ROLE OF CHEVRONS IN ENGINE NOISE CONTROL

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ABSTRACT

Aircraft noise has been an issue of enormous environmental, financial, and technological impact. FAA statistics has forecast that aviation is likely to grow over the next 20 years at an average rate of 3.8% per year [1] for which the use of jet engines as the prime power plant is inescapable. Most commercial aircrafts are equipped with turbofan engines due to their capability of providing higher performance and lower noise when compared with turbojet engines. Dominant noise sources of turbofan engines are from the fan (including the stator) and the exhaust (also referred to as the jet).The noise produced in these two areas during takeoff and landing has a profound impact on the communities surrounding the airports. As a result, aircraft noise has been the target of strict FAA regulations, making turbofan engine noise suppression became the subject of intensive research and development. One of the significant sources of aircraft noise in modern jet aircraft is the turbulence generated in the shear layers around the engine's exhaust. A number of flow control approaches have been applied to modify the flow structures in the shear layer and the radiated sound. One of the simplest and widely accepted approaches is the application of chevrons to the trailing edge of the nozzles. The purpose of this paper is to focus on the development, features & techniques of sound suppression of chevrons nozzles.

KEY WORDS: Chevron, noise reduction, saw tooth, inner & outer shear layer, variable geometry, centre rotating vortex, active chevron.

1.0 INTRODUCTION

Aircraft noise is a significant concern to those who live near any large airport. As the volume of air traffic increases, so does the impact on those increasing numbers who live near busy airports. The regulatory response to limiting aircraft noise is embodied in Federal Aviation Regulation [2] in the Unites States and in International Civil Aeronautics Organization [3] elsewhere which impose limits which become increasingly stringent with time. Manufacturers of aircraft and aircraft engines face the technical challenge of making aircraft simultaneously quieter, more powerful, and more efficient. The conflicting requirements of these goals motivate researches to apply flow control to one source of aircraft noise that will result in acoustic benefit while minimizing the impact on performance.

One of the more significant sources of aircraft noise in modern jet aircraft is the turbulence generated in the shear layers around the engine's exhaust. Commonly on large commercial aircraft there are two such shear layers generating noise, the inner and outer shear layers. The inner shear layer is the layer between the primary or core flow and the secondary or fan flow. The outer shear layer lies between the secondary flow and the free stream. At any useful operating condition we will have a significant shear velocity across one or both of these shear layers. These shear layers are unstable and the instabilities lead to vortex roll-up and transition to turbulence. ***The coherent structures and turbulent eddies generate non-equilibrium pressure fluctuations which are radiated as sound.*** A number of flow control approaches have been applied to modify the flow structures in the shear layer and the radiated sound.

The simplest and widely accepted approach for noise reduction which has begun entering service on the commercial fleet is the application of chevrons to the trailing edge of the nozzles. Unlike conventional, round nozzles, chevron nozzles employ serrations on the trailing edge. ***Chevrons are saw tooth-like patterns at the trailing edge of jet engine nozzles that help reduce noise from the ensuing jet.*** It has been known from past experimental studies with laboratory-scale jets that small protrusions at the nozzle lip called 'tabs' would suppress 'screech' tones. In the 1980's and 1990's the tabs were explored extensively for mixing enhancement in jets. These studies advanced the understanding of the flow mechanisms and suggested that the technique might have a potential for reduction of 'turbulent mixing noise' that is the dominant component of jet noise for most aircraft. These chevrons typically impinge slightly into the higher-speed flow and cause the flow passing over them to turn and curl around their trailing edges, thus introducing a rotating component to the velocity field. The net effect of each chevron is to shed a pair of stream wise vortices. These vortices speed the mixing between the flows and bring them more quickly to a low-shear condition. This has been shown to reduce the overall level of noise produced. It typically reduces the sound pressure level (SPL) at low frequencies at the expense of increasing the levels at higher frequencies. This paper serves as an overview of the chevron technology & jet noise reduction using chevron nozzles.

