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Evaluation of the effectiveness of typical casing treatments for a low-speed compressor by an integral method

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ABSTRACT

A novel integral method is proposed to quickly assess the effectiveness on stability improvement with end-wall casing treatments. With this low-cost method, efficacies for various casing treatment configurations can be evaluated instead of calculating the entire performance curves, which can be used in place of expensive and costly experiments. The underlying mechanism for this approach is based on the hypothesis that the spike stall precursors can be triggered by the forward spillage of the rotor tip leakage flow, and the onset condition of such a spillage is determined by the axial momentum balance within the rotor tip region. Based on the simulation, a series of control volumes are set at the rotor tip region in order to catch the axial momentum balance between the incoming main flow and the reversed tip leakage flow. Cumulative axial momentum distributions for these control volumes named as "bell-shaped curves" are presented to evaluate the effectiveness of different configurations. The axial location of the bell curve peak indicates the time- and spatial-averaged interface position between the main flow and tip leakage flow, which moves upstream during throttling. Three types of typical casing treatments: multiple circumferential grooves, skewed axial slots and self-injection configurations for a low-speed in-house compressor are evaluated by their bell-shaped curves. Among these configurations, the skewed axial slots has the most downstream of the peak, followed by the multiple-grooves, while the self-injection configuration shows the least. Based on an existed experimental result for a double-groove configuration, the effectiveness of the three studied casing treatments are predicted by their locations of the bell-shape curve's peak without simulating the entire performance curves. The assessments are then validated by experiments.

1. Introduction

Casing treatments (CT) are widely investigated as the passive method to favorably alter the stall point of axial compressor. Maintaining considerable stall margin extension with minimal efficiency decrement, while also addressing part speed operability is the design concept in this topic [1]. Experimental and numerical efforts have been dedicated to develop a more complete understanding on why the casing treatments are useful and how they can work better [2–4]. Two of the more successful designs examined are the axial slot type casing treatment and the circumferential groove type casing treatment. Fujita and Takata [5] investigated the effectiveness of the axial skewed slot, circumferential groove and the axial slot. Among those tested configurations, the skewed slots showed the highest stall margin improvement and the slot-type casing treatments showed higher efficiency penalty than circumferential grooves.

Although huge processes have been achieved, it is still a tough task for designing a satisfactory casing treatment configuration. For a given CT, the effectiveness can be different when it is applied in various circumstances. Even for the same compressor, stall margin extensions are usually irregular at different rotating speed. The modern powerful computers make it possible to utilize numerical simulations, especially with the advanced high-fidelity computational models, to explore in details the flow structures and the stalling mechanism with and without casing treatments [6]. However, due to the complexity of the stall phenomena, the mechanism of the stall margin improvement by CT is still not completely clear. Also it still remains a big challenge to accurately and reliably predict the CTs' effectiveness before actually testing them. For the compressor industry, the most common design approach is to establish a database of casing treatments through extensive experimentations, which can be very time-consuming and costly.

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Nomenclature

NS	Near stall point
MF	Main flow
TLF	Tip leakage flow
SMI	Stall margin improvement
SC	Smooth casing
CT	Casing treatment
CS	The casing surface
BT	The bottom surface
Z_-	The left surface of the control volume
Z_+	The right surface of the control volume

Symbols

Z	The axial