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ANALYSIS OF AUTOMOTIVE COOLING FAN NOISE USING FREE-WAKE PANEL METHOD AND ACOUSTIC ANALOGY

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INTRODUCTION

Acoustic consideration of automotive cooling fans has become imperative due to new regulations and the call for environment-friendly products. Although the dominant source of noise for most axial fans are known to be of dipole (due to surface pressure fluctuations) in nature, the formidability of flow field calculations have kept many attempts of analysis to only those of empirical formulations. The rapid advances in computer technology have, however, motivated the development of a non-compact fan noise analysis tool with the flow field data from accompanying flow analyzer. The main challenge in this venture lies in bridging the gap between the two different time scales involved in solving for the flow field and the acoustic field.

The present work describes the noise prediction procedure and the result of the developed numerical analysis tool, which couples time domain acoustic analogy with flow field analysis via free-wake panel method. The time domain acoustic prediction utilizes one of the most rigorous formulations, and is implemented for use in predicting aerodynamic noise of the most complex geometries often found in axial fan blades. Although free-wake panel methods usually yield relatively accurate results when predicting the flow field around axial fans, its use in aerodynamic noise prediction has been limited by two shortcomings. The time resolution of flow analysis is usually of an order larger than that required for noise predictions. Free-wake panel method also suffers from wake instabilities in the absence of free-stream as in static fan operations. Since the two problems are not irrelevant, a solution is sought which will resolve the two problems at once. The prediction method is applied to an axial fan operating with shroud and the resulting noise predictions show a favorable agreement with the measured data.

NUMERICAL FORMULATION AND PROGRAM DESCRIPTION

Farassat [1] has formulated the following equation, which is very convenient in embodying the time-domain analysis of Ffowcs Williams-Hawkings equation into a computer code. The formulation does not lose the generality of being able to handle blades of arbitrary shape and motion while enhancing the accuracy of the code by eliminating numerical time differentiation.

$$p'(\vec{x},t) = p'_T(\vec{x},t) + p'_L(\vec{x},t)$$

$$4\pi p'_L(\bar{x},t) = \frac{1}{c_0}\int_{f=0}\left[\frac{\dot{l}_i\hat{r}_i}{r(1-M_r)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{l_r - l_i M_i}{r^2(1-M_r)^2}\right]_{ret} dS + \frac{1}{c_0}\int_{f=0}\left[\frac{l_r\left(r\dot{M}_i\hat{r}_i + c_0 M_r - c_0 M^2\right)}{r^2(1-M_r)^3}\right]_{ret} dS$$

$p'_T(\vec{x},t)$ and $p'_L(\vec{x},t)$ represent thickness and loading terms, respectively, and correspond to the monopole and dipole terms in the theory of acoustic analogy. The quadrupole source from Lighthill stress tensor, T_{ij} is neglected in this study since only low speed rotating-blades are considered. The monopole term is also neglected since the airfoil is thin and since the tip speed is not high enough to cause any significant noise through volume displacement of fluid. ρ_0 and c_0 are the density and speed of sound in the undisturbed medium while the acoustic pressure is written as p'. l_i is the force per unit area exerted on the fluid by the solid surface and v_n is the surface normal velocity. The dots in $\dot{M}_i$ and $\dot{l}_i$ denote time differentiation with respect to the retarded time, and the subscript r denote the direction towards the observer.

The computer program has been developed taking full advantage of the formulation. The calculations are performed on the surface of the blade, which is divided into a number of panels used for integration. The primary convenience of the formulation lies in the fact that other than the retarded time calculation, which in the subsonic case is simple with Newton iteration, the coding is straightforward with all the terms in the integrand calculated in the blade fixed frame. The contributions of all the panels at an observer position for a desired range of observer times are summed up to yield acoustic pressure time history, which is Fourier transformed into frequency domain.

The flow solver is a classic potential flow solver, utilizing singularity panels on the body surfaces and the wakes trailing from the bodies. If the flow is assumed inviscid, incompressible, and irrotational, the velocity potential of the flow must satisfy Laplace's equation, $\nabla^2\Phi = 0$. The establishment of algebraic equations are well documented in various literatures [2] and will not be iterated here. The 'free-wake' panel method derives its name from the principle in which the wake panels are free to evolve in shape according to the velocities dictated by the solution. The free-wake is time stepped, with a new row of panels shed into the flow with each time step. Increase in temporal resolution of the flow solution is thus equivalent to additional computation of velocities at the new panel points, with the number of calculations proportional to $N_p^2 N_t$ (N_p: number of wake panels, N_t :number of time steps). Therefore, the CPU time scales approximately with the cube of the number of time steps. For the flow data to be used as input for acoustic calculation, pressure data per few degrees or less are required, while for flow only calculations, pressure data per over ten degrees usually suffices. The time resolution refinement, then, places heavy burden on the computer capacity, requiring a way to use fewer wake panels to simulate the wake field. The problem of wake instability commonly observed in rotating blades must also be addressed. The instability of the wake is mainly due to numerical errors and partially reflects the physics that flow-field of axial fans are indeed turbulent. The instability can be inhibited by introducing numerical damping, which in this case, is attained by increasing the core value of the wake. Using smaller time steps, however, one is able to use smaller core values leading to more realistic wake geometry. But even with the smallest time steps, correct wake geometry cannot be obtained if the far wake is not modeled correctly.

