Stator Vane-Based Active Control of Turbofan Engine Noise

I. Vinogradov and Y. Zhou

Abstract Active control of rotor–stator interaction noise is studied numerically based on the surface oscillation of stator vanes. The problem is formulated in terms of 3D Euler equations linearized around uniform steady flow. Governing equations are solved with an explicit numerical technique based on a high-order approximation of spacial derivatives. It is found that the acoustic response with actuation on the suction side of the vanes differs considerably from that on the pressure side. The noise radiation also exhibits a strong dependence on the actuation frequency and position on the vane. Noise reduction of up to 80 % can be achieved.

Keywords Active noise control · Fan noise

1 Introduction

A significant portion of engine noise for modern transport aircraft comes from the fan stage, and is expected to be increased further with the introduction of ultra high bypass ratio engines. Traditional ways of noise reduction such as increasing rotor–stator distance and covering parts of the duct with acoustic liners are not effective for those engines, and alternative techniques are needed.

Active control is based on the idea that it is possible to generate a secondary acoustic field which can cancel upstream and/or downstream propagating sound waves. This work considers the case to mount oscillating actuators on the stator

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vanes. Tonal noise is produced by the interaction between vanes and rotor wakes. Arranging actuators at the same location as the sources of noise to cancel may minimize the required input power (Curtis 1999).

One problem with active control in turbomachinery is to generate a secondary acoustic field of adequately high intensity. Therefore, it is important to have a clear understanding of how the position and size of the actuators and other parameters influence the acoustic response. Numerical simulation is highly suitable for this task but existing studies are mostly based on 2D techniques. This work aims to develop a 3D numerical simulation of sound produced in turbomachinery and to investigate the fundamentals of sound generation, propagation, and active control based on stator-mounted actuators.

2 Description of the Problem and Numerical Method

A stator is modeled as an isolated annular cascade of 24 vanes inside an infinite coaxial duct of inner radius r_h and outer radius r_t, $r_h/r_t = 0.6$. A cylindrical coordinate system (x, θ, r) is used, as shown in Fig. 1. Flow inside the duct is assumed to be subsonic, inviscid, and non-heat conducting, while the flow variables $(\boldsymbol{u}, \rho, p)$ are represented as a sum of the steady flow variables $(\boldsymbol{U}, \rho_0, p_0)$ and small-amplitude unsteady distortions $(\tilde{\boldsymbol{u}}, \tilde{\rho}, \tilde{p})$, viz.:

$$(\boldsymbol{u}, \rho, p)(x, \theta, r, t) = (\boldsymbol{U}, \rho_0, p_0)(x, \theta, r) + (\tilde{\boldsymbol{u}}, \tilde{\rho}, \tilde{p})(x, \theta, r, t), \quad (1)$$

where t, ρ, p, U and $\tilde{\boldsymbol{u}}$ denote time, density, pressure, steady and unsteady velocity vectors, respectively. (U_x, U_θ, U_r) and $(\tilde{u}_x, \tilde{u}_\theta, \tilde{u}_r)$ represent axial, circumferential, and radial velocity components of steady and unsteady parts, respectively. It is assumed that $|\tilde{\boldsymbol{u}}| \ll |\boldsymbol{U}|$, $|\tilde{\rho}| \ll |\rho_0|$ and $|\tilde{p}| \ll |p_0|$. Steady flow is assumed to be axial and uniform, while the evolution of the unsteady variables is described by Linearized Euler equations. Rotor wakes are modeled as a vortical gust imposed upstream (Atassi et al. 2004),

$$(\tilde{\rho}, \tilde{u}_x, \tilde{u}_\theta, \tilde{u}_r, \tilde{p}) = (0, -(m_g U_x)/(\omega r), 1, 0, 0)\exp(i(m_g\theta - \omega t)), \quad (2)$$

where m_g is circumferential wave number and ω is frequency. Vanes have zero thickness and are placed along the steady flow streamlines, a single blade passage with θ varying from 0 to $2\pi/24$ is considered. Vane surface at $\theta = 0$ and $\theta = 2\pi/24$ will be called suction side and pressure side, respectively. Actuators are

