AIRCRAFT NOISE AND ITS SUPPRESSION

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Apart from the task for which they were conceived, many industrial products generate side effects which are unwanted, but unavoidable. When such effects give rise to public concern, remedies have to be sought in the form of technical solutions that eliminate or minimize the annoyances. The gas turbine aero-engine, conceived as a prime mover for propelling aircraft, needs the Earth's atmosphere for functioning – like man who needs the same atmosphere for living. The environmental effects of the jet engine are noise and exhaust emissions, features that are external to the engine and do not bear directly on the purpose of propelling the aircraft.

K e y w o r d s: aircraft, aircraft engine, noise, noise suppression

1 INTRODUCTION

Most technological advances are accompanied by some degree of apprehension about their potentially catastrophic effect on safety and the environment. History provides countless examples. Notable in the field of transportation are the applications of the steam engine to the locomotive, the internal combustion engine to the horseless carriage, and the whole array of engines used in the flying machine. Immediate public safety is usually the primary concern, but pollution and noise are also cited as possible sources of long-term harm to the human species. Although the passage of time has seen some of these concerns justified, humanity has learned to live with them, whilst exploiting to the full the benefits of a wide variety of transportation modes. Indeed, in developed nations, the quality of life would be downgraded considerably without the benefit of fast, reliable and diverse modes of transport. As a result, the cost of environmental protection is considered a necessary burden.

2 NOISE AND ITS IMPACT ON THE HUMAN COMMUNITY

It is easy to see why noise became an issue. The early jets were noisy - extremely so. Apart from heavy construction plant, unsuppressed motor-cycles and emergency service sirens, they were the loudest source of noise in the community. Moreover, the noise of the jet drew attention to the rapidly increasing numbers of aircraft. The noise and frequency of operation around major airports combined to catalyse public reaction in these areas. As a result, by the early 1960s, airport owners were forced to establish local noise limits, which aircraft were not permitted to exceed. Noise-monitoring systems were installed around the airport boundaries and in the communities to police the statutory limits. In some cases, noisy long-range aircraft were forced to increase their climb performance by departing "lightweight", with only sufficient fuel to take them to a less sensitive airport, where they could then take on the fuel needed to complete their mission.

The commercial airline industry has remained invested in the advancement of payload capacity for decades, and the industry is frequently moving toward greater means of propulsion. This requires constant technical investigation of means for increasing power and efficiency of existing turbojet and turbofan engines while significantly reducing engine acoustic levels. Engine noise has become a serious concern for many airports and surrounding communities. Without noise-reducing technologies, the Federal Government, airline companies, and nearby schools must spend millions of dollars on soundproofing installments to avoid the negative impacts of jet noise on schools and neighborhood communities around airports.

The defense industry is also very concerned with reducing noise levels in order to develop advanced stealth technology for future military vehicles. Stealth research is strongly dependent on reduced noise and infrared signatures, and ongoing research in noise-reduction benefits both of these technologies. Over the course of the past few decades, the field of aero acoustics has emerged to address many of these challenges and develop the enabling technologies needed to advance the next generation of aerospace vehicles.

Modern commercial aircraft employ high bypass ratio (HBPR) engines with separate flow, nonmixing, short-duct exhaust systems. These propulsion systems are known to generate significantly high noise levels due to the high-speed, high-temperature, and high-pressure nature of the exhaust jet, especially during high-thrust conditions such as those required for takeoff. [1], [2], [3]

3 NOISE IMPRESSION

Energy conversion within the jet engine, necessary for the generation of thrust, requires large masses of air to be processed. Part of the energy is absorbed by oscillations of air molecules that give rise to sound waves. Although the energetic content of sound waves is small, propagation is unconstrained and only lightly damped.

Classical parameters to characterize sound are *frequency* and *intensity*. Frequency denotes the number of oscillations per unit time, usually expressed in Hertz = 1/s (1 Hertz = 1 oscillation per second). Intensity is considered to be an objective physical quantity that defines the noise impression. It is a measure of the acoustic power emitted from a source, and is frequently expressed in the dimension of Watts per square meter (W/m^2).