An ultimate wake sink disk is introduced to overcome these problems. It can be shown that helical vortex lines representing rolled-up vortices can be replaced by a sink disk on the cap of a circular cylinder with ring vortices [3]. The strength of the sink disk is given by $\frac{N_{blade}\Gamma_{\max}}{2\pi R_w \tan\phi}$, where N_{blade} is the number of blades, $\Gamma_{\max}$ is the maximum circulation, and ϕ is the angle between the tip vortex and the plane of blade rotation. Replacing the infinite extent of tip vortices with a sink disk reduces the calculation load drastically while providing the effect of far wake components. To prevent the number of wake panels from increasing indefinitely, wake relaxation (discarding one panel while adding one on the other side) option is added to simulate the refined flow field with as small number of wake panels as possible.

SIMULATION RESULTS AND DISCUSSION

The automotive cooling fan used for result validation is shown in Fig. 1. 10 divisions in the radial direction were used while 20 divisions were used to wrap around the airfoil. The shroud is also modeled to simulate as closely as possible the actual flow field of the fan. The initial wake geometry is also shown. The wake sink disk, not shown in the picture, is placed 1.5R away from the plane of blade revolution. The location was chosen from observing a tentative low-resolution calculation, which indicated piling up of wake panels in the vicinity. The radius of the sink disk is 0.8R, considering the contraction of the wake. With the wake disk accounting for the far wake effect, a flow field calculation of high temporal resolution is carried out with an interval of three degrees (120 calculations per revolution). The core value used in this calculation is 5% of the fan radius. The resulting wake geometry is shown in Fig. 2. Only the inner and tip boundaries of the wake sheet are shown for clarity.

Figure 3 shows the predicted and measured acoustic spectra at a number of locations. The actual SPL values are not specified, but the data are plotted respect to the same scale so that the directivity of the noise propagation can be estimated. The frequency data are A-weighted. The noise is measured in an anechoic chamber measuring 5m*5m*3.8m, with a cut-off frequency of 80Hz and a background noise level of less than 20dB(A). The spectrum is obtained through B&K 4550 spectrum analyzer. The points of observation are varied keeping a constant distance of 1m from the fan center. The increase in the overall noise level as the observer nears the axis of rotation is typical of the unsteady loading noise. Comparison of the results shows good agreement with the experimental data, especially for the first few harmonics of blade passing frequency. Of the discrete peaks in experimental data, the fourth harmonic shows a distinguished value, which is a result of modal interference of the seven-bladed fan and the four-cornered shroud. The over-predictions in the higher frequency range are the result of insufficient number of panels used for shroud modeling. Current version of the prediction code does not take into account the effects of diffraction and interference with the shroud of the fan, consideration of which could generate some complex phenomena.

CONCLUSIONS

Aerodynamic noise from automotive cooling fan has been predicted using acoustic analogy in conjunction with free-wake panel method. The time scale gap between the two methods has been bridged successfully. The prediction results agree well with the measured noise spectra, especially toward the axis of rotation where the unsteady dipole noise radiation is greatest. Further refinement of the prediction method is currently being sought through addition of structures such as hub and support struts that are present in a real situation. Interaction of propagating waves with these obstructions must also be considered.

2. J. Katz and A. Plotkin, *Low-Speed Aerodynamics* (McGraw Hill, New York, 1991)
3. “A Potential Based Panel Method for the Analysis of Marine Propellers in Steady Flow,” J. Lee, Ph. D. dissertation, MIT, (1987)

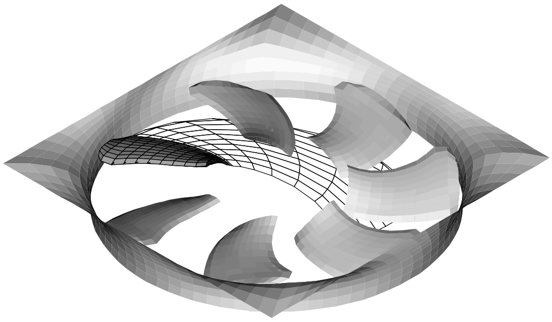


Fig. 1 Fan geometry with initial wake panels
(only the inner surface of shroud shown)

