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Report On

Assessment of different aircraft engine noise reduction technologies

Submitted to

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By



Abstract

Exposure to loud aircraft engine noise affects individuals worldwide. Constant exposure to this noise results in headaches, sleep deprivation, anxiety, and chronic heart disease. Airports are implementing stricter rules and require aircraft to respect their maximum permissible level of noise production. Researchers have been searching for ways to help reduce this noise. One evolution was high bypass ratio (HBPR) engines. HBPR engines allow higher amounts of air to bypass the nozzle; thus, lower and higher velocity air can mix while creating less turbulence and noise by up to 50 percent. Another finding was chevrons which are saw tooth shaped edges around the nozzle that facilitate the mixture of the two types of air. They create smaller vortices resulting in noise reduction of 3 percent. Since HBPR engines have a greater impact on noise reduction, research is being done on achieving ultra-high bypass ratio engines and the effect they will have on noise reduction. The current solution is to combine chevrons and HBPR engines.

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List of symbols

\dot{m}_e = mass flow rate of hot combustion exhaust flow from the core engine (kg/s)

\dot{m}_0 = the mass rate of total air flow entering the turbofan = $\dot{m}_c + \dot{m}_f$ (kg/s)

\dot{m}_c = the mass rate of intake air that flows to the core engine (kg/s)

\dot{m}_f = the mass rate of intake air that bypasses the core engine (kg/s)

V_f = the velocity of the air flow bypassed around the core engine (m/s)

V_{he} = the velocity of the hot exhaust gas from the core engine (m/s)

V_o = the velocity of the total air intake = the true airspeed of the aircraft (m/s)

T = Thrust in Newton or Pounds

\dot{m} = mass flow rate of air entering engine inlet (kg/s)

V_e = exhaust velocity of air from fan and gas generator (m/s)

V_i = Free stream velocity of air entering the engine inlet (m/s)

V = velocity in feet/s

H = fuel heating value in British thermal units per pound

“h” = fuel flow rate in pounds per hour

J = Joule’s constant = 778 foot-pounds per British thermal unit

η = overall efficiency

List of acronyms

BPR.....Bypass Ratio

HBPR.....High Bypass Ratio

CFD.....Computational fluid dynamics

AST.....Advanced Subsonic Technology

ASE.....Aero systems engineering

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Introduction

Every day, about six million people around the world get on a plane to travel. The total number of flights scheduled per day surpasses one hundred thousand [1]. This means, aircraft noise can be often heard by people especially those who either live or work close to airports. Most of the noise produced by an aircraft comes from its engines [2]. The most common propulsion system for modern aircraft is the gas turbine engine [3]. This engine has several types but they all work based on the same principle. First, air is sucked into the engine through the front blades. Then, air enters the compressor where it gets squeezed and compressed by the many small blades that are spinning. After that, air enters the combustion chamber where fuel is injected and starts burning. Once this step is over, air enters the high and low pressure turbines where energy is extracted from the hot and expanding air. This energy is used to spin the shaft which the turbines and compressor are attached to. Finally, the burning gas goes through the nozzle which is where thrust is created. The nozzle also conducts the exhaust gases back to the free stream [4].

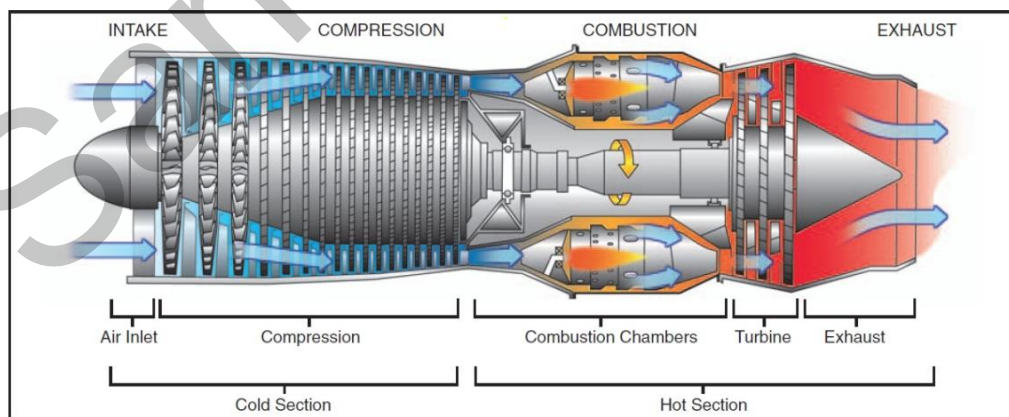


Figure 1: Gas turbine engine [5]

