Active Control of the Tip Clearance Noise and Aerodynamic Performance of Axial Turbomachines

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1. Introduction

Axial turbomachines have a radial gap between the casing and the rotor blades. The static pressure difference between the suction and the pressure side of impeller blades produces a secondary flow over the tip of the rotor blades. This tip clearance flow is important for the aerodynamic and acoustic performance of the machine. The pressure rise and efficiency drop and the usable range of the performance characteristic is diminished as the rotor flow is stalled at higher flow rates.

Previous work at DLR-Berlin [1] – [3] investigating the effects of varying tip clearances on noise and performance showed the existence of a broad-band noise source for large tip-casing clearances. This source appeared in the rotor wall pressure spectrum at about half the blade passing frequency (BPF) and radiated a fluctuating tonal component into the far field, the tip clearance noise (TCN). Interpretation of the spectra and circumferential mode analyses led to the model of a rotating source mechanism, called rotating instability (RI), which moves relative to the blade row at a fraction of the shaft speed, similar to the cells of rotating stall (Kameier [1], Kameier and Neise [2]).

Kameier [1] was successful in reducing the tip clearance noise and to increase the aerodynamic performance by mounting a turbulence generator into the tip clearance gap (see also Kameier and Neise [3]). The aim of the present work is to reproduce and possibly improve the effect achieved with the turbulence generator without modifications of the tip clearance gap itself to make the method applicable also to flow machines where the tip clearance gap is changed, e.g., due to usage of different stagger angles of the impeller blades.

2. Experimental facility

The test fan is a low-speed high-pressure axial fan with outlet guide vanes. The principal impeller dimensions are as follows: impeller diameter $D = 452{,}4$ mm; hub-to-tip ratio $\varepsilon = 0.62$; NACA 65 blade profile; blade number $Z = 24$; blade chord length at the tip $c = 43$ mm; maximum bade thickness 3 mm; blade stagger angle at the tip $\theta = 27°$. The design speed is $n = 3000$/min. The stator row comprises $V = 17$ non-profiled vanes. The axial distance between rotor and stator at the outer circumference is $\Delta x/c = 1.3$. The tip clearance can be varied by exchanging casing segments while the impeller diameter remains constant. All experiments reported here were made with the tip clearance gap $\zeta = s/c = 5.6\%$. Figure 1 shows the experimental setup with its major dimensions.

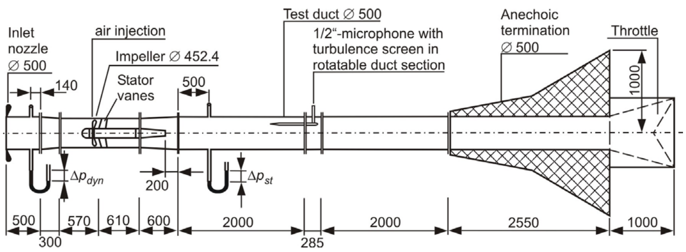

Figure 1: Experimental setup (dimensions in mm).

In the outlet duct a ½-inch microphone equipped with a turbulence screen is mounted in a rotatable duct section to measure the circumferentially averaged sound pressure level at a specified radial distance from the duct axis. To measure the unsteady blade pressure, a miniature pressure sensor is mounted on the suction side of one impeller blade at 36% of the chord length without changing the original outer blade contour. The radial distance from the blade tip is 7% of the chord length.

To control the flow conditions in the tip clearance gap, steady air is injected into the gap through $Z_{noz} = 24$ slit nozzles which are distributed evenly over the circumference and mounted flush with the inner casing wall. Another injection configuration is a circumferential slit in the casing. The axial position of the air injection is $\xi = x/c = 16.6\%$ downstream of the blade leading edges. This is the point of maximum thickness of the impeller blade profile. The radial angle between the jet axis and the interior casing wall is 15°, the jet direction is the same as the main flow direction in the fan duct.