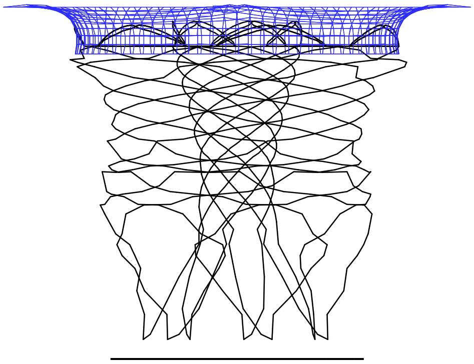
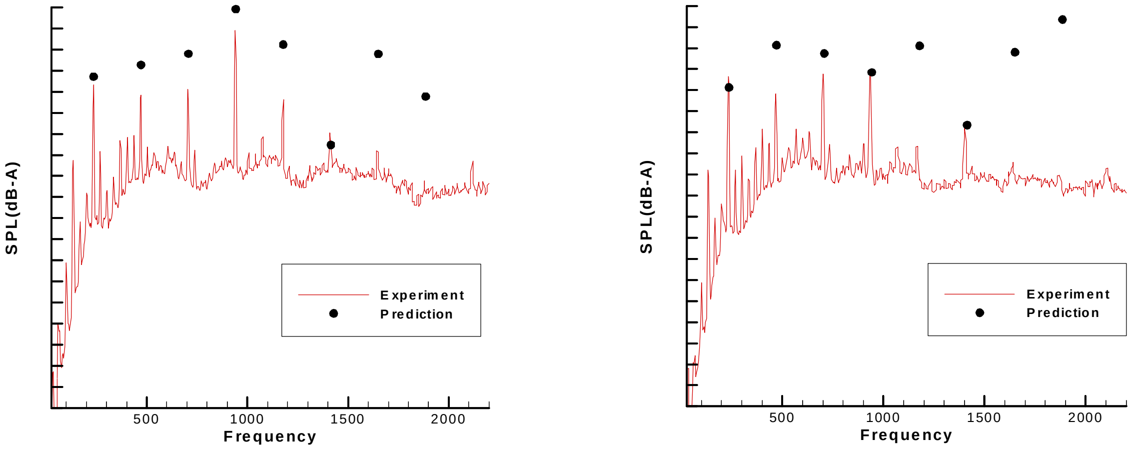
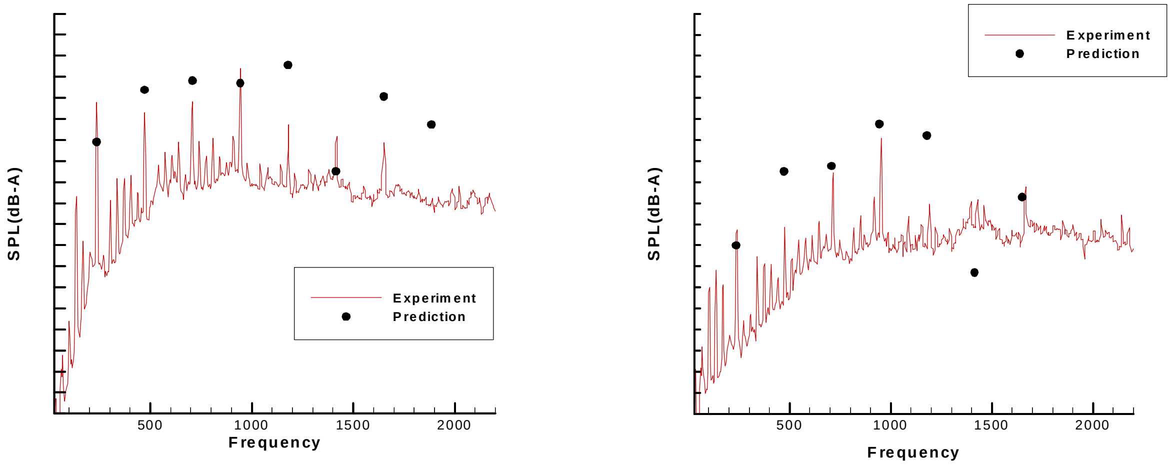


Fig. 2 The wake geometry



(a) Microphone on the fan axis

(b) Microphone 30 deg from the fan axis



(c) Microphone 60 deg from the fan axis

(d) Microphone on the plane of blade rotation

Fig. 3 Comparison of measured and predicted noise spectra, 1m away from the hub center