Taylor & Francis
Taylor & Francis Group

AVIATION
ISSN 1648-7788 print / ISSN 1822-4180 online
2012 Volume 16(1): 25–32
doi:10.3846/16487788.2012.679770

TECHNOLOGIES FOR JET NOISE REDUCTION IN TURBOFAN ENGINES

Mofid Gorji-Bandpy[1], Mohammadreza Azimi[2]

Department of Mechanical Engineering, Babol Noshirvani University of Technology, P.O. Box 484, 47148-71167 Babol, Mazandaran, Islamic Republic of Iran
E-mail: [2]m_r_azimi1991@yahoo.com (corresponding author)

Received 24 November 2011; accepted 29 February 2012

MOFID GORJI-BANDPY, *PhD, Eng.*
Education: MSc (Eng.), Faculty of Engineering, Department of Fluid Mechanics and Heat Transfer, University of Tehran, Iran, 1976–1978; PhD, School of Engineering, Division of Mechanical Engineering, University of Wales College of Cardiff (UWCC), Cardiff, UK, 1987–1991.
Affiliations and functions: full time professor, Department of Mechanical Engineering, Noshirvani University of Technology, Babol, Iran (since 1979), visiting professor, Department of Mechanical and Industrial Engineering, University of Toronto, Canada, and coordinate supervisor, University of Guildford, Surrey, UK (since 1997).
Research interests: propulsion systems, fluid mechanics, and turbo-machinery.
Publications: author of more than 200 scientific articles, 9 textbooks, and 1 book chapter.

Mohammadreza AZIMI, *Eng.*
Date of birth: 1991.
Education: 2004–2007 – National Organisation for Development of Exceptional Talents.
2008–2012 – BSc., Department of Mechanical Engineering, Noshirvani University of Technology, Babol, Iran.
Affiliations and functions: BSc Department of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran.
Research interests: turbo-machinery and propulsion systems.
Publications: author of 2 articles and 3 conference presentations.

Abstract. Turbofan engines are commonly used for commercial transport due to their advantages of higher performance and lower noise. Jet noise is one of the principal noise sources of turbofan aeroplane engines and remains an acute environmental problem that requires advanced solutions. The ever-increasing demand for quieter engines requires the exploration of alternative techniques that could be used by themselves or in conjunction with existing methods. Significant progress continues to be made with noise reduction for turbofan engines. Analytical and semi-empirical models have been developed to investigate the influence of some design tools when they are employed in a multidisciplinary optimisation framework. This paper discusses the major components of jet noise in turbofan engines and presents a review of jet noise reduction technologies.

Keywords: turbofan engine, noise reduction, engine noise, jet noise.

1. Introduction

Noise from aircraft are a second source of noise only to road traffic noise in drawing complaints from public about noise pollution, therefore, the reduction of noise around airports is one of the most urgent and crucial matters for aircraft and engines. The first generation of subsonic jetliners was very noisy because of the high exhaust velocity of their engines. By the introduction of the high bypass ratio turbofan, the noise level was reduced remarkably, by 20–30 dB (Smith 1989). This was simply achieved by the same thrust being produced with a larger mass flow rate, hence lower exhaust speed. The associated gains in propulsive efficiency led to much lower fuel consumption, making the high-bypass turbofan the only choice for commercial aircraft developed in the 1980s and afterwards. Significant reduction in jet noise was achieved by producing the same thrust with larger mass flow rate, hence the lower exhaust speed in modern high-bypass engines. In recent decades, aircraft noise mitigation has been investigated by many researchers (Narkiewicz, Pietrucha 1998; Žilienė, Stankūnas 2002; Vanker *et al.* 2009).

There are two main noise sources in today's commercial turbofan engines: fan/compressor noise (not discussed in this paper) and the exhaust (also referred to as the jet). Among the sources of aircraft noise, jet engine noise is the dominant noise. Jet noise itself is composed of turbulent mixing noise and, in the case of imperfectly expanded jets, shock noise. Jet mixing noise is a strong characteristic of jet exhaust velocity. Consequently, noise reduction strategies are aimed at increasing the bypass ratio to lower nozzle exit velocities and designing bypass and core flows to improve mixing with each other and the atmosphere. If jet exhaust velocity is greater than the local speed of sound, very high levels of broadband shock-associated noise and screech tones can be generated.

To facilitate future growth in air transportation while ensuring compliance with the increasingly stringent noise regulations, researchers must investigate noise reduction technologies. In this paper, the main technologies for jet noise reduction in current turbofan engines will be presented.

2. Jet noise

The trend of aircraft engine noise has been the growing dominance of turbofan noise in the radiated acoustic field. Particularly during high thrust operation, such as take-off, reported sound levels radiated by turbofans are 15–20 dB greater than the broadband noise (Thomas *et al.* 1997). Furthermore, higher bypass ratio engines being the norm, the noise levels can only be expected to rise. In modern high bypass ratio turbofan engines, the jet contributed to about half of overall noise generation. Jet noise is due to the high-velocity, high-temperature core jet mixing with low-velocity, low-temperature atmospheric gases and in the case of imperfectly expanded jets, shock noise (Tam, Chen 1994).

