Experimental Investigation of Jet Flow Fields with Chevron Nozzles

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Abstract. With the rapid development of the aircraft industry, more regulations on aircraft noise are established. The turbulent jet is one of the major sources of noise in the aircraft, extensive researches on noise reduction has been investigated, especially for chevron. In this project, the near-nozzle flow fields of three chevron nozzles and one circular nozzle from a subsonic jet are investigated experimentally. This paper presents the results the comparison between four nozzles (CN0, CN1, CN2 and CN3) in terms of radial mean velocity, turbulent intensity and the selected nozzles are compared to baseline and each other with respect to turbulent kinetic energy spectra. CN0 is the baseline circular nozzles, CN1 is the standard chevrons nozzle, CN2 is a chevron with alternating angles and CN3 is chevron with more number of chevrons. Fluctuated velocity profiles were measured at x/D = 2 at different radial locations along characteristic direction using hot-wire technique. The purpose of these measurements and comparison is to study the variations in the flow field with the different configurations of chevron, which might be related to the acoustic field. CN1 nozzle has a 40dB turbulent kinetic energy reduction compared to the baseline nozzle CN0, and CN2 has the highest turbulent flow field, which is a mixture of low, medium and high velocities corresponds to three directions. CN3 has the most similar mean velocity and turbulence intensity profiles, this may be caused by the under developing jet flow field.

1. Introduction

1.1. Motivation
With the rapid development of the aircraft industry, aircraft generated noise become a concerning problem. The high-velocity jet engines exhaust is responsible for the majority of noise, especially during take-off and landing. Based on the Lighthill’s eighth power law [4] as shown in Eq. (1) below:

$$\text{Sound Power} \propto \text{jet area} \times (\text{jet velocity})^B$$

(1)

The overall radiated sound power from a jet nozzle is proportional to the eighth power of its exit velocity. There was a 20 dB noise reduction with the introduction of large bypass ratio turbofan which lowers the exhaust speed from the 1960s to 2000s, after that the rate of reduction has been levelled off; it is more difficult to reduce aircraft noise. Meanwhile, the Advisory Council for Aeronautics Research in Europe (ACARE) also set goals - the aircraft noise needs to reduce by 10dB [5]. Further noise
reduction has been a popular topic of research recently, and a valid aeroacoustics solution has been published by NASA [6]. NASA has developed sawtooth edges, known as chevron and used these at the back of nacelle and engine exhaust nozzle. The jet noise is effectively reduced by the introduction of chevron, therefore cost of for sound insulation on the fuselage can be saved as well as weight and fuel saving. The working principle for chevron is controlling the air mixing that passing through and around the core engine. Yet, the mechanism of sound generation and reduction in the aerodynamics point of view has not been fully understood.

Therefore, this experimental investigation is to provide the aerodynamic analysis of different shapes of jet exit nozzles of the near-field flows. Velocity profiles can be measured via experiment and turbulence statistics can be established, then the turbulent kinetic energy spectra can be generated. Based on these data, the best nozzle shape can be selected from three chevron nozzles and a suggestion of further shape modification for the exit nozzle of a civil aircraft can be made.

1.2. Background Theory

1.2.1. Jet flow. Jet flow from circular nozzle has been experimentally investigated by hot-wire anemometry techniques and the general mean velocity profiles from the jet nozzle have shown in fig. 1; which indicates 3 growth phases: undeveloped (potential core), developing zone, and fully development zone. In this project, the measurements are taken in the first region only.

![Figure 1. Jet Flow Development](image)

Hot-wire anemometry techniques can be used to measure the variables occurring in turbulent flows, such as fluctuating velocity components or temperature, and there are different types, for example, constant temperature anemometer (CTA) and constant current anemometer (CCA). The advantages using hot wire anemometer is that single point measurements can be obtained at high acquisition rate, enabling spectral analysis of the turbulent flow. Recently, researchers tend to use this anemometry to investigate the turbulent field and establish the turbulence model [7]. Other methods like Particle Image Velocimetry (PIV) can also be used for investigating the unsteady jet flow fields in sequential frames. PIV measures highest frequency is limited to approximately 25 kHz [8].