2.0 OCCURANCE OF NOISE

The significant noise sources originate in the fan or compressor, the turbine, and the exhaust jet or jets. The generation of the noise from these components increases with greater relative airflow velocity. Exhaust jet noise varies by a larger factor than that of the compressor or turbine, so a ***reduction of exhaust velocity has a stronger influence than equivalent reductions in the others.*** Jet exhaust noise is caused by the violent turbulent mixing of the exhaust gases with the atmosphere and is influenced by the shearing action caused by the relative speeds between the exhaust jet and the atmosphere. Turbulence created near the exhaust causes a high frequency noise (small eddies) and further downstream of the exhaust causes low frequency noise (large eddies). In addition, a shock wave is formed when the exhaust velocity exceeds the speed of sound. A reduction in noise level can be accomplished when the mixing rate is accelerated or the exhaust velocity relative to the atmosphere is reduced. This can be achieved by changing the pattern of the exhaust jet.

Compressor and turbine noise results from the interaction of pressure fields and turbulence for rotating blades and stationary vanes. Within the jet engine, the exhaust jet noise is of such high level that the turbine and compressor noise is insignificant during most operating conditions. However, low landing-approach thrusts cause a drop in exhaust jet noise and an increase in low pressure compressor and turbine noise due to greater internal power handling. The introduction of a single stage low pressure compressor significantly reduces the compressor noise because the overall turbulence and interaction levels are diminished. Also, the combustion chamber is another source of noise within the engine. However, because it is 'buried' within the engine's core, it does not have a predominant contribution. The relative importance of various noise sources is shown in the figure below.

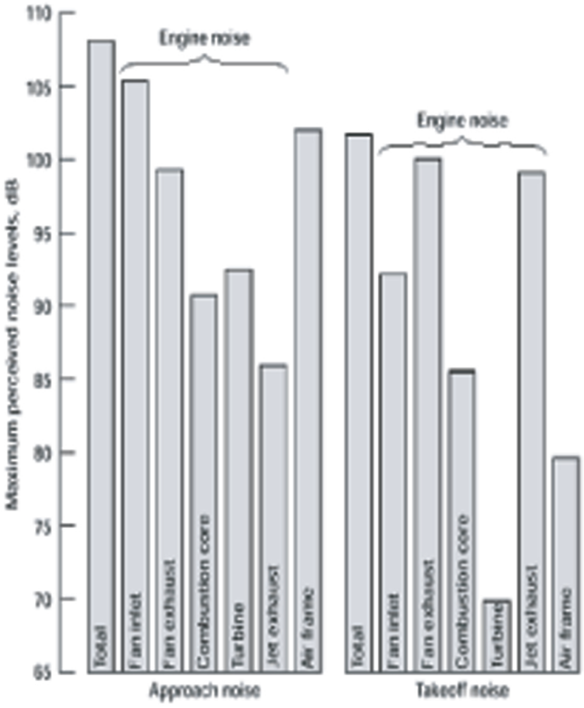

Figure 1: Aircraft relative Noise Sources [4]

3.0 NASA'S APPROACH FOR SOLUTION

With the forecast development of future high-thrust engine technology, NASA recognized the importance of investing in jet noise-reduction research starting in the 1960s[5]. In 1995, NASA's Advanced Subsonic Technology (AST) steering committee and technical working group decided to launch the Separate-Flow Nozzle (SFN) Jet Noise Reduction program with a goal of developing technologies that would achieve a minimum of a 3 Effective Perceived Noise Level (EPNLdB) reduction in jet noise while avoiding any significant loss in thrust[6]. The results from the noise studies conducted under the SFN program reveals following:

a) The test results showed that inward-facing chevrons on the core (primary) nozzle and flipper tabs on the core nozzle were sufficient in reducing the noise levels to those desired [7].

b) Additional chevrons on the fan (secondary) nozzle made additional contributions to overall noise reduction by shifting the noise further into the high-frequency range, making it more susceptible to atmospheric dampening.

Due to the efforts of NASA's SFN program, the chevron nozzle had become a promising new concept and would enter a period of continued interest and refinement over the next decade. In 2000, NASA's Glenn Research Center performed model scale tests using chevron nozzles on turbojet engines used by smaller business-class jets. The researchers determined a 2 EPNLdB reduction in noise was possible using the 6 and 12-chevron nozzles . In March 2001, these results were validated at full scale during flight tests conducted on a Learjet 25 at Estrella Sailport near Phoenix, AZ [8].