Turbojet, turbofan, turboprop, and turboshaft are all different types of gas turbine engines. A turbofan has a fan attached to its front while a turboprop has a propeller. The main difference between a turbojet and turboshaft is that in the latter, an additional power section containing turbines and an output shaft is incorporated.

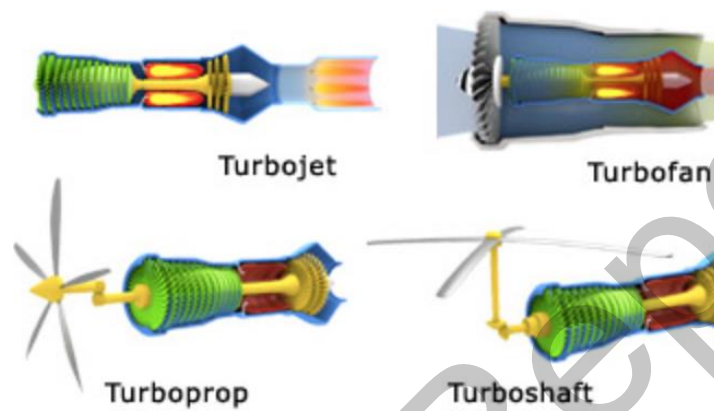


Figure 2: Different types of gas turbine engines [6]

All these engines work based on the Brayton cycle introduced in Thermodynamics II which has been illustrated below:

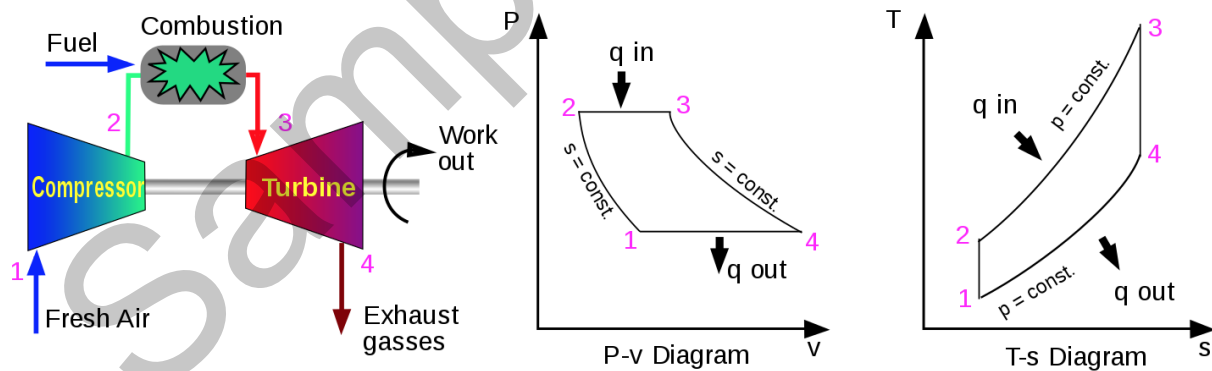


Figure 3: Brayton cycle [7]

We can see that in the compressor (1→2), energy is added to the fluid and its temperature and pressure rise to a level suitable to sustain combustion. Then, in the combustion chamber

(2→3), the air temperature increases. As the turbine (3→4) absorbs energy from the fluid, its pressure drops.

As mentioned before, aircraft engines are one of the primary sources of noise especially during take-off. Constant exposure to this noise can have severe health effects on individuals. One of these effects is sleep disturbance which occurs due to increased awakenings. As a result, many people might try to resolve this problem by using non-prescribed sleep medication.

Fragmentation of sleep can also cause the level of stress hormones to increase which can then create vascular dysfunction and high blood pressure and finally lead to heart disease. Another effect noise can have on people's health is hearing impairment. Jet engines are capable of producing sounds as high as 140 dB and constant exposure to this level of noise may result in hearing loss [8]. In order to understand how loud that is, a comparison has been made between the regular, day to day noises we hear and that of an airplane.