1.2.2. Jet Noise. Jet noise research was originated by J. Lighthill with his two-part paper I. General theory and II. Turbulence as a Source of Sound (1952, 1954) [4, 9]. These papers give the birth of the ‘Aeroacoustics’. The concept of aeroacoustics is that noise can be generated by either turbulent fluid motion or aerodynamic forces and surface interaction. Moreover, periodically varying flows can also generate noise [10].

Jet noise prediction models have needed turbulence statistics based on acoustic analogies. Davies et al. (1963) made spatial and time measurements of cold, low Mach number jets, deriving that space-scales and time-scales from their measurements [11]. T. Christopher (1998) has provided the evidence of jet mixing noise is made up of two components, one is from the large turbulence structures (instability waves), and the other is from the fine-scaled turbulence. This principle is suitable for both supersonic and subsonic jets [12, 13]. Therefore, in this project, the jet noise is predicted by high- and low-frequency.
Since the relationship between the turbulent kinetic energy spectra and the mean radiating source were not well correlated [14].

1.2.3. Chevron. The concept of reducing noise using different shapes of nozzles has initiated by the studies of tabs in the 1980s and 1990s. Tabs, which are thin and slab-like shown on the left of fig.1, were studied on mixing enhancement in jets, and from the experiment observations that it also has a noise benefit. In the 1990s, chevron was developed based on tabs, with gentle mixing characteristics to minimise thrust penalty [15].

Chevron nozzle has a sawtooth pattern, shown on the right in fig.2, can be used on the trailing edge of jet exhaust, and its protrusions in the nozzle geometry modify the flow-field characteristics. Extensive studies have been carried out to evaluate chevron nozzle designs.

Bridges and Brown (2004) have investigated chevron nozzle geometric parameters: number of chevrons, length (the length of chevrons along the jet axis), angle (deviation of the chevron from the jet axis) on the flow and acoustic fields. Chevron nozzles give rise to axial vorticity, increasing the mixing layer growth rate into the potential core [16]. The triangular cuts of the nozzle induce streamwise vorticity into the shear layer and this leads to increasing mixing and potential core length reduction [17]. The counter-rotating vortices produced by the notch between chevrons have a trend to destroy the others and that this process reduces radial transport, especially in high-penetration designs. Therefore, the shear layer growth rate is increased and the jet decays more rapidly.

Chevrons were not seen to reduce the overall acoustic noise level, but they change in noise level in the spectrum over certain frequency ranges. Chevron penetration was identified as the most relevant parameter, allowing a reduction of effective perceived noise level (EPNL) 2-3 EPNdB at low frequencies for certain positions of the observer [18].

Callendar et al. (2010) used Particle Image Velocimetry (PIV) measurements of jets originated by four different nozzles and confirmed that chevron penetration affects the mixing intensity, which may be related to the sound generation mechanism. Larger penetration produces greater reductions of noise at low frequencies but also increases it at high frequency. The authors concluded that there are two essential physical principles induced by chevrons nozzles. The first is the enhanced mixing that increases the decay rate of the potential core, reducing jet noise near the range of the frequency peak. The second mechanism is the increase of turbulence in the shear layer that generates high-frequency noise [19], which is proved by Violato and Scarano (2011) [20].

Violato and Scarano (2011) found that for the jet flow in circular nozzle, the axial vorticity induced by streamwise pairs on the vortex ring is staggered in phase opposition at the regions of interaction, where primary instabilities grow; in the chevron jet, the axisymmetric ring-like coherence of circular jets is replaced by streamwise flow structures of azimuthal and radial vorticity in jets emerging at the nozzle exit [20]. Furthermore, the authors proved the theory that the radial vorticity are stronger and the axial vorticity becomes weaker at nozzle exit and this also concluded by Bridges and Brown (2004) [16]. The difference between the circular and chevron jet flow is the turbulent level at the nozzle exit, the
vorticity ratio of chevron jet is 5 times larger than that of the circular jet and they level out with the formation of ‘C’ structure. The shear layer is organized in ‘C’ shaped vortices which, inducing inwards radial flow may be responsible for the tilting of the streamwise structures towards to the jet axis.