One of the measures of auditory magnitude of noise to include subjective effects is termed *perceived noise level (PNL),* defined as:

$$PNL = 10\frac{\log PN}{\log 2} + 40 \qquad (1)$$

Perceived noise level (PNL) is a nondimensional logarithmic parameter derived from *perceived noisiness* PN. The value of 40 represents the auditory magnitude of a standard noise source (PN = 1) perceived by normal speech. The unit of perceived noisiness PN is the decibel, commonly written PNdB.

The unit recommended by the International Standardization Organization (ISO) to describe the noise on the ground produced by aircraft is the *effective perceived noise level* (EPNL). This unit is in widespread use for aircraft certification. This unit is commonly used to express noise annoyance. It takes into account the pitch as well as the sound pressure (deciBel) and makes allowance for the duration of an aircraft flyover. Figure 1 compares the noise levels of various jet engine types.

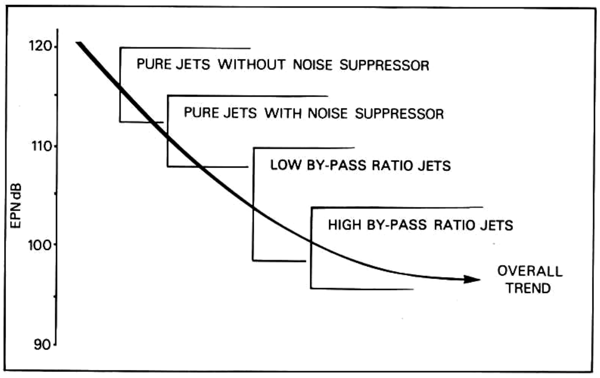

Figure 1 Comparative noise levels of various engine types [1]

4 AIRCRAFT NOISE SOURCES

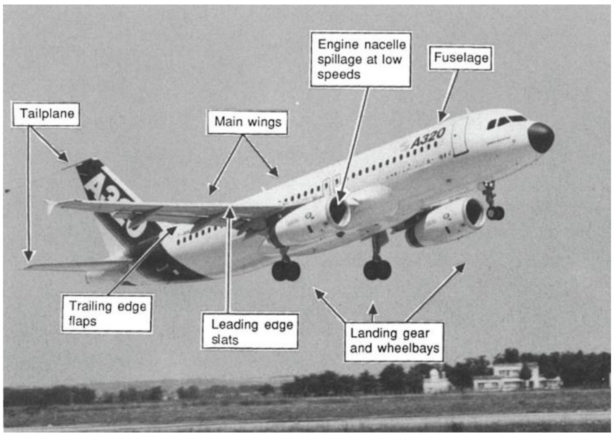

Figure 2 Sources of airframe noise [1]

Noise, or unwanted sound, is generated whenever the passage of air over the aircraft structure or through its power-plants causes fluctuating pressure disturbances that propagate to an observer in the aircraft or on the ground below. Since the flight condition cannot be maintained unless these air- and gas-flows are controlled efficiently, there are ample opportunities for sound to be produced. Fluctuating pressure disturbances result from inefficiencies in the total system and occur whenever there is a discontinuity in the airflow-handling process, particularly in the engines, where power generation involves large changes in pressure and temperature. This is not to say that the airframe itself is devoid of sound-producing opportunities, for it has a large surface area and, in the configuration that is adopted for take-off and approach, both the landing gear and high-lift devices (slats and flaps) create significant amounts of turbulence.

To the community beneath the aircraft, the self-generated noise from the airframe is normally significant only during the approach phase of operation, where the sources shown in Figure 2 can combine to exceed the level of each major noise source in the power-plant. For this reason, airframe noise has been thought of as the ultimate aircraft noise "barrier". [1][2]

5 ENGINE NOISE

To understand the problem of engine noise suppression, it is necessary to have a working knowledge of the noise sources and their relative importance. The significant sources originate in the fan or compressor, the turbine and the exhaust jet or jets. These noise sources obey different laws and mechanisms of generation, but all increase, to a varying degree, with greater relative airflow velocity. Exhaust jet noise varies by a larger factor than the compressor or turbine noise, therefore a reduction in exhaust jet velocity has a stronger influence than an equivalent reduction in compressor and turbine blade speeds.