A primary source of jet engine noise is the shear region of exhausted air streams, where different high-velocity air streams mix with each other and slower moving ambient air. Mixing of the jet core and bypass exhausts and mixing with the atmosphere produce a broad sound frequency spectrum. The shape of the spectrum reflects the fact that the eddies that comprise the turbulent mixing process vary considerably, increasing in size progressively downstream of the exhaust nozzle and decaying in intensity as the average exhaust velocity falls and the mixing becomes complete. Jet mixing noise is a strong function of jet exhaust velocity. Consequently, noise reduction strategies are aimed at increasing bypass ratio to lower nozzle exit velocities and designing bypass and core flows to improve mixing with each other and the atmosphere. If the jet exhaust velocity is greater than the local speed of sound, very high levels of broadband shock-associated noise and screech tones can be generated. These noises are usually controlled by careful design of the jet nozzles, however.

Numerous experiments confirm that most large-scale turbulent mixing noise comes from the region around the end of the potential core (Mikkelsen, Bridges 2000; Panda, Zaman 2001; Panda, Seasholtz 2002; Hileman, Samimy 2001; Narayanan *et al.* 2002; McLaughlin *et al.* 1975; Troutt, McLaughlin 1982). This leads to noise reduction via reduction of the convective Mach number. Mixing secondary air with the primary exhaust reduces the velocity of the faster of the flows so Mach wave radiation can be reduced by surrounding the primary jet with secondary flow so that the primary eddies become subsonic with respect to the secondary flow, while ensuring that the secondary eddies are subsonic. In a jet with fixed exit flow conditions, reduction of the Mach number entails controlling convective velocity and controlling the medium surrounding the instability wave. The former requires some form of excitation that can change convective velocity not only at the nozzle exit but also five to twenty diameters downstream, depending on the length of the potential core. The latter scheme is more plausible as it involves manipulation of a secondary stream. Today all commercial aircraft engines have a secondary stream, the bypass flow.

In coaxial jets, as created by separate flow turbofan engines, the primary (core) jet is initially surrounded by the secondary (bypass) stream, which acts as a moving medium. In the coaxial exhaust of typical engines, the secondary stream becomes fully mixed well up-stream at the end of the primary potential core. As a result, a substantial part of the core noise source region is not covered by the secondary flow. Some noise reduction certainly occurs, but not near the levels one would expect

(Papamoschou 2002). The end of the potential core is associated with very strong turbulent fluctuations. There are two convective Mach numbers that influence noise emission: one for primary instability with respect to the secondary stream and the other for secondary instability with respect to the ambient. In non axisymmetric arrangements there is also an azimuthal dependence of the mean flow variables. Which of the two convective Mach numbers is more important depends on the volume and intensity of noise sources associated with each distribution. Various methods have been developed to reduce the generation of jet noise in turbofan engines.

2.1. Offset nozzles

In a turbofan engine, several parameters such as stream temperatures, nozzle geometry, velocity ratio and inflow conditions are indeed expected to have significant effects on the physical mechanisms taking place. The primary stream of coaxial jets is for instance usually strongly heated, which might affect noise generation. The exhaust velocities, Mach numbers, and mass flow rates are largely fixed by the engine cycle, and one has little freedom to alter them. In broader terms, in a dual-stream jet, shaping exhaust flow away from traditional configurations has the potential for significant noise reduction; therefore, substantial noise reduction is achievable by reshaping the nozzle from coaxial to eccentric. The essence of eccentric nozzles is to offset an annular stream with respect to the primary stream. When this is done, noise on the 'fat' side of the annular stream gets reduced relative to the noise of the concentric case. It is a directional attenuation of noise with obvious practical relevance (Zaman, Papamoschou 2006).

Eccentric or severely offset nozzles are probably not viable because of the drastic redesign of the nacelle and the messy flow path in the outer nozzle. In flight, if the annular stream could be underneath, less noise would be heard on ground. An experiment done by D. Papamoschou and M. Debiasi at Mach 1.6 cruise showed that the eccentric arrangement is 6.5 dB quieter than the mixed-flow arrangement and 5 dB quieter than the coaxial configuration (Papamoschou, Debiasi 2003). They indicate that the eccentric exhaust is free of strong Mach wave radiation and that the acoustic benefit of the eccentric arrangement, combined with faster climb afforded by the modified engine, leads to a reduction of 14 dB in EPNL. Compared to the baseline engine, the specific fuel consumption of the modified engine is about 13% less at subsonic climb and 3% less at supersonic cruise. D. Papamoschou and M. Debiasi in another study at the University of California-Irvine (Papamoschou, Debiasi 2001) used eccentric dual-stream jets with a normal velocity profile and showed considerable noise reduction in the direction of the thickened secondary (outer) flow.

Researchers have independently observed similar benefits of offset co-annular nozzles (Harper-Bourne 2001). The jets were high-speed, and the bypass ratios were small. The noise reduction trends observed in those experiments were verified in a larger rig at NASA Glenn Research Center (Harper-Bourne 2001; Zaman 2004).