NASA continued to expand its research efforts by funding the new Quiet Technology Demonstrator (QTD) program, conceived by Rolls-Royce and the Boeing Company, in early 2000[9]. Their approach to the reduction of jet noise was adapted from NASA's SFN program and employed similar chevron nozzles. The QTD program performed static model testing and in-flight validation of these technologies on higher bypass-ratio engines typically used by larger commercial aircraft.

In 2001, NASA also, initiated the Quiet Aircraft Technology (QAT) program. This program sought to meet goals of reducing noise by 50 percent in 5 years and 75 percent in 20 years relative to best-in-fleet 1997 technology[10]. Under this program, research into jet exhaust has shown that jet noise can be controlled by varying the nozzle lip geometry. Standard jet nozzles feature an axi-symmetric conical exhaust. Adding chevrons, scallops (a type of asymmetric geometry like saw tooth) or other asymmetric lip geometry strengthens stream wise vortices which increase jet plume mixing resulting in a reduced overall sound pressure level. In 2004, NASA's Langley Research Center (with the Boeing Company under contract number NASI-00086) took a closer look at exploiting the pylon (connection manifold to the wing) interaction with the exhaust jet and examined azimuthally varying chevrons. The study concluded that T-fan (top) chevrons could reduce the overall far-field jet noise of nozzles with pylon interaction better than the existing uniform chevrons.

Building on the success of the initial QTD program, Boeing successfully conducted a follow-on effort"QTD2" in the summer of 2005. PAA (Propulsion Airframe Aero acoustics) T-fan chevron, was chosen for QTD2 flight testing. For the PAA T-fan chevron plus core chevron configuration, peak jet-mixing noise levels were reduced by up to two dB relative to the baseline production nozzle configuration. Figure 2 shows results measured at a community noise microphone for a high power setting at an aft angle. Data from unique advance noise reduction features were successfully tested aboard the 777 airplane including low-noise concepts for landing gear. A QTD3 Flight test program is currently being planned to test even more advanced noise reduction technologies[11]. The combined results from each of these programs led to the development of a more refined and more efficient chevron nozzle for use on soon-to-be, modern-day commercial aircraft.

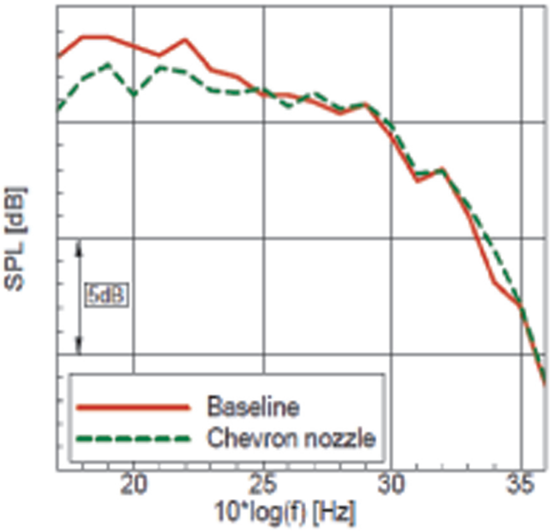

Figure 2: Spectral plot of jet noise reduction for the PAA T-fan + core chevron configuration earlier chevron designs often produced[12]

