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FAN NOISE REDUCTION INCLUDING THE EFFECTS OF SWEPT-AND-LEANED VANES AND ACOUSTIC TREATMENT

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A swept and leaned stator is an effective means of the passive control of fan interaction noise. Based on the three-dimensional analysis, it's found that the selection of vanes sweep and lean may change the modal pressure distributions of the sound. And the sound propagation in the duct also affects the aerodynamic response on the vanes, which is regarded as the main sound source of fan interaction noise. Meanwhile, the acoustic liners optimization is aimed at the greatest attenuation of sound in an engine nacelle. In this process, the noise source models are usually assumed to be one single mode or multi propagating modes with equal energy. In this paper, the transfer element method is employed in order to include the stator and the acoustic treatment at the same time. The transfer element for a stator is established based on the three-dimensional lifting surface method. The effect of a duct liner is modelled by monopole sources. All the elements are finite length and coupled at the interface planes by solving a linear system. The results show that the optimal range of the liner's impedance may be greatly changed when including the effect of vanes sweep and lean. Further reduction of fan interaction noise is expected for the system acoustic design in the nacelle.
Keywords: transfer element method, fan noise, swept-and-leaned vanes, acoustic liner

1. Introduction

In order to reduce the noise levels in modern commercial turbofan engine, the locally/non-locally reacting liners are extensively used as the acoustic treatment in intake and bypass ducts [1]. The specific acoustic impedance on the wall represents the acoustic properties of a liner at a particular frequency, and should be designed for the maximum sound absorption. Many analytical [2] and numerical simulations [3] of sound propagation through the nacelle have been applied in the process of liner optimisation. The input of sound source is normally considered in term of acoustic modes. For fan tonal noise which is induced by the interaction of rotor wakes with the downstream stator, the pioneering work of acoustic modes analysis is made by Tyler and Sofrin [4]. In most practical situation, a number of modes with multiple combinations of circumferential and radial modes can propagate in the duct. The weighting of modes is normally assumed to be equal amplitude or equal energy.

The benefit of swept-and-leaned stators for fan noise reduction has been observed experimentally [5]. Using the two-dimensional strip theory, Envia & Nallasamy [6] explained this control effect in term of the influence on the phase of the harmonic upwash along the vane span so as to increase wake intersections per vane. Three-dimensional analysis on this issue [7-10] indicated the important influence of the ducted sound propagation on this issue. The coupling between the radial wave-number of the incident gust and the propagating radial acoustic order may change the control effect of a swept stator. When the circumferential acoustic mode order is small, the leaned stator may bring an inverse effect on the fan noise reduction at some condition. Moreover, the swept-and-lean vanes changed the radial acoustic modes distribution.

If an acoustic liner and a swept-and-leaned stator are placed in the duct at the same time, the aerodynamic response of the vanes on an incident disturbance can be affected as the presence of the liner. Also, the input sound source for liner optimization can be different as the variation of swept-and-leaned vanes configuration.

In order to study the interaction between a swept-and-leaned stator and a liner, a benchmark case is proposed in this paper. The analytical solution based on the transfer element method [11] is briefly introduced. After that, some primary results are presented to show the great importance of this interaction effect on the fan noise reduction.

2. Problem description

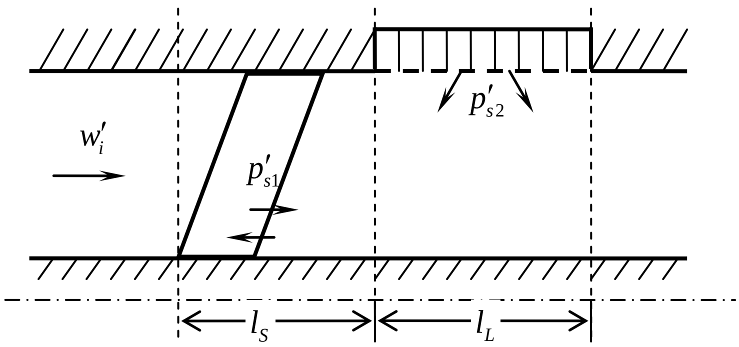


Figure 1: Diagram of the computing model.