2.2. Chevrons

Offsetting the nozzles to an eccentric geometry did not offer an attractive engineering solution for high-bypass engines. Notwithstanding the possible losses and imbalances caused by the new flow path, an eccentric arrangement would require a new nacelle structure and radical redesign of propulsion systems such as thrust reversers (Papamoschou, Nishi Kimberley 2004). The most successful technique for reducing jet noise from high-bypass engines involves the installation of chevron mixers. Chevrons or serrations added to the nozzle geometry protrude into the flow and generate axial vorticity and therefore enhance the mixing of core, fan and ambient air streams. Placed around the trailing edge of either the core or fan exhaust nozzle, they promote mixing of the jet flow and result in lower bulk jet velocity and lower noise. Chevrons are saw-tooth shapes at the end of the nacelle, with tips that are bent very slightly into the flow, and they work by strengthening streamwise vortices that increase mixing within the plume to hasten jet potential core decay. Mixing occurs by penetrating the chevron tip at a small distance into the flow and producing streamwise vortices from the pressure differential across the chevron. Mechanical chevrons are relatively simple to manufacture and install. As passive devices with a fixed geometry, they have the disadvantage of only being optimised for one flight condition, however. They cannot adapt to changes in the flow environment and adjustments cannot be made to compensate for changing flight operations or installation effects (Henderson *et al.* 2006). Enhanced mixing usually increases the smaller scales of motion and thus adds to high frequency noise. The breakdown of larger scale turbulence into small-scale turbulence however reduces low frequency noise at its peak. In 1996, NASA tested a concept that utilised chevron nozzles. The nozzles allowed the core and bypass flows to mix in a way that reduced low frequency mixing noise from highly turbulent flows (Uzun, Hussaini 2007). NASA studied the amount of EPNL reduction for the following nozzle configurations: chevrons were installed only on the fan exhaust, only on the core exhaust, and on both. Greater EPNL reduction was obtained when the chevrons were simultaneously on both the fan and core exhaust nozzles. Chevrons penetrating the boundary layer of the core flow provided even greater noise reduction, achieving an EPNL benefit of up to 2.5 dB and only a 0.50% loss in thrust (Mikkelsen, Bridges 2000).

D. Papamoschou and K. A. Nishi Kimberley used an alternative that was thought to provide equal or greater acoustic benefit while minimizing modifications (Papamoschou, Nishi Kimberley 2004). The most promising configuration involves the use of deflector vanes installed near the bypass duct that cause the bypass plume to tilt relative to the core plume. In effect, this method creates eccentricity not at the nozzle exit but further downstream. D. Papamoschou and K. A. Nishi Kimberley also simulated the exhaust of turbofan engines with bypass ratios of 4.5 and 6.0. The secondary stream was deflected downwards by means of vanes installed inside the bypass duct in the proximity of the duct exit. Two pairs of convergent bypass ducts with vanes installed at azimuth angles 70 and 110 with respect to the vertical constitute one of the most promising configurations. A substantial benefit in EPNL occurs when the vanes have dissimilar angles of attack, with the upper pair at smaller incidence than the lower pair. The best arrangement offered a 5.3-dB reduction in the sum of flyover and sideline EPNL.

2.3. Fan flow deflector

The main concept of a fan flow deflector (FFD) is to keep the exhaust coaxial but deflect the secondary (fan) flow using vanes or similar devices in the secondary flow path. Realistic applications would involve simultaneous downward and sideward deflections for suppression of noise underneath the aircraft and on the sideline. The method has been tested in a variety of experiments using co-annular nozzles (Papamoschou 2004a, b).

Noise produced by fine-scale turbulence dominates the acoustic spectrum at observational angles in the upstream direction, and noise resulting from large-scale structures radiates in the downstream direction. Large-scale mixing noise is the most intense noise source in turbulent pressure-matched jets and radiates at angles close to the jet axis. Fan flow deflection (FFD) technology targets suppression of large-scale turbulent mixing noise from aircraft engines. The overarching principle of the FFD method is reduction in the convective Mach number of turbulent eddies that generate intense downward and sideward sound radiation. The deflectors thicken the low speed flow underneath the core jet, resulting in lower noise emission towards the ground. One aspect of the noise suppression mechanism involves extending the 'secondary core' of the jet. In a coaxial separate-flow turbofan engine, this is achieved by tilting in the general downward direction, by a few degrees, the bypass (secondary) plume relative to the core (primary) plume. Mean flow surveys show that the misalignment of the two flows causes a thick, low-speed secondary core on the underside of the high-speed primary flow, especially in the region near the end of the primary potential core which contains the strongest noise sources. The secondary core reduces the convective Mach number of the primary eddies, thus hindering their ability to generate sound that travels to the downward acoustic far field (Papamoschou, Shupe 2006). Another role of the FFD is to direct some of the fan stream underneath the core stream, thus reducing velocity gradients and turbulent kinetic energy production on the underside of the jet. Elongation of the secondary core inflectional layer and contraction of the primary potential core prolongs the region of the primary shear layer that is 'silenced' by the fan flow. As mentioned, reduction in the velocity gradient is expected to reduce the production rate for turbulent kinetic energy, k. Previous experiments and computations in dual-stream nozzles with fan flow deflectors have shown reduced values of k on the underside of the jet (Shupe *et al.* 2007). Importantly, the experiments have shown a correlation between velocity gradients and the end of the potential core of the jet (Dippold *et al.* 2007). Given that the jet has a finite axial extent, it is thus possible to reduce k throughout the underside of the jet. In turn, reducing k is expected to reduce the noise source correlation between reduction in velocity gradients and directional noise suppression from asymmetric dual-stream jets. M. Nielsen and D. Papamoschou investigated trends of high-frequency noise reduction, in the direction of peak emission, versus the distortion of the velocity field in the jet plume. They observed that fan flow deflection increases the volume of the secondary core (in the downward and sideline azimuth directions) and decreases the volume of the high-speed region (Nielsen, Papamoschou 2008). In other words, the physics of noise reduction apparently involves 'shielding' high-speed noise sources with an enlarged secondary core in combination with the compaction of those sources.

