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Prediction of tonal ducted fan noise

J. de Laborderie [1],*, S. Moreau

Department of Mechanical Engineering, University of Sherbrooke, Sherbrooke, Qc, Canada J1K 2R1

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ABSTRACT

This study introduces an analytical model aiming at predicting the tonal acoustic sources generated and radiated by the rotor–stator interaction in a fan stage. This model is able to cope with complex three-dimensional stator geometries and it fully accounts for cascade effects, characteristic of modern fan stages. It is based on a proper description of the rotor wake coupled with an analytic cascade response function and with an acoustic analogy. The proposed model is validated for the first time against acoustic sources and sound power measurements, on the Advanced Noise Control Fan from NASA. On this configuration representative of an actual fan stage, the model is shown to predict tonal sources and powers accurately, in function of the rotational velocity and of the stator-vane count. Another realistic configuration, namely the low-pressure CME2 research compressor, is then considered in order to demonstrate the suitability of the model to be used as a design tool in an industrial context. A parametric study concerning both the stator vane sweep and lean angles is performed on this rotor–stator stage. The model produces predictions consistent with studies from literature, quantifying the effectiveness of swept and leaned vanes as a tonal noise reduction mechanism. This parametric study allows defining an optimal stator design for minimal noise emission.

1. Introduction

In the future of aircraft propulsion, the Ultra-High Bypass Ratio (UHBR) turbofan architecture is promising as it leads to an overall efficiency improvement and to a decrease of pollutants emission with respect to the current generation of aeroengines. In particular, the gain in propulsive efficiency is partly reached with a larger fan diameter. However the larger nacelle associated with this configuration implies a drag increase that is detrimental to the overall engine efficiency. Thus a UHBR nacelle has to be shortened. This in turn induces shorter rotor–stator distances, more pronounced inlet and outlet distorsions and less efficient passive treatment that reduces fan noise propagating outside of the nacelle. Therefore, in the frame of fan noise source reduction, the current work aims at improving fan noise modelling. As stated by several authors, e.g. Groeneweg et al. [1], Envia et al. [2] and Peake and Parry [3], the interaction of fan wakes with the downstream outlet guide vanes (OGVs) represents the main source of fan noise, a trend growing with the expected decrease of the rotor–stator spacing in UHBR. A blade wake is composed of a mean velocity deficit creating a periodic fluctuation in time and in the azimuthal direction in the stator reference frame. Convected with the mean flow, these wakes interact with the vane leading edges generating pressure fluctuations on the whole vane surfaces. This unsteady loading radiates acoustic waves

* Corresponding author.
E-mail addresses: jerome.de.laborderie@usherbrooke.ca (J. de Laborderie), stephane.moreau@usherbrooke.ca (S. Moreau).
[1] Present address: CERFACS, CFD team, 31057 Toulouse, France.

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propagating within the nacelle, at the blade passing frequency (BPF) and its higher harmonics. This mechanism corresponds to the rotor–stator interaction tonal noise. Moreover turbulent structures present in blade wakes, upon interaction with the downstream vanes, generate random wall pressure fluctuations that radiate to form the rotor–stator interaction broadband noise [4]. The current study focuses on fan tonal noise as it becomes crucial in UHBR because of the less efficient passive treatment as well as the decrease of the rotor–stator gap creating a larger interaction of the rotor wakes with the stator.