1.3. Aims
The aims of this project are to find out the velocity profiles and turbulence intensity near the exit nozzle field with three different configurations of chevrons from a jet flow, then find out the flow mechanisms experimentally, thus finding out which configuration is better. After the experiment, all the data would be compared and used to predict the noise level.

This project has potential that gives the gridlines of modification of the structure of chevron nozzles. Furthermore, it may also have the benefit that uncovers the jet noise reduction mechanisms.

2. Experimental Procedure
In this project, an experiment was set up to compare a baseline case of a circular nozzle without chevrons to several different configurations of chevron nozzles. Measurements of the fluctuating velocities at the same axial distance x/D = 2 for different radial locations from a jet flow were taken using hot wire anemometer system. The results compared the velocity profile and turbulent intensity by each case. Therefore, energy spectra could be established, and compared them by pairs, and eventually select a most ‘noise reduction’ one and the suggestion for adjustments of modern chevron can be made.

2.1. Chevron Shape Selection
First, a baseline circular nozzle 0 (CN0) is generated, and a ‘standard’ chevron nozzle 1 (CN1) is created. Based on the previous study, the penetration (difference in radius from tip to base) of the chevron nozzle is the most important factor effect the flow and acoustic fields [16], and therefore the chevron nozzle 2 (CN2) with altering angles has been carried out. Besides, the number and length of chevrons are also key factors, thus more chevrons with different sizes are used for chevron nozzle 3 (CN3). The parameters of the four chevrons are shown in table 1 and the computational chevron nozzle models are shown in fig. 3.

| Table 1. Chevron Parameters |
|-----------------------------|
| Units | CN0 | CN1 | CN2 | CN3 |
| Number | 0 | 6 | 5 | 3 | 6 | 6 | 12 |
| Length | mm | 0 | 24 | 24 | 24 | 24 | 24 | 24 | 12 | 12 | 12 |
| Angle | ° | 10 | 10 | 6 | 20 | 10 | 10 | 10 |
| Penetration | mm | 0 | 2.12 | 4.37 | 2.12 | 1.59 | 1.06 |
| Diameter | mm | 46 | 41.7 | 46 | 37.2 | 41.8 | 42.8 | 45.9 |

Figure 3. Chevron Nozzles (CN0, CN1, CN2 and CN3)

2.2. Jet flow
A small subsonic jet flow was simulated by a hair dryer. The source of the air jet flow was initialised by the fan which gave a high turbulent air flow. For this experiment, laminar jet flow is needed. As a result,
honeycomb and screens were used as filters mounted in designed pipes to reduce the lateral turbulence and eddies of the flow. The graphical illustration is shown in fig.4. Two cross-sections of the pipes have also shown in the down-left corner. Moreover, the pipes are manufactured in the workshop by lathe and milling machines.

![Image](image.png)

**Figure 4. Jet Flow Filter**

Four chevrons nozzles are firstly created using PTC Creo Parametric 3.0 and produced using additive manufacturing techniques. The flange connectors are implanted between the pipes and chevrons, gives an easy approach of changing different chevron nozzles during the experiments.

In this experiment, a single hot-wire probe, which is a 5 µm diameter, 1.25mm long platinum-plated tungsten cable-equipped miniature wire (Dantec model 55P16), was used to perform measurements [21]. The calibration of the hot wire probe has been done associated with Flow Master. The hot wire anemometry system has a constant temperature anemometer (CTA) module (Dantec model 56C17) and this is used for fluctuated velocity measurements [22].

2.3. Experiment Set Up

![Image](image.png)

**Figure 5. Data Flow Chart**

Two systems are used in this experiment, traverse and hot wire. For traverse system, a 3-axis traverse was used to move the probe to the measurement positions at the nozzle exit, and the hot wire was mounted on the traverse as shown in fig. 6. Measurements were recorded only after steady state flow condition was reached. For the hot wire system, the fluctuated voltage signals were acquired and transferred to Analogue Digital Converter (ADC488/8S). A binary file has been created on the computer. Both of the two systems are controlled by an acquisition code developed in QBasic, the whole process is shown in fig. 5.
Since the jet flow went through circular/chevron nozzles have axisymmetric characteristics, meaning that the measurements of the same radian have the same or similar values, linear measurements along certain directions were taken for each nozzle as shown in fig. 8. The dashed line would be used for the mirror data in the results section.