4.0 CHEVRON & ITS ROLE

One way of understanding the chevron nozzle flow is in terms of vortex distributions. Introduction of stream wise vortex pairs is necessary. These vortices appear to have a 'calming effect' reducing the overall turbulence in the shear layers. With the baseline nozzles, the vortices in the shear layer are primarily composed of the azimuthal component. Such vortices concentrate into the discrete ring-like (or helical) coherent structures. These structures go through contortions and interactions while propagating downstream. Their dynamics are unsteady and vigorous giving rise to high turbulence intensities. In contrast, the stream wise vortices are part of the steady flow feature and have a 'time-averaged definition'. They persist long distances and do not involve in vigorous dynamics like the coherent azimuthal structures. Furthermore, the only source of vortices in the flow is the efflux boundary layer of the nozzle. The chevrons simply redistribute a part of it into the stream wise component at the expense of the azimuthal component. Thus, the chevrons arrest the vigorous activity of the azimuthal coherent structures to some extent via introduction of the stream wise vortices. The result often is a reduction in the turbulence intensities that correlates with the noise reduction. Until complex vortex motions can be directly linked to sound generation, the reduced turbulence intensity is the most direct connection to the noise reduction. With the addition of the fan chevrons the surface pressure distributions were seen to change favorably, as shown in Figure 3, resulting in less nozzle base drag. Overall, the pressures became more positive on the core nozzle cowl as well as on the center plug. The higher pressures, especially on the core cowl on the left in Figure 3 (involving larger surface area), qualitatively explain the improvement in the thrust. The increased base pressures must be a result of the stream wise vortices from the fan chevrons.

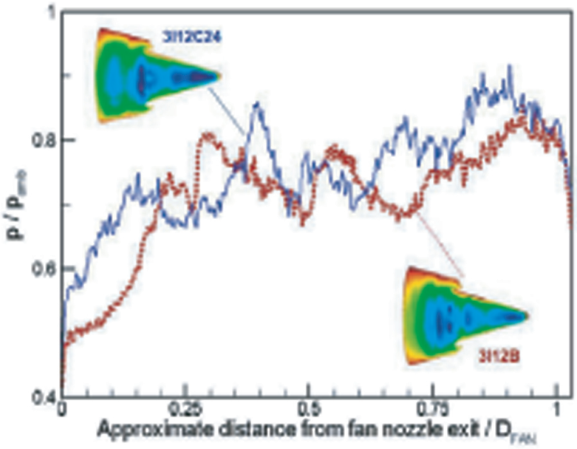

Figure 3: Surface pressure distribution obtained nozzles by pressure-sensitive-paint experiment for indicated nozzles.[13]

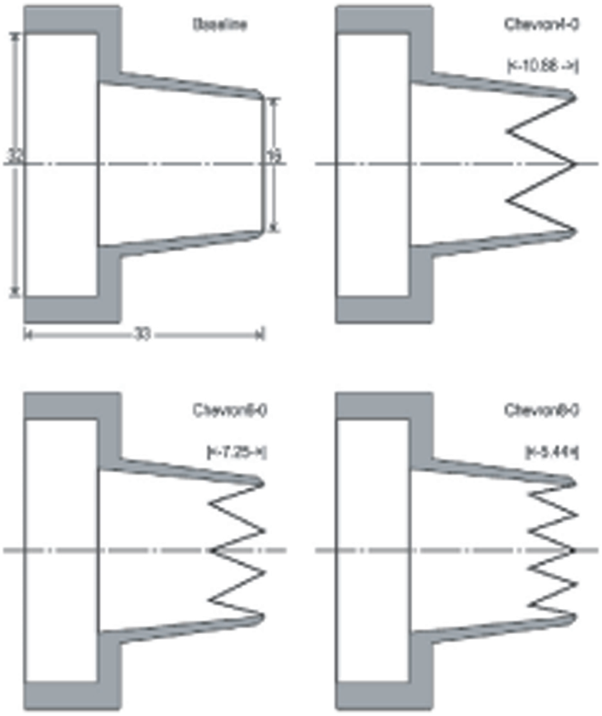

Figure 4: Dimensions of the fabricated in millimeter (section plane passes through the chevron tip)[13]

In simple words, Chevrons reduce the jet noise component of the engine noise. Since jet noise is important during take-off, the benefit of chevrons is best realized during that portion of a commercial flight. Since chevrons are zigzag or saw-tooth shapes at the end of the nacelle, with tips that are bent very slightly into the flow, this creates vortices that form at each chevron, enhancing the mixing rate of the adjacent flow streams. As previously mentioned, the jet noise is due to turbulent mixing between jets and the noise generation mechanism is very complex. When the chevrons enhance mixing by the right amount, the total jet noise reduces. If the mixing is too much, the chevrons make the noise go up. If the mixing is too little, no noise reduction benefits are realized.

