On Aerodynamic Noise Sources in Rotor-Stator Stages Induced by Inflow Distortions

Michel Roger, LMFA, Ecole Centrale de Lyon, France,
Stéphane Moreau, Sherbrooke University, Québec, Canada
& Majd Daroukh, CERFACS, France

Long Abstract

Introduction

In many ducted axial-flow fan architectures including a rotor-stator stage, the blade and vane counts (B, V) are tuned to each other in order to ensure the cut-off of the wake-interaction noise (WIN) at the blade-passing frequency (BPF), and as far as possible also the higher harmonic 2BPF, depending on the rotational Mach number. The tuning is based on Tyler & Sofrin's rule, stating that at the harmonic mBPF or $mB\Omega$, the spinning modes of radiation generated by the interaction have numbers of lobes $n=mB-sV$, s being any relative integer, and associated tip phase speeds $\Omega_n=\Omega_s=mB\Omega/n$. A subsonic phase speed ensures the cut-off of a mode, so that the low-noise design is equivalent to avoid small absolute values of n. Yet in many practical cases the expectedly cut-off tones are actually observed, which indicates that the ideal periodicity is lost or that other source mechanisms take place. Apart from structural stator heterogeneity [1], one candidate is the ingestion of a more or less stationary azimuthal inflow distortion. Indeed as a rotor blade crosses such a distortion, it experiences periodic loads with the fundamental period of rotation. This generates rotor distortion noise at the same BPF harmonics as WIN but also makes the velocity deficit in the wake of a blade vary in time with the same rotational period. The passing wakes are identical at a given stationary observation point whereas their shape varies as a function of the azimuthal coordinate θ or the tangential coordinate $y=R_0\,\theta$ at the radius R_0. As a result the modal structure of the WIN deviates from the expected one because the stator vanes experience different excitations and associated fluctuating loads. The proposed paper is first aimed at quantifying this effect for a stationary model inlet vortex, using simple analytical techniques. It also compares the relative contribution of the WIN with respect to the rotor distortion noise. In a second step a more realistic random slow motion of the vortex will be introduced in the model in order to investigate the spectral broadening of the tonal noise. Furthermore numerical simulations will be post-processed to characterize the effect of an inlet distortion on the wakes of a rotor in a more realistic way [2]. Only the WIN in the presence of an inlet vortex is discussed in this abstract.

1. Methods

For a first assessment of the effect of inflow distortions, a free-field radiation model of a rotor-stator system can be considered, ignoring the effect of the duct on the sound radiation (an in-duct formulation will be included in the final paper). Analytical expressions of the sound field are derived using the same approach as in reference [1]. The test-case configuration presented below is made of a B-bladed rotor and V OGVs with B=17, V=23. The model inlet vortex has a Gaussian variation of the axial velocity profile and its half-width is 4% of the perimeter. It causes a Gaussian variation of 10% of both the width and the depth of the rotor wakes, Sample results are reported in figure 1 for the BPF. The directivity the sources would have in free field and in homogeneous inflow conditions (grey surface) is axisymmetric. The sound is emitted normal to the fan axis, which is known to correspond to cut-off conditions when the system is embedded in a duct. In fact the wake interaction generates the dominant spinning radiation mode of order n= -6 at the BPF according to Tyler & Sofrin's rule. This mode corresponds to modes with the same azimuthal order and arbitrary radial orders in the duct. All of these modes are cut-off. In the presence of the inlet vortex, the directivity pattern (colored surface in figure 1) is only moderately modified but the small distortion corresponds to additional modes, some of which with low orders will produce cut-on modes in the duct. The corresponding modal spectra are plotted in figure 2 in an arbitrary decibel scale. In homogeneous conditions only the mode -6 is found (red symbol) whereas with the inlet vortex other modes emerge (black dashed-line envelope). The modes of orders between -3 and 3 (blue-line range in the figure) will give rise to cut-on modes in the duct. As a result the WIN contribution to the BPF is expectedly transmitted through the duct in the presence of the vortex whereas it cannot be with a homogeneous inflow.