Tilting the bypass stream is possible by means of fixed or variable vanes installed near the exit of the bypass duct. Two types of deflectors have been investigated so far: airfoil-shaped vanes mounted at various azimuth angles and a wedge-shaped deflector located at the top of the nozzle. Both devices can be internal or external to the bypass duct, although for commercial applications it is strongly preferred that the vanes are internal to avoid shock losses. In a study by D. Papamoschou, subscale aero acoustic experiments simulated the exhaust flow of a turbofan engine with a bypass ratio of 6.0 (Papamoschou 2004c) Deflection of the bypass stream resulted in suppression of the overall peak sound pressure level by 4.5 dB and the effective perceived noise level (EPNL) by 2.8 dB. For the nozzle configuration used, the trust loss is estimated at approximately 0.5% with the vanes activated and 0.15% with the vanes deactivated.

Wedge-shaped fan flow deflectors have been studied for low-bypass and high-bypass configurations (Papamoschou 2006). Experimentations with a variety of wedge shapes and sizes showed that porous wedge deflectors have superior aerodynamic features that enhance their potential as noise reducing agents and also clarified that the wedge angle was the most critical parameter. At the same base dimension, wedges with large angles reduced downward emitted noise significantly, while those with small angles produced little reduction. J. Xiong *et al.* used experiments and computations to analyse the flow field of full turbofan nozzle equipped with porous wedge-shaped deflectors (Xiong *et al.* 2011). They concluded that the flow field is affected not only by the porosity of the deflectors but also by the illumination angle. The illumination angle, defined with respect to the free stream flow, has a profound impact on the flow field through and around the porous surface. For negative free stream illumination angles, there is no direct path for the flow to pass through the surface. Instead, flow through the perforations is driven by the pressure difference across the surface. D. Papamoschou tested two types of deflectors in 'classic' laboratory nozzles with parallel exit flow lines and in 'realistic' nozzles with convergent flow lines characteristic of turbofan engines (Papamoschou, Nishi Kimberley 2005). Vanes provide noticeable noise reduction for both types of nozzles, although noise reduction in the realistic nozzle was superior to that in the classic nozzles. Tests of an internal wedge-type deflector however showed practically no noise benefit in a classic nozzle, while there was significant benefit in a realistic nozzle. The discrepancy between classic and realistic nozzles was observed in a small-scale experiment at U. C. Irvine and in large-scale experiments at NASA Glenn Research Center (Zaman, Papamoschou 2006).

In another study, A. D. Johnson *et al.* investigated the optimisation of the implementation of fan flow deflection for jet noise suppression from a supersonic turbofan nozzle with a bypass ratio of 2.7 (Johnson *et al.* 2011). They also considered the addition of a porous wedge-shaped fan flow deflector and show FFD increases the EPNL reductions to 5.0 dB and 3.9 dB in the downward and sideline directions, respectively. D. Papamoschou examined the potential of pylon-based, deployable flaps to reduce noise of separate flow turbofan engines with a bypass ratio of 8 (Papamoschou 2009). He tested three types of deflectors: solid flaps, porous flaps made of coarse perforations, and porous flaps made of fine perforations. It is shown that all the deflectors reduce noise sources near the end of the primary potential core. Accordingly, the fine perforation flaps provided superior acoustic results, yielding estimated EPNL benefits of 2.1 dB in the downward direction and 1.0 dB in the sideline direction.

It thus became evident that the shape of the baseline nozzle plays a role in the efficacy of the FFD method and that a systematic study of FFD in nozzles of varying shape was necessary for further understanding of the technique and for design considerations.

2.4. Micro jet

As an alternative, a microinjection system, impacting the main jet, has also been suggested. The micro jets are injected onto the primary jet near the nozzle exit with variable port geometry, working fluid, and driving pressure. Micro jets have been shown to produce large effects on supersonic primary jets. This is apparently due to a weakening of shock structure, resulting in an attenuation of shock-associated noise.