3. Results for steady air injection

3.1 Air injection through slit nozzles

The experiments were conducted at the impeller design speed $n = 3000$/min with steady air injection using $Z_{noz} = Z = 24$ nozzles which is equal to the number of impeller blades. The nozzles were evenly distributed over the circumference. Experiments with reduced impeller speed, different numbers of nozzles, different nozzle distributions, including results for the fan efficiency and for unsteady air injection were reported by Neuhaus and Neise [4].

Figure 2 shows the aerodynamic and acoustic performance curves with different air injection rates through slit nozzles at the axial position $\xi = 16.6\%$. This is the best position based on the needed mass flow rate, compare Neuhaus and Neise [5]. The injected mass flow is given in percent of the maximum mass flow delivered by the fan (i.e., at $\varphi = 0.3$). The non-dimensional fan performance parameters flow coefficient φ and pressure coefficient ψ are defined as

$$\varphi = \frac{Q}{A \cdot U} \tag{1}$$

$$\psi = \frac{\Delta p}{\frac{\rho}{2} \cdot U^2} \tag{2}$$

where Q is the volume flow of the fan, A is the cross-sectional area of the casing at the impeller, U is the tip speed of the rotor, Δp is the total pressure rise of the fan and ρ is the density of the air.

With steady air injection, the fan pressure rise at low flow rates increases, and the stall point is shifted towards lower flow rates. With an injected mass flow rate of $m_{in} = 0.8\%$, the stall point is shifted from $\varphi = 0.2$ to 0.16. The usable range of the fan characteristic is 40% larger than without air injection. At the operating point $\varphi = 0.16$ the pressure rise increases to $\psi = 0.4$.

The sound pressure characteristic in the outlet duct without air injection exhibits the occurrence of TCN at operating points near $\varphi = 0.2$. Only at these operating points with TCN it is possible to reduce the radiated sound pressure. At higher flow coefficients and high injected mass flow rates the radiated level is increased.

To demonstrate the influence of the air injection on RI and TCN, Figure 3 shows spectra of the sound power in the fan outlet duct and the wall pressure on the rotor blade suction side at the operating point $\varphi = 0.2$ where TCN occurs. Without air injection and with $m_{in} = 0.3\%$, TCN and RI are clearly visible in the spectra. When the injected mass flow rate is raised up to $m_{in} = 0.6\%$, TCN and RI are fully suppressed. The level of the BPF-component is found to increase with the injected air flow which is due to the interaction between the jets from the nozzles and the impeller blades. Despite the increase in BPF-level, the overall sound pressure level is reduced, e.g., at $m_{in} = 0.8\%$ from 119 dB to 116 dB, where the BPF level increases from 104 dB to 112 dB. The fan tone level is increased even more when the air injection is higher. Thus, for this air injection configuration, the increase in BPF-level limits the achievable improvement in aerodynamic performance and TCN reduction.

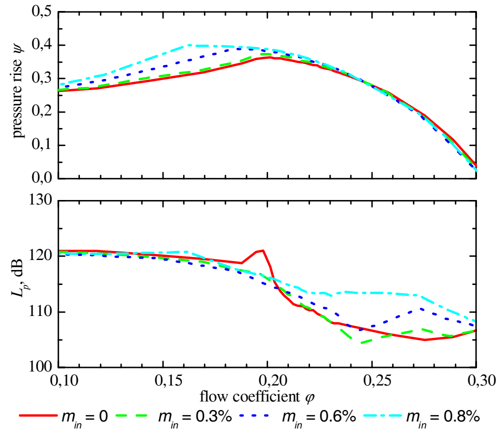

Figure 2: Pressure coefficient and sound pressure in the outlet duct as functions of the flow coefficient for different steady air injection mass flow rates through slit nozzles; n = 3000/min, $Z_{noz} = 24$, $\xi = 16.6\%$, $\zeta = 5.6\%$.