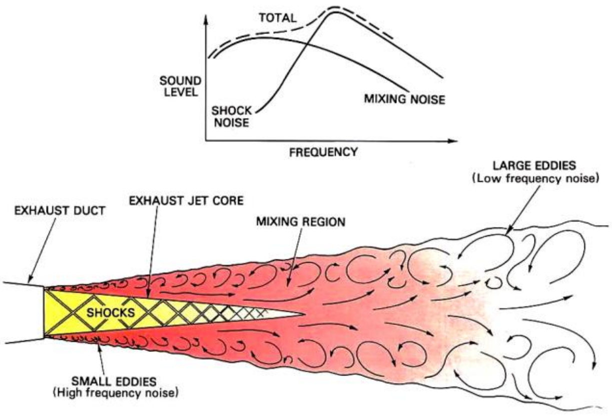

Figure 3 Exhaust mixing and shock structure [3]

Jet exhaust noise is caused by the violent and hence extremely turbulent mixing of the exhaust gases with the atmosphere and is influenced by the shearing action caused by the relative speed between the exhaust jet and the atmosphere. The small eddies created near the exhaust duct cause high frequency noise but downstream of the exhaust jet the larger eddies create low frequency noise. Additionally, when the exhaust jet velocity exceeds the local speed of sound, a regular shock pattern is formed within the exhaust jet core. This produces a discrete (single frequency) tone and selective amplification of the mixing noise, as shown in Figure 3.

Compressor and turbine noise results from the interaction of pressure fields and turbulent wakes from rotating blades and stationary vanes, and can be defined as two distinct types of noise; discrete tone (single frequency) and broadband (a wide range of frequencies). Discrete tones are produced by the regular passage of blade wakes over the stages downstream causing a series of tones and harmonics from each stage. The wake intensity is largely dependent upon the distance between the rows of blades and vanes. If the distance is short then there is an intense pressure field interaction which results in a strong tone being generated. With the high bypass engine, the low pressure compressor (fan) blade wakes passing over downstream vanes produce such tones, but of a lower intensity due to lower velocities and larger blade/vane separations. Broadband noise is produced by the reaction of each blade to the passage of air over its surface, even with a smooth airstream. Turbulence in the airstream passing over the blades increases the intensity of the broadband noise and can also induce tones.

With the pure jet engine the exhaust jet noise is of such a high level that the turbine and compressor noise is insignificant at all operating conditions, except low landing-approach thrusts. With the bypass principle, the exhaust jet noise drops as the velocity of the exhaust is reduced but the low pressure compressor and turbine noise increases due to the greater internal power handling.

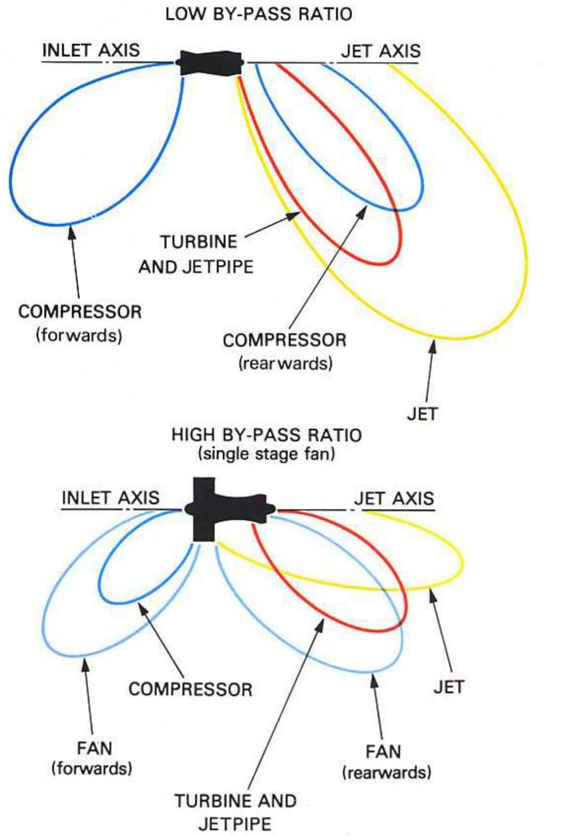

Figure 4 Comparative noise sources of low and high by-pass engines [3]