In recent decades, injection of micro jets at the nozzle exit to the main jet flow has been investigated by many researchers (Camussi *et al.* 2007; Zaman 2007; Greska *et al.* 2003; Greska, Krothapalli 2005; Greska *et al.* 2004; Harrison *et al.* 2007a, b). F. S. Alvi *et al.* found that the use of micro jets could be very effective in eliminating screech and impingement tones from supersonic jets (Alvi *et al.* 2000). T. Castelain *et al.* experimentally studied the effect of micro jets at Mach 0.9, and they found that the maximum number of micro jets did not imply maximum reduction in the sound pressure level (Castelain *et al.* 2006).

The impact of injection on jet noise depends on the injector configuration, injector operating condition, type of noise source targeted, and number of flow streams (single or dual) in the main jet. The micro jet velocity (which is proportional to the main jet velocity), the longitudinal distance of injection, and the number of micro jets are the three parameters that mainly contribute to the optimisation of noise reduction. In addition, the optimised micro jet configuration is obtained by a balance between low-frequency attenuation and high-frequency noise generation due to the interaction between micro jets and the main jet-mixing layer (Castelain *et al.* 2006). Experimental studies have investigated the impact of the injector's shape, size, injection angle, yaw angle, pressure, momentum flux, and mass flow rate on the radiated jet noise. While results have been reported for single and dual stream jets operating at subsonic and supersonic speeds, the variation in the injection parameters and operating conditions used in the experiments has been significant.

Chevrons and micro jets can be used simultaneously. The combination of these methods, which are sufficient technologies for noise suppression in jet engines, is more beneficial than each method alone. Fluidic chevrons are used to enhance mixing in the jet shear layer and break up large-scale structures which contribute significantly to the perceived noise level (Thomas, Joslin 2002). The unique feature of this method is that it applies micro jets to the shear layer at the tip of the chevrons. The strategic location of the micro jet-chevron injection is a critical design parameter. According to M. B. Alkislar and G. W. Butler, at a 150-degree nozzle inlet angle and at 100-D distance, the isolated chevron and/or micro jet reduction is only about 1 dB, whereas the micro jet-chevron combination is 2 dB (Alkislar, Butler 2007).

The narrow band spectra at aft angles also show the better performance obtained by the combination at a large range of frequencies. Furthermore, no additional high frequency lift has been observed in any measured at radiation angle with the application of micro jets in combination compared to isolated chevron cases. T. Castelain *et al*. showed that maximum noise reduction was not obtained by using a maximum number of micro jets since the modification of coherent structures in the flow resulted from a combination of the spacing, diameter, number and velocity of the micro jets (Castelain *et al.* 2008).

2.5. Supersonic

Supersonic jet noise consists of three main components: turbulent mixing noise, screech tones, and broadband noise. High-speed jet noise is dominated by Mach wave emission, which arises when turbulent eddies in the jet travel with supersonic velocity relative to the surrounding medium, radiates in the downstream direction, and is caused by the supersonic convection of eddies relative to their surrounding medium (Nielsen, Papamoschou 2009; Tam 1995; Avital *et al*. 1998; Tam, Chen 1994; Tam *et al*. 1992).

Reducing the Mach wave emission is a key challenge for making high-speed transport environmentally acceptable (Seiner, Krejsa 1989). Mach wave radiation has been the subject of numerous analytical, computational and experimental investigations (Mitchel *et al.* 1994; Seiner *et al*. 1994; Trout, McLaughlin 1982). This component of noise can be substantially removed by operating the jet at pressure-matched conditions. Turbulent mixing noise manifested as Mach wave emission in high-speed jets is by far the most difficult noise source to control. Several concepts have been developed to reduce high-speed jet noise, usually involving efforts to enhance the mixing between the jet and the surrounding air. These methods reduce the length of the high velocity region of the jet where noise is generated in some way (Tam, Chen 1994; Plencner 1998).

Supersonic jet noise reduction, however, remains a problem that has impeded the wide-scale development of supersonic air travel. Nevertheless, interest has been shown recently in the development of supersonic business aircraft, an indication that supersonic transport can have a niche in a market where saving time often results in crucial financial benefits. Development of a supersonic business aircraft would 'leverage' the extensive know-how and technologies developed for military airplanes but hinges on the effective reduction of take-off noise generated by the supersonic jets exhausting from the engines of such aircrafts (Debiasi, Papamoschou 2001). So far, the bulk of the supersonic noise suppression effort has encompassed mixing enhancement and ejector approaches (Nagamatsu *et al.* 1972; Tillman *et al.* 1992), which typically lead to large and heavy power plants (Plencner 1998). One may wonder whether supersonic engines will follow the same evolution as subsonic engines, leading to supersonic high-bypass turbofans. The issue is not as simple, though. High bypass ratio generally causes worse, not better, efficiency at supersonic speeds.

As well as the other main components of supersonic jet noise, screech tones and broadband noise are associated with the shock cell system in imperfectly expanded jets. Screech is a discrete tone emitted by imperfectly expanded jets. It has a significant upstream propagation component and thus can cause damage to the engine nozzle structure (Hay, Rose 1970). Screech is thought to be generated and sustained by a resonant feedback loop that comprises the following elements: sound generated by passage of eddies through shock cells, upstream propagation of the sound toward the nozzle lip, and cogeneration of new eddies by the coupling of the sound with the shear-layer instability (Tam 1995; Raman 1998; Powel 1953).