Jet plane at takeoff	110-140dB
Loud rock music	110-130dB
Chain saw	110-120dB
Thunderstorm	40-110dB
Vacuum cleaner	60-80dB
Normal voices	50-70dB
Whisper	20-50dB
Purring cat	20-30dB
Falling leaves	10dB
Silence	0dB

Figure 4: Amount of sound created by different sources [9]

In order to prevent noise related health problems from occurring, certain rules and regulations have been put in place to control the maximum level of noise created by aircraft. Since the 1970s, noise limits for aircraft have been set and included in Annex 16 of the International Civil Aviation Convention. The goal of this section is to make sure aircraft designs include the latest noise reduction technology available [10]. The noise footprint of aircraft is closely monitored by airports. When a plane flies close to an airport, the noise monitoring stations scattered out around the arrival and departure part monitor every movement of the aircraft. Most airports have mandatory constant descent approaches which means that the aircraft should not level off. This measure has been put in place in order to avoid the thrust coming up as each time this happens, more noise is created by the jet engine [11].

Motivations and objectives

The motivations behind this research is improving people's lives by reducing the amount of noise they are exposed to everyday and helping aircraft manufacturers meet the requirements set by the airports and authorities. Amongst the various technologies implemented on aircraft engines, few of them were able to drastically decrease the noise level and therefore have been further investigated.

Objectives:

- Assess the current noise reduction technologies for gas turbine engines
- Determine the impact of those technologies on society and public health

Literature survey

High bypass engines

At the engine exhaust, air exits at a very high speed and temperature and comes in contact with the surrounding air which possesses a different speed. The main source of jet engine noise is the turbulent mixing of shear layers in the engine's exhaust. These shear layers consist of instabilities that create highly turbulent vortices. These vortices create pressure fluctuations responsible for sound [12].

The greatest improvement in jet engine noise reduction came with the high bypass ratio engines. In these types of engines, a large amount of air enters the huge fan in the front and bypasses the core of the engine to be ejected directly into the exhaust stream [13]. Thus, this air will possess a lower speed than the jet exhaust and therefore, the vortexes created are less intense resulting in much less noise. Once the slower bypass air encapsulates the jet exhaust, it takes away some of its noise as well. The high bypass ratio engines were able to reduce engine noise by 30 to 50 percent which was quite significant.

The bypass ratio (BPR) of an engine is defined as the ratio between the mass flow rate of the bypass stream to the mass flow rate going through the core. High BPR engines were actually first created to reduce engine fuel consumption and create more thrust but noise reduction resulted as a positive side effect [14]. The equation relating bypass ratio to thrust (T) can be seen below:

Equation 1:

$$T = \dot{m}_e V_{he} - \dot{m}_0 V_0 + BPR (\dot{m}_c V_f) \quad [15]$$

\dot{m}_e = mass flow rate of hot combustion exhaust flow from the core engine

\dot{m}_0 = the mass rate of total air flow entering the turbofan = $\dot{m}_c + \dot{m}_f$

\dot{m}_c = the mass rate of intake air that flows to the core engine

\dot{m}_f = the mass rate of intake air that bypasses the core engine

V_f = the velocity of the air flow bypassed around the core engine

V_{he} = the velocity of the hot exhaust gas from the core engine

V_o = the velocity of the total air intake = the true airspeed of the aircraft

BPR = Bypass Ratio

The concept of increased bypass ratio was tested by NASA using wind tunnels. The earliest turbofan engines which arrived in the 1960s had a bypass ratio of 1 or 2. As these engines improved, a higher bypass ratio was observed and nowadays, many engines have a BPR of 4-6 [12]. The greater the bypass ratio, the higher the amount of energy extracted from the hot exhaust of the gas generator.

