Accounting for sweep and lean in the design-to-noise of rotor-stator stages

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Introduction

The benefit of stator sweep and lean (see Fig. 1) on rotor-stator interaction tonal noise is analysed by using an analytical model. This model is to be integrated in a fan design-to-noise procedure under development [1, 2, 3]. The level of rotor-stator interaction tones depends on the vane unsteady loading. This can be modified positively by increasing the rotor-stator spacing. This method benefits from the rapid decay of the rotor potential field and also from the viscous wake dissipation. Furthermore, due to the interstage swirl that tilts the wakes, the excitation at the stator is not constant over the blade span: destructive acoustic interferences are built which reduce the noise. When the stator distance to the rotor is sufficiently large (let us say one or two chords), this last effect mostly contributes to the noise reduction. The introduction of stator vane lean and sweep can strongly amplify this effect [4, 5, 6].

Model description

The problem is treated under the assumption that linear duct acoustics is applicable. The sound waves propagate within an annular duct of constant cross-section with a uniform background flow. The effect of swirl on the acoustic propagation is neglected. The acoustic pressure field is decomposed into a sum of modes (m, n),

$$p(x, r, \theta, t) = \sum_{m,n} A^{\pm}_{mn} f_{mn}(r) e^{i(k^{\pm}_{x,mn}x + m\theta - \omega t)}, \qquad (1)$$

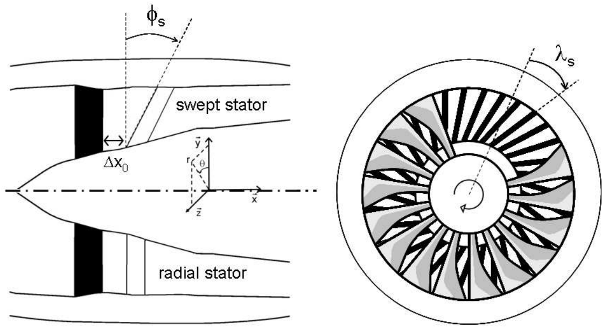
with A_{mn} the amplitude, $k_{x,mn}$ the axial wavenumber, and f_{mn} the radial shape. A power duct transfer function H_{mn} is introduced. This function can be expressed as

$$H^{\pm}_{mn} = \frac{1}{(kR)^2} \frac{S^{\pm}_{mn} C^{\pm}_{mn}}{\alpha_{mn}} \qquad (2)$$

(see Ref. [2]), where α_{mn} is the cut-on factor, C_{mn} a convection factor, and S_{mn} a source function depending on the sweep and lean. Unsteady loading noise is modelled by a line of acoustic dipoles distributed along the leading edge of the stator vanes. The axis of these dipoles is perpendicular to the stator leading edge, the stagger angle of which is denoted by χ. For correlated dipoles excited by the rotor wake impinging on the stator, the modal source function is equal to

$$S^{\pm}_{mn} = \frac{3V}{2} \left| \int_{\eta R}^{R} g(r) F^{\pm}_{mn}(r) e^{i\Delta\varphi_{mn}(r)} dr \right|^2, \qquad (3)$$

where V is the vane count, R the duct radius, η the hub-to-tip ratio, g a radial weighting of the source, F_{mn} the dipole acoustic efficiency (given with no lean in Eq. 4),



cross-sectional view *front view*

Figure 1: Stator (ϕ_S) sweep and (λ_S) lean.

$$F^{\pm}_{mn}(r) = f_{mn}(r) \left(\frac{k^{\pm}_{x,mn}}{k} \cos(\chi + \frac{\pi}{2}) + \frac{R}{r} \frac{m}{kR} \sin(\chi + \frac{\pi}{2}) \right), \qquad (4)$$

and

$$\begin{aligned} \Delta\varphi_{mn}(r) &= \left(k^{\pm}_{x,mn} - hB \frac{\Omega_R - \Omega_{swirl}(r)}{M_x c_0} \right) \Delta x(r) \\ &\quad + (m - hB)\Delta\theta_\lambda(r). \end{aligned} \qquad (5)$$