The introduction of a single stage low pressure compressor (fan) significantly reduces the compressor noise because the overall turbulence and interaction levels are diminished. When the bypass ratio is in excess of approximately 5 to 1, the jet exhaust noise has reduced to such a level that the increased internal noise source is predominant. A comparison between low and high by-pass engine noise sources is shown in Figure 4.

Listed amongst the several other sources of noise within the engine is the combustion chamber. It is a significant but not a predominant source, due in part to the fact that it is 'buried' in the core of the engine. Nevertheless it contributes to the broadband noise, as a result of the violent activities which occur within the combustion chamber.

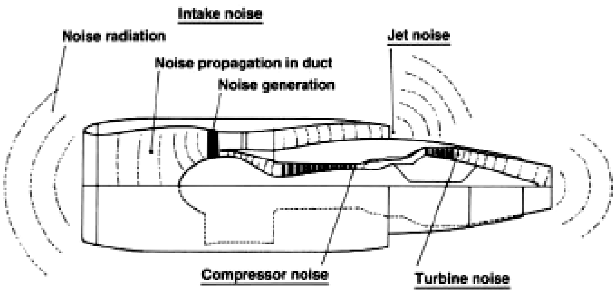

Figure 5 Sources of engine noise [2]

According to Lighthill's theory, the radiated sound intensity may be written as:

$$P \approx \rho . d^2 . c^n \tag{2}$$

where: ρ pair density, d nozzle exit diameter, c exhaust velocity.

Noise level, therefore, will increase with engine mass flow rate (being proportional to air density ρ) and the square of the diameter d of the noise source. The influence of velocity c can only roughly be estimated, by assuming a value for the exponent n. [2][4][3]

6 NOISE SUPPRESSION

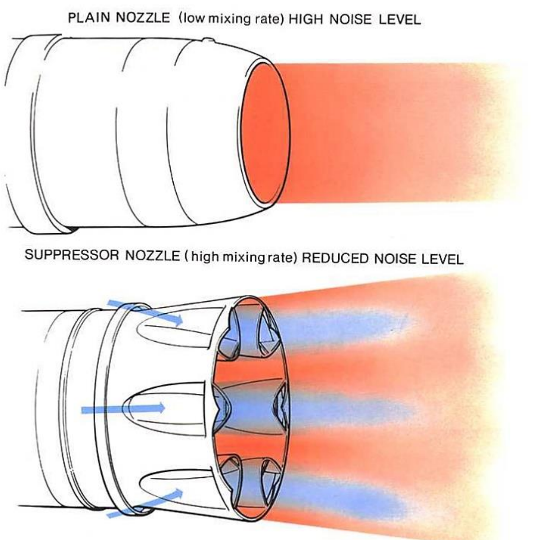

Figure 6 Change of exhaust jet pattern to reduce noise level [3]

Noise suppression of internal sources is approached in two ways; by basic design to minimize noise originating within or propagating from the engine, and by the use of acoustically absorbent linings. Noise can be minimized by reducing airflow disruption which causes turbulence. This is achieved by using minimal rotational and airflow velocities and reducing the wake intensity by appropriate spacing between the blades and vanes. The ratio between the number of rotating blades and stationary vanes can also be advantageously employed to contain noise within the engine.

Sources of noise at the output of the engine is gas stream flowing from the nozzle at high speed into a quiet environment and its mixing with the surrounding atmosphere. Silencers at the output of engine operates on the following principles:

- extender accelerates the mixing of the exhaust gas flow with the surrounding air by increasing gas stream surface which is caused by splitting it into several smaller streams;
- by the reduction of cross section streams will shift the predominant frequencies in higher frequencies, thereby the rapid loss of sound power;
- extender reduces the absolute flow velocity at the outlet by increasing of the flow cross-section nozzle.