Up to 70% of a turbofan engine's thrust is related to its fan [16]. The reason why most modern aircraft are powered by turbofan engines is that they consume less fuel than other types of engines. The explanation behind its higher efficiency comes from Newton's second law of motion. Using this law, we can conclude that a certain amount of thrust can be produced by two ways. The first way is by adding a small increment of velocity (ΔV) to a large mass flow of air and the second is by the addition of a large increment of velocity to a small mass flow of air. The amount of energy needed, in this case fuel, is lower for the first case than the second one. The equation below proves that to obtain a certain thrust level, the mass flow rate must increase as ΔV decreases [17].

Equation 2

$$T = \dot{m} (V_e - V_i) = \dot{m} \Delta V$$

T = Thrust

\dot{m} = mass flow rate of air entering engine inlet

V_e = exhaust velocity of air from fan and gas generator

V_i = Free stream velocity of air entering the engine inlet

This increase of efficiency for turbofan is related to the larger air-flow capacity of the fan engine at a certain thrust level. For evidence, the overall propulsion system efficiency at various speeds for different propulsion systems was compared as seen below:

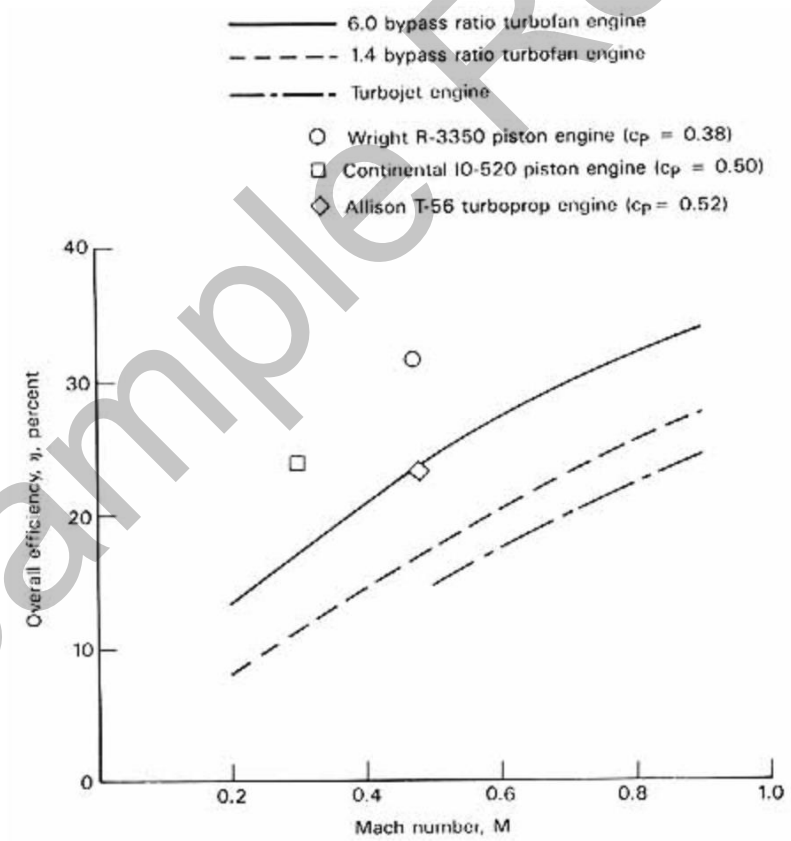


Figure 5: Overall efficiency for various propulsion systems [18]

Overall efficiency is defined as [18]:

Equation 3

$$\eta = 3600TV/HhJ$$

Where:

T = thrust in pounds

V = velocity in feet/s

H = fuel heating value

“h” = fuel flow rate

J = Joule’s constant

When choosing the optimum bypass ratio for a specific aircraft, trade studies must take place.

The factors taken into account during this study include performance requirement of aircraft, fan weight, fan size, and engine component efficiencies.

When testing the high bypass ratio (HBPR) engines, it was observed that it had an important effect on engine noise. The energy extracted by the gas generator to drive the fan was reducing the noise. This is due to the fact that HBPR engines have separate flow, non-mixing, and short-duct exhaust systems. Since most of the air flow in this type of engine is at a low velocity, the average velocity it obtains by getting mixed with the much higher velocity engine exhaust is a lot less.