In this paper, a simplified computing model, as illustrated in Fig. 1, is used to study the mutual effects between the swept-and-leaned vanes design and the liner optimization. In an infinitely long uniform duct with an annular cross-section, an incident gust interacts with an annular stator cascade and generates the sound. A locally reacting liner is placed behind for noise reduction. The vortical disturbance is convected by the uniform flow, and may be written generally as

$$w'_i = W_{m_g n_g} \cdot \mathrm{e}^{i(k_z z + m_g \varphi + n_g \bar{r} - \omega t)} \tag{1}$$

where $k_z = \frac{\omega}{U}$, and $\bar{r} = \frac{\pi(r-r_h)}{r_d - r_h}$. The wave-number n_g indicates the radial phase variation. The relative sound power change (RAPC) is calculated to quantify the noise reduction.

$$\mathrm{RAPC} = 10 \log(\wp/\wp_0) \tag{2}$$

$\wp_0$ denotes the sound power in a hard-wall duct with an radial stator(no sweep or lean).

3. Analytical solution

The annular cascade and liner are the different acoustic elements. Wang & Sun[11] developed a Transfer Element Method (TEM) to include various elements in the engine. The acoustic element of a rotor or stator was established based on the three-dimensional lifting surface method[12]. The liner element was established based on the Equivalent Surface Source (ESS) [13], in which the impedance surface was modelled by monopole sources. The scattering acoustic field inside these elements was derived as the explicit expression of the acoustic, vortical and entropic perturbations at the interface planes between two adjacent elements. The whole system matrix can be built through the boundary conditions of acoustic pressure continuity and particle velocity continuity at the interface. And the states at all interface planes can be solved if the input sources are given. This method can be used to study the multi-segmented liners optimization and the interaction effects between the sound source and propagation in the engine system. Similar concept of ‘acoustic elements’ of the rotor and stator was put forward by Hanson[14] to study the acoustic reflection and transmission through multi-cascades. The coefficients in the transfer matrix contain more clear meaning to be understood.

3.1 General formulation of a transfer element

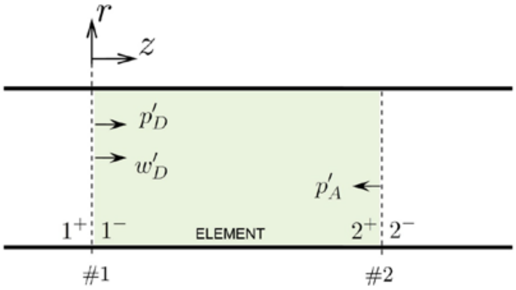


Figure 2: General form of the transfer element.

The analytical solution of the problem concerned in this paper is just based on these works, and brief derivation is presented below. As shown in Fig. 2, an element is mapped out by the interface #1 and interface #2. In a hard-wall duct, the pressure can be written as

$$\begin{aligned} p'_D &= \sum_m \sum_n D^1_{mn} \cdot \psi(k_{mn} r) e^{i\alpha_2 z} e^{i(m\varphi - \omega t)} \\ p'_A &= \sum_m \sum_n A^2_{mn} \cdot \psi(k_{mn} r) e^{i\alpha_1 (z-l)} e^{i(m\varphi - \omega t)} \end{aligned} \tag{3}$$

$\psi(k_{mn} r)$ is the Bessel function for an annular duct. The axial vortical velocity can be expressed as

$$w'_D = \sum_m \sum_n W^1_{mn} \cdot \psi(k_{mn} r) e^{i\alpha_3 z} e^{i(m\varphi - \omega t)} \tag{4}$$

The state vector is $\mathbf{A} = [A^1_{mn}, D^1_{mn}, W^1_{mn}, A^2_{mn}, D^2_{mn}, W^2_{mn}]^T$, and the scattering field is only related with the disturbance propagating into the element. So we have

$$\begin{bmatrix} A^{S,1}_{mn} \\ D^{S,2}_{mn} \\ W^{S,2}_{mn} \end{bmatrix} = \begin{bmatrix} S^{1,1}_{A,D} & S^{1,1}_{A,W} & S^{1,2}_{A,A} \\ S^{2,1}_{D,D} & S^{2,1}_{D,W} & S^{2,2}_{D,A} \\ S^{2,1}_{W,D} & S^{2,1}_{W,W} & S^{2,2}_{W,A} \end{bmatrix} \begin{bmatrix} D^1_{mn} \\ W^1_{mn} \\ A^2_{mn} \end{bmatrix} \tag{5}$$

