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Alleviation of spike stall in axial compressors utilizing grooved casing treatment

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Abstract This article deals with application of grooved type casing treatment for suppression of spike stall in an isolated axial compressor rotor blade row. The continuous grooved casing treatment covering the whole compressor circumference is of 1.8 mm in depth and located between 90% and 108% chord of the blade tip as measured from leading edge. The method of investigation is based on time-accurate three-dimensional full annulus numerical simulations for cases with and without casing treatment. Discretization of the Navier–Stokes equations has been carried out based on an upwind second-order scheme and k-ω-SST (Shear Stress Transport) turbulence modeling has been used for estimation of eddy viscosity. Time-dependent flow structure results for the smooth casing reveal that there are two criteria for spike stall inception known as leading edge spillage and trailing edge backflow, which occur at specific mass flow rates in near-stall conditions. In this case, two dominant stall cells of different sizes could be observed. The larger one is caused by the spike stall covering roughly two blade passages in the circumferential direction and about 25% span in the radial direction. Spike stall disturbances are accompanied by lower frequencies and higher amplitudes of the pressure signals. Casing treatment causes flow blockages to reduce due to alleviation of backflow regions, which in turn reduces the total pressure loss and increases the axial velocity in the blade tip gap region, as well as tip leakage flow fluctuation at higher frequencies and lower amplitudes. Eventually, it can be concluded that the casing treatment of the stepped tip gap type could increase the stall margin of the compressor. This fact is basically due to retarding the movement of the interface region between incoming and tip leakage flows towards the rotor leading edge plane and suppressing the reversed flow around the blade trailing edge.

1. Introduction

Compact engines are accompanied by compressors of lower numbers of stages and blades, which in turn causes aerodynamic loading of each stage to be increased, whilst keeping a compressor within a safe margin performance and a high efficiency.

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Rotating stall is known as one of the critical unsteady flow phenomena in dynamic compressors. This phenomenon, as a result of separation of flow from the blade surfaces, moves along the blade row in the circumferential direction. These separated circulatory flows, known as the stall cells, can produce blockages to the main flow within the blade passages. The rotating stall also changes pressure distributions on the blade surfaces in a periodic manner. Therefore, it would be responsible for noise generation and excitation of blade vibrations in different modes. The consequent unsteady forces may cause the compressor blades to be subjected to fatigue and fracture phenomena.

Control of flow instabilities is an effective method in improving a compressor's performance, which can be achieved by active or passive techniques. Of effective methods in active control of the blade tip unsteadiness can be referred to tip injection[1] and end wall bleeding or suction.[2] It is recognized that upstream injection[1] and downstream bleeding[2] can be led to increasing the stall margin of the compressor to a certain extent. Of the passive control methods for alleviation of the unsteadiness can be referred to casing treatment. Since the late 50 decades, this method has been known as an efficient method in enhancing the flow stabilities of compressors by improving the flow conditions near the blade tip and weakening the tip leakage vortex strength.[3–10]

Up to now, various types of casing treatments such as mounting slots or grooves over the rotor blade tip have been employed to enhance the compressor performance. Wilke and Kau[3] have described the impact of axial slots on the flow field in a transonic rotor blade row. They presented their results based on time-accurate three-dimensional numerical simulations of a high pressure compressor front stage with and without casing treatment. Two different axial positions of the casing treatment consisting of axial slots were tested for their impact on flow stability and efficiency. They clearly showed that the modified casing treatment stabilized the tip leakage vortex and reduced its influence on the flow inside the blade passage.

Another method of casing treatment, which is introduced as stepped tip gap, is similar to circumferential grooves and has been applied to both subsonic and transonic compressors.[4,5] Thompson et al.[5] have explored experimentally the effects of different stepped tip gaps and blade tip clearance levels on the performance of a transonic axial flow compressor, and found that for small and intermediate clearances, stepped tip gaps could improve overall pressure ratio, efficiency, and flow range for a wide range of operating conditions.

Rabe and Hah[6] studied experimentally and computationally the effectiveness of circumferential grooves on the stall margin of a transonic axial compressor. They claimed that the reason for the stall margin improvement was a reduction in flow incidence near the pressure side from the leading edge, which had dominant effects on flow structure. They also found that the shallow grooves were very effective in extending the stall margin.

Lu et al.[4] have reviewed the effects of stepped tip gaps on the flow field and performance of axial compressors based on experimental and computational methods, and performed parametric studies of blade tip clearance levels and step profiles of eight different geometries, considering flow simulations. Steady-state Navier–Stokes equations have been considered for their flow simulations. Shabbir and Adamczyk[10] have tried to numerically understand the physical mechanism responsible for improvement of the stall margin of a low speed rotor blade row due to existence of circumferential casing grooves and proved its effectiveness in enhancement of its operating range.

The flow field in the tip region of a rotor blade row is inherently unsteady and oscillatory. Hence, in addition to performing various kinds of casing treatments in enhancing the compressor stall margin, some researchers like Rae and Breuer,[11] Mailach et al.[12] and Zhang et al.[13] focused on studying the characteristics of this complex flow in details. Some investigations have been carried out to study the relation between the unsteady tip leakage flow and the spike stall inception as precursor of the fully developed rotating stall. The link between the tip leakage flow and the rotating stall has also been studied through three-dimensional simulations by some researchers.[14–16] Hoying et al. have considered movement of the tip leakage vortex towards the blade leading edge as a practical feature of the spike stall.[14] Vo et al. have introduced two transient phenomena in the tip leakage flow fields, known as leading edge spillage and trailing edge backflow at the blade tip, which are responsible for spike stall.[15]

Most of the researches are restricted to the casing treatment effects on the general performance of axial compressors. Unsteady flow field in the rotor blades tip region, particularly under high loadings, is not well studied up to now. In the current research work, the effects of grooved type casing treatment for the suppression of the spike stall is studied for an isolated axial compressor rotor blade row at near-stall conditions, utilizing unsteady numerical simulation of the tip leakage flow.

2. Model specifications and numerical scheme

The present investigation is carried out for a low speed isolated axial compressor rotor blade row subjected to other investigations experimentally or numerically.[17,18] Fig. 1 shows the model geometry and the computational grid structure. The model is comprised of 12 blades designed based on NACA-65 airfoil series. Geometric specifications of this rotor blade row are listed in Table 1.[17] The test Reynolds number based on the blade midspan chord length, the rotational speed of the rotor blade row, and the blade tip clearance size are 3.77×10^5, 1300 r/min, and 2 mm, respectively.

A grooved type casing treatment all around the compressor circumference has been considered. It is 1.8 mm in depth located between 90% and 108% of the blade tip chord measured from its leading edge (see Fig. 1(a)). In Fig. 1(a), C_x is the rotor blade tip axial chord length. This type of casing treatment has already been studied by Lu et al., but for a rotor blade row of a different geometry and aerodynamic performance.[4] They applied a grooved casing treatment for their rotor with different depths and widths for small, medium, and large tip clearance sizes. They concluded, from their experimental and numerical investigations, that the groove located within 90%–108% of the blade tip chord enhanced the performance of the blade for the medium tip gap size (1.9% of the blade tip chord length).

The well-known commercial flow solver package of Fluent has been used for the current study. The adopted solver is a three-dimensional, viscous, time-accurate code that utilizes a finite volume scheme for solution of the governing equations