5.0 UNIFORM VS VARIABLE GEOMTRY CHEVRON

In the initial designs the individual chevron plan forms of a chevron nozzle had uniform shapes. Extensive wind tunnel tests, conducted at the Boeing Low Speed Aero acoustic Facility resulted in a non-uniform nozzle design that had significantly larger chevrons near the strut and progressively smaller chevrons near the keel. Such chevron designs produce enhanced mixing near the strut due to higher immersion into the fan stream [14]. However, since greater chevron immersion may increase engine thrust loss and high-frequency noise, chevrons with less immersion are located near the keel. In order to balance the conflicting design objectives of maximizing noise reduction and minimizing the thrust loss, the concept of a variable geometry chevron fan nozzle was developed. This concept enables fan chevron immersion at takeoff, where community noise reduction is most critical, and allows for chevron alignment with the flow for the cruise segment of flight, which is most critical for fuel efficiency.

The variable geometry chevron (VGC) design incorporated flexures made of a shape memory alloy embedded into the chevrons (ref figure 5 & 6 below). These flexures react to the local temperature.

Figure 5: Variable geometry fan chevrons (inset shows individual chevron with cover removed) [15]

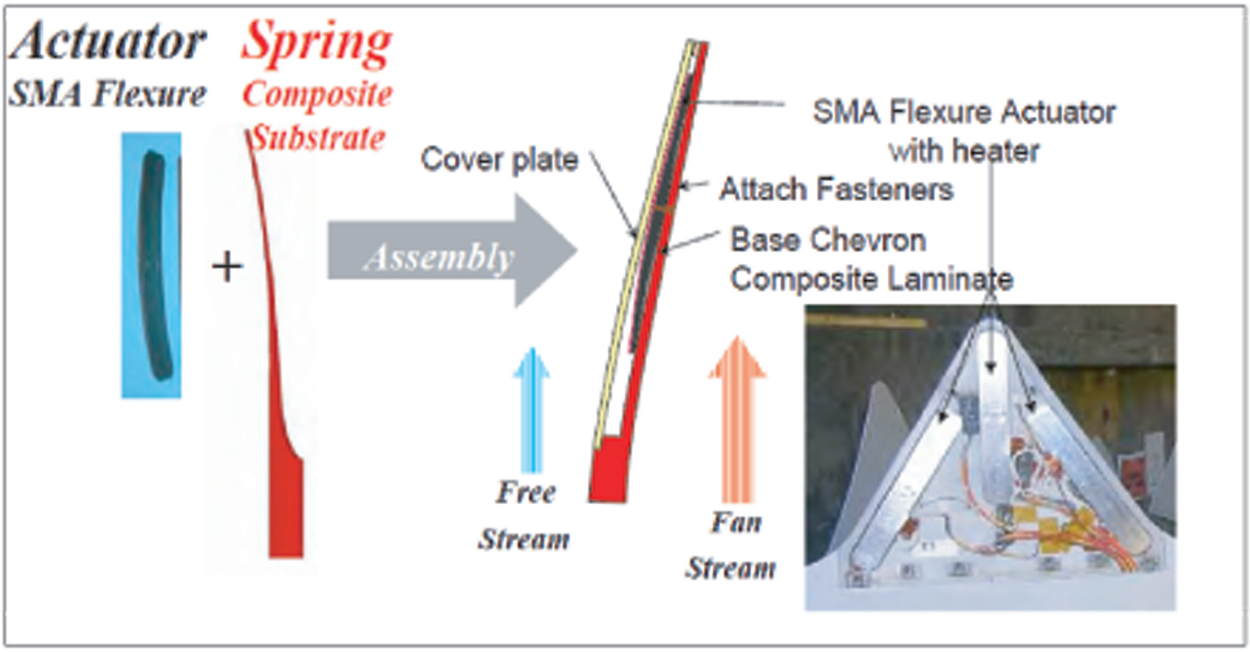

Figure 6: Detailed design of Shape Memory Alloy used for variable geometry chevrons [16]

Shape memory alloys have the unique characteristic to change shape at a specific temperature (ref figure 6). Thus for take-off the chevron nozzle can be one shape and then once out of noise sensitive regions they can be another for aerodynamically efficient shape. The primary challenge was to produce an SMA based system which would be capable of providing sufficient operational stiffness and high movement whilst still being cost effective and safe.