The coefficient $S^{I',I}_{T',T}$ means a wave of type T at interface #I scatters into a wave of type T' at interface #I'. The source vector is given at the interface as $\mathbf{B} = [A^{B,1}_{mn}, D^{B,1}_{mn}, W^{B,1}_{mn}, A^{B,2}_{mn}, D^{B,2}_{mn}, W^{B,2}_{mn}]^T$. In this paper, this vector is given as the output waves in an uncoupled environment. In other word, it is the acoustic and vortical waves induced by interaction of the incident gust with the isolated stator. It can also represent rotor wakes. The stator vector is the sum of the scattering vector and the source vector, so we get the system equation as follows:

$$\begin{bmatrix} A^1_{mn} \\ D^1_{mn} \\ W^1_{mn} \\ A^2_{mn} \\ D^2_{mn} \\ W^2_{mn} \end{bmatrix} = \begin{bmatrix} 0 & S^{1,1}_{A,D} & S^{1,1}_{A,W} & S^{1,2}_{A,A} & 0 & 0 \\ S^{1,1}_{D,A} & 0 & 0 & 0 & 0 & 0 \\ S^{1,1}_{W,A} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & S^{2,2}_{A,D} & S^{2,2}_{A,W} \\ 0 & S^{2,1}_{D,D} & S^{2,1}_{D,W} & S^{2,2}_{D,A} & 0 & 0 \\ 0 & S^{2,1}_{W,D} & S^{2,1}_{W,W} & S^{2,2}_{W,A} & 0 & 0 \end{bmatrix} \begin{bmatrix} A^1_{mn} \\ D^1_{mn} \\ W^1_{mn} \\ A^2_{mn} \\ D^2_{mn} \\ W^2_{mn} \end{bmatrix} + \begin{bmatrix} A^{B,1}_{mn} \\ D^{B,1}_{mn} \\ W^{B,1}_{mn} \\ A^{B,2}_{mn} \\ D^{B,2}_{mn} \\ W^{B,2}_{mn} \end{bmatrix} \tag{6}$$

$\mathbf{S}$ represents the coupling matrix, and the state vector can be solved to be $\mathbf{A} = [1 - \mathbf{S}]^{-1}\mathbf{B}$.

3.2 Transfer element of the stator

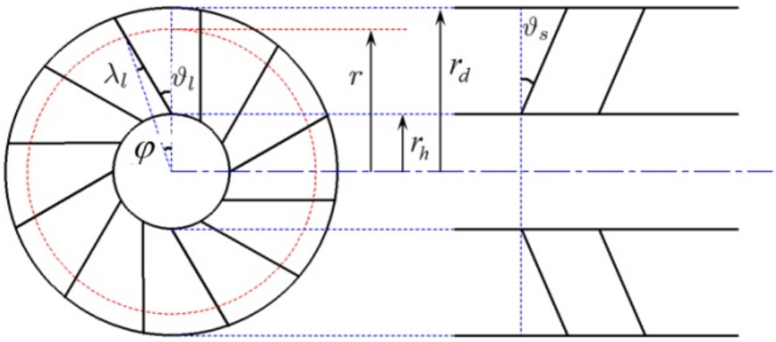


Figure 3: Sketch of swept and leaned vanes.

As shown in Fig. 3, ϑ_s is the vane sweep angle and ϑ_l is the vane lean angle. The dominant sound source of the interaction between an incident disturbance and a stator is the unsteady surface pressure on the vanes acting as the dipole source. TEM employed the three-dimensional lifting surface method to calculate the aerodynamic response on the vanes. By using the boundary condition on the vane surface, an integral equation for the unsteady surface loading is deduced,

$$-w_n = u'_\varphi \cdot \cos\lambda_l - u'_r \cdot \sin\lambda_l = \int_{s_0} \Delta p_0(r', z', \omega) \cdot K \cdot ds_0 \tag{8}$$

where w_n is the incident velocity component that is perpendicular to the vane surface. u' is the induced perturbation velocity. The detailed expression of the kernel function K can be found in [10-12].

