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# MAIN FAN NOISE MITIGATION TECHNOLOGIES IN TURBOFAN ENGINES

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**Abstract.** Aircraft noise and emissions have been of concern since the beginning of commercial aviation. The continuing growth in air traffic and increasing public awareness have made environmental considerations one of the most critical aspects of commercial aviation today. To deal with this problem, aircraft manufacturers and public establishments are engaged in research on technical and theoretical approaches for noise reduction concepts that should be applied to new aircraft. While jet noise was the dominating contributor in the early jet engine designs, the noise emitted by the fan has become important with the reduction in jet speed and its control requiring an immense research effort. This paper concerns the main fan noise mitigation technologies in turbofan engines.

**Keywords:** aircraft noise, turbofan engines, engine noise, fan noise, fan noise mitigation.

## 1. Introduction

Aircraft noise is second only to road traffic noise in drawing complaints from the public about noise pollution. The control of aircraft noise in the vicinity of airports from the late 1960s to the present day has been achieved by setting statutory noise limits and monitoring aircraft noise (Žilienė, Stankūnas 2002; Gorji-Bandpy, Azimi 2012b). Engine noise is one of the major contributors to the overall sound level as aircraft operate near airports. Turbofan engines are commonly used in commercial transport due to their advantage of higher performance and lower noise (Huf 2007). Since the turbofan engine is a large contributor to aircraft noise, any overall reduction in aircraft noise must include engine noise reduction. Analytical and semi-empirical models have been developed to investigate the influence of some design tools employed in a multi-disciplinary optimization framework. The most dominant sources of engine noise come from two parts of the engine: the jet exhausting at the rear (Gorji-Bandpy, Azimi 2012a) and the blades of the fan at the front.

Noise reduction techniques can be broadly classified into passive and active methods. Passive control involves reducing the radiated noise by energy absorption, while the active method involves reducing the source strength or modifying the acoustic field in the duct to obtain noise reduction. Noise caused by fans during take-off and approach has become a major annoyance in high bypass ratio turbofan engines. Therefore, aircraft and engine manufacturers are facing increasing pressure to reduce exterior noise levels. The use of large fans and inlet ducts means that fan noise is nowadays one of the principal sources of engine noise (Hanson 2001; Astley *et al.* 2011; Glegg, Jochault 1997; Lauer *et al.* 2009). In this paper, an overview of major accomplishments from recent research on fan noise reduction will be presented.

## 2. Fan noise

A broadband noise level characterizes the acoustic signature of the aircraft engine with dominant discrete tones at blade passing frequency (BPF) and its harmonics. Among the discrete tones, the noise level at BPF tone is usually the loudest. When the propagating acoustic modes reach the opening of the inlet, they radiate into the far field. The radiation process is complicated due to the diffraction effects and the acoustic impedance change at the inlet opening, and ground based perception of engine noise depends to a large extent on the position of the aircraft in relation to its observer (Rao 1999). According to C. J. Trefny and J. W. Wasserbaur (1986), "the forward-propagated fan noise is a significant component during takeoff and approach". J. M. Tyler and T. G. Sofrin (1962) noted, "The discrete frequency compressor whine is more objectionable than broadband exhaust noise".

Broadband noise is generated by the interaction of random disturbance, e.g. the disturbance associated with turbulence boundary layer flows over rotor blades, stators, shroud, ingested atmospheric, and blade tip vortex shedding. Broadband noise tends to dominate the spectrum at low flow coefficients when the stage is heavily loaded and is very near to or in stall. The sound that propagates in an aircraft turbofan inlet duct is almost entirely due to the fan. Fan tone noise is highly dependent on engine power, or fan speed. The generation of fan noise depends on many factors. The dominant source of fan tone noise is usually the rotor/stator interaction while broadband noise is due to turbulence. Airport communities bear the full brunt of discrete frequency noise. In particular, discrete frequency radiation is a result of the rotor speed, blade number, and the homogeneity of the flow field (Rao 1999). This article briefly describes some of the currently employed solutions to the problem of fan noise.

