Numerical Modelling of Wake-Jet Interaction with Application to Active Noise Control

Graham Ashcroft[1] and Jan Schulz[2]
[1] *Institute of Propulsion Technology, German Aerospace Center, Porz-Wahnheide, 51147 Cologne, Germany, Email: graham.ashcroft@dlr.de*
[2] *Technische Universität Berlin, Sonderforschungsbereich 557, Sekr. HF 1, Müller-Breslau-Str. 8, 10623 Berlin, Germany, Email: jan.schulz@dlr.de*

Introduction

Fan noise is a major contributor to the overall noise produced by modern high-bypass-ratio turbofan engines [1]. Techniques for the reduction of fan noise are therefore of foremost importance in engine design. In this work we investigate a novel active control strategy for the reduction of the tonal noise in axial turbomachinery developed recently in cooperation between DLR and TU Berlin [2]. In contrast to conventional active noise control experiments, in which loudspeakers are used to generate the secondary anti-phase sound field, the required anti-phase sound field in this approach is produced by additional aerodynamic sound sources. These are generated by disturbing the flow field around the blade tips by either placing small flow obstructions such as piezo-electric actuators upstream of the rotor blades or by blowing air into the blade tip region. The general principle is illustrated below in Figure 1 for the case of the high-speed jets.

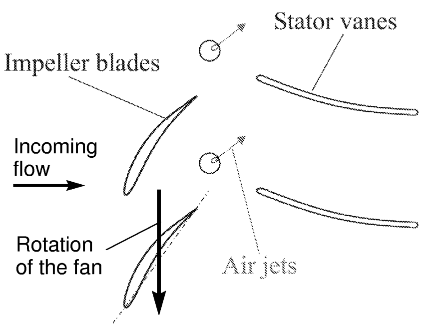

Figure 1: Schematic of fan blades with injection nozzles.

Here the rotor and stator profiles are shown together with the injection nozzles. To disturb the flow high-speed air is blown into the tip region through small nozzles located in the casing. The interaction of the passing rotor wake with the high-speed jets creates the secondary anti-phase sound field. By varying the position of the nozzles relative to the stators the phase and amplitude of the secondary sound field can be controlled.

The aim of this work is to gain a better understanding of the wake-jet interaction and therefore the noise generation mechanisms of the secondary field. To this end numerical simulations are performed. Details of the numerical method employed and configuration investigated are provided in the following sections.

Numerical Model

Numerical simulations are performed with DLR's TRACE code. TRACE (Turbomachinery Research Aerodynamic Computational Environment) is a parallel Reynolds-Averaged Navier-Stokes flow solver developed at the Institute of Propulsion Technology in Cologne to investigate turbomachinery aerodynamics and related phenomena. A detailed description of the TRACE code may be found in [3] and the references therein.

Numerical simulations are performed for the rotor and jet alone to study the plane waves generated at blade passing frequency (BPF). To simplify calculations the axial fan configuration sketched in Figure 1 is idealized as a linear cascade with the profiled blades replaced by flat plates with chord length, l, of 53.6 mm and a stagger angle of 50^o. The pitch-to-chord ratio is taken as unity. The jet nozzles are orientated orthogonal to the cascade walls with one jet per blade passage. The computational domain comprises a single blade passage with periodic boundary conditions employed along the upper and lower domain boundaries. An axial Mach number of 0.2 is considered with an inflow angle of -30^o. The linear cascade translates with a Mach number of 0.333, providing an effective blade passing frequency of 2150 Hz. The prescribed inlet Mach number of the high-speed jets is 0.6.

Results and Discussion

Two-dimensional Simulations

In the first stage of investigation the jet is idealized as a circular cylinder and the flow field is modelled as two-dimensional with a total of approximately 35,000 computational cells in the domain. A snapshot of the computed flow field for the baseline configuration with an axial gap of $0.6l$ (between the rotor trailing edge and the axis of the cylinder) is shown below in Figure 2 in terms of vorticity iso-contours.

	$0.2l$	$0.4l$	$0.6l$
Diameter $0.2l$	119 dB	111 dB	102 dB
Diameter $0.1l$	115 dB	108 dB	100 dB

Table 1: Effect of axial spacing and rod diameter on sound field radiated upstream (m = 0, 1 BPF).

The rotor wake and its interaction with the circular cylinder are clearly seen. The flow around the cylinder is itself characterized by the periodic shedding of discrete vortices leading to the formation of the familiar Karman vortex street.