For the incident gust, the vane upwash velocity is

$$w_n = w'_i \cdot \cos\lambda_l \tag{9}$$

So the relevant $\Delta p_0^B(r'_0, z'_0)$ can be solved. Using the generalized Lighthill's equation, the source vector B in this element can be given.

For the disturbance ${p'_D}^1$, ${p'_A}^2$ or ${w'_D}^1$, the concerned perturbation velocity that is perpendicular to the vane surface can be expressed as follows:

$$\begin{aligned} w'_n(r_0, z_0)|_{D^1_{mn}} &= \frac{i}{\rho_0 U} \frac{g_{mn}(r_0)}{\alpha_2^{mn} - \omega/U} D^1_{mn} \cdot \psi(k_{mn} r_0) e^{i\alpha_2^{mn} z_0} e^{i(m\varphi_0 - \omega t)} \\ w'_n(r_0, z_0)|_{A^2_{mn}} &= \frac{i}{\rho_0 U} \frac{g_{mn}(r_0)}{\alpha_1^{mn} - \omega/U} A^2_{mn} e^{-i\alpha_1^{mn} l} \cdot \psi(k_{mn} r_0) e^{i\alpha_1^{mn} z_0} e^{i(m\varphi_0 - \omega t)} \\ w'_n(r_0, z_0)|_{W^1_{mn}} &= \frac{W^1_{mn}}{i\alpha_3} g_{mn}(r_0) \cdot \psi(k_{mn} r_0) e^{i\alpha_3 z_0} e^{i(m\varphi_0 - \omega t)} \end{aligned} \tag{10}$$

where $g_{mn}(r) = \frac{im}{r}\cos\lambda_l(r) - \frac{\psi'(k_{mn} r)}{\psi(k_{mn} r)}\sin\lambda_l(r)$. And by solving the respective integral equations, all the scattering coefficients in the coupling matrix can be expressed explicitly. That is, the transfer element of the stator can be established.

3.3 Transfer element of the locally reacting liner

In TEM, the effect of the duct liner is modelled by equivalent monopole source, which avoid the solution of a difficult complex eigen-value problem. The solution of the scattering field can be written in the form of

$$p'_s(\vec{x}, t) = -\int_{-T}^{T} \int_{s(\tau)} \rho_0 \tilde{V}'_n \frac{D_0 G}{D\tau} ds(\vec{y}) d\tau \tag{11}$$

in which $\tilde{V}'_n = V'_n e^{-i\omega\tau}$is the convected velocity normal to the liner surface. Based on the displacement continuity condition, it can be expressed in terms of the locally acoustic particle velocity V_n^f.

$$V_n' = \frac{\partial \eta}{\partial \tau} + U\frac{\partial \eta}{\partial z'} = V_n^f + \frac{U}{i\omega}\frac{\partial V_n^f}{\partial z'} \tag{12}$$

And for an infinite length liner, V_n^f can be expanded a sine-series:

$$V_n^f = \sum_{k=1}^{\infty} V_k(r', \varphi')\sin\frac{k\pi z'}{l} \tag{13}$$

By using the impedance boundary condition, we have

$$\frac{\tilde{p}'}{-\tilde{V}_n^f} = \frac{\tilde{p}_i' + \tilde{p}_s'}{-\tilde{V}_n^f} = Z_{zk} \tag{14}$$

The detailed derivation is also omitted here, and the final algebraic equations for V_k can be expressed as

$$\sum_{k=1}^{\infty}(z_{jk} + \delta_{jk}\cdot Z_{zk})V_k = -I_j \tag{15}$$

in which $I_j = \frac{2}{l}\int_0^l p_i' \sin\frac{j\pi z}{l}dz$. And,

$$\begin{aligned} I_j^{D_{mn}^1} &= \frac{2}{l}D_{mn}^1\psi_m(k_{mn}R)\int_0^l e^{i\alpha_2 z}\sin\frac{j\pi z}{l}dz \\ I_j^{A_{mn}^2} &= \frac{2}{l}A_{mn}^2\psi_m(k_{mn}R)\int_0^l e^{i\alpha_1(z-l)}\sin\frac{j\pi z}{l} \end{aligned} \tag{16}$$

For each acoustic mode in the state vector, the respective velocity coefficients V_k can be solved. And the scattering acoustic field can then be expressed as the explicit expression of D_{mn}^1 and A_{mn}^2. That is, the transfer element of the liner can be established. The liner does not response to the vertical disturbance.

