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PREDICTION OF LOW FREQUENCY SOUND GENERATION FROM AN AXIAL FAN

M. Åbom, H. Bodén

MWL, Dept. of Vehicle Engineering, Teknikringen 8, SE-10044, Stockholm, Sweden

Tel.: +46 8 790 7944 / Fax: +46 8 790 6122 / Email: matsa@fkt.kth.se

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ABSTRACT
This paper treats the acoustical analysis of a 6 blade road tunnel fan, a so called jet fan, in the plane wave frequency domain. First, a model was developed for simulating the acoustic environment of the fan including the short duct where the fan is mounted, coupling between the duct openings, the effect of reflective surfaces, i.e. ground or roof proximity, the effect of inlet and outlet duct flanges, the flow velocity effects on the inlet and outlet impedances. As the second step a model for the sound generation of the fan based on an acoustic one-port model was developed. This 1D model was used to predict the sound power generated by the fan and to find the optimal fan position in the duct. Experiments have been carried out to validate the numerical results.

1 - INTRODUCTION
Sound generation from road tunnel fans is of great competitive importance for the companies manufacturing the fans. In the work presented here a low frequency, plane wave region, model for the sound generation from this type of fan has been developed. It has been shown that in the plane wave region a ducted axial flow fan can be described as an acoustic two-port source [1]. The source strength can be modeled as a dipole source, see e.g. [2-3]. The jetfan is mounted in a short duct, which means that any change in the duct system upstream of the fan will change the inflow conditions and consequently change the acoustic source strength.
The problem of obtaining an acoustic source model is therefore more complicated for this type of fan than for a fan mounted in a long duct. The approach taken in this project has therefore been to build a theoretical model for the sound generation from the jetfan starting from the primary fan sound generating mechanisms. The main assumption is that the complex sound generating mechanisms will result in time varying 1-D thrust, which generates the plane wave sound field. A preliminary study showed that disturbed inflow conditions, i.e. turbulence ingestion and non-uniform inflow, were major sound generating mechanisms.
The sound power spectrum of such a fan is shown in Fig. 1. In the present case the tonal part of the spectrum consisting of the blade passing frequency and its harmonics dominates. As shown by Hanson [4] the incoming turbulence is not isotropic but highly anisotropic. The simulation code developed to simulate the turbulence-generated fan unsteady thrust, started from the work of Sevik [5], based principally on a correlation approach for the turbulence.

2 - TWO-PORT THEORY FOR THE FAN AND THE DUCT SYSTEM
The fan is considered as a 1-D dipole source located at the impeller duct cross section. The flow velocity V_0 is considered as uniform over the duct cross section when calculating the acoustic propagation. It is possible to calculate the spectrum of the fan sound pressure and acoustic velocity in the duct from the knowledge of the effective axial dipole strength spectrum of the fan, the transfer matrices of the duct and the impedances of the duct openings. The model for an active 2-port source [1] can in the frequency domain be formulated by using a scattering-matrix and a source strength vector. The inlet and discharge ducts can be modeled as chains of two-port matrices, each of which can be represented in scattering matrix form, i.e. using the travelling wave pressure amplitudes, see Fig 2.

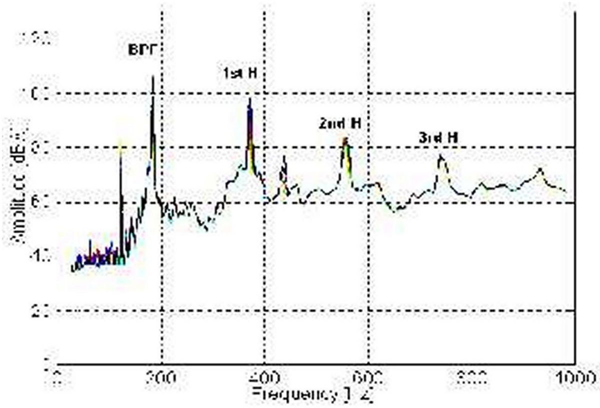

Figure 1: Typical fan sound power spectrum.

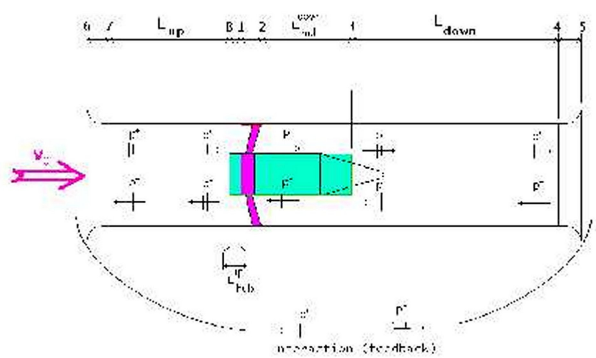

Figure 2: The two-port scattering matrix model for the fan and the duct system.