The variables h, Ω_R, Ω_{swirl}, M_x, and Δx define the loading harmonic, the rotor angular speed, the swirl angular speed, the axial Mach number and the leading edge position relative to the rotor trailing edge, respectively. The term $\Delta\varphi_{mn}$ represents a phase shift accounting for the fact that the dipole sources distributed along a swept and leaned leading edge are excited at different times by the oncoming rotor wakes. This time delay is responsible for destructive interferences that mostly explain the noise reduction of the rotor-stator interaction tones. Note that without sweep and lean, the phase shift $\Delta\varphi_{mn}$ is constant over the radius when $\partial\Omega_{swirl}/\partial r = 0$. In this case the modal source function $S^{\pm}_{mn}$ reduces to Eq. 14b given in Ref. [2]. If the rotor trailing edge is radial and the sweep angle ϕ_S is constant over the whole blade profile, then

$$\Delta x(r) = \Delta x_0 + (r - \eta R) \tan\phi_S \qquad (6)$$

where Δx_0 is the rotor-stator distance taken at the hub. A lean angle λ_s, constant over the whole stator profile, yields an azimuthal angular shift $\Delta\theta_\lambda$ given by

$$\tan\Delta\theta_\lambda(r) = \frac{\tan\lambda_S}{1 + \frac{1}{\cos^2\lambda_s \left(-1 + \sqrt{1 + \frac{(r/(\eta R))^2 - 1}{\cos^2\lambda_S}} \right)}} \qquad (7)$$

As shown hereafter, Ω_{swirl} in Eq. 5 influences the angle of incidence of the wake on the stator. Two swirl models are tested here: i) a rigid body swirl for which the swirl

<table>
<tr><td colspan="5">duct</td></tr>
<tr><td>R=0.56 m</td><td>η=0.3</td><td colspan="3">$\Delta x_0/c_R$=1 (up) or 2 (down)</td></tr>
<tr><td colspan="5">rotor (trailing edge)</td></tr>
<tr><td>B =18</td><td>c_R=0.223 m</td><td>ϕ_R=0°</td><td colspan="2">λ_R=0°</td></tr>
<tr><td colspan="5">stator (leading edge)</td></tr>
<tr><td>V =42</td><td>c_S=0.127 m</td><td>ϕ_S</td><td>λ_S</td><td>χ=37.5°</td></tr>
<tr><td colspan="5">operating point</td></tr>
<tr><td>sideline</td><td>RPM=5210</td><td>M_x=0.6</td><td>π=1.378</td><td>$M_{swirl_{50}}$=0.46</td></tr>
</table>

Table 1: Test case (inspired from [4, 5]).

angular speed is constant over the radius, and ii) a free vortex design for which the blade circulation Γ is spanwise constant, the latter model being the more realistic one for fan applications.

$$\begin{aligned} U_{swirl}(r) &= \Omega_{swirl} \times r && \text{rigid body swirl,} \\ U_{swirl}(r) &= \Gamma/2\pi r && \text{free vortex.} \end{aligned} \quad (8)$$