The second component of shock-associated noise is broadband in nature and propagates in lateral and upstream directions. In spectral amplitude it rises rapidly with frequency to a main peak and then decreases at higher frequencies. Broadband shock noise is believed to consist of acoustic waves generated by supersonically convicting, coherent, wavelike disturbances arising from the interaction of large-scale turbulent structures with the nearly periodic shock cell system of imperfectly expanded jets (Tam 1987; Tam, Tanna 1982). It was demonstrated that the addition of a secondary flow to a supersonic jet can reduce Mach wave emission when the convective velocity of the jet eddies are also subsonic values, provided that the secondary flow eddies are also subsonic with respect to the ambient (Papamoschou 1997; Papamoschou, Debiasi 1999). This method, called Mach wave elimination, achieved appreciable noise reduction in a pressure-matched jet with velocity of 920 m/s (Papamoschou 1997). Specifically, WE seek to minimise the convective Mach numbers of turbulent eddies throughout the jet flow field. This includes the end of the potential core, a region of vigorous mixing and strong noise generation. In a coaxial arrangement, application of the secondary streams stretches the primary potential core. The end of the primary core can easily extend past the reach of the secondary flow, thus reducing the effectiveness of the technique. The eccentric arrangement has been shown to prevent significant elongation of the primary potential core (Murakami, Papamoschou 2002). It also doubles the thickness and potential core length of the secondary flow in the downward direction, thus making the technique very effective at suppressing Mach wave emission towards the ground. More generally, the MWE results illustrate the potential for noise reduction by shaping the mean flow of the primary and secondary streams.

Experiments on the wave elimination technique showed significant gains in noise reduction. D. Papamoschou investigated the noise suppression in a fixed cycle, bypass ratio three supersonic engine (Papamoschou 2004a). Subscale experiments showed that, relative to the mixed-flow exhaust, the coaxial separate-flow exhaust with vanes reduces the peak overall sound pressure level by 8 dB and the effective perceived noise level by 7 dB and the noise-equivalent specific thrust on take off is reduced from 490 to 390 m/s. Results also showed that by this method noise reduction of 13 dB with mixed-flow exhaust and noise reduction of 20 dB with the aforementioned suppression scheme can be achieved.

3. Conclusion

In this paper, we have reviewed the main mechanisms involved in the generation of aerodynamic noise in modern aircraft for civil transportation. Various methods have been developed to reduce jet noise in turbofan engines. Examples of these technologies have been presented, such as the use of eccentric and actuate nozzles instead of conventional coannular nozzles, the installation of chevron mixer on exhaust nozzles, applying fan flow deflectors (FFD) at the exit of nozzles, the use of micro jets that are injected onto the primary jet near the nozzle exit, and the employment of fluidic chevrons.

This will be particularly useful, for instance, to assess the influence of noise mitigation devices on aircraft operating cost. We believe that this work may be useful for rapid access to information in the field of aircraft noise reduction.

References

Alkislar, M. B.; Butler, G. W. 2007. Significant improvements on jet noise reduction by chevron-microjet combination, *AIAA Paper* 3598: 21–23.

Alvi, F. S.; Elavarasan, R.; Shih, C., *et al.* 2000. Active control of supersonic impinging jets using microjets, *AIAA Paper* 2236: 26–29.

Avital, E. J.; Sandham, N. D.; Luo, K. H. 1998. Mach wave radiation in mixing layers. Part I: analysis of the sound field, *Theoretical and Computational Fluid Dynamics* 12: 73–90. http://dx.doi.org/10.1007/s001620050100

Camussi, R.; Guj, G.; Tomassi, F., *et al.* 2007. Air injection through microjets in low Mach number turbulent jet flows, *AIAA Paper* 3644.

Castelain, T.; Bera, J. C.; Sunyach, M. 2006. Noise reduction of a Mach 0.7-0.9 jet by impinging microjets, C*omptes Rendus Mécanique* 334(2): 98–104. http://dx.doi.org/10.1016/j.crme.2006.01.001

Castelain, T.; Sunyach, M.; Juve, D., *et al.* 2008. Jet-noise reduction by impinging microjets: an acoustic investigation testing microjet parameters, *AIAA Journal* 46(5): 1081–1087. http://dx.doi.org/10.2514/1.29411

Debiasi, M.; Papamoschou, D. 2001. Cycle analysis for quieter supersonic turbofan engines, *AIAA* 3749.

Dippold, V.; Foster, L.; Wiese, M. 2007. Computational analyses of offset stream nozzles, *AIAA Paper* 3589.

Greska, B.; Krothapalli, A. 2005. The near-field effects of microjet injection, *AIAA Paper* 3046.

Greska, B.; Krothapalli, A.; Arakeri, V. 2003. A further investigation into the effects of microjets on high speed jet noise, *AIAA Paper* 3128.

Greska, B.; Krothapalli, A.; Burnside, N., *et al*. 2004. High-speed jet noise reduction using microjets on a jet engine, *AIAA Paper* 2969.

Harper-Bourne, M. 2001. Physics of jet noise suppression, in *Proceedings of Jet Noise Workshop, NASA GRC.* Cleveland, NASA CP 211152.