### 2.1. Swept and leaned

The primary mechanism generating forward-radiated fan noise is the stator/rotor interaction. The discrete-frequency noise generated by unsteady blade row interactions between rotor and stator blades is of particular concern for the design of advanced turbofan engines, since jet noise is reduced considerably by the introduction of high bypass flows (Yamasaki, Tajima 1998; Gorji-Bandpy, Azimi 2012b). Many of the modern fan designs use a fan sweep near the tip to reduce aerodynamic losses associated with shocks and improve the stall margin. There is also evidence that additional mass flow through the fan can be achieved. The designs were aggressive and some experienced part-speed flutter problems. Swept stators have been found to reduce fan noise by increasing the phase changes from hub-to-tip of the unsteady aerodynamics producing the sound and by increasing the effective distance from the fan to the stator vanes. The three most common types of interaction are rotor blade chopping through the wakes of upstream stators, wakes from rotor blades impinging on downstream stators, and the pressure fields of the rotors reflecting nearby objects. The most important interaction type is generated as a result of periodic impingement of fan wakes on the outlet guide vanes (OGV) (Envia, Nallasamy 1998). The periodic cutting of rotor wakes causes rotor-stator interaction noise by the stator vanes. The strength of the interaction is related to the efficiency with which unsteady pressure distribution on the vanes couples to the acoustic modes of the bypass duct (Groeneweg *et al.* 1991). The pressure distribution, in turn, depends on the upwash, induced by the rotor wake on the stator. Through this dependence, the source strength is strongly influenced by the spanwise phase of the upwash (Envia *et al.* 1996). Significant upwash phase variation can cause noise cancellation between contributions from different locations along the vane span resulting in weaker interaction tones. For the most part, the number of individual rotor wakes that intersect a given vane controls variation in the span wise phase of the up wash. This number is determined, primarily, by the kinematics of the rotor wakes in relation to the stator vanes. Swirl variation from hub to tip introduces a tangential shift between the circumferential positions of the wakes along the span. The shift increases with downstream distance causing the tip wakes to advance ahead of the hub wakes.

Sweep is defined as the axial displacement of the vane leading edge from its baseline position. Similarly, lean is defined as the circumferential displacement of the vane leading edge from its baseline position. Generally, this shift becomes large enough that wake sheets from more than one blade intersect a single vane. When chosen properly, sweep and/or lean reduce rotor-stator interaction tone noise. To reduce noise, sweep and lean must be chosen in such a way so as to increase wake intersections per vane (Envia, Nallasamy 1998). Since the early 70s, several theoretical and experimental studies have hinted at the potential of sweep and lean for reducing rotor-stator tone noise (Rao 1972; Kazin 1973; Adamczyk 1974; Hayden *et al.* 1977; Schultenm 1982; Envia, Kerschen 1984, 1986, 1990). In a more recent experimental study, the benefits of OGV sweep and lean for reducing fan noise were convincingly demonstrated for a representative modern low-speed fan stage (Woodward *et al.* 1997). The results show that, compared to the radial one, swept and leaned OGV provides significant reductions in the level of rotor-stator interaction tone noise for a wide range of operating conditions. A set of simple design rules is proposed for implementing sweep and lean in practical fan stage geometries. Sweep for which the vane tip is downstream of its root, and lean in the direction of the fan rotation reduce the strength of the interaction tones with the size of reduction dependent on the amount of sweep and lean chosen (Envia, Nallasamy 1998).

### 2.2. Trailing edge blowing

With regard to noise reduction, one flow control concept that is being studied is fan wake management. This concept attempts to manage the low momentum fluid in the fan blade wakes caused by viscous losses on the airfoil. Mitigation can involve suction to remove low momentum fluid or flow injection to energize the wake and fill in the momentum deficit.