There was only one direction used for CN0 nozzle (orange); two directions as the peak (grey) and groove (red) of CN1 nozzle were being investigated. Similarly, CN2 has three directions: high peak (purple), low peak (blue) and groove (green). Eventually, CN3 also has three directions high peak (green), middle peak (blue) and low peak (purple). The colour for each direction would correspond to further use in this paper. Nine measurements for each direction are equally spaced of 5mm originated from the centre.

As the project is focused on the near-field flow field, all the measurements are acquired at x/D=2, where the distance between the hot wire probe and the nozzle exit is twice of the chevron nozzle diameters.
3. Results AND DISCUSSION

3.1. Mean Velocity and Turbulence Intensity profiles

Mean velocity profiles can be established by averaging all the fluctuated velocities by MatLab over the jet exit velocity \( (U_0) \). The jet exit velocity \( (U_0) \) was calculated by averaging the velocity measurements made around the jet centre at approximately 5 mm downstream of the nozzle tip, which gives 1.35 m/s. Therefore the Mach and jet Reynolds numbers of all four nozzles tests are 0.004 and 3836 respectively in this project. The turbulence intensity can be calculated by the Eq. (2):

\[
Turbulence \; Intensity = \frac{u'}{\bar{U}}
\]  

(2)

Where \( u' \) is the Root-Mean-Square (RMS) of the turbulent velocity fluctuations at the certain location over a specific period of time, and \( \bar{U} \) is the average velocity at the same location during same time period.

3.1.1. Baseline CN0 and Literature. Maia et al. (2014) have studied the flow field of a subsonic jet exiting from a circular nozzle (SMC000) and a chevron nozzle (SMC006) using hot wire techniques [23]. The SMC00 series was first introduced in the a NASA paper studied the influence of geometric parameters of chevron nozzles on the acoustic field and flow field carried out by Bridges and Brown (2004) [16]. The diameter of the chevron was 12.3 mm and the jet exit velocity is 43.27 m/s, this leads to the Mach and Reynolds number 0.13 and 35000 respectively.

![Figure 8. Mean Velocity Profile of CN0 and Literature (Imaginary mirror data is shown in dash line).](image)

The non-dimensional radial profiles of the mean velocity profile and turbulence intensity for two axial positions, which are \( x/D = 1 \) and \( x/D = 5 \) in literature are cross-plotted with the experiment results as shown in fig. 9 and 10. The \( y \) is the distance from the measured position to the jet centre, the \( U_0 \) is the jet exit velocity.
The experiment results were expected to be consistent with the literature data. Both resultant profiles show the similar tendencies with literature in between $x/D = 1$ and $x/D = 5$. However, it is worth to notice that the experiment velocity profile is narrower than that of in literature. This may because a low Reynold number is used in this project (35000 against 3836). The experiment gives a lower value of the central velocity ratio, which may indicate a shorter potential core than that of the literature. Bridge and Brown (2004) has found that the length of the potential core is significantly affected by temperature [16]. The calibration of the hot wire carried out in the wind tunnel at room temperature 20 degrees, while the jet exit flow used in the experiment is about 37 degrees, hence the experiment central velocity ratio should be closer to the case ($x/D=5$) in literature and this will be discussed under the uncertainty section. Still, all the 4 nozzles were tested in the same temperature condition. For turbulence intensity curves, the literature data is lower curve since the $\bar{U}$ for the experiment is much lower (43.27 m/s against 1.35m/s), therefore, the values are higher than the results data proportionately. Overall, the baseline nozzle (CN0) experiment data are valid and can be used for the further comparisons to other chevron nozzles in this project.