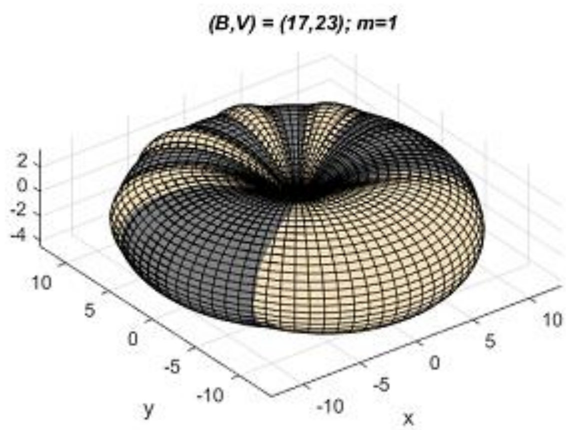

Figure 1. Free-field directivity pattern of the disturbed rotor-stator WIN at the BPF. Fan axis along the vertical direction, pointing at inlet.

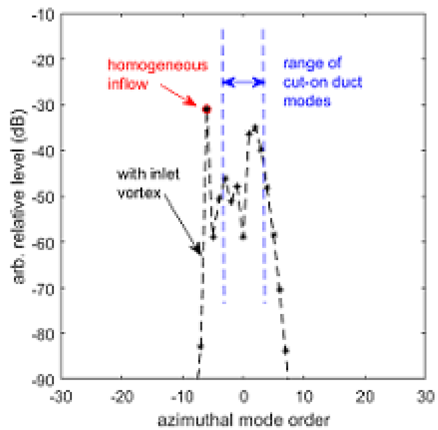

Figure 2. Envelope of the free-field azimuthal modal spectrum of WIN at the BPF for a far-field observer at 30° from axis..

The quantification of the effect of an inlet vortex, or of any other inflow distortion, in terms of variations of the wake parameters is a point of major interest for fan manufacturers, especially at the early design stage, together with the quantification of the vortex itself. The latter has been shown to always take place on installed fans (except for turbofans in forward flight), for instance by Sturm et al. [3]. Simple estimates of the wake variations can be produced based on empirical correlations (see for instance Lieblein [4]) or by post-processing numerical simulations [2]. Both approaches will be discussed in the final paper, and the turboengine configuration presented by Daroukh et al. and shown in Figure 3 will also be considered in this assessment.

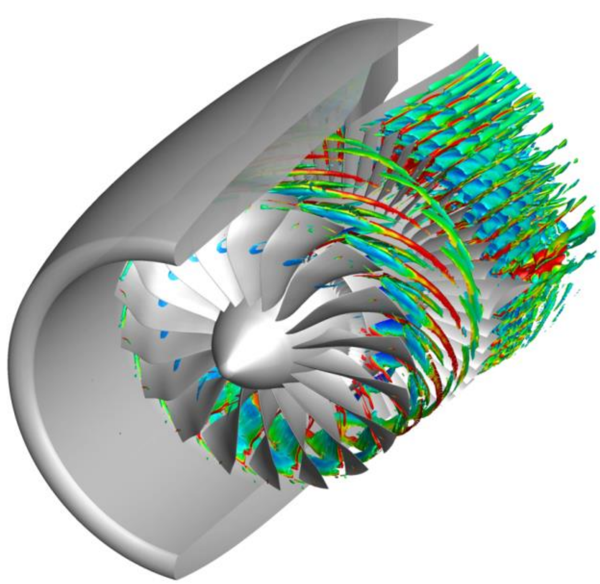

Figure 3. Iso Q-criterion for the turbofan configuration

References

[1] M. Roger & P. Caule. Assessment of the effect of stator inhomogeneity on rotor-stator tonal noise, *ISROMAC 15*, 2014.

[2] M. Daroukh, S. Moreau, N. Gourdain, J. Boussuge, C. Sensiau, "Influence of distortion on fan tonal noise," 22nd AIAA/CEAS Aeroacoustics Conference, Lyon, France, May 2016.

[3] M. Sturm, M. Sanjose, S. Moreau, T. Carolus, Aeroacoustic simulation of an axial fan including the full test rig by using the Lattice Boltzmann Method, Fan 2015, International Conference on Fan Noise, Technology and Numerical Methods, Lyon, France, April 2015.

[4] S. Lieblein. Incidence and deviation-angle correlations for compressor cascades. *Journal of Basic Engineering*, 82(3):575–584, 1960.