would affect noise. The chevron nozzle placed under a specific condition requires a particular arrangement and boundary layer thickness to reduce noise [15].

The aim of this paper is to predict acoustic power level by using CFD simulation of high bypass turbofan engine with round and chevron nozzle models with boundary conditions from numerical calculations and actual power setting parameters during take-off and landing.

2. Acoustic Power

2.1 Sound power level (SPL)
The sensitivity of a human’s ear is expressed in logarithmic, which is measured using a decibel scale, as known as sound pressure level (SPL) [16]. This is given in terms of the root mean square of the fluctuating pressure-time history \( P_{rms} \) and reference pressure, \( P_{ref} \), is defined by:

\[
\text{SPL} = 20 \log_{10} \left( \frac{P_{rms}}{P_{ref}} \right)
\]  

(2.1)

Where:  
\( \text{SPL} \) = sound pressure level (dB), \( P_{rms} \) = root mean square of pressure fluctuation (Pa), \( P_{ref} \) = reference sound power (Pa)

2.2 Sound intensity level (IL)
Sound intensity level (IL) is a logarithmic measure of the power of a sound relative to a reference value [17, 18]. Sound intensity level, \( I_L \), also measured in dB, is defined by:

\[
I_L = 10 \log_{10} \left( \frac{I}{I_{ref}} \right)
\]  

(2.2)
Where:
\[ I_L = \text{sound intensity level (dB)}, \]
\[ I = \text{sound intensity (w/m}^2\), \]
\[ I_{ref} = \text{reference sound intensity (w/m}^2\) \]

2.3 Effective perceived noise level (EPNL)
The most commonly used metric to obtain a measurement of the perceived loudness of a sound is the dB(A) level. The dB(A) level is subjected to the sensitivity of the human’s ear and can be directly measured using a sound level meter. Other measures of annoyance include a perceived noise level (PNL) and an effective perceived noise level (EPNL). They are used in assessing aircraft noise [16]. Noise evaluation measure for the aircraft is the effective perceived noise level in EPNdB [19]. There are three measurement points: lateral full-power, fly over and approach reference noise measurement points. For an aircraft with two turbofan engines, it will use the following formulae to calculate maximum permissible noise levels and corresponding speed of the aircraft while being assessed. The equations are as follows:

For full-power noise reference,
\[ EPNdB = 80.87 + 8.51 \log M \] (2.3)

For approach noise reference,
\[ EPNdB = 86.03 + 7.75 \log M \] (2.4)

For take-off speed,
\[ V_{T/O} = V_2 + 10 \, kt \] (2.5)

For approach speed,
\[ V_{L/D} = V_{ref} + 10 \, kt \] (2.6)

Where:
\[ EPNdB = \text{effective perceived noise level (dB)} \]
\[ M = \text{maximum take-off mass (Ton)} \]
\[ V_{T/O} = \text{take-off speed (kt)} \]
\[ V_2 = \text{take-off safety speed (kt)} \]
\[ V_{L/D} = \text{landing speed (kt)} \]
\[ V_{ref} = \text{landing reference speed (kt)} \]

3. 3D Simulation

3.1 CFD modelling
A full-scaled turbofan engine model was constructed in SolidWorks simulation software. Geometries of the engine were taken from Trent 1000 high bypass turbofan aircraft engine specifications [20]. The fan air inlet diameter and length of the engine were 2.850 and 4.738 m, respectively. Figure 1(a) shows a side view of the turbofan engine with a round nozzle and (b) is an isometric view of the round nozzle model.

![Figure 1. Round nozzle model (a) side view (b) isometric view.](image-url)
The number of chevrons and patterns were adopted from Boeing 787 Dreamliner aircraft as shown in Figure 2(a), side view of a turbofan engine with added chevron patterns at the bypass nozzle. Figure 2(b) shows an isometric view of the chevron nozzle model.

As can be seen in Table 1, the simulation was performed using external flow analysis with three streams at mean sea level conditions. Both models were simulated with take-off and landing conditions and complied with aircraft noise measurement procedures [19], which were calculated by using equations (2.5)-(2.6). Ambient airstream velocity for take-off and landing were determined to be 170 and 146 kt, respectively.

