Discussion: "Criteria for Spike Initiated Rotating Stall" (Vo, H. D., Tan, C. S., Greitzer, E. M., 2008, ASME J. Turbomach., 130, p. 011023)

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The paper "Criteria for Spike Initiated Rotating Stall" by Vo et al. (2008, ASME J. Turbomach., ***130****, p. 011023) provides a very important contribution to the understanding of spike-type stall inception in axial-flow compressors by demonstrating that spike-type disturbances are directly linked to the tip leakage flow of the rotor. The computational study of Vo et al. leads to the conclusion that two conditions have to be fulfilled simultaneously for the formation of spike-type stall: (i) axial backflow at the leading edge plane and (ii) axial backflow at the trailing edge plane. The objective of the present technical brief is to support these findings by corresponding experimental results.*
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Introduction

The material in this technical brief was obtained from an experimental investigation of three different single-stage axial-flow low-speed compressors [1]. The characteristics of the compressors measured for a tip clearance-to-chord ratio of $s/l=0.015$, are presented in Fig. 1, showing the nondimensional inlet-stagnation to outlet-static (total-to-static) pressure rise ψ_{ts}.

Experimental Setup and Instrumentation

At the last stable operating point of each compressor, the slope of the total-to-static pressure characteristic is clearly negative. Therefore, following Camp and Day [2], spike-type stall inception has to be considered for all stages. Four pressure probes were used to detect the circumferential as well as the radial evolution of the initial disturbance. The unsteady pressure traces were measured simultaneously upstream (probes 1 and 2) and downstream (probes 3 and 4) of the rotor. Probes 1 and 2, two pitches apart and 2 mm or 45 mm immersed, respectively, are two 90 deg cranked total pressure probes facing the rotor at an angle of 60 deg. Probes 3 and 4, also two pitches apart but only 2 mm immersed, are two calibrated cylindrical pressure probes with a 45 deg downstream directed axis angle of the measuring holes. For further details concerning the setup, the reader is referred to [1].

The accuracy of the Kulite™ XCS-062-5D sensors used as the probe's heads is sufficient in order to resolve the given pressure magnitudes as well as the fluctuations in time (see [3]). Some thoughts have to be given to the time-dependent aerodynamic characteristics of a fast response pressure probe. Since the probe head, which is placed into the flow, represents a solid boundary, the surface pressure at a given point always contains contributions from the inertial effects in the flow around the body. The effect was investigated on a small sphere in a periodically pulsating jet by Kovasznay et al. [4]. According to the theory developed in [4], the contribution of the inertial term was estimated to be less than 3% of the steady term within the present investigation. This is due mainly to the small size of the probes. Even though different types of probes were used in the present setup upstream and downstream of the rotor (see [1]), the contributions from the inertial term would effect all probes in the same way, reducing the error concerning temporal and quantitative resolution even further. Therefore, the accuracy of the described instrumentation is considered to be sufficient for the following qualitative signal analysis.

Rotor Flow During Stall Inception

A selected result of the instantaneous pressure measurements for probes 1 and 3 is shown in Fig. 2 for stage 2 with a tip clearance-to-chord ratio $s/l=0.015$. The starting point for the following analysis and discussion is the total pressure trace of probe 1 (close to the casing, upstream of the rotor). During stable compressor operation, the total pressure trace is formed by the upstream effect of the corresponding rotor blades. A first disturbance of the total pressure upstream of the rotor is shaped like a spike and represents a distinct pressure and suction peak of small circumferential extension (Saathoff et al. [5]). Proceeding from the initial spike, the disturbance grows in circumferential as well as radial direction until, after less than ten rotor revolutions, again a steady state, fully developed stall, is reached.

In order to gain insight into the corresponding tip clearance flow field phase-locked, ensemble-averaged casing, wall pressure distributions were measured (see [1]). An analysis of the associated pressure fluctuations reveals high values in a band-like area slightly upstream of the tip clearance vortex due to the interaction of the incoming flow and the axially backward directed tip clearance flow. For a near stall flow rate, this upstream interaction zone is aligned with the rotor inlet plane while the pressure fluctuations reach a maximum. This is a common result for all three compressors. This situation turns out to be the critical condition for spike-type stall inception because further throttling of the compressor leads to an unsteady spillage of tip clearance flow ahead of the rotor blade leading edge. In this regard, the outcome of the present analysis of the measured casing wall pressure distributions agrees

