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PERIODIC WAKE IMPINGEMENT AND STALL DRIVING LOSS IN AXIAL COMPRESSORS

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OBJECTIVES

- Evidence by experiment the calming effect of wake interactions in transitional boundary layers.
- Identify practical means for exploiting this process for reducing profile loss in axial compressors.
- Study by unsteady computational fluid dynamics axial compressor rotor tip stall with unshrouded blading.
- Evaluate numerically a passive flow control strategy for improving stall margin.

BACKGROUND AND INTRODUCTION

Improvements in material and manufacturing technology over the last four decades have produced a drive to reducing the number of blades in axial turbomachine blade rows. Reducing the blade count offer attractive savings in the manufacturing cost, maintenance cost, and in the weight of axial turbomachines. By reducing the blade count in both stators and rotors for a given shaft speed, the frequency by which trailing edge wakes shed by the upstream blade row interact with the downstream blade row reduces. Intuitively, this should lead to a monotonic decrease in the stage loss with decreasing blade count, a trend that however was not confirmed in tests on blading under a strong adverse streamwise pressure gradient [1].

The disturbances generated by on-coming wakes play a vital role in preserving the efficiency and the integrity of compressors. This is manifest in both the midspan locations and also at locations close to the hub or to the casing. This discussion is limited to midspan locations, where wake disturbances affect the quasi-two dimensional flow. The engines of contemporary aircraft are particularly susceptible to loss of efficiency and stall margin, therefore the present discussion is relevant to those phenomena.

Another area in which unsteady aerodynamic effects play a significant role in determining the performance of axial compressors is stall and surge. One example of a highly loaded rotor is the NASA rotor 37 test case [2] that features rotor tip stall.

Of specific interest to this axial rotor is the role rotor tip leakage has in triggering a rotating stall that progresses as an unsteady aerodynamic effect from one blade passage to the next one, opposite to the direction of rotation of the fan. Under certain operating conditions, the number of passages affected by stall increase rapidly over time, leading to surge. Effective means for delaying the onset of stall and therefore extending the stall margin of axial compressors have been subject of intense research activity. Casing grooves [3], sweep and dihedral [4], and non-axisymmetric slots [5] are some examples of designs tested numerically and experimentally.

This work evaluates a recirculation channel type design that aims to interfere with the rotor tip leakage and thereby provide a self-actuating passive flow control to the rotor blade tip, to extend the stall margin without incurring in a penalty in the stage efficiency away from stall.

METHODOLOGIES

Experiments are performed on a flat plate (Fig. 1) in the 1.00 m × 1.15 m working section of the University of Leicester low speed closed loop research wind tunnel (the Charles Wilson wind tunnel). A flat plate carries a long laminar separation bubble, caused by a strong adverse pressure gradient. The Reynolds number, based on the plate length of 2.41 m, is 1.4×10^6. During the tests, the wind tunnel velocity is set to this target Reynolds number. The free stream turbulence level is less than 0.2%.

The roof of the test section is contoured to provide the desired strong adverse pressure gradient, providing self-similar conditions with a Hartree [6] β parameter of -0.221 over the streamwise range between 0.4 m and 0.7 m from the flat plate leading edge ($x = 0$). The converging section of the wind tunnel include the first 150 mm of the flat plate, terminating at the throat.

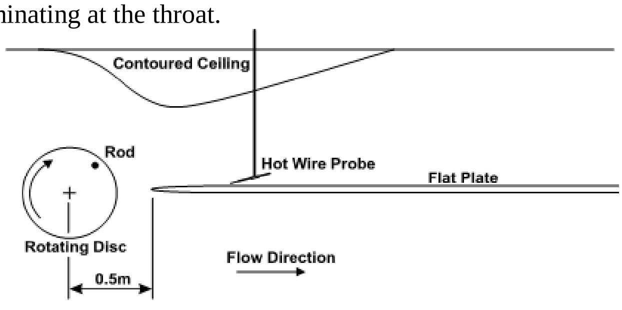

Fig. 1. Flat plate installation with flat plate, fairing, hot wire traverse and upstream wake generation.