Harrison, S.; Gutmark, E.; Martens, S. 2007a. Jet noise reduction by fluidic injection on a separate flow exhaust system, *AIAA Paper* 439.

Harrison, S.; Gutmark, E.; Martens, S. 2007b. Jet noise reduction by fluidic injection on a separate flow exhaust system, *AIAA Paper* 439.

Hay, J. A.; Rose, E. G. 1970. In-flight shock-cell noise, *Journal of Sound and Vibration* 11: 411–420. http://dx.doi.org/10.1016/S0022-460X(70)80003-7

Henderson, B.; Kinzie, K.; Whitmire, J., *et al.* 2006. Aeroacoustic improvements to fluidic chevron nozzles, *AIAA Paper* 2706.

Hileman, J.; Samimy, M. 2001. Turnelance structures and the acoustic far field of a Mach 1.3 jet, *AIAA Journal* 39(9): 1716–1727. http://dx.doi.org/10.2514/2.1529

Johnson, A. D.; Xiong, J.; Rostamimonjezi, S., *et al.* 2011. Aerodynamic and acoustic optimization for fan flow deflection, in *Proceedings of 49th AIAA Aerospace Sciences Meeting.*

McLaughlin, D. K.; Morrison, G. D.; Troutt, T. R. 1975. Experiments on the instability waves in a supersonic jet and their acoustic radiation, *Journal of Fluid Mechanics* 69(11): 73–95. http://dx.doi.org/10.1017/S0022112075001322

Mikkelsen, K.; Bridges, J. 2000. Acoustics and thrust of separate flow exhaust nozzles with mixing devices for high-bypass-ratio engines, *AIAA Paper* 1961.

Mitchell, B. E.; Lele, S. K.; Moin, P. 1994. Direct Computation of Mach wave radiation in an axisymmetric supersonic jet, *AIAA Journal* 35(1): 1574–1580. http://dx.doi.org/10.2514/2.15

Murakami, E.; Papamoschou, D. 2002. Mean flow development in dual-stream compressible jets, *AIAA Journal* 40(6): 1131–1138. http://dx.doi.org/10.2514/2.1762

Nagamatsu, H. T.; Sheer, R. E.; Gill, M. S. 1972. Characteristics of multitude multishroud supersonic jet noise suppressor, *AIAA Journal* 10(3): 307–313. http://dx.doi.org/10.2514/3.50091

Narayanan, S.; Barber, T. J.; Polak, D. R. 2002. High subsonic jet experiments: turbulance and noise generation studies, *AIAA Journal* 40(3): 430–437. http://dx.doi.org/10.2514/2.1692

Narkiewicz, J.; Pietrucha, J. 1998. Reduction of helicopter vibration and noise level by active control technology, *Aviation Scientific Works* 3: 83–85.

Nielsen, P.; Papamoschou, D. 2008. Optimization of fan flow deflection for supersonic turbofan engines, *AIAA Paper* 3061.

Nielsen, P.; Papamoschou, D. 2009. Mean flow – acoustic correlations for dual-stream asymmetric jets, in *Proc. of 47th AIAA Aerospace Sciences Meeting.*

Panda, J.; Seasholtz, R. G. 2002. Experimental investigation of density fluctuations in high-speed jets and correlation with generated noise, *Journal of Fluid Mechanics* 450: 97–130. http://dx.doi.org/10.1017/S002211200100622X

Panda, J.; Zaman, K. B. M. Q. 2001. Density fluctuation in asymmetric nozzle plumes and correlation with far field noise, *AIAA Paper* 0378.

Papamoschou, D. 1997. Mach wave elimination from supersonic jets, *AIAA Journal* 35(10): 1604–1611. http://dx.doi.org/10.2514/2.19

Papamoschou, D. 2002. Noise suppression in moderate-speed multistream jets, in *Proc. of 8th AIAA/CEAS Aeroacoustics Conference.*

Papamoschou, D. 2004a. Engine cycle and exhaust configurations for quiet supersonic propulsion, *Journal of Propulsion and Power* 20(2): 255–262. http://dx.doi.org/10.2514/1.9251

Papamoschou, D. 2004b. Mean flow and acoustic of dual-stream jets, *AIAA Paper* 0004.

Papamoschou, D. 2004c. New method for jet noise suppression in turbofan engines, *AIAA Journal* 42(11): 2245–2253. http://dx.doi.org/10.2514/1.4788

Papamoschou, D. 2006. Fan flow deflection in simulated turbofan exhaust, *AIAA Journal* 44(12): 3088–3097. http://dx.doi.org/10.2514/1.22552

Papamoschou, D. 2009. Pylon based jet noise suppressors, *AIAA Journal* 47(6): 1408–1420. http://dx.doi.org/10.2514/1.37780

Papamoschou, D.; Debiasi, M. 1999. Noise measurements in supersonic jets treated with the Mach wave elimination method, *AIAA* 37(2): 154–160. http://dx.doi.org/10.2514/2.702

Papamoschou, D.; Shupe, R. S. 2006. Effect of nozzle geometry on jet noise reduction using fan flow deflectors, in *Proc. of 27th AIAA Aeroacoustics Conference.*

Papamoschou, D.; Diabesi, M. 2001. Directional suppression of noise from a high-speed jet, AIAA *Journal* 39(3): 380–387. http://dx.doi.org/10.2514/2.1345

Papamoschou, D.; Diabesi, M. 2003. Conceptual development of quiet turbofan engines for supersonic aircraft, *Journal of Propulsion and Power* 19(2).