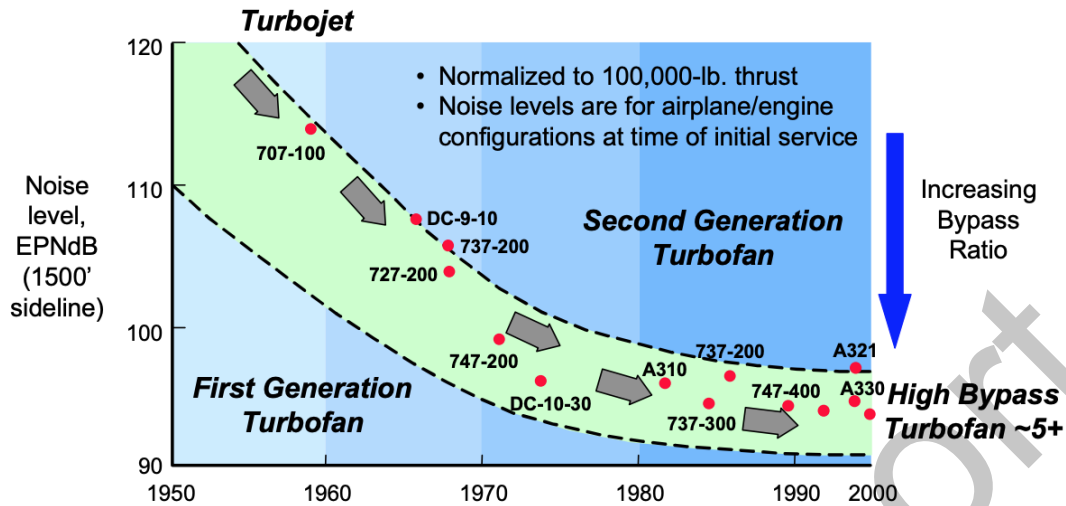


Figure 6: Noise level vs. engine bypass ratio [19]

During the process of creating the HBPR engines, thermodynamics design and Computational Fluid Dynamics (CFD) were used. CFD is a software introduced in Fluid Dynamics II which helps analyze and solve problems involving fluid flows through numerical analysis and data structures. Understanding the cycle of a turbofan was also crucial in creating this technology. Even though higher BPR leads to greater efficiency, the maximum thrust does not increase proportionally which is why researchers are trying to find a way to do so. The next generation of engines might be created to have ultra-high bypass ratios but research and testing are being conducted to assess whether this would be feasible or not [20]. The technology that we have today has enabled us to create aerodynamic designs and manufacturing processes for various engine sections such as the fan and compressor. Improvements still need to be made in order to be capable of targeting what we want to obtain in theory.

Chevron technology

In the late 1990s, many engine production companies became interested in creating noise reduction devices. This interest emerged after NASA announced its Advanced Subsonic

Technology (AST) program which was initiated to address engine fan noise. Boeing also decided to join the search for a better way to reduce engine noise. After a few years of research, chevrons were introduced. Chevrons are saw tooth patterns visible on the back edges of some engines and they aim at decreasing the noise by controlling the vortices created by both the jet exhaust and the bypass air. The way that chevrons are formed allows them to generate vortices themselves. These vortices are very small and controlled and they can encapsulate the relatively high speed bypass air that is coming out. The shape of the chevrons also allows for a smooth mixing of the hot and cooler air. In engines that do not have chevrons, the bypass air rubs up against the surrounding air which leads to the creation of uncontrolled vortices and noise. The design of chevrons was aided through CFD simulations. Structural design and mechanics of material were used in order to determine the material that was best suited for this technology. One challenge that came with the post processing of the CFD results and explaining the acoustic benefits of chevrons was that there was not enough information on the noise generation mechanisms. Therefore, correlating the results to noise reduction using the proper criteria became difficult.

During the testing of chevrons, many configurations were examined in order to come up with a design that would reduce engine noise while not impacting its thrust negatively. The reason why thrust reduction is a matter of concern is that engines with chevrons are less aerodynamic than old engines. This comes from the fact that once a vortex emerges, energy is taken away from the object that created the vortex. Since chevrons generate vortices, they reduce the amount of thrust the engine can produce.