More specifically, fan trailing edge blowing is a means to reduce fan exit guide vane noise at the source by filling the wake deficit created by the upstream fan before it impacts the stator.

After trailing edge blowing the number of loading harmonics and the amplitude of unsteady loading are reduced. Trailing edge blowing is applicable to rotors as well as stators and has wide application in the gas turbine engine. It can be used to reduce other effects of unsteady flow, such as high cycle fatigue, in turbofan and compressor blades. Research by Th. Leitch (1997) on experimental inlet demonstrated the effectiveness of trailing edge blowing in decreasing the discrete frequency sound levels radiated by high-speed turbofan simulator on which an inlet with four supporting struts was mounted. The struts modified the flow field ingested by the rotor by introducing circumferential variations in axial velocity. These wakes increase the radiated far-field sound pressure level at the blade passing frequency and its harmonics. Th. Leitch (1997) and C. A. Saunders (1998) reported maximum reductions of far-field noise levels of 7 dB and 6 dB, respectively. Th. Leitch used a generic inlet with four struts. The results from experimental research by Th. Leitch and C. A. Saunders clearly demonstrate that trailing edge blowing from upstream stators can be effective for reducing unsteady stator/rotor interaction and the subsequent forward-radiated fan noise (Leitch *et al.* 2000). I. A. Waitz *et al.* (1995) used numerical and experimental methods to investigate the effect of wake modification on the acoustic radiation from a rotor. They employed trailing edge blowing and boundary layer suction to rotor blade to minimize the wake. Estimates of background and radiated noise levels were obtained by a two dimensional, linearized panel method. Predictions based on experimental aerodynamic data suggested reductions that were greater than 10 dB in the dominant tones. I. A Waitz *et al.* (1995) concluded that wake management is feasible for high-bypass turbofan engines, also, that trailing edge blowing is more effective than boundary layer suction. W. J. Park and J. M. Cimbala (1991), T. Corcoran (1992), and G. R. Naumann (1992) experimented with several blowing techniques and configurations. They report significant reduction in time-mean wake deficits downstream of a flat plate. T. Corcoran (1992) showed that trailing edge blowing reduces Reynolds stress, vorticity and velocity fluctuations within one chord length downstream. G. R. Naumann (1992) experimented with various blowing configurations, a continuous slit and a set of discrete jets, with and without vortex generators. This work showed that the most effective method of trailing edge blowing is to use a set of discrete jets, and that the presence of vortex generators enhances the mixing of the wake with jets. They also noted that the fluid characteristics of re-energized wakes are highly dependent upon the method that was used to generate them.

### 2.3. Bifurcated inlet

Inlet distortion is the physical distortion of inlet, which results in the non-uniformity of the inlet core flow. Usually IGV wake disturbances and potential disturbances are referred to as aerodynamic gust forcing functions (Feiereisen *et al.* 1998). The IGV wake disturbance (or vortices disturbance), a result of viscous action on the upstream IGV surface, is generated by velocity losses of the flow over downstream rotor blades. A bifurcated two-dimensional (2-D) supersonic inlet is one of several inlets considered. The bifurcated 2-D inlet design incorporates a rectangular inlet opening that gradually changes to a circular cross-section at the fan face. The bifurcated ramp or splitter plate centre body is adjustable to obtain appropriate shock wave conditions with the inlet for the engine at transonic and supersonic flights.