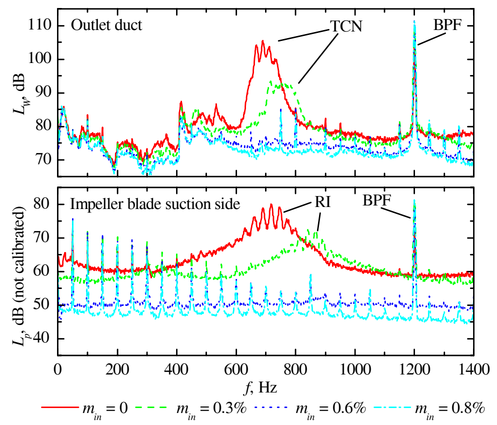

Figure 3: Spectra of sound power in the fan outlet duct and wall pressure on the rotor blade suction side for different steady air injection rates through slit nozzles; n = 3000/min, $Z_{noz} = 24$, $\xi = 16.6\%$, $\zeta = 5.6\%$, $\varphi = 0.2$.

3.2 Air injection through a circumferential slit

To avoid the increase in fan tone level observed in the previous experiments, an optimised injection configuration was developed. A circumferential slit arrangement was designed to produce a uniform air flow over the whole circumference of the casing. With this configuration, there is no unsteady interaction between the injected air and the impeller blades any more.

The results for the characteristic curves and sound spectra are shown in Figure 4 and Figure 5. With $m_{in} = 1.5\%$ air injection, the usable range of the fan characteristic is enlarged by 62%, and the fan pressure is increased from $\psi = 0.29$ to 0.41 at $\varphi = 0.14$. The radiated sound pressure level is reduced over a large range of flow coefficients. The higher the injection rate, the larger the range of flow coefficients where the sound pressure level is reduced.

When the injected air flow is lower than $m_{in} = 0.8\%$, rotating instability and tip clearance noise are still visible in the blade wall pressure spectrum and sound pressure spectrum, respectively (Figure 5). When the injected mass flow rate is 0.8%, RI and TCN disappear. There is no increase in BPF level, not even when the air injection rate is large. Thus, simultaneous improvements in the aerodynamic and acoustic fan performance are possible for all air injection rates tested.

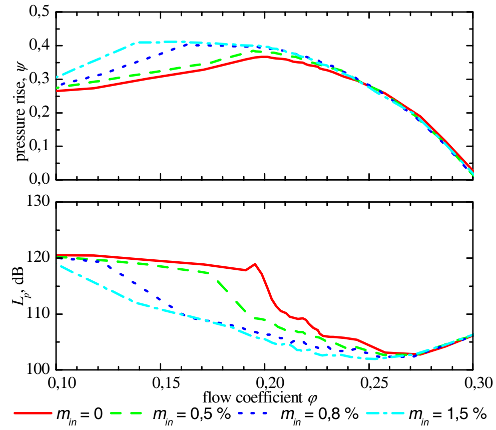

Figure 4: Pressure coefficient and sound pressure in the outlet duct as functions of the flow coefficient for different steady air injection mass flow rates through a circumferential slit arrangement; n = 3000/min, $\xi = 16.6\%$, $\zeta = 5.6\%$.

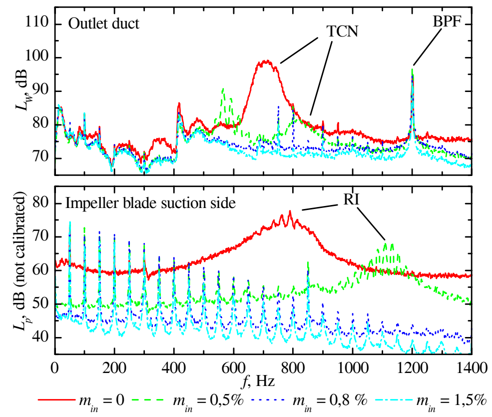

Figure 5: Spectra of sound power in the fan outlet duct and wall pressure on the rotor blade suction side for different steady air injection rates through a circumferential slit arrangement; n = 3000/min, $\xi = 16.6\%$, $\zeta = 5.6\%$, $\varphi = 0.2$.

4. References

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