We also need to know the termination impedances of the inlet and outlet openings with flow. In the literature semi-empirical results were found: Davies [6] for the inlet case, and Munjal [7] for the outlet case. There might also be acoustic coupling between the two duct openings and interaction with a nearby reflective surface, i.e. the road tunnel roof. We have modeled the interactions by considering the inlet and outlet as monopole sources and the reflective surface as two image sources. We can now for any position x inside the duct calculate the value of the acoustic velocity in the frequency domain. From the velocity at the fan position and the fan thrust we can calculate the sound power generated by the fan.

3 - AEROACOUSTIC MODEL FOR THE FAN THRUST

Incoming turbulence and non-uniform inflow create a fluctuating angle of attack and a fluctuating pressure field around the fan blades resulting in narrow-band and broadband unsteady blade forces, see Fig. 3.

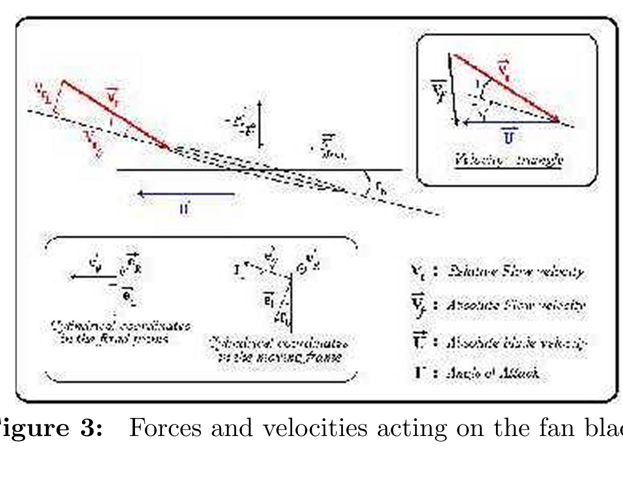

Figure 3: Forces and velocities acting on the fan blade.

Using the work of Sevik [5] and Martinez [8] we can express the force for each fan strip element as,

$$F\left(R_s\right) = \frac{1}{2}\rho_0 \cdot c_s \cdot \left\{ C_p^s\left(\bar{\Gamma_s}\right) \cdot \left[V_r^0\right]_s + \left[\frac{dC^s\left(\Gamma\right)}{d\Gamma}\right] \cdot v_{r\perp}^s \right\} \cdot \left[V_r^0\right]_s \tag{1}$$

To calculate the force we need to

- determine the steady velocity profile $V_r{}^0$ upstream of the fan,
- model the unsteady velocity profile v_r upstream of the fan,
- find the pressure coefficient $C_p(\Gamma)$ for the blade radial strip,
- derive the value of the derivative of the pressure coefficient over the angle of attack.

The last step is usually carried out in the spatial frequency domain. The derivative of the pressure coefficient versus the angle of attack is modeled using the well-known Sears function.
A computational code to predict the low frequency unsteady forces for axial fans in turbulent flow has been developed. Broadband forces are predicted by the use of a correlation method, for an isotropic or axi-symmetric turbulence inflow and for given advance coefficient, turbulence length scale and turbulence level. The derivations follow the theory of Sevik [5] except that the velocity correlation has been modified to incorporate fan rotational effects [9]. An approximate model for the axi-symmetric turbulence case has been defined by introducing a longitudinal correlation function. Numerical calculations of the fan thrust spectrum has been performed for isotropic and "quasi-axi-symmetric" turbulence models.
Fig. 4 presents the effect of the integral length scale for the isotropic case. As we can see an increase of the length scale L gives an increase of the thrust around the blade passing harmonics especially around the first tone. This phenomenon is called haystacking.