The best effect is obtained by combining these three principles. An unfortunate consequence of the use of silencers is the reduction of thrust by the increase of loss at the outlet. Literature suggests that reducing the noise by 10 dB will thrust decrease by 1%, a reduction of 30 dB decreases thrust by 13%.

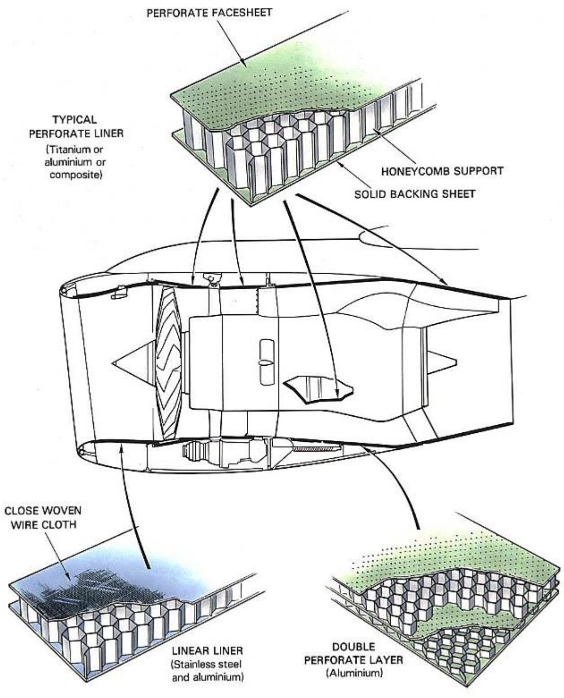

Figure 7 Noise absorbing materials and location [3]

Deep corrugations, lobes, or multi-tubes, give the largest noise reductions, but the performance penalties incurred limit the depth of the corrugations or lobes and the number of tubes. For instance, to achieve the required nozzle area, the overall diameter of the suppressor may have to be increased by so much that excessive drag and weight results. A compromise which gives a noticeable reduction in noise level with the least sacrifice of engine thrust, fuel consumption or addition of weight is therefore the designer's aim.

Noise absorbing 'lining' material converts acoustic energy into heat. The absorbent linings (Figure 7) normally consist of a porous skin supported by a honeycomb backing, to provide the required separation between the face sheet and the solid engine duct. The acoustic properties of the skin and the liner depth are carefully matched to the character of the noise, for optimum suppression. The disadvantage of liners is the slight increase in weight and skin friction and hence a slight increase in fuel consumption. They do however, provide a very powerful suppression technique. [1][2][3][4]

7 CONSTRUCTION AND MATERIALS OF NOISE SUPPRESSORS

The corrugated or lobe-type noise suppressor forms the exhaust propelling nozzle and is usually a separate assembly bolted to the jet pipe. Provision is usually made to adjust the nozzle area so that it can be accurately calibrated. Guide vanes are fitted to the lobe-type suppressor to prevent excessive losses by guiding the exhaust gas smoothly through the lobes to atmosphere. The suppressor is a fabricated welded structure and is manufactured from heat resistant alloys.

Various noise absorbing lining materials are used on jet engines. They fall mainly within two categories, lightweight composite materials that are used in the lower temperature regions and fibrous metallic materials that are used in the higher temperature regions. The noise absorbing material consists of a perforate metal or composite facing skin, supported by a honeycomb structure on a solid backing skin which is bonded to the parent metal of the duct or casing. [3]

8 THE CHEVRON NOZZLE: A NOVEL APPROACH TO REDUCING JET NOISE

The ability to control the area of the fan nozzle will enable the next generation of quieter, more efficient, and cleaner commercial jet engines. Current commercial turbojet engines have fixed fan nozzles with a design that is a compromise between efficient cruise operation and suitability for take-off and landing. In general cruise operation would be more efficient with a smaller diameter nozzle; however the optimal cruise design point is often unacceptable for take-off as it will cause the engine to stall. Variable area fan nozzles (VAFN) avoid the current design compromises and allow optimal nozzle geometry for all flight phases. In addition to improved efficiency, varying the fan nozzle area, and hence the engine bypass ratio, is an extremely effective means of reducing community noise during takeoff and approach.