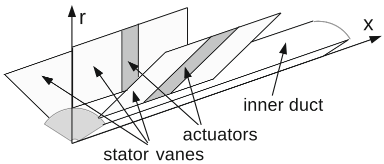
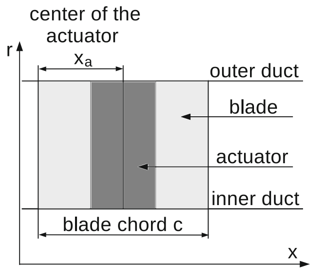


Fig. 1 Stator cascade

Fig. 2 Stator-mounted actuator



modeled as stripes (Figs. 1, 2), are mounted on each vane at the axial position x_a (Fig. 2) oscillating with the same ω as the gust. Non-dimensional variables, normalized with mean radius r_m, steady flow speed of sound c_0 and density ρ_0, are used. Non-impermeability condition is imposed at the rigid surfaces. The same boundary condition as (Farassat and Dunn 1999) is deployed for the surfaces of actuation. Non-reflecting boundary conditions (Atassi and Ali 2002) are imposed at the inlet and outlet of the domain, and the quasi-periodicity boundary condition (Atassi et al. 2004) is used at the free streamlines. The governing equations are solved in frequency domain with an explicit numerical technique based on a high-order approximation of spacial derivatives. The current approach is the extension of the algorithm used to analyze gust-cascade interaction noise (Vinogradov 2006).

3 Results and Discussion

The following uniform distribution of steady flow parameters is used:

$$(\rho_0, U_x, U_\theta, U_r, p_0) = (1, 0.5, 0, 0, 1/\gamma), \tag{3}$$

where γ is the ratio of specific heats. The chord length is $c = 0.3491$, the actuator axial span is $0.2c$ and $m_g = 16$. Three cases with $\omega = 10$, 14 and 20 are examined corresponding to two, four, and seven downstream and upstream propagating modes, respectively. For each ω actuator position x_a was varied from $x_a = 0.2c$ to $x_a = 0.8c$.

In the absence of incoming gust, the entire noise radiation results from actuation. Figure 3 presents the dependence on the actuator position x_a of the downstream radiated modal power for suction- and pressure-side actuations. Each mode is denoted as $(m\ ,n)$ where m is its circumferential wave number and n is the number of zeroes of its pressure eigenfunction. It can be seen that the acoustic response differs greatly between suction- and pressure-side actuations. The dominant mode is (16 ,0) for the former and (8,0) for the latter, except for approaching $x_a = 0.2c$ (near the leading edge) where both modes contribute comparably. The x_a has a significant influence on the acoustic response; even a small change may considerably alter the sound radiation. The ratio of downstream-to-upstream-radiated power is also influenced by x_a (Fig. 4). Note that the actuation amplitude is fixed. The problem is linear and the entire sound field is actuator-induced; the total power and the contribution from each mode are proportional to the square of the amplitude. As such, relative quantities such as the ratios of modal-to-total (Fig. 3) or downstream-to-upstream radiated power (Fig. 4) are independent of the amplitude.

In the presence of an incoming gust (2), downstream radiated sound power depends on the phase and amplitude of actuator oscillations. As such, steepest decent method (Press et al. 1992) was deployed to search for the optimum phase and amplitude in terms of the minimized downstream radiated sound power for given ω and x_a When actuation is imposed simultaneously on both sides of the vane, the optimum phase and amplitude of each actuator were obtained similarly. Meanwhile, the upstream radiated sound power is subjected to two constraints, i.e., under its level without control (c1) and allowing an increase by 10 % of the gust-induced downstream radiated power (c2). Figure 5 shows that x_a has a pronounced impact on the noise reduction, compared with the reference level, i.e., no control when the actuation amplitude is made zero. Due to the distinct distributions of power among propagating modes (Fig. 3), actuation on the pressure side is much more effective than on the suction side. Evidently, the control performance is greatly enhanced when actuation is imposed on both sides of the vane (Fig. 5). Active control using jets near the rotor suggested a difficulty in reducing noise when multiple propagating modes are present (Steger et al. 2010). There are seven propagating modes for the case considered but a good performance can still be achieved given a right x_a. Further investigation is underway to improve the control performance and to understand the physical mechanisms behind.