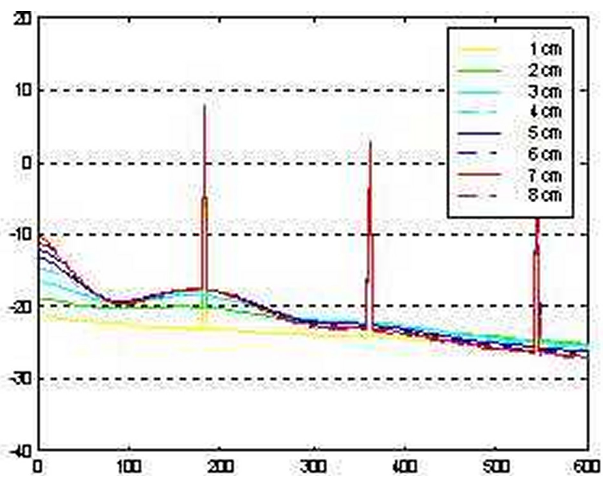

Figure 4: Calculated fan thrust for different integral length scales (isotropic turbulence).

4 - MEASUREMENTS

The objective of the experimental investigation was to fully characterize the aeroacoustic response of a six-bladed fan running in different aerodynamic and acoustic configurations consisting of non-uniform steady flow, incoming turbulence and different fan locations. Hot-wire anemometry was used for the flow measurements. During the aerodynamic and turbulence measurements, simultaneous acoustic sound power measurements were made using ISO 3741-3742. Some examples of the turbulence autocorrelation measurements are presented in Fig. 5 for different configurations: with turbulence generation grids or without. Hanson [4] has for the same type of experiment (static tests) concluded that the incoming turbulence is not isotropic but highly anisotropic. The integral length scale in the axial direction can be as large as the duct diameter which in this case is 40 cm. Basically, the "unsteady distortion" process consists of the elongation of turbulent eddies when they are sucked towards the blades by the steady but non-uniform mean flow. Each eddy is also chopped several times as it passes through the fan. This gives spectrum peaks at multiples of blade passing frequency. By using grids it is possible to decrease the axial length scale of the turbulence.

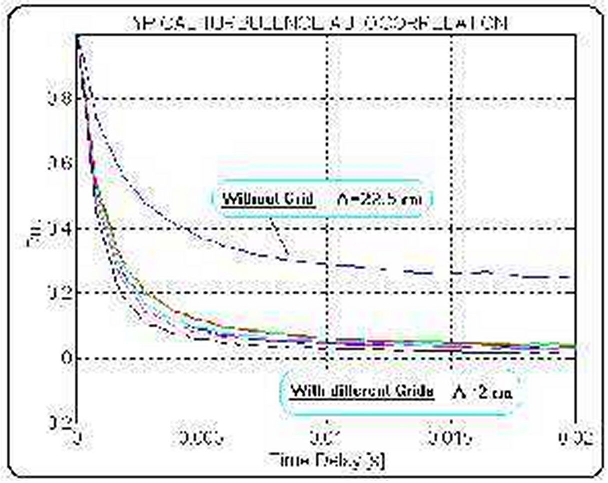

Figure 5: Turbulence autocorrelation measurement without and with upstream mounted grids.

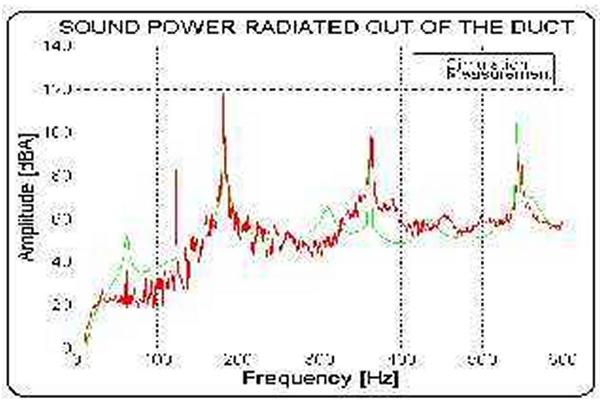

Figure 6: Comparison between the simulated and measured sound power level from the fan duct.

Fig. 6 shows a comparison between the simulated and measured sound power level from the fan duct. As can be seen the agreement is good.

5 - CONCLUSIONS

A computer code for predicting the low frequency sound generation from an axial fan mounted in a short duct has been developed. The code includes a model for simulating the acoustic environment of the fan including the short duct where the fan is mounted, coupling between the duct openings and the effect of reflective surfaces. The sound generation mechanisms considered are non-uniform inflow and inlet turbulence. The inflow conditions have been determined by experiments. A model for the sound generation of the fan considered as a 1-D dipole source was developed. The model was used to predict the sound power generated by the fan and to find the optimal fan position in the duct. Comparisons with experiments showed a good agreement in the plane wave frequency range.

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