![Figure 2](image-url)

**Figure 2.** Chevron nozzle model (a) side view and (b) isometric view.

**Table 1.** Boundary conditions for 3D simulation.

| Boundary                  | Value     | Unit          |
|---------------------------|-----------|---------------|
| Air density ($\rho$)      | 1.225     | kg/m$^3$      |
| Air pressure ($p$)        | 1.01325x10$^5$ | N/m$^2$    |
| Air viscosity ($\mu$)     | 1.7894x10$^{-5}$ | kg/m·s |
| Air temperature ($T$)     | 288.16    | K             |

**3.2 Numerical calculation**

Air velocity, temperature and pressure produced at the fan section were calculated from the following equations (3.1)-(3.4), which were based on a 3-spool turbofan engine with a bypass ratio of 10 [21]. The equations are as follows:

$$P_{02} = P_a (1 + \eta_d \frac{\gamma_c - 1}{2} M_a^2)^\frac{\gamma_c}{\gamma_c - 1}$$  \hspace{1cm} (3.1)

$$T_{02} = T_a (1 + \frac{\gamma_c - 1}{2} M_a^2)$$  \hspace{1cm} (3.2)

$$P_{03} = P_{02} \pi_f$$  \hspace{1cm} (3.3)

$$T_{03} = T_{02} (1 + \frac{\pi_f \gamma_c - 1/\gamma_c - 1}{\eta_f})$$  \hspace{1cm} (3.4)

Where:
- $P_{02}$ = fan inlet pressure (N/m$^2$),
- $P_a$ = local air pressure (N/m$^2$),
- $\eta_d$ = diffuser efficiency (-),
- $\gamma_c$ = specific gas ratio (-),
- $M_a$ = Mach number (-),
- $T_{02}$ = fan inlet temperature (K),
- $T_a$ = local air temperature (K),
- $P_{03}$ = fan outlet pressure (N/m$^2$),
- $\pi_f$ = fan pressure ratio (-),
- $T_{03}$ = fan outlet temperature (K),
- $\eta_f$ = fan efficiency (-)
The exhaust gas velocity, pressure and temperature were validated with an engine operation data sheet [20] during full-power and idle operations before performing the simulation. It can be seen from the data in Table 2 that the boundary conditions to be used in the simulation during take-off and landing. Figure 3 represents the computational domain of the chevron nozzle model.

**Table 2. Boundary conditions during take-off and landing.**

| Configuration | Boundary | Ambient stream | Fan | Exhaust gas |
|---------------|----------|----------------|-----|-------------|
| Take off      | Velocity (m/s) | 87.45          | 284.53 | 632.55 |
|               | Temperature (K) | 288.16         | 297.85 | 1048.24 |
|               | Pressure (N/m²) | 1.01325×10⁵  | 1.01325×10⁵  | 1.97932×10⁵ |
| Landing       | Velocity (m/s) | 75.0           | 280.87 | 255.8 |
|               | Temperature (K) | 288.16         | 297.66 | 473.98 |
|               | Pressure (N/m²) | 1.01325×10⁵  | 1.01325×10⁵  | 1.01325×10⁵ |

*Use $P_{MSL}$ since $P_{Critical} < P_{MSL}$. 

**Figure 3.** Chevron nozzle model computational domain.

4. **Result and discussion**

The table below illustrates peak velocity, acoustic power level and turbulent intensity, which were taken from the observation area around the fan nozzle where the highest noise was produced. From this data (see Table 3), it can be seen that the peak velocity at the nozzle of the round model was less than the chevron model for both take-off and landing. The chevron pattern increased velocity by 5.4% during take-off, and 21.5% during landing. However, the acoustic power level was reduced by 58.9% during take-off and 67.4% during landing. A possible explanation for this might be that chevrons were more effective in noise reduction at low power operation.

**Table 3. Results of peak value at fan nozzle area.**

|                  | During take off |         | During landing |         |
|------------------|-----------------|---------|----------------|---------|
|                  | Round model     | Chevron model | Round model  | Chevron model |
| Velocity (m/s)   | 476.21          | 501.98   | 408.35         | 496.04  |
| Acoustic power level (dB) | 105.95    | 43.57    | 145.77         | 47.51   |
| Turbulent intensity (%) | 1.88       | 0.37     | 7.91           | 0.44    |

This study confirms that the landing phase with a low power setting produced a higher noise than take-off with full-power. The difference in velocity between take-off and landing was 14.2%. The round nozzle model increased noise levels from 105.95 dB to 145.77 dB, which was an increase of 37.6% while the chevron nozzle increased noise level by 9% from 43.57 dB to 47.51 dB. A possible explanation for these results may be the turbulent intensity increased from 1.88% to 7.91%, which was
considered to be in the medium to high-turbulent flow. The chevron nozzle reduced turbulent intensity from 1.88% to 0.37% during take-off and from 7.91% to 0.44% during landing. It has been suggested that turbulent flow from the chevron nozzle was considered to be low-level turbulence.