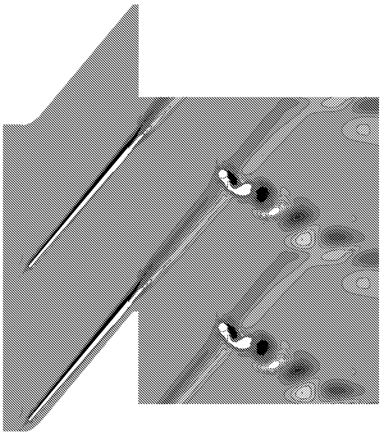

Figure 2: Instantaneous vorticity distribution showing rotor and cylinder wakes.

This unsteadiness generates a strong tonal noise component at the vortex shedding frequency. This is unrelated to the blade passing frequency, depending rather on the cylinder diameter and the absolute velocity of the flow past the cylinder. The tone generated at the BPF is rather dependent on the periodic interaction of the rotor field with the cylindrical rods. The strength of this tone is expected to depend on the rotor wake profile and geometry of the cylindrical rods. To examine the effects of these features on the strength of the tone at the BPF a number of further simulations were performed with different axial spacings and rod sizes. The findings of these calculations are summarized in Table 1.

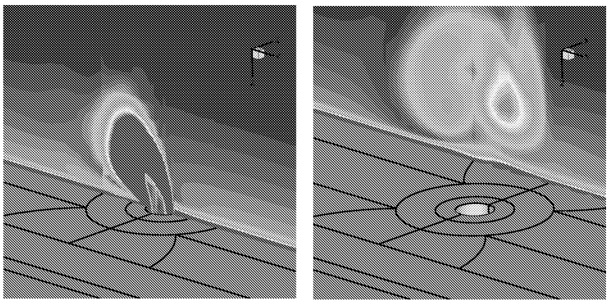

Figure 3: Vortical structures downstream of the transverse jet.

As expected the smaller the axial gap the larger the amplitude of the radiated sound. For both geometries it is interesting to observe the degree of increase in amplitude as the axial spacing is reduced. The sharp increase is not consistent with the slow axial decay of the wake, but rather suggests potential flow interaction effects are the source of the rapid increase in amplitude. To verify the importance of potential flow interaction effects, an inviscid simulation was performed for the largest cylinder at the smallest axial spacing. Analysis of the results revealed a strong tone with a sound pressure level of 113 dB at the BPF, confirming the importance of potential flow interaction effects.

Three-dimensional Simulation

Following the initial two-dimensional simulations a fully three-dimensional simulation was performed with the transverse jet positioned an axial distance of $0.2l$ downstream of the rotor trailing edge. The structure of the mean flow in the immediate region of the jet is shown in Figure 3 in terms of absolute vorticity contours. In the first figure the jet may be seen emerging from the nozzle. The flow immediately downstream of the nozzle (second figure) is characterized by the emergence of a counter-rotating vortex pair. The cross-flow itself is deflected as if it were blocked by a rigid obstacle. Furthermore, analysis shows the potential field of the jet, in the immediate region of the nozzle, to be similar to the potential field of the circular cylinders considered in the previous section. It is therefore to be expected that the noise generated by the interaction of the jet's potential field with the rotor blade will be qualitatively and quantitatively similar to that from the rotor-rod interaction. Analysis of the data revealed a tone of amplitude 98 dB at the BPF in the three-dimensional simulation. The relative weakness of the tone is a consequence of the limited spanwise penetration of the jet into the cross-flow, and the absence of a solid surface (cylinder) to scatter the rotor potential field.

Conclusions

Numerical simulations have been performed to study the interaction of a rotor wake with a high-speed transverse jet. Initial two-dimensional simulations, with the transverse jet represented by a circular cylinder, investigated the effects of axial spacing and cylinder diameter on the tonal noise at the BPF. Results have shown potential flow interactions to be important noise sources over the range of axial spacings considered. Reducing cylinder diameter was found to weaken the amplitude of the radiated sound by reducing both potential flow and viscous wake interaction noise contributions.

The flow in the immediate region of the jet shows many of the features observed in the two-dimensional cylinder flow. Furthermore, the potential fields are similar. As a source of sound however the jet is much weaker as: (i) it is confined to the tip region; and (ii) is not capable of scattering the potential field of the rotor as the cylinder may.

References

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