Journal of Sound and Vibration 391 (2017) 73–94

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Three-dimensional analysis of vane sweep effects on fan interaction noise

Weiguang Zhang [a], Xiaoyu Wang [a,*], Xiaodong Jing [a], An Liang [b], Xiaofeng Sun [a]

[a] Fluid and Acoustic Engineering Laboratory, Beihang University, 100191 Beijing, China
[b] Chinese Aeronautical Establishment, 100012 Beijing, China

ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form
8 November 2016
Accepted 7 December 2016
Handling Editor: P. Joseph
Available online 14 December 2016

Keywords:
Fan interaction noise
Passive control
Sweep
Three-dimensional
Lifting surface method

ABSTRACT

The lifting surface method is an efficient solution for fully three-dimensional aerodynamic response of an annular cascade to the unsteady disturbances. Based on this response function, a prediction model for fan tonal and broadband interaction noise has been established. Three dimensional effects, including primarily the annular geometry and the radial non-uniformity of the upwash, can be fully taken into account. In this paper, a thorough analysis of vanes sweep effects is carried out by particularly considering the great dependence of the annular cascade aerodynamic response and modal acoustic field upon the radial phase profiles of incident disturbances. For fan tonal noise, different control behaviors of the forward and backward swept vanes are observed when the radial non-uniformity in the incident gust is introduced. The argument suggests that sweep should be selected so as to increase the wake intersections per vane, until it is larger than the number of cut-on radial acoustic modes. For fan broadband noise, the backward sweep succeeds in reducing the sound power level for a wide range of frequencies. Due to the statistical average effect, the efficiency relies much on the shape of the turbulence spectrum. And the sweep angle should be large enough to guarantee a preferable reduction to the fan broadband noise.

1. Introduction

Fan interaction noise, induced by the impingement of periodic rotor wake or stochastic turbulence on a downstream cascade, is concerned as a significant sound source of turbofan engine [1]. The essential starting point for the analytical prediction is to calculate the unsteady surface loading distribution on the stator vanes exposed to the normal inflow velocity disturbance. The development of two-dimensional models based on linear cascades with flat plates is an very important and practical contribution to this issue [2–5].

But as the hub-to-tip ratio decreases, the query on its feasibility arises. Three-dimensional effects were then emphasized by using linear Euler numerical simulations [6,7] or lifting surface methods [8,9]. In general, the three-dimensional effects are observed as the strong connection between the annular cascade aerodynamic response and the acoustic propagation in the duct. In the first instance, the three-dimensional unsteady surface pressure distribution for small hub-to-tip ratio is different with the results calculated by two-dimensional strip theory, even in the absence of radial phase variation of the

* Corresponding author.
E-mail addresses: zhangweiguang@buaa.edu.cn (W. Zhang), bhwxy@buaa.edu.cn (X. Wang), jingxd@buaa.edu.cn (X. Jing), liang_an@sina.com (A. Liang), sunxf@buaa.edu.cn (X. Sun).

http://dx.doi.org/10.1016/j.jsv.2016.12.014

incident gust excitation [6,7]. Some quasi-three-dimensional models made further corrections when the incident gust contained a phase variation in the radial direction, such as the response function proposed by Glegg [10]. But strictly, the induced unsteady surface pressure in different radial slices should interact. This effect is not included in the quasi-three-dimensional models yet. The annular geometry also requires the cascade radiated modes perfectly match with duct modes. A typical work is Posson's correction [11] to Glegg's blade response function. Besides, the wall acoustic treatments embedded in an annular duct may have an influence on the cascade response. For instance, Wang and Sun [12] presented a transfer element method (TEM) to study the interaction of the stator and acoustic liners. One more thing involved with three-dimensional effect, span-wise non-uniformity of the steady main flow velocity and swirling effect play an important role in the noise generation and propagation. A lot of discussions have been made by Peake [13] and Atassi et al. [14].