3.1.2. CN0 and CN1. The CN1 is the most common chevron nozzle and this configuration has been already used on Boeing-787. It sports chevrons on the nacelles, or fan housings [24]. The two radial profiles of CN0 and CN1 nozzles are cross-plotted in fig. 11 and 12, where ‘G’ stands for Groove direction and ‘P’ represents Peak direction. It is easy to see that the mean velocity profiles for the CN0 are wider than those generated by CN1 and the central velocities of CN1’s peak and groove are lower, this may lead to the potential core reduction. Maia et al. stated that at the end of the potential core, the low-frequency noise is likely to be generated since the low wavenumber structure generated at the end of the potential core [23]. A shorter potential core means that less low-frequency noise.
The CN1 also produced significant changes in the turbulent field. All the peaks are shifted further away from the centre of chevron, and peak turbulent has been increased in the peak direction, meaning that the chevron has enhanced the mixing process and spreading the jet radially, and this may lead to an increase in turbulent kinetic energy, meaning an increase of the high-frequency turbulent content [16, 19, 23].

3.1.3. CN0 and CN2. Based on the previous acoustic studies, the penetration of the chevron nozzle is the most important geometric parameter for controlling the sound frequency. By changing the penetration, low and high frequency can be a trade-off to obtain an acoustic benefit. For instance, a higher penetration chevron nozzle provided low-frequency harmless sound while the smaller penetration nozzle gives a high-frequency unbearable noise. The principle was found by Viswanathan in 2003 [25]. In addition, Callender et al. (2010) have also claimed that the chevron penetration dominates the degree or growth of the air mixing and hence the trade-off between low- and high-frequency benefit. Violent air mixing can produce further potential core length reduction, and gives
further noise reduction at the low-frequency range. Yet, the violent mixing also generates extra high-frequency noise. In order to get the optimal design, the mean velocity and turbulent intensity profiles of CN2 are used to predict the air mixing level as shown in fig. 13 and 14. It was expected that alternating the angle can give a balanced the low- and high-frequency sound and provide minimal noise [19].

Figure 12. Mean Velocity Profile of CN2 (Imaginary mirror data is shown in dash line)

Figure 12 shows the CN0 and CN2 mean velocity profile, where ‘G’ stands for Groove direction, ‘HP’ and ‘LP’ represent High Peak and Low Peak direction. The velocity profile in the groove direction gives the highest velocities and slowest changing rate radically and the overall trend are similar to the CN0 nozzle. The velocities in the low-peak directions have a high initial value and decay rapidly. In contrast, the velocity tendency in the high-peak direction have a lower initial value and decay slowly at first, and then rapidly at around y/D=0.35 and becomes the lowest values among velocities of three directions. Overall, flow fields of CN2 nozzle is a mixture of low, medium and high velocities.

With respect to turbulence intensity, these three directions have different maximum values at different peak location. The aggressiveness of the mixing may lead to a balance of the low- and high-frequency acoustic benefits.

Figure 13. Turbulence Intensity profiles of CN2
3.1.4. CN0 and CN3. As Bridges and Brown (2004) have reported that the number of chevrons is not a key parameter that influencing the noise level. For the CN3 nozzle, 24 triangular cuts with different size are used. It was expected that some findings may be concluded, however, there are no significant differences obtained in both mean velocity and turbulence intensity profiles compared with the circular nozzle. The increased velocities of CN3 may indicate that more number of triangular cuts reduces the effect of chevron, which also consistent with findings by Bridges and Brown (2004) [16].

![Velocity profile](image1)

**Figure 14.** Velocity Profile of CN3 (MP = Middle Peak) (Imaginary mirror data is shown in dash line)

However, another reason could also be the explanation of this phenomena since the axial downstream position x/D = 2 is used, the jet flow may remain the laminar flow which has the top-hat velocity profile as shown in fig. 1. This also may indicate that a longer potential core. Still, more measurements for different streamwise positions such as x/D = 3, 5, 10 are needed to be investigated.