Boeing is currently demonstrating practical and realizable VAFN technology for future aircraft. Concepts have been developed for such devices that are deployed using shape memory alloy (SMA) actuators. Shape Memory Alloys convert thermal energy into mechanical energy by way of a thermally induced micro-structural change in the material. The Austenitic phase of the material is stable at high temperatures, while the Martensitic phases are at equilibrium at low temperatures. A thermally induced change in the SMA microstructure results in a macroscopic actuator shape change.

Figure 8 Flight test hardware for Variable Geometry Chevrons [6]

The Boeing VAFN concepts follow several years of successful design and test of SMA actuators to vary the geometry and shape of fan nozzles and other aerodynamic devices. In 2005 and 2006 Boeing conducted full-scale flight test and static engine test of Variable Geometry Chevrons on a 777-300ER. These tests demonstrated the technology readiness of SMA Actuators for controlling the shape of complex aerostructures. The flight test hardware is shown in Figure 8. Three SMA actuators were integrated into each chevron and were controlled via a simple PID controller to vary the nozzle geometry and correlate the geometry with fan exhaust noise.

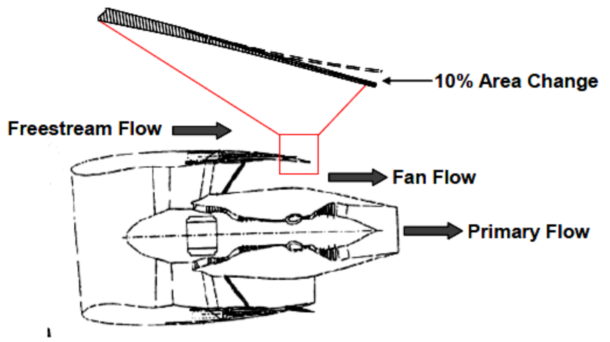

Figure 9 Variable Area Fan Nozzle concept [6]

Many tests and analysis of VAFNs have verified their benefit on commercial jet engines. The jet engine fan nozzle controls the engine back pressure and ensures the efficient conversion of exhaust gas potential energy to kinetic energy during the gases expansion to ambient pressures. Also opening up the exit area of the nozzle decreases the fan velocity and the associated jet noise. In addition a VAFN provides the ability to set the optimum area for the engine working point for a given flight condition, thus minimizing the thrust specific fuel consumption (TSFC) during that portion of the flight. Significant benefits can be achieved on commercial fan nozzles engines with area changes on the order of just 10 - 20%, see Figure 9.

A typical system consists of bimetallic actuators rely on passive return of actuator to the initial position by spring or other structural elements after exposure action value (temperature). These elements, however, at the time of deflection actuator acting against the motion, thus shown to reduce the response time and follows the displacement amplitude. The need for dynamic management of secondary nozzle with an acceptable response time because engineers have designed a system actuators with opposite deviations, which is also the reason why is needed to use trio actuators in every segment of the nozzle. To overcome the forces acting on the nozzle wall segments at airflow shrinking diameter is necessary until a pair of actuators (for contraction), while in the opposite case (for expansion) just to open the nozzle as well as to overcome the inertia of the neighboring actuators a bimetal actuator.

The nozzle was tested in Boeing's Quiet Air Facility in Seattle Washington. Fully expanded Mach number was varied up to 1.1. The control system was used to maintain a constant diameter with varying nozzle flow conditions and to vary the diameter under constant flow conditions. Acoustic data by side line microphones and flow field measurements at several cross-sections using PIV was collected at each condition.

The nozzle was first controlled over a range of diameters while the nozzle flow was held constant at 0.9 Mach. The nozzle's diameter and the controller set point vs. time are shown in Figure 10. Reasonably good control is demonstrated for both increasing and decreasing diameters. The large overshoot shown at about 100 minutes was caused by an unknown perturbation in the test or control system which resulted in an overheating of the contracting actuators for a short period of time.