These features can have a big impact on the tendency predictions as the design parameters changed. For example, a three-dimensional prediction model for broadband interaction noise was established by the authors [15] through employing the three-dimensional lifting surface method as a new response function. The variation of sound power spectra with different vane numbers mainly involves with the propagation of cut-on acoustic modes in an annular duct. So this trend is well captured by this model, along with a good agreement with the experimental data.

For fan tonal noise, the swept and leaned vanes were proved to have sizeable reduction, both theoretically and experimentally [16]. Using the strip-theory as the unsteady aerodynamic response function of the vane and coupling to duct propagation modes, the work developed by Envia and Nallasamy [17] provided reasonable predictions for the trends. An practical design selection was suggested in term of the influence on the wake intersections per vane so as to increase the span-wise phase variation of the upwash. But there is no doubt that three-dimensional effect is critical to the discussion of vanes sweep effect on the passive control of fan interaction noise. The calculation of three-dimensional lifting surface method made by Schulten [9] confirmed that a strong span-wise phase variation of the pressure jump distribution is induced by the vanes sweep effect. The span-wise variation of vanes geometry, e.g. sweep or lean, does not just affect the phase of the incident upwash in the leading edge, but also has a significant relationship with the three-dimensional cascade aerodynamic response and the propagating acoustic modes in the duct. The numerical analysis made by Elhadidi and Atassi [7] showed that forward and backward swept vanes have a similar effect on the noise reduction when no phase variation of the incident gust. But neither of these three-dimensional models has particularly considered the radial non-uniformity of the incident gust in detail, when they are employed to discuss the vanes sweep effect.

From a perspective of analytical process of predicting the fan broadband interaction noise, the main difference from tonal noise prediction is that the sound power level (SPL) is solved by the integration weighted by statistical turbulence wavenumber spectrum. The sweep effect on fan broadband noise has been studied by Logue and Atassi [18]. But as a large number of response functions need to be calculated in the process, it's quite time-consuming to apply this state-of-the-art numerical solution to the design of vanes sweep and lean on the broadband noise reduction at the present stage.

By applying the lifting surface method as the response function to calculate the unsteady surface loading distribution, the vanes sweep effect both on fan tonal and broadband interaction noise fall within the scope of discussion in this paper, with an emphasis on the three-dimensional aspects. As the limitation of the lifting surface method, the vanes are assumed to be zero-thickness plate with no stagger or camber angle. For typical fan designs, the rotor wake is usually skewed for a swirling flow. The radial wavenumber of the incident gust is introduced to characterize the radial phase variations. For fan tonal noise, some necessary supplement to the two-dimensional design selection principle should be done. An extended discussion on the forward-swept stator has also been carried out. For broadband interaction noise, the shape of the turbulence spectrum is found to be important to the noise reduction.

2. Fan noise prediction theory

2.1. Generalized expressions of the interaction noise in the duct

The starting point is the definition of the sound energy in a straight duct with isentropic and irrational axial flow. Φ is the Fourier transform of the acoustic potential ϕ, so the acoustic intensity may be defined by

$$\mathbf{I}_\omega = -\mathrm{i}\rho_0\omega\Phi^*\left[\nabla\Phi + \frac{U}{c_0^2}\left(\mathrm{i}\omega\Phi - U\cdot\nabla\Phi\right)\right] \tag{1}$$

Via the integration of acoustic intensity cross section, the sound power propagating upstream and downstream can be expressed as follows,

$$\wp^\pm = \int\langle\mathbf{I}_\omega^\pm\rangle\cdot\mathbf{n}\mathrm{d}S;\quad \mathbf{n}^\pm = \pm(0, 0, -1) \tag{2}$$

The disturbance fluid density and velocity can be solved by using the following relationships,

$$\mathbf{u}' = \nabla\phi,\quad p' = -\rho_0\frac{\mathrm{D}\phi}{\mathrm{D}t},\quad \rho' = \frac{p'}{c_0^2} \tag{3}$$