With an adjustable centre body, the flow condition at the fan face can also be controlled at subsonic conditions. The bifurcated 2-D inlet also incorporates inlet guide vanes right in front of the fan face. An older version of a bifurcated 2-D supersonic inlet, designed by NASA, was tested by R. Wangger (1995). The NASA-designed bifurcated 2-D inlet did not have inlet guide vanes (IGV). Since the tests were conducted at ground-static conditions and the inlet had a bellmouth, a significant boundary layer separation was recorded at the cowl lip. K. C. Miller (1996) made a continued effort to examine the performance of the NASA-designed bifurcated 2-D inlet without the IGV. His tests were ground-static too but were conducted with a bellmouth to reduce cowl lip boundary layer separation. Both studies documented the aeroacoustic and aerodynamic performance of the bifurcated 2-D supersonic inlets at two different fan speeds. Comparisons were made between the performances of the bifurcated 2-D supersonic inlets and the axisymmetric supersonic inlets. C. A. Hanuska (1998) conducted another aeroacoustic experiment on a new bifurcated 2-D supersonic inlet with IGV. This bifurcated 2-D supersonic inlet, designed recently by the Boeing Company, differed from the old NASA-designed inlet, because the Boeing bifurcated 2-D supersonic inlet had IGV. By C. A. Hanuska, the aim was to evaluate the use of flat plate IGV and airfoil IGV on the effects of "soft chocking" to reduce noise. The results by S. M. Li *et al.* (2001) showed that variation in the distance between the trailing edge of the bifurcated ramp of the inlet and the fan face had a negligible effect on the total noise level. However, the axial spacing of the fan face of the inlet guide vanes (IGV) has a first order effect on the aeroacoustics of the bifurcated 2-D inlet. Up to a 5 dB reduction in the overall sound pressure level and up to a 15 dB reduction in the blade passing frequency tone were observed when the IGV were moved from a 0.8 chord of rotor blade upstream of the fan face to a 2.0 chord of the blade upstream. Noise reduction approaches aim to control the noise at its source by designing noise control features and to absorb the sound generated by the source with acoustic liners.

### 2.4. Acoustic liner

A successful method for reducing noise further, even in ultra-high bypass ratio engines, is to absorb sound created within the engine (Azimi *et al.* 2014). Acoustically absorbent material, or acoustic liners, can be placed on interior surfaces. Probably the most common passive method of noise control is the use of acoustic liners. The liners absorb the radiated acoustic energy, thereby reducing the far-field noise levels. The acoustic liner may cover most of the available surface, both in the inlet and exhaust ducts, resulting from an optimization procedure involving antagonist factors like the installation of anti-icing systems. Liners are usually manufactured in sections, of which each covers a part of the duct‘s circumference. This facilitates the manufacturing and installation of the lining inside the nacelle. The sections are joined together by longitudinal strips or splices. The splices will be acoustically hard. This means that there will be discontinuities in the acoustic impedance around the circumference of the duct. The type of acoustic liners employed is, typically, locally reacting cavity linings. The specific acoustic impedance of this type of liners depends on the properties of the lining, the mean flow and the frequency of the sound (McAlpine, Wright 2006). In general, it is more difficult to attenuate the fan tones as engine power is increased, notably at high supersonic fan speeds. However, the use of liners increases engine weight, which is undesirable. Also, future developments will see an increase in the bypass ratio, while the inlet length will not be scaled according to diameter. This will make liners less effective. Their confined length always limits their performance; in particular, when aero-engines where multiple dominant tones are related to buzz saw noise or to the rotor-stator interaction noise are considered. Several authors have studied the concept of non-uniform liners. D. L. Lansing and W. E. Zorumski (1973) appears to be the first published work on the axially segmented liner using mode-matching techniques. This type of axially segmented liner is of interest because it could be used to increase the attenuation of fan tones at high supersonic fan speeds. J. F. Unruh (1976) first examined how the liner's length, as well as its impedance, may be tuned to optimize attenuation. Also, both K. J. Baumeister (1979) and M. S. Tsai (1982) realized that the first segment of lining acts as a scatterer, which facilitates the attenuation of the sound in adjacent lined segments. However, K. J. Baumeister concluded that the use of optimized axially segmented liners fails to offer sufficient advantage over a uniform liner to warrant their use, except in low frequency, single-mode application. In a circular-section lined duct with circumferentially varying wall impedance, it is not possible to separate r and y in order to find analytic expressions for the modes of the duct. W. Watson (1981) and C. R. Fuller (1984a, 1984b) proposed an analytical solution to this type of problem. Separating the x-dependence and then expressing both the mode shapes and wall impedance as Fourier series expansions in y solved the wave equation. Then the solution can be found, in principle, by solving a system of Eigen equations. The fan tones are the harmonics of the blade passing frequency (BPF), which is generated by rotor-stator interactions and other similar mechanisms, such as interaction with mean flow distortion and scattering by liner discontinuities. In aero-engines operating with supersonic fan tip speeds, for example at engine "cutback" and "sideline" operating conditions (nominally about 80–85 and 90–95% of fan speed), an acoustic signature containing energy spread over a range of harmonics of the engine shaft rotation frequency will be generated. The name "buzz-saw" noise or multiple pure tones is generally used to describe this component of fan noise. The pressure signature attached to a supersonic ducted fan will be a saw-tooth waveform. The non-linear propagation of a high-amplitude irregular saw-tooth upstream inside the inlet duct redistributes the energy amongst the buzz-saw tones (McAlpine, Fisher 2002). "Buzz-saw" noise is radiated from a turbofan inlet duct when the fan tip speed is supersonic. A. McAlpine and M. J. Fisher (2002) showed that the principal source of buzz-saw noise is not always the rotor-alone pressure field. Non-rotor-alone scattered tones can be a significant source of buzz-saw noise at low supersonic fan speeds. "Buzz-saw" noise is the principal tone noise source radiated from a turbofan inlet duct at supersonic fan speeds. The noise source consists of a set of tones, known as engine orders (EO) that are the harmonics of the engine's shaft rotation frequency. These EO tones are the buzz-saw noise. The level of the scattered modes can be significantly reduced by the existence of the buzz saw noise.