![Turbulence Intensity](image2)

**Figure 15.** Turbulence Intensity Profile of CN3 (Imaginary mirror data is shown in dash line)
3.2. Possible further chevron shapes

After the mean velocity and turbulence intensity profiles comparison of the CN1, CN2 and CN3 chevron nozzles to the baseline CN0 nozzle, several deductions can be found.

First, CN1 and CN2 nozzles are more effective designs than CN3 nozzle, the characteristics of CN3 is found similar to the CN0 circular nozzle at the near nozzle flow field. If compared CN1 to CN3, the length and number of chevrons have limited influence on chevron can be conducted since other parameters are the same.

Second, the innovantional CN2 nozzles may give a similar or even better noise reduction than traditional CN1 due to the high level of turbulent mixing. The only difference in CN1 and CN2 is the altering angles of the triangular cuts and this proved that the penetration is the key factor of the chevron nozzle. Further research can be focused on CN2 nozzle. In order to identify the frequency range and sound power of CN2 nozzle, Turbulent kinetic energy spectra at downstream position x/D=2 are created and analysed and compared with those of CN0 and CN1 nozzle.

3.3. Turbulent kinetic energy spectra

The spectra was calculated through the discrete Fourier transform of a time series of velocity measurements. The Matlab toolbox of Fast Fourier Transform (FFT) was applied for continuous data. Due to the limitation of the experiment equipment, the acquisition rate cannot be exceeding 2 kHz, thus 1 kHz was used and the frequency range for sectra was limited to 500 Hz. The sampling time is 10 seconds. Therefore, 10,000 are generated for each single point. The FFT was calculated with these points. The power spectra were shown in decibels [26].

The energy spectra were generated by one downstream position x/D=2 and several radial positions, \( \eta = 0 \) for each nozzle, and \( \eta \) is defined as Eq. 3:

\[
\eta = \frac{y - y_{0.5}}{\delta_c}
\]

Where \( y_{0.5} \) is the radial position at which the velocity is equal to the half jet exit velocity and \( \delta_c \) is the shear layer thickness [23].

Hence, \( \eta \) corresponds to the shear layer centre, and this point has the highest velocity gradient and peak turbulence intensity. For CN0 nozzles, this position is located at \( y/D = 0.65 \); for CN1 nozzles, both peak and groove, \( \eta = 0 \) relates \( y/D = 0.65 \); and for CN2, \( \eta = 0 \) of the high peak, groove and low peak occurs at \( y/D = 0.54, 0.87 \) and 0.54 respectively.

![Figure 16. Comparison of spectra for CN0 and CN2 (x/D = 2)](image)
Figure 16 shows the CN0 and CN2 power spectra. It is clear to see that there are reductions for power in decimals. The maximum reduction approximately 30dB is shown between the CN2 low peak (y/D=0.54) and CN0 nozzle (y/D=0.65). This means that the lower level of turbulent kinetic energy at low frequencies.

The second spectra is comparing the kinetic energy of CN1 and CN2 as shown in fig. 17, the CN1 groove gives a lower power than all the values produced by CN2 nozzle. Further noise reduction may be applied. It was also expected that there were different in shedding frequency, which means the corresponding frequency for the apex of energy spectra. It is difficult to obvious, but CN1 (red groove direction) has a higher shedding frequency than that of CN2 (green groove direction), this may indicate noise has shifted to higher frequencies by CN1 chevron nozzle.

3.4. Uncertainty

3.4.1. Uncertainty of a mean velocity sample. The uncertainties of each set of velocity are determined by flow master calibration (2%), A/D board resolution (0.13%) and experiment conditions, which includes probe positioning (0.015%), temperature variation (4%), ambient pressure (0.6%) and humidity (0.06%). Hence, the sample weighted uncertainty is around 6%. These are calculated by standard uncertainty equations provided by Dantec Dynamics [27].