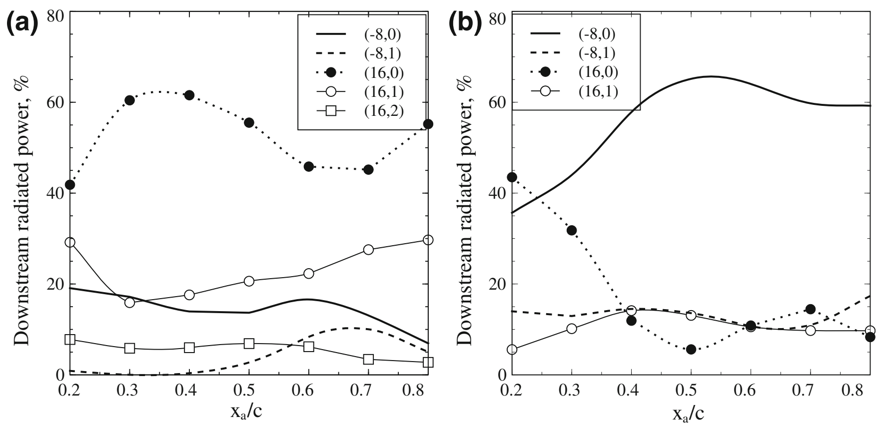


Fig. 3 Dependence on x_a of actuator-induced modal power as a percentage of the total power, actuation is imposed at $\omega = 20$ on **a** the suction side and **b** the pressure side

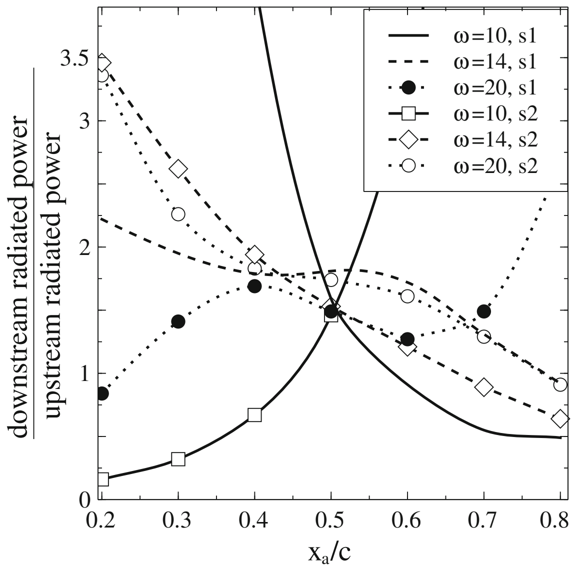


Fig. 4 Dependence on x_a of the ratio of downstream-to-upstream radiated actuator-induced powers, s1 and s2 denote suction- and pressure-side actuation, respectively

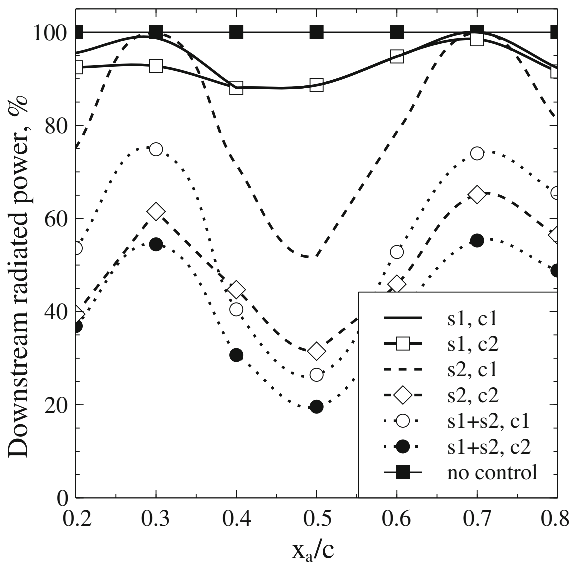


Fig. 5 Downstream radiated power under control ($\omega = 20$), c1 and c2 are constraints imposed on upstream radiated power

4 Conclusions

Investigation has been conducted on active control of rotor–stator interaction noise based on unsteady actuation on stator vanes. The following conclusions can be drawn:

1. The proposed control has been demonstrated to be highly effective, reducing downstream radiated noise by up to 80 % given actuation on both sides of the vane and the optimum actuation position.
2. The control performance may depend on, *inter alia*, the actuation frequency, the side of the vane where actuation is imposed, and the axial position of actuation.
3. The present technique allows an effective control of noise even when multiple modes are present given the right position of the actuators.

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