In another study by A. McAlpine *et al.* (2007), the effect of an acoustic liner on buzz-saw noise has been examined. Their study shows that the principal source of buzz-saw noise is not always the rotor-alone pressure field. Non-rotor-alone scattered tones can be a significant source of buzz-saw noise at low supersonic fan speeds. However, at sideline, the rotor-alone field is well cut-on. At this fan speed, the rotor alone modes are predicted to remain the principal noise source of fan tone noise. The level of the scattered modes at sideline can be reduced with thinner splices. However, at high fan speeds, thinner splices are not predicted to lead to an increase in the overall sound power transmission loss. This is because the rotor-alone pressure field is well cut-on and poorly absorbed by the duct liner. Acoustic liners in current aircraft engines are generally located in the inlet and/or the aft fan duct. If the liner is placed nearer to the fan rotor, or over the rotor, preliminary tests (Sutliff, Jones 2008) suggested that significant additional noise attenuation could be realized. D. L. Sutliff *et al.* (2009) used a Foam-Metal Liner (FML) installed in close proximity to the fan. In their study, two FML designs were tested and compared to the hardwall baseline. Traditional single degree-of-freedom liner designs were also evaluated to provide a comparison. They showed that the FML achieved up to a 5 dB Acoustic Power Level (PWL) overall attenuation in the forward quadrant, equivalent to the traditional liner design.

## 3. Conclusions

In this paper we have used a bibliographical approach to describe mechanisms involved in the generation of aerodynamic noise in modern aircraft for civil transportation. Various methods have been developed to reduce the generation and propagation of turbofan noise. A review of the main established technologies for fan reduction and those currently under evaluation is also presented. Examples of these technologies have been presented and include: scarf inlets, active noise control, forward swept fans, swept and leaned stators, fan trailing edge blowing, and acoustic treatment placed over the fan. This will be particularly useful, for instance, to assess the influence of a fan noise mitigation device on the aircraft operating cast. We believe that this work may be useful for a rapid access to information in the field of aircraft noise reduction.

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