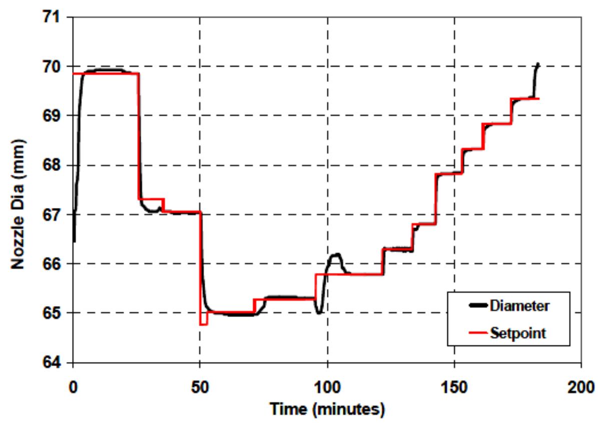

Figure 10 Variable nozzle diameter at constant flow conditions [6]

For the purpose of measuring noise were on the test aircraft deployed noise sensors. On Figure 11 is shown the noise power spectrum, which corresponds to the intensity value of sound pressure levels in dB. For comparison of averages is the area bounded by the spectrum. The solid contour line is for the minimum diameter nozzle flow compared to two other diameters shown by the dashed and dotted lines. When the nozzle is opened to 67mm (2.65”) the source extent is significantly reduced at first, as shown by large dashed line. However, further opening to 70mm (2.75”) moves the source peak location closer to the nozzle exit and the extent is increased. This is compatible with the results obtained from the sideline data. The flow character change by possible partial separation could be the source of such behavior. [5][6]

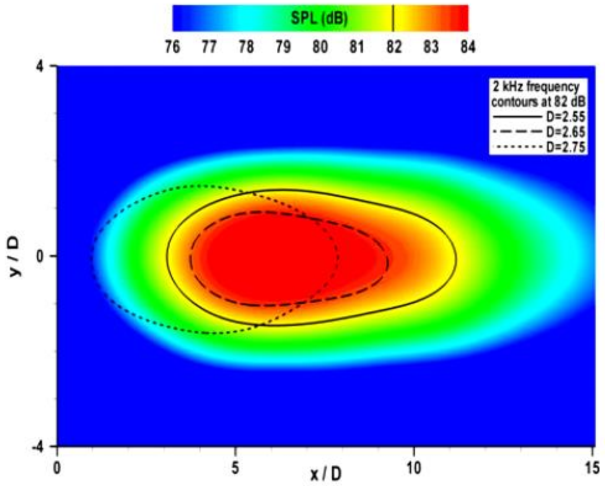

Figure 11 Noise source mps for 3 nozzle diamters [6]

9 CONCLUSION

The international community is demanding quieter, cleaner, and more efficient commercial transportation aircraft. The aviation industry is responding with the development of new technologies towards achieving those goals. A significant reduction in noise and improved fuel consumption can be achieved by varying the area of a commercial jet engine’s fan nozzle. A larger diameter at takeoff and approach can reduce jet velocity reducing noise. Adjusting the diameter in cruise, to account for varying Mach number, altitude, etc., can optimize fan loading and reduce fuel consumption and emissions. Boeing recently tested a scaled variable area jet nozzle capable of a 20% area change. Shape Memory Alloy actuators were used to position 12 interlocking panels at the nozzle exit. A closed loop control system was used to maintain a range of constant diameters with varying flow conditions and to vary the diameter under constant flow conditions. Acoustic data by side line microphones and flow field measurements at several cross-sections using PIV was collected at each condition.

A subscale proof of concept demonstration of a variable area jet nozzle was demonstrated using SMA actuators configured in an antagonistic design. A simple PID feedback controller maintained constant diameter with varying nozzle flow parameters and vary diameter control with constant flow conditions. Area control of 0% to 20% expanded area at Mach rates up to 1.1 was shown. Acoustic data by side line microphones showed a significant reduction in nozzle noise when the area was expanded. Flow field measurements at several cross-sections using PIV showed significant effects from the joints between the interlocking panels.

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