Time-dependent computational fluid dynamic simulations of the flow through the NASA rotor 37 are obtained by solving the unsteady Reynolds Averaged Navier-Stokes equations with the realizable $k-\epsilon$ turbulence closure model. The inviscid fluxes in the governing equations are evaluated by the Roe flux difference split approximate Riemann solver and the third-order MUSCL scheme is used to estimate the gradients of the flow state inside each unit cell. The solution is time-advanced by implicit time integration [7].

MAIN RESULTS

The presence of the laminar separation bubble is confirmed by instrumenting the flat plate by a streamwise array of microphones, mounted inside the flat plate casing. 24 microphones are installed along the flat plate centreline and cabled through the flat plate trailing edge. Fig. 2 shows a space-time diagram of the recorded pressure from the microphones, using levels of grey. The flat plate is equipped with three loudspeakers close to the flat plate leading edge. What is interesting to notice, and relevant to turbomachinery flows, is that the intermittent operation of the loudspeakers causes regions of relatively unperturbed flow between loudspeaker duty cycles. These temporary regions of quiet flow are shown in Fig. 2 by a uniform grey tone level in between patches of striations.

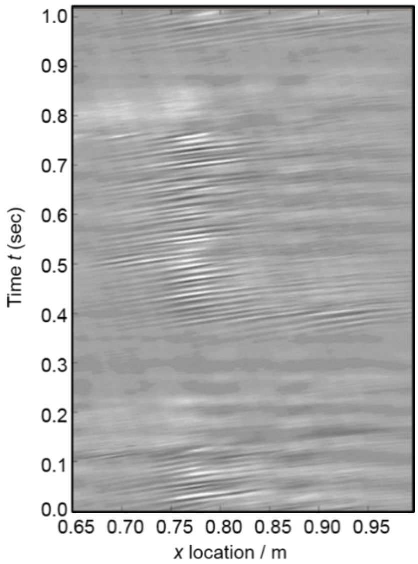

Fig. 2. Results from microphone array showing turbulent spots and calmed region.

Unsteady flow leading to rotating stall is observed by time-dependent RANS simulations of the NASA rotor 37. Fig. 3 visualizes the axial flow velocity distributions at 0.99 blade span after applying an increase in the back pressure at t_{rev} = 0.0 revs. The pitchwise periodicity of the flow among the rotor passages starts to collapse. At t_{rev} = 8.0 revs., the axial velocity distribution shows the development of reversed axial velocity regions in some rotor passages. Eventually, this flow separation causes a large-scale breakdown of the flow structure through the rotor. Following this observation, a delay in the tip stall onset is sought by controlling this separating flow near the casing.

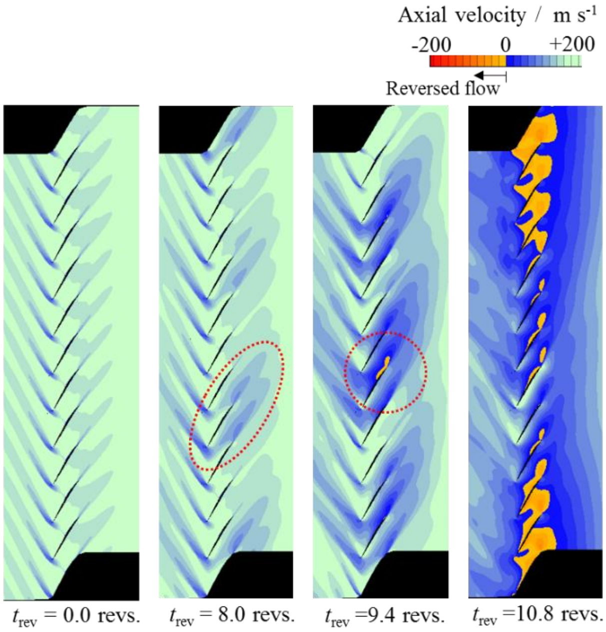

Fig. 3. Axial velocity iso-color levels at the 0.85 blade span showing time-dependent evolution of tip stall.

SUMMARY AND CONCLUSION

The temporary presence of a calmed region may explain lower profile loss with a higher blade count.

The time-resolved CFD provides some useful insights in the stall inception process of a highly loaded axial compressor. These simulations reveal the effectiveness of a recirculating type casing treatment for improving the stall margin of the axial compressor.

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