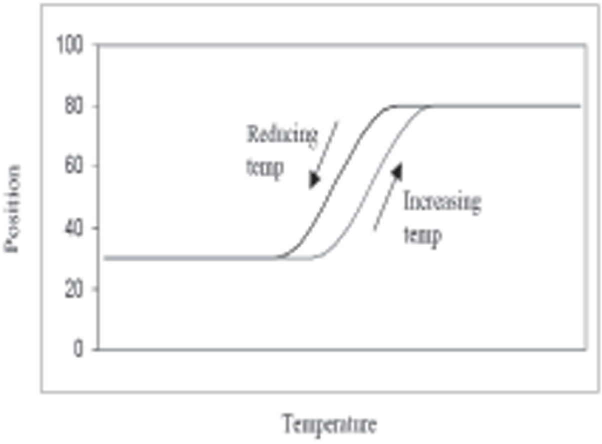

Figure 7: Position/Shape Control by SMAs (Shape Memory Alloys) [17]

6.0 ADVANCED TECHNOLOGIES

6.1 Mechanical Chevron

Mechanical chevrons are created by cutting serrations in the trailing edge of a nozzle and deflecting the serrations into the flow. These devices mix the streams and result in a reduced volume of high-speed flow. When properly designed, chevrons reduce low frequency noise and do not significantly increase high frequency noise. The number of chevrons, the serration geometry and the penetration depth of the mixers as well as many other factors affect the acoustic radiation resulting from the chevron or tabbed nozzle. Computational fluid dynamic simulations of the flow fields associated with chevron and nozzles show that significant off axis mixing occurs for both types of mixers. Comparisons between numerical results and acoustic measurements indicate that some of the most aggressive mixers produce unacceptable levels of high frequency noise.

6.2 Fluidic Chevron

Fluidic chevron uses air injected near the trailing edge of the nozzle to simulate the mixing characteristics of mechanical chevrons. It has the potential for active control. Alternating fluidic chevrons are produced by injecting air into the core and fan streams near the trailing edge of the core nozzle. Comparisons are made between the acoustic characteristics of alternating fluidic chevrons and fluidic chevrons produced by injecting air only into the core stream flow.

Fluidic chevron uses the concept of micro jet fluidic injection, a successful device in reducing jet noise in subsonic and supersonic flows. Nitrogen, water and water saturated with a long-chain polymer have been used for the injection fluid. A shortcoming of this approach is that large mass flows, on the order of 20% to 50% of the core mass flow, may be needed to achieve 2 to 3 dB reduction in overall sound pressure levels at the peak jet noise angle. Fluidic chevrons are achieved by injecting air through slots cut in the core nozzle near the nozzle trailing edge. The air is injected at a much lower pressure than that used by micro jet injection and much lower injection mass flow rates are used to achieve noise reduction. Core fluidic chevrons can be configured so that the injected air is directed only into the core stream (inflow injectors) or alternated in between the flow injected in the core stream and the flow injected in the fan stream as the slots are located around the core nozzle perimeter. Preliminary studies with inflow fluidic chevrons indicate that these types of mixers reduce overall sound pressure levels over that of a round nozzle as a result of reductions in low frequency noise. However, increased high frequency noise is also produced by these types of chevrons. One new innovation focuses on the replacement of mechanical chevrons with fluidic jets that simulate the metal serrations, ultimately leading to noise reduction. Recent studies have shown that this approach offers heightened flexibility and holds promise for even greater reductions in sound. The ability to switch off the fluid injectors during cruise conditions, as well as the ability to avoid all thrust losses, makes this emerging concept very desirable. A recent study conducted by the University of Cincinnati showed that, currently, reductions of up to 4 decibels might be achievable using fluidic chevrons [18].