Chevrons can be designed onto the core nozzle and/or the fan nozzle as illustrated below:

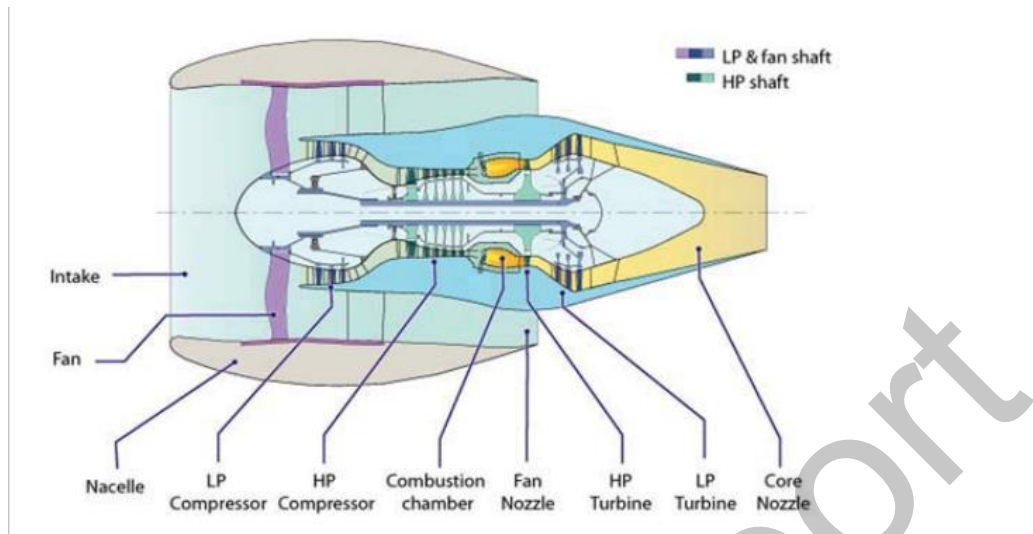


Figure 7: Fan nozzle and core nozzle [21]



Figure 8: Chevrons located on both core nozzle and fan nozzle [22]

Chevrons can differ in the number of teeth they have as well as their orientation (inward, outward, or straight teeth). The chevrons selected for wind tunnel testing were going to be put onto engines with a bypass ratio of 5.

In order to figure out how effective each chevron was, they were compared to the noise produced when no chevron was added to an engine. In the figure below, a basic engine (with no chevron, denoted as 3BB) is compared to a case with 12 chevrons on the core nozzle and none on the fan nozzle (denoted as 3C12B) and another case with also 12 chevrons on its core nozzle but with an inward bend of 6 degrees (denoted as 3I12B).

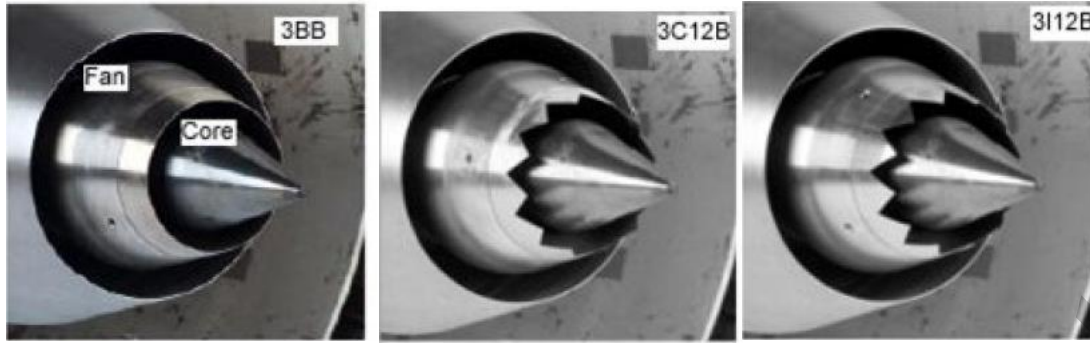


Figure 9: Different types of chevrons [23]

The slight extra penetration from the inclined chevron created a significant difference in noise reduction as it improved from 1.2 to 2.1 (EPNdB) as seen below:

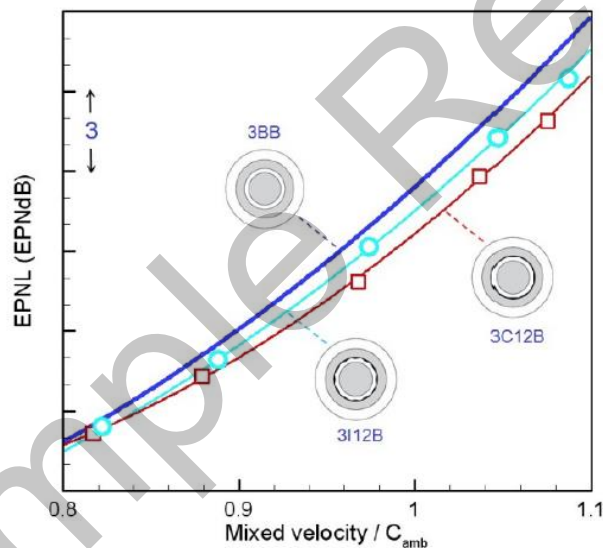


Figure 10: Noise level in different chevron configurations [23]

Continuous tradeoff had to be done on various chevron models in order to finally come up with a design that resulted in the greatest noise reduction and least thrust penalty. Aero systems engineering (ASE) was chosen to conduct the thrust measurements. Only a few chevron configurations that showed high noise reduction capabilities went to this test round. ASE Fluidyne was trusted by the industry and therefore made them a better candidate for

convincing the people responsible for implementing chevrons on their engines to do so. First, static thrust measurements (with no simulated flight effects) were assessed to compute the thrust loss in percentage for different chevron configurations such as 3C12B and 3I12B. The result came as 0.06% and 0.1% thrust penalty respectively. Once calculations were done with simulated flight effect, the thrust loss increased. In the case of 3C12B, thrust penalty went from 0.06% to 0.55% and for 3I2B it went from 0.1% to 0.32%. Once chevrons were added to the fan nozzle, the loss of thrust decreased. A limited number of configurations that yielded the greatest gain in noise reduction with minimal effect on thrust were taken to the wind tunnel test labs. Finally, the model with 12 inward-bent-chevrons on the core nozzle and 24 regular chevrons on the fan nozzle (3I12C24) was determined to be the best option as it gave a 2.71 EPNdb noise benefit while only causing 0.06% thrust loss [23].

The result obtained through the chevron technology was a great achievement as it can help decrease the physical and psychological stress that people in constant exposure to noise might experience. Even though it was observed that adding chevrons to the fan nozzle resulted in less thrust penalty than adding them only to the core nozzle, the interactions of these devices are subtle as there is a lot to learn about their aerodynamics and acoustics. NASA's jet noise research programs have decided to conduct studies to better comprehend these unknown mechanisms in order to further improve these technologies. Even though noise reduction was achieved through this method, there is always room for improvement. Other chevron configurations could be developed that might result in less thrust loss and more noise reduction. By creating quieter engines, aircraft manufacturers are able to reduce the amount of

sound insulation installed in aircraft. Sound insulation is heavy and reducing its amount helps decrease the overall aircraft weight.

Conclusion and recommendation

Constant exposure to loud noise such as aircraft engine noise can lead to various mental and physical illnesses. With the increase of strict rules and regulations at airports for maximum noise emission, researchers have been seeking for new ways to help improve the situation. Two of the most commonly used technologies are chevrons and high bypass ratio engines. Chevrons are saw-tooth shaped nozzle extensions that allow for smooth interaction between high and low velocity air. During the design process, compromise had to be made between the total thrust loss and the amount of noise reduced as certain chevron configurations had negatively affected the thrust. High bypass ratio engines had the greatest impact on noise reduction. These engines allow for a great amount of air to bypass the core which leads to the creation of low intensity vortexes and therefore, less noise. Further developments are being made to create ultra-high bypass ratio engines that could lead to even quieter planes.

One recommendation would be to accelerate the research and testing of ultra-high bypass ratio engines in order to be able to implement them on new aircraft. Another would be to study about the interactions of chevrons and the nozzle in order to further improve its design.

This paper contains information on what methodologies were used to come up with these technologies and could benefit anyone who is looking for explanation on how these technologies work, what impact they have on the environment, and how to improve them including engine developers and researchers.

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Sample Report