Example of application

This analytical model is now applied to a fan rotor-stator stage, with properties (see Tab. 1) similar to the Allison fan used in Ref. [4, 5]. Flow and stagger angles were estimated at mid span. All presented results are normalised with regard to the radial stator case ($\phi_s = 0°$ and $\lambda_s = 0°$) at the upstream position ($\Delta x_0 = c_R$, with c_R the rotor chord). Figure 2 intends to demonstrate the importance of the swirl on wake interaction tones (here the dominant 2BPF tone). With a *rigid body swirl*, the radial pattern of the wakes leaving the rotor remains unchanged as they convect downstream. As a consequence, the radial phase is constant over the stator vane span. This case is the loudest one and features a symmetrical behaviour with regard to the sign of sweep angle, since potential field interactions and wake expansion are not accounted for. Furthermore the results do not depend on the rotor-stator spacing. With the *free vortex model*, the amplitudes are much lower over the whole range of sweep. For the case without sweep, the predicted level is 5 dB lower (resp. 7.5 dB) for a rotor-stator spacing of one (resp. two) rotor chord(s). This reduction is explained by the fact that the wakes are tilted while they are convected downstream, which induces a radial phase shift on the stator vanes. This effect increases with the rotor-stator spacing. Compared to the rigid body swirl, the curves are now asymmetrical with respect to the sign of sweep angle: substantial benefits are achieved for rearward sweep but slight tonal amplification is found for forward sweep. The results presented in Fig. 3 for the upstream position indicate that lean is beneficial only for positive angles (i.e. in the direction of the rotor rotation). All these observations are in good agreement with Ref. [4, 5].

Outlook

This method can be extended to account for the wake expansion, the chordwise distribution of loading, the reduction of the flow component normal to the stator vanes, and the slightly increased length of the leading edge. These aspects also affect broadband uncorrelated noise.

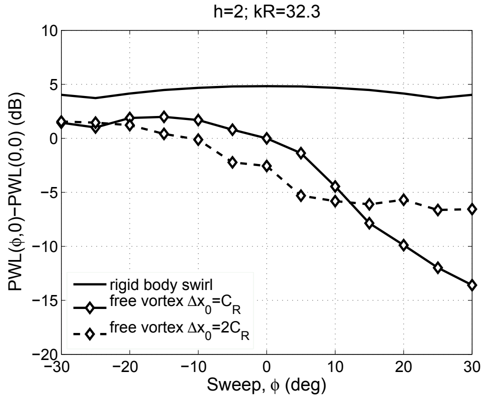


Figure 2: Influence of swirl on total radiated sound power; 2BPF, no stator lean, uniform weighting $g = 1$.

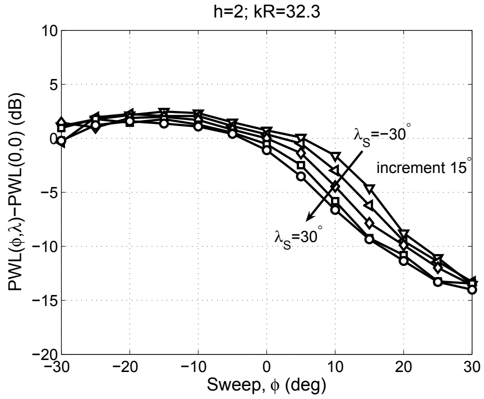


Figure 3: Influence of sweep and lean on total radiated power; 2BPF, free vortex design, stator in upstream position.

References

[1] Moreau A., Guérin S.: Development and application of a new procedure for fan noise prediction. 16th AIAA/CEAS Aeroacoustics Conference, 7-9 June 2010, Stockholm, AIAA-Paper 2010-4034.

[2] Guérin S., Moreau A., Tapken U.: Relation between source models and acoustic duct modes. 15th AIAA/CEAS Aeroacoustics Conference, 11-13 May 2009, Miami, Florida (USA), AIAA-Paper 2009-3364.

[3] Moreau A., Guérin S., Busse S.: A method based on the ray structure of acoustic modes for predicting the liner performance in annular ducts with flow. NAG/DAGA 2009, International Conference on Acoustics, 23-26 March 2009, Rotterdam.

[4] Woodward R.P., Elliott D.M., Hughes C.E., Berton J.J.: Benefits of swept and leaned stators for fan noise reduction. 37th Aerospace Sciences Meeting and Exhibit, 11-14 January 1999, Reno, Nevada (USA), A99-16363.

[5] Envia E., Nallasamy M.: Design selection and analysis of swept and leaned stator concept. J. Sound Vib.**228**(4) (1999), 793-836.

[6] Elhadidi B., Atassi H.M.: Passive control for turbofan tonal noise. AIAA J. **43**(11) (2005), 2279-2292.