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Analytical and numerical prediction of harmonic sound power in the inlet of aero-engines with emphasis on transonic rotation speeds

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ABSTRACT

Tone noise radiated through the inlet of a turbofan is mainly due to rotor-stator interactions at subsonic regimes (approach flight), and to the shock waves attached to each blade at supersonic helical tip speeds (takeoff). The axial compressor of a helicopter turboshaft engine is transonic as well and can be studied like turbofans at takeoff. The objective of the paper is to predict the sound power at the inlet radiating into the free field, with a focus on transonic conditions because sound levels are much higher. Direct numerical computation of tone acoustic power is based on a RANS (Reynolds averaged Navier–Stokes) solver followed by an integration of acoustic intensity over specified inlet cross-sections, derived from Cantrell and Hart equations (valid in irrotational flows). In transonic regimes, sound power decreases along the intake because of nonlinear propagation, which must be discriminated from numerical dissipation. This is one of the reasons why an analytical approach is also suggested. It is based on three steps: (i) appraisal of the initial pressure jump of the shock waves; (ii) 2D nonlinear propagation model of Morfey and Fisher; (iii) calculation of the sound power of the 3D ducted acoustic field. In this model, all the blades are assumed to be identical such that only the blade passing frequency and its harmonics are predicted (like in the present numerical simulations). However, transfer from blade passing frequency to multiple pure tones can be evaluated in a fourth step through a statistical analysis of irregularities between blades. Interest of the analytical method is to provide a good estimate of nonlinear acoustic propagation in the upstream duct while being easy and fast to compute. The various methods are applied to two turbofan models, respectively in approach (subsonic) and takeoff (transonic) conditions, and to a Turbomeca turboshaft engine (transonic case). The analytical method in transonic appears to be quite reliable by comparison with the numerical solution and with available experimental data.

1. Introduction

Turbofans are the main sources of aircraft noise (airframe noise also becomes significant in approach for large airliners), and fan is more annoying than jet in high-bypass-ratio engines (e.g., see Chapter 3 of [1]). In another aeronautical domain, turboshaft engines can dominate rotor noise for medium-size helicopters at takeoff [2,3]. Same tools are used to predict the

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sound field of ducted fans or axial compressors, and it is why they are associated here. The study is focused on upstream propagation of the tones that are the main spectral components due to rotors, far above the broadband continuum.

The fan of an aircraft engine remains subsonic in approach flight. Acoustic radiation is controlled by the blade passing frequency (BPF) and its harmonics, generated by flow interactions between rotor and stator (outlet guide vanes, OGV). Sound power is expected to be roughly constant along the inlet duct if there is no acoustic lining on the wall. An objective of the present study is to check the energy conservation along the nacelle and to assess the free-field radiated sound power, using direct CFD data issued from numerical simulations based on RANS (Reynolds averaged Navier–Stokes) equations. General equations of sound intensity and power in irrotational flows were proposed by Cantrell and Hart [4] (they are reminded in Appendix A.1), and their implementation in the *elsA* CFD code from ONERA [5,6] is briefly described in Section 2. It is also noticed that the ducted sound power is maintained in the radiated free field, and this can be checked using a Kirchhoff approximation by taking the duct exit cross-section as integration surface [7] (see Appendix A.2).

On the contrary, the turbofan around design conditions (at takeoff) and the axial compressor of a turboshaft engine are usually transonic, i.e., the helical speed is supersonic at the blade tip but remains subsonic near the hub. Upstream acoustic radiation is dominated by the harmonics of the shaft rotational frequency, which are called multiple pure tones (MPT) or buzz-saw noise [8]. These tones are generated by the shock waves attached to the rotor blades. Slight differences between them, mainly due to random deviations of blade stagger angles, are increased along the intake duct due to nonlinear propagation. This explains why not only BPF and its harmonics are generated, but also MPT [9,10]. Indeed, amplitudes of the saw-teeth, Δp, can exceed one tenth of the atmospheric pressure. Sound power is dissipated towards expansion waves during nonlinear propagation. This phenomenon has been known for a long time either theoretically [11] or through experiments in ducts filled with various gases [12]. Another objective of the paper is to predict that decrease in order to determine the sound power actually radiated in the free field. An analytical model was proposed by Morfey and Fisher in 1970, when high-bypass-ratio turbofans appeared with their transonic fans [13]. Similar theories were also developed by Hawkings [9] and Fink [14] at that time, as well as a slightly different approach [15,16]. Recently, previous works were extended through a semi-analytical model using a nonlinear wave equation to describe the modal propagation in a cylindrical duct (however, mean flow velocity was neglected) [17].

A comprehensive analytical prediction of shock-wave generation and propagation is proposed in Section 3 because it can support numerical simulations and it leads to very fast calculations. It is based on an original merging of several studies. The initial pressure jump is estimated for a normal shock wave. Then, the model of Morfey and Fisher is reminded. It is two-dimensional which seems to be rather valid because shock waves are generated on the supersonic outer slice of a blade. It is completed by an improved computation of sound power taking into account that acoustic waves become three-dimensional when propagating in the intake duct [18]. The main hypothesis of the above method is that all the blades are identical such that predictions are limited to the blade passing frequency and its harmonics. The results can thus be directly compared to the present RANS computations that are restricted to one blade channel [18,19]. However, decreases of BPF and its harmonics are actually larger due to an energy transfer towards MPT [20,21] which has been validated by comparisons with measurements on scaled fans [22,23,24]. This effect can be easily estimated using a statistical approach whose main features are summarized in Appendix B [10].

Finally, three applications are discussed in Section 4: a subsonic turbofan model called LNR2, a transonic turbofan model tested in the European project FANPAC, and the transonic axial compressor of a helicopter turboshaft engine from Turbomeca.

2. CFD computation of sound power due to rotor-stator interaction or to a transonic rotor

2.1. Features of the elsA CFD solver

The *elsA* solver, developed at ONERA since 1997, is a multi-application aerodynamic code based on a cell-centred finite volume method for structured meshes. Solving the compressible, three-dimensional Reynolds averaged Navier–Stokes (RANS) equations, *elsA* allows us to simulate a great variety of aerospace configurations such as aircraft, space launchers, missiles, helicopters and turbomachines. Therefore, a wide range of numerical tools and models are implemented.

Conventional numerical tools are provided in *elsA* for turbomachinery applications such as a cell-centred space discretization scheme of Jameson with artificial viscosity, and a second-order accurate Roe scheme for transport equations of turbulence models.

Several time-integration schemes are available in *elsA* to perform steady and unsteady computations. Explicit or implicit schemes, such as a pseudo-time approach (Dual time stepping) or the Gear method, are available. Time integration can be solved either by an implicit residual smoothing phase with a 4-step Runge–Kutta technique or by an implicit LU scalar relaxation phase associated to a backward Euler scheme. Convergence acceleration techniques such as local time stepping and multi-grid method are available for steady computations in order to reduce the total CPU time.

Suitable boundary conditions for turbomachinery configurations have been implemented for steady flow applications: coincident and non-coincident matching conditions have been developed for the treatment of periodic conditions on boundaries, and a steady multi-stage condition using pitch averaging for the treatment of the rotor–stator interface. Different types of inlet, outlet, and wall conditions are also available. For acoustic applications, as the current non-reflecting