4. Results and discussion

The category-4 benchmark problem of the Third Computational Aeroacoustics Workshop [15] is normally used to validate the aerodynamic response of a stator interacting with the incident gust. Elhadidi & Atassi [9] also used the same stator geometry to explain the passive control effect of vanes sweep and lean on fan tonal noise reduction. Based on this model, we add a finite locally reacting liner behind the stator, and refer to it as the benchmark case. The diagram of the computing model is presented in Fig. 1, and the input parameters are listed below.

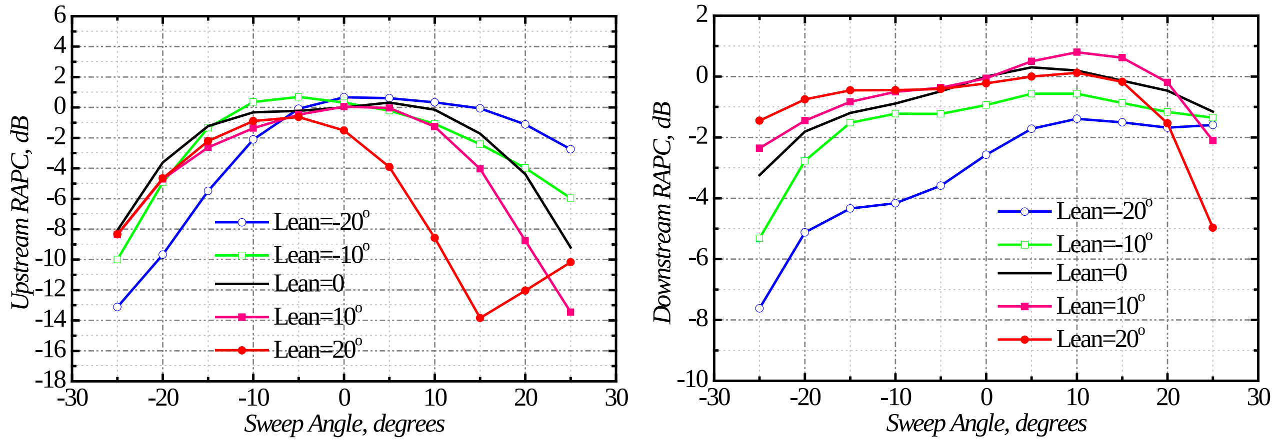
The circumferential mode numbers m can be determined from the Tyler-Sofrin condition ($m = m_g - qV$). At the reduced frequency $\omega = 3\pi$, two acoustic modes (-8,0) and (-8,1) are cut-on. The radial wave-number n_g of the incident gust also has a great influence on the aerodynamic response on the vanes and the radial acoustic mode distribution. Some more comprehensive discussion can be found in [10]. But in order to simplify the discussion, n_g is just set to be zero in this paper.

Table 1: Input parameters of the benchmark case

<table>
<tr><th colspan="2">Duct</th><th colspan="2">Stator</th><th colspan="2">Liner</th></tr>
<tr><td>Hub/tip ratio</td><td>0.5</td><td>m_g
(number of rotor blade)</td><td>16</td><td rowspan="5">Element length</td><td rowspan="5">$3b$</td></tr>
<tr><td>Axial Mach number</td><td>0.5</td><td>n_g</td><td>0</td></tr>
<tr><td>Rotor tip Mach number</td><td>0.79</td><td>Number of stator vanes</td><td>24</td></tr>
<tr><td rowspan="2">Reduced frequency</td><td rowspan="2">3π</td><td>Vane chord length, b</td><td>$2\pi r_d/V$</td></tr>
<tr><td>Element length</td><td>$2b$</td></tr>
</table>

The two stator configurations, which are vanes sweep and lean, are mostly discussed separately. We first present the related acoustic power changes with different selections of swept-and-leaned vanes. The stator is isolated in the duct, and there is no liner behind. The results of upstream and downstream RAPC are shown in Fig. 4.The x-coordinate stands for the sweep angle, and each line is the results with a fixed lean angle.