Several types of Computational Aero-Acoustics (CAA) methods aiming at the prediction of fan tonal noise have been developed [2]. Among them, a first category uses Reynolds-Averaged Navier–Stokes (RANS) equations to compute the viscous blade wakes downstream of the rotor. This vortical excitation is then imposed at the inlet of a stator domain on which the linearised Euler equations are numerically solved. This approach has for instance been implemented within the LINFLUX code, that computes the vane row acoustic response in the frequency domain, by Montgomery and Verdon [5], Verdon [6] and Prasad and Verdon [7]. The method of Atassi et al. [8] also uses linearised Euler equations to predict the acoustic response of the vane cascade. With such an approach, actual vane and duct geometries are accounted for in the source and near-field acoustic prediction. A second category of methods, based on the Unsteady Reynolds-Averaged Navier–Stokes (URANS) equations, has been successfully surveyed by several authors [9–12]. These approaches allow considering a realistic flow, particularly the vane mean loading and the influence of the stator on the rotor wakes, in the acoustic prediction. However the computational cost associated with these numerical methods still prevents them to be routinely used in an industrial context, especially for pre-design and parametric studies. This is the reason why analytical approaches represent an interesting compromise as they provide fast and exact solutions of simplified problems. The response function of Amiet [13], extended by Paterson and Amiet [14], Moreau et al. [15] and Roger et al. [16], deals with the interaction of an aerodynamic gust with a single airfoil in free-field. In this model, suited for low solidity rotors without external casings such as helicopter rotors, propellers, contra-rotating open rotors and ventilators, the airfoil is modelled as an infinitely thin flat plate immersed in a uniform inviscid flow with zero incidence (neither vane camber nor mean loading). The asymptotic analyses of Myers and Kerschen [17] and Evers and Peake [18] allow considering some mean loading effects in the response. For low solidity ducted fans, as proposed by Glegg [19] for instance, the isolated response can be coupled with Green's function tailored to a duct developed by Goldstein [20]. However cascade effect, i.e. the influence of the neighbouring vanes on the source generation and radiation of a given vane, has to be considered in a modern fan stage where vanes overlap. For the interaction of a gust with a rectilinear flat plat cascade, the models are based on the resolution of an integral equation, using the acceleration potential method [21] or the lifting surfaces methods [22], leading to the LINSUB code for instance [23–26]. Namba and Schulten's and Zhang et al.'s model [27–29], also based on a lifting surface method, account for an annular cascade and the casing walls, but are limited to vanes with zero stagger angle and no radial geometrical variations. Another group of cascade models is based on a closed-form analytical solution of the integral equation with the Wiener–Hopf technique, successively extended by Mani and Hovray [30], Koch [31], Peake [32] and Glegg [33]. Posson et al. [34] extended Glegg's work to the calculation of the unsteady vane loading and of the pressure field in the vane passage. In the cascade model of Hanson [4], also based on the Wiener–Hopf technique and Glegg's blade response, the strip theory approach allows accounting for variable stator geometry along the duct height, but the acoustic power is evaluated in free field and decorrelated from one strip to another one. Finally, another approach consists in considering the actual annular distribution of acoustic sources on the stator vanes as well as their radiation within an annular duct, contrary to the free field acoustic radiation from a rectilinear cascade. In the model of Ventres et al. [35], the unsteady vane loading is obtained via a numerical resolution of the integral equation then radiated with the annular duct Green's function of Goldstein [20]. This model, developed for fan tonal and broadband noise applications, has been extended by Meyer and Envia [36], Nallasamy and Envia [37] and Grace et al. [38]. Finally the model of Posson et al. [39], using a purely analytical solution for the acoustic sources and the in-duct radiation with Goldstein's analogy, has been applied and validated for fan broadband noise predictions.

Tonal fan noise modelling is challenging mainly because the sound emission is sensitive to the stator geometry and because the excitation and the vane response are correlated along the duct height. This is why the present model, based on the analytical cascade response function of Posson et al. [34], uses a radial strip approach in order to consider a complex stator geometry, with variable stagger, sweep and lean angles for the vanes. Moreover this cascade response is coupled with Green's function developed by Goldstein [20] so as to account for the annular duct geometry and an axial mean flow in the acoustic propagation. The aerodynamic excitation is decomposed into skewed gusts that are coupled with the 3D cascade response to ensure a correct representation of the radially correlated vane response. Although this tonal noise model has already been used in preliminary studies [40,41], the first objective of the paper consists in performing a complete description of this cascade based acoustic model, in focusing particularly on the complex stator geometry and the aerodynamic excitation. Then Section 3 aims at validating the model against experimental data collected on the Advanced Noise Control Fan (ANCF) configuration [42,43]. The latter is representative of an actual fan stage of a modern aeroengine and exhaustive available datasets allow performing trends with the vane count and the rotational velocity. Finally the model is evaluated in Section 4 on the CME2 axial compressor stage [44], at higher reduced frequencies than on the ANCF configuration. Parametric studies on the vane geometry are performed in order to highlight the model capability of handling complex stator configurations and of determining an optimal acoustic design.