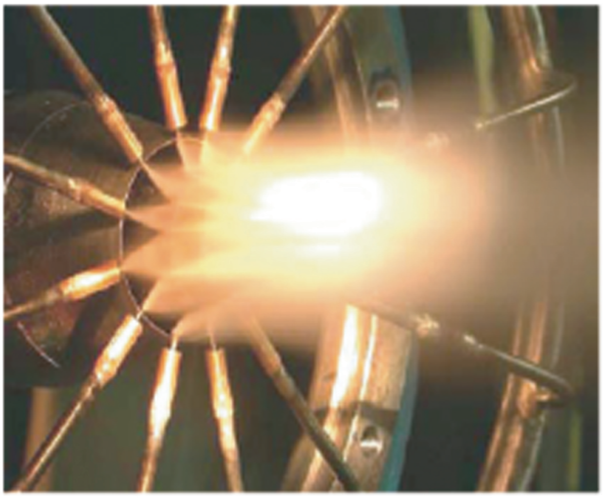

Figure 8: "Fluidic chevrons" or fluid jets used to simulate mechanical chevrons (AIAA 2009-3372) (Boeing image).[19]

6.3 Active Chevrons

Jet exhaust-nozzle chevron systems are a proven noise reduction technology, but much is yet to be learned about their parametric design space and a tradeoff between noise reduction at takeoff/landing. However, thrust loss at cruise has slowed their incorporation into production engines. One means of simultaneously addressing some parametric design issues and the tradeoff of noise reduction and thrust penalty is the development of active (deployable) chevrons. The active chevron application appears to be ideal for shape memory alloy (SMA) actuation technology because SMA actuators can be thermally activated, they can produce large force and stroke. The quasi-static nature of active chevron requirements alleviates issues associated with the limited frequency response of the thermo elastic shape memory effect. Shape memory alloys exhibit a phase transformation that is driven by temperature and stress. The thermally induced phase transformation is responsible for the well-known shape memory effect (SME). Shape memory alloys can recover a large strain by the SME when heated in an unconstrained configuration and generate large forces when strain recovery is prevented. Thus, the general concept for a SMA-enabled active chevron entails deploying the chevron under the actuation authority of pre strained SMA actuators. It is noted that the transformation temperatures of commercially available SMA materials limit their application to the bypass nozzle of typical commercial engines [20]. SMA actuators can be employed in various ways to enable active chevrons. Research showed that at least 25% greater recovery strains can be achieved through one-way actuation as compared to two-way actuation.

7.0 DISAVDANTAGE OF CHEVRON & ALTERNATIVES

A disadvantage of chevrons is that they impinge into the flow and produce a reduction in thrust. This thrust loss is an acceptable trade at take-off, but at cruise, where the need for noise reduction is less, the cost is less justified. An alternative which has shown promise is to introduce similar vortical motion into the shear layers by directly blowing air into the shear layers at an angle to the main flow. Pairs of steady blowing jets can create counter rotating vortex pairs just as chevrons do. A significant advantage of such blowing is that, it can be turned off when not needed. The bleed air required to drive the small jets introduces an undoubted performance penalty, but once the aircraft has left the noise-sensitive airport environment, the bleed can be turned off and the penalty is not incurred at cruise.

8.0 CONCLUSION

Jet noise is an issue of enormous environmental, financial and technological impact. This paper has discussed specifically a summary of development of chevron technology and its role in reducing jet noise and also about some advancement to chevron technology that will define the next generation of noise-reducing technologies and contribute to the aeronautics industry for years to come. It is extremely difficult to reduce jet noise while not impacting anything else negatively due to the constraints imposed by the engine and aircraft system requirements. Chevrons are unique as a jet noise reduction technology, in that they can have a relatively small impact on weight, performance and operability. Employment of variable geometry chevrons and fluidic jets will most likely be seen in future engine designs to achieve better noise attenuation. However, as the demand for air travel continues to increase, more stringent noise regulations will be enacted to better accommodate communities near airports. Thus, more intensive research and development is still needed for the advancement of chevrons role in reducing engine noise.

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