Papamoschou, D.; Nishi Kimberley, A. 2004. Turbofan noise reduction via deflection of the bypass stream, *AIAA Paper* 0187.

Papamoschou, D.; Nishi Kimberley, A. 2005. Jet noise suppression with fan flow deflectors in realistic shaped nozzle, *AIAA Paper* 0993.

Plencner, R. M. 1998. Engine technology challenges for the high-speed civil transport plane, *AIAA Paper* 2505.

Powell, A. 1953. On the mechanism of chocked jet noise, *Proceedings of the Physical Society* 66: 1039–1056.

Raman, G. 1998. Advances in understanding supersonic jet screech, *AIAA Paper* 0279.

Seiner, J. M.; Bhat, T. R. S.; Ponton, M. K. 1994. Mach wave emission from a high-temperature supersonic jet, *AIAA Journal* 32(1): 2345–2350. http://dx.doi.org/10.2514/3.12298

Seiner, J. M.; Krejsa, E. 1989. Supersonic jet noise and the high speed civil transport, *AIAA Paper* 2358.

Shupe, R. S.; Zaman, K. B. M. Q.; Papamoschou, D. 2007. Effect of wedge-shaped deflectors on flow fields of dual-stream jets, *AIAA Paper* 3659.

Smith, M. J. T. 1989. *Aircraft Noise*. 1st ed. Cambridge: Cambridge University Press, 120–134. http://dx.doi.org/10.1017/CBO9780511584527.005

Tam, C. K. W. 1987. Stochastic model theory of broadband shock associated noise from supersonic jets, *Journal of Sound and Vibration* 116(2): 265–302. http://dx.doi.org/10.1016/S0022-460X(87)81303-2

Tam, C. K. W. 1995. Supersonic jet noise, *Annual Review of Fluid Mechanics* 27: 17–43. http://dx.doi.org/10.1146/annurev.fl.27.010195.000313

Tam, C. K. W.; Chen, P. 1994. Turbulent mixing noise from supersonic jets, *AIAA Journal* 32(9): 1774–1780. http://dx.doi.org/10.2514/3.12173

Tam, C. K. W.; Chen, P.; Seiner, J. M. 1992. Relationship between instability waves and noise of high-speed jets, *AIAA Journal* 30(7): 1747–1752. http://dx.doi.org/10.2514/3.11132

Tam, C. K. W.; Tanna, H. K. 1982. Shock associated noise of supersonic jets from convergent-divergent nozzles, *Journal of Sound and Vibration* 81(3): 337–358. http://dx.doi.org/10.1016/0022-460X(82)90244-9

Thomas, R. H.; Farassat, F.; Clark, L. R., *et al*. 1997. Azimuthal patterns of the radiated sound field from a turbofan model, *AIAA Paper* 1588.

Thomas, R. H.; Joslin, R. D. 2002. *Flow and noise control: review and assessment of future directions*. NASA/ TM211631.

Tillman, T. G.; Paterson, R. W.; Presz, W. M. 1992. Supersonic nozzle mixer ejector, *AIAA Journal of Propulsion and Power* 8(2): 513–519. http://dx.doi.org/10.2514/3.23506

Troutt, T. R.; McLaughlin, D. K. 1982. Experiments on the flow and acoustic properties of a moderate Reynolds number supersonic jet, *Journal of Fluid Mechanics* 116: 123–156. http://dx.doi.org/10.1017/S0022112082000408

Uzun, A.; Hussaini, M. 2007. Noise generation in the near-nozzle region of a chevron nozzle jet flow, *AIAA Paper* 3596.

Vanker, S.; Enneveer, M.; Rammul, I. 2009. Noise assessment and mitigation schemes for Estonian airports, *Aviation* 13(1): 17–25. http://dx.doi.org/10.3846/1648-7788.2009.13.17-25

Xiong, J.; Johnson, A. D.; Liu, F., *et al.* 2011. Modeling of wedge-shaped porous flaps for jet noise reduction, in *Proc. of 49th AIAA Aerospace Sciences Meeting.*

Zaman, K. B. M. Q. 2004. Noise and flow-field of jets from an eccentric coannular nozzle, in *Proc. of 42nd AIAA Aerospace Sciences Meeting* 0005.

Zaman, K. B. M. Q. 2007. Subsonic jet noise reduction by microjets with various injection port geometries, *AIAA Paper* 3643.

Zaman, K. B. M. Q.; Papamoschou, D. 2006. Effect of wedge on coannular jet noise, in *Proc. of 44th AIAA Aerospace Sciences Meeting and Exhibit.*

Žilienė, D.; Stankūnas, J. 2002. Analysis of influence of aircraft noise limitations following requirements of European Union on sector of Lithuania air transport services, *Aviation* 6: 34–40.