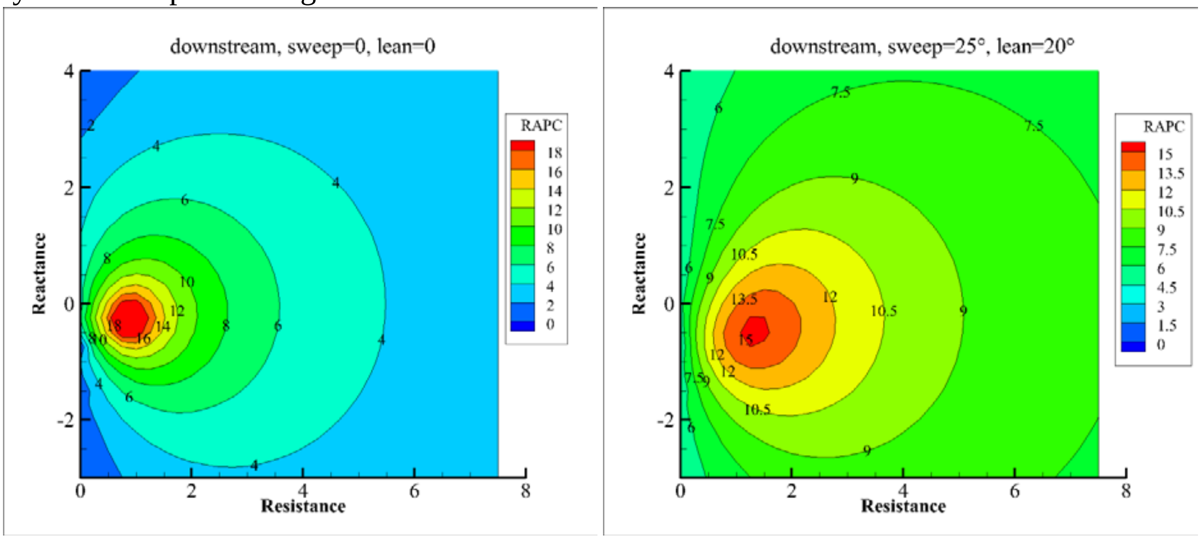
When the stator is of no lean angle, only a slight noise reduction for downstream is gained with a large sweep angle. As the upstream wavelength is smaller than the downstream wavelength for the propagating duct modes, the upstream acoustic mode is more sensitive to the relative axial position changes on different radial positions for a swept stator. Therefore, a stronger noise reduction for upstream is induced. Under certain conditions, a good selection of swept-and-leaned vanes can have a much better control performance compared with that of the swept-only vanes.



(a) upstream (b) downstream

Figure 4: RAPC with different selections of swept-and-leaned vanes.

When a locally reacting liner is placed behind the stator, the generated noise can be absorbed. Two different configured stators are used for comparison. One is with the radial vanes, and the other is with swept-and-leaned vanes. Downstream RAPC via liner resistance and reactance is presented in Fig. 5. For a maximum noise reduction, the optimal range of the liner impedance is changed when the swept-and-leaned stator is introduced. Near the optimal impedance range, the overall RAPC does not increase, although the vanes are swept-and-leaned. The design of vanes sweep and lean makes positive contribution to the reduction if the liner impedance is chose to be away from the optimal range.



(a) $\vartheta_s = 0°, \vartheta_l = 0°$ (b) $\vartheta_s = 25°, \vartheta_l = 20°$

Figure 5: Downstream RAPC via liner resistance and reactance.

5. Conclusion

The swept-and-leaned stator configuration and the acoustic liner optimization are both the effective methods of fan noise reduction. The transfer element method was used to study the mutual effect between these two control measures. The results presented in this paper confirmed that the acoustic interaction between the stator and liner is of great importance on the overall noise reduction. The system optimization needs to be investigated for further reduction of fan interaction noise.

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