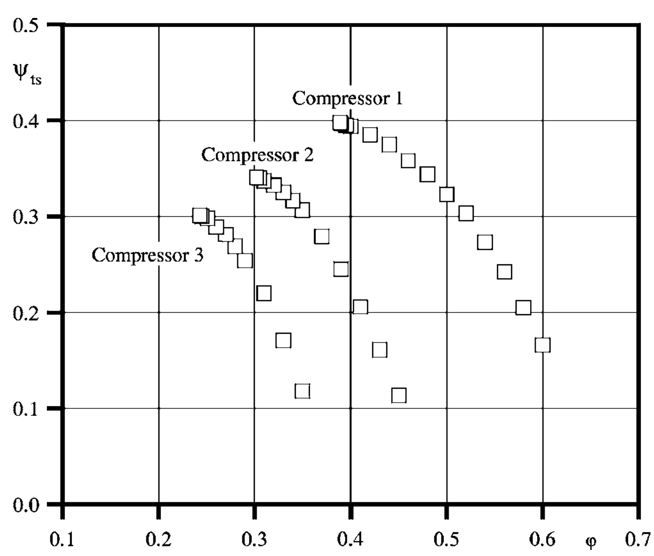

Fig. 1 Single-stage compressor characteristics

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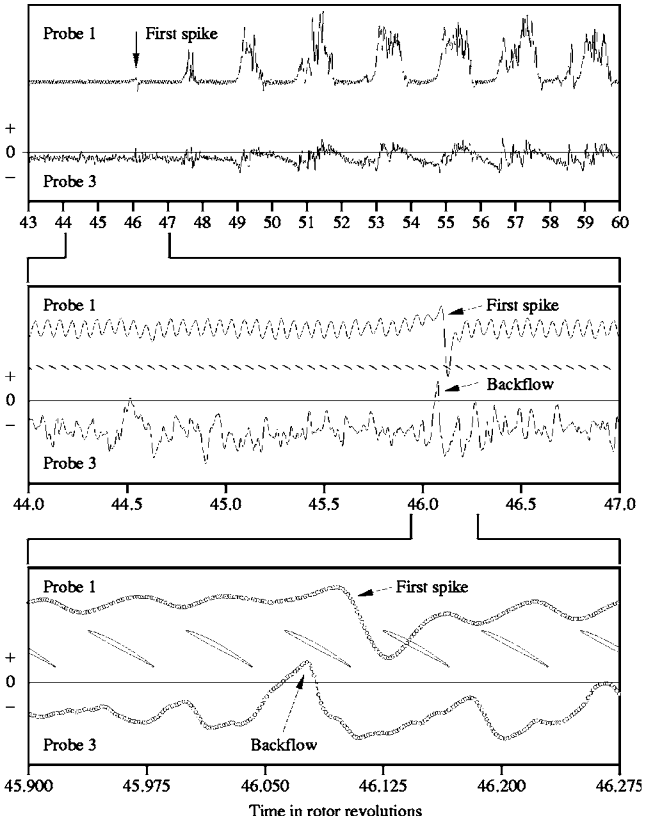

Fig. 2 Unsteady pressure distributions up- and downstream of the rotor (Compressor 2)

well with the findings of Vo et al. [6]. Both investigations do not show any blade stall (severe blade boundary layer separation) in the tip region.

According to Vo et al. [6], there is a second condition for spike-type stall inception to occur. This second condition, the appearance of locally confined, unsteady backflow at the rotor outlet close to the casing wall, must be fulfilled simultaneously with the first condition. This numerical result was the reason to additionally investigate the rotor outlet flow during the inception process parallel to the rotor inlet flow utilizing two downstream probes as described above. The specially calibrated probes indicate a change from axial downstream to axial upstream flow by a change of sign of the measured pressure coefficient.

The second pressure trace obtained from probe 3 for compressor 2 is given in Fig. 2, top frame. During data reduction, trace 3 was shifted in the rotor direction to compensate for the circumferential distance (exactly one pitch) between the two probes. Trace 1 shows the evolution of an initial spike into a fully developed stall cell as has been explained before. The corresponding signal of probe 3 shows axially backward directed flow exactly at the position of the first spike in trace 1. This means that the critical point is found, where the conditions described by Vo et al. [6] are fulfilled for the first time during stall inception. The simultaneity of the occurrence of spikes in the leading and trailing edge pressure traces was observed every time compressor 2 was taken into stall. Identical results were found for compressors 1 and 3.

A close-up of the traces is shown in the middle frame of Fig. 2, demonstrating more clearly that the first spike in trace 1 directly links up with a backflow-indicating spike in trace 3. Spikes of this type occur several times, irregularly distributed along the circumference before the first spike in trace 1 can be detected. Figure 2, bottom frame, represents a still closer view of the pressure signals together with the rotor tip cascade. The arrangement of the cascade and the pressure signals indicates that backflow occurs near the trailing edge and spills forward near the leading edge of the same blade. From these results, it was concluded that spike-type stall inception starts with local spots of backflow at the rotor outlet next to the casing. For the three-stage configurations investigated, this result was found and could be repeated. These findings are, furthermore, confirmed by a corresponding experimental low-speed model investigation of a high-pressure compressor stage (see [7]).

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