Figure 4. Velocity plot during take-off (m/s) (a) Round nozzle (b) Chevron nozzle.

Figure 5. Acoustic power level plot during take-off (dB) (a) Round nozzle (b) Chevron nozzle.

Figure 6. Turbulent intensity plot during take-off (%) (a) Round nozzle (b) Chevron nozzle.
From the data in Figures 4-9, it shows the velocity, acoustic power level and turbulent intensity plot for round and chevron nozzle models during take-off and landing.

As can be seen from the Figures (above), it is apparent that the chevron nozzle was capable of reducing noise by up to 98.26 dB during landing and 62.38 dB during take-off. A slower flight during landing produced a higher turbulent intensity, which caused higher noise regardless of the engine power setting. Maximum noises allowable in EPNdB from equations (2.3)-(2.4) were calculated for a 228-ton maximum take-off mass aircraft, which were 101 dB for take-off and 104.3 dB for landing. On the other hand, the round nozzle model produced a larger jet shear area and higher turbulent intensity, which exceeded the allowable noise level.
5. Conclusion

This study has identified that turbofan models with round and chevron nozzles were simulated using take-off and landing conditions, which complied with the International Civil Aviation Organization (ICAO) measurements of aircraft noise [19]. The results of this investigation show that the prediction of acoustic power level for both take-off and landing were demonstrated successfully using actual engine operation parameters. The results of this study indicate that this simulation predicts the acoustic power level closest to the real flight operation. It was found that the chevron is capable of reducing noise level down to permissible levels for operations. The present study adds to the growing body of research that indicates turbulent intensity was the most crucial aspect of noise generation in a high bypass ratio turbofan engine.

References

[1] Durmaz V 2011 EMAJ. 1(2) 13-20
[2] Torija A J and Self R H 2017 JATM. 67 157-68
[3] Filippone A 2014 Prog. in Aero. Sci. 68 27-63
[4] Epstein A H 2014 AIAA J. 52(5) 901-911
[5] Howie D 2015 The magazine Rolls-Royces. 146 12-15
[6] Kempton A 2011 Acoustic Liner for Modern Aero-Engines Rolls-Royce (UK: University of Southampton)
[7] Kanmaniraja R Freshipali R Abdullah J Niranjan K Balasubramani K and Kumar V 2014 Int. J. Aero Mech. Eng. 8(9) 1530-1536
[8] Bridges J and Brown C A 2004 AIAA. Paper. 2004-2824
[9] Tide P S and Babu V 2009 Numerical predictions of noise due to subsonic jets from nozzles Appl. Acoust. 70 321-332
[10] Sadanandan R Dheeraj R Aswin B Akshay K and Radhakrishnan A 2018 Int. Res. J. of Eng. & Tech. 5(5) 3201-3204
[11] Tide P S and Srinivasan 2008 Int. Mech. Eng. 223 51-67
[12] Rask O Harrison S Munday D Harris C Mihaescu M and Gutmark E 2007 AIAA. paper. 2007-5631
[13] Henderson B and Wernet M 2015 JSV. 351 119-142
[14] Lee I Zhang Y and Lin D 2019 Appl. Acoust. 150 246-267
[15] Fontaine R A 2014 PhD Thesis University of Illinois at Urbana-Champaign USA
[16] Glegg S and Devenport W 2017 Aeroacoustics of low Mach Number Flows (London: Elsevier) chapter 1 pp 3-8
[17] Garrett S 2017 Understanding Acoustics (Switzerland: Springer) chapter 10 pp 546-52
[18] Anselmet F and Mattei P 2016 Acoustics, Aeroacoustics and Vibrations (New Jersey: Wiley) chapter 5 pp 149-55
[19] ICAO 2011 Annex 16: Environmental Protection Volume I-Aircraft Noise (Canada: ICAO)
[20] EASA 2017 Rolls-Royce Trent 1000 Type Certificate Data Sheet: E.036 (United Kingdom: EASA)
[21] Sforza P M 2017 Idealized cycle analysis of jet propulsion engine Theory of Aerospace Propulsion (London: Butterworth-Heinemann) chapter 3 pp 85-171