In this case, the temperature is a crucial factor for CTA measurement, [28], hence the uncertainty of temperature is shown as an example [27].

\[ U(U_{\text{temp}}) = \frac{1}{\sqrt{3}} \cdot \frac{1}{U} \cdot \frac{1}{(T_w-T_0)} \cdot \left( \frac{A}{B} \cdot U^{-0.5} + 1 \right)^{0.5} \tag{4} \]

In addition, for gas, variations in density are also need to be included in the uncertainties:

\[ U_{\text{gastemp}} = \frac{1}{\sqrt{3}} \cdot \frac{\Delta T}{273} \tag{5} \]

Where \( T_w \) is the sensor temperature 190°, \( T_0 \) is the ambient reference temperature 20°, \( \Delta T(17°) \) is the temperature difference in the calibration (20°) and experiment (37°). \( U \) is the jet exit velocity. \( A \) and \( B \) are the King’s Law constants, which are 0.5044 and 0.8259 respectively in this case. Hence, \( U(U_{\text{temp}}) = 0.31\% \) and \( U_{\text{gastemp}} = 3.60\% \).
3.4.2. **CN3 manufacture.** Four nozzles were investigated in this project as shown in fig. 3 and 4. It was planned to manufacture them by a high-resolution 3D printer. However, this machine was broken after finishing CN0, CN1 and CN2. Another 3D printer was used for manufacture CN3, where the surface is not as smooth as previous ones and the edge of the triangular cuts is not that sharp and clear. Although surface grinding of CN3 was applied afterwards, it is evitable that there are uncertainties in nozzle dimensions and surface finishing, and these are possible reasons that the mean velocity profiles of the CN3 nozzles are wider and higher than that of CN0.

3.5. **Further Study**
This study is focused on the near-nozzle flow field of the cold subsonic jet through the chevron; far-field locations can also be instigated. Noise level is predicted by the turbulent kinetic energy spectra, while in the further experiment, the sound sensor such as microphones. Since there was only one speed used in this experiment, different jet velocities with different Reynolds numbers could also be studied. In addition, high temperature jet could also be used.

Further investigation of the CN2 and CN3 nozzle can be analysed using other techniques, for example, computational methods large-eddy simulation (LES) and experimentally method PIV and etc. If tailored the CN2 nozzle design parameters to the nozzle exhaust conditions carefully, a better noise ‘reduction’ aircraft - balancing the low- and high-frequency sound – can be applied in the near further.

4. **Conclusion**
From this study, the mean velocity and turbulence intensity profiles at x/D = 2 of baseline CN0 nozzle are consistent with literature data. Compared CN1 (with chevrons) to CN0 nozzle (without chevrons), the CN1 has narrow mean velocity profiles in both peak and groove direction and higher values of turbulence intensity, which may increase the high-frequency noise caused by the finer scales of turbulence [13]. Compared CN2 (with altering angle chevrons) to CN0 nozzle, the flow fields of the CN2 nozzle is a mixture of low, medium and high velocities corresponds to high peak, low peak and groove direction respectively, and the mean velocity curve of CN0 is about the average of these velocities. For the turbulence intensity, the three directions have their own characteristics and this aggressiveness of mixing may lead to a tradeoff of the low- and high-frequency acoustic benefit. In addition, from the turbulent kinetic energy spectra, it is a maximum 30dB reduction in low-frequency. Compared CN1 to CN2 nozzle, CN1 nozzle showed a 10 dB more reduction and gives a potential that shifting noise to a higher frequency. Compared CN3 (with more number of chevrons) to CN0, since the measurements were taken at x/D = 2, jet flow was still under developing, therefore the mean velocity and turbulent intensity profiles of CN3 for three directions are similar to those generated by CN0. The overall uncertainty for this project was approximately 6% and 4% was attributed to the temperature. There is no actual acoustic measurements made in this experiment, and it is difficult to predict the noise based on the Freund (2001), the turbulent kinetic energy spectra and noise spectra haven’t related to each other. Therefore, the noise can only be summarised in high- and low-frequency. Chevron nozzle reduces low-frequency noise in low frequency and shifts the noise to the high frequency range.

In order to achieve ACARE 2020’s goal, the advice is to mount more chevron nozzle instead of the circular nozzle with CN1 nozzles. CN1 nozzle gives a better result in noise reduction than CN2 nozzle. However, more researches are needed for CN2, by carefully adjusting the parameters, it might give a similar or better noise attenuation.

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