Passive Strategies for Reducing Jet-Installation Noise

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Introduction

Aircraft noise levels have been significantly reduced with the introduction of high-bypass ratio turbofan engines, particularly jet noise due to turbulence mixing [1]. This, however, has led to engines with larger diameters and a closer coupling between them and the airframe gives rise to an acoustic source known as jet-installation noise (JIN). In more detail, this source is generated by the impingement of unsteady pressure waves from the jet mixing-layer on the airframe surfaces and their scattering as noise at the wing trailing edge [2]. Jet-installation noise becomes relevant particularly during take-off and approach conditions since the deployed flaps are located closer to the turbulent jet flow. At the full aircraft level, computations of acoustic footprint have shown that installation effects increase the overall produced noise and are the dominant source for a significant amount of time during the aircraft flyover [3]. The large role played by JIN in the overall aircraft noise emissions thus imposes the need for understanding the physical mechanisms behind sound production and the development of potential mitigating solutions.

Characteristics of Jet-Installation Noise

The trailing-edge scattering mechanism results in a low-frequency broadband noise increase with respect to the isolated jet levels, whereas at relatively higher frequencies, acoustic waves from turbulence-mixing noise in the jet are reflected on the lower side of the wing, augmenting the noise for an observer on the ground [4, 5]. The low-frequency noise increase is also more pronounced in the upstream direction of the jet axis, whereas turbulence-mixing noise is still dominant towards downstream of the axis [6]. It should be noted that this phenomenon occurs even when there is no direct grazing of the jet on the airframe; the pressure fluctuations that impinge on the wing, and are scattered at the trailing edge, are usually of evanescent nature [7]. Otherwise, grazing flow produces a turbulent boundary layer on the surface, further increasing noise at low frequencies [8].

The far-field noise signature of an installed jet is strongly dependent on the jet development and its turbulent characteristics, as well as the location of the scattering surface with respect to the jet itself in both axial and radial directions [9]. Therefore, potential solutions for JIN can target either the jet development by changes to the nozzle geometry and flow properties, or the scattering surface by changing its position with respect to the jet, its geometry (addition of sweep, for example [10]) or its structural properties (impedance).

Nozzle-Focused Solutions

Modifications to the nozzle geometry and, consequently, to the characteristics of the turbulent jet flow can be performed in order to target JIN reduction. A typical nozzle-focused noise reduction solution is the application of chevrons at the outlet. Originally conceived for turbulence-mixing noise reduction, chevrons tend to enhance the mixing of large-scale structures and thus reduce the coherence of the noise sources in a turbulent jet [11]. As a result, in terms of far-field noise, chevrons reduce sound pressure levels at low frequencies while increasing them at high frequencies [11].

Chevrons have been assessed for JIN reduction and a noise decrease of up to 2.6 dB at the spectral peak of an installed jet configuration has been achieved. Azimuthally varying chevrons in particular perform better than uniform ones, likely due to a further suppression of the axisymmetric mode of the jet noise sources [12]. However, although the chevrons provide some benefits, they are still not sufficient to bring the noise of the configuration back to isolated jet levels, and thus the trailing-edge source is still present.

The chevrons act particularly better for JIN reduction at low jet Mach number and at polar angles upstream of the nozzle outlet. In terms of modal energy, the chevrons redistribute it towards higher frequencies, thus changing

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the characteristics of the installed jet spectrum [13]. Considering near-field pressure fluctuations on the wing, it has also been shown that chevrons can reduce the spanwise coherence of the pressure field at the trailing edge, consequently further reducing the scattered noise [14].

Likewise, lobed nozzles (with a non-circular outlet) also have potential for JIN reduction. The lobed structure of a jet changes the characteristics of instability waves, including both the temporal growth rate and convection velocity [15]. Therefore, it is likely that for a lobed nozzle the scattered noise itself is not reduced, but instead the peak frequency location is shifted, usually towards lower frequencies. Other nozzle shapes have been shown to reduce JIN, such as bevelled nozzles (in comparison to a round one), which offer noise reduction in all directions, especially perpendicularly to the scattering surface [16]. A rectangular nozzle reduces noise along its minor axis, perpendicularly to the surface, while increasing noise along the major one [16].

Airframe-Focused Solutions

One concept that has recently become the subject of intensive research is the application of permeable materials for mitigating aeroacoustic sound sources [17, 18]. With respect to JIN reduction, the goal of these materials is to modify the impedance of the surface close to the edge, in order to reduce the discontinuity at that region, thus providing a smoother transition from the surface to the flow [19]. Moreover, open-cell permeable materials allow for flow communication, which could mitigate the pressure imbalance and dampen fluctuations caused by the impingement of turbulent structures from the jet on the lower side of the wing/flap [20].

For the JIN in a configuration comprised of a flat plate placed in the vicinity of a single-stream jet, measurements by Rego et al. [21] have shown that a noise reduction in the order of 9 dB at the spectral peak is achieved by replacing the solid trailing edge of the surface with a permeable material. This mitigation is due to a better pressure balance between the upper and lower sides of the plate and a reduction in the spanwise pressure coherence at the plate trailing edge, which reduces the intensity of the noise scattered in that region [22]. The amplitude of noise reduction is also connected with the properties of the permeable material, such as porosity and permeability/resistivity, up to a certain threshold. However, for a partially porous surface, scattering still occurs at the solid-permeable junction, which becomes the location of the dominant acoustic source [22].

The application of permeable surfaces for JIN reduction has also been evaluated in complex configurations, comprising an airframe with deployed flaps and a nearby jet flow from a nacelle [23]. This configuration allows for the assessment of noise reduction under forward flight conditions, which not only alter the turbulent characteristics of the jet, but also introduces the complexity of the flow around the wing. Perforated flaps with a gradient permeability increase towards the trailing edge are studied in order to minimize the impact in the aerodynamic characteristics [23]. An overall reduction of 3 dB is obtained with the permeable flaps throughout the frequency range where JIN is the dominant source, thus demonstrating their effectiveness as a noise reduction solution. In terms of performance, a slight increase in drag, in the order of 0.5%, and a 7% reduction in lift are obtained, which are linked to the generation of vortices at the spanwise positions where the perforations start [23].

Another concept with potential for JIN reduction is the application of liner technology on the airframe surfaces. It has been shown that turbulent boundary-layer trailing-edge noise on a flap, which is a broadband source, can be reduced by up to 6 dB through the addition of Helmholtz resonators in the structure (the whole flap conceived as a liner composite structure) [24].

A similar concept has been studied for JIN reduction, applied to a flat plate in the vicinity of a turbulent jet [25]. Due to the small thickness of the plate, a Helmholtz resonator with a curved cavity is developed, with the perforated face-sheet placed on the side of the surface facing the jet (reflected side). By designing the resonator with an appropriate resonance frequency (i.e., the spectral peak in the installed jet configuration), noise reduction of up to 7 dB can be obtained [25]. A final concept comprised by a combination between trailing-edge perforations and acoustic liners upstream have been shown to provide the best results in terms of noise reduction. In this case, the resonators are designed to target the noise generated by the solid-permeable junction of the plate are able to completely mitigate this source, thus bringing the noise levels close to those of an isolated jet [25].

Conclusions

Nozzle-focused solutions targeting jet-installation noise reduction have a low impact on acoustics but also low impact on overall performance, whereas airframe-focused solutions largely reduce noise, but at the cost of lift reduction/drag increase. The described concepts, however, offer significant potential and a proper optimization of the geometry and operating conditions can likely lead to significant acoustic benefits with minimal performance degradation. A combination between the different solutions described in this work is likely to provide the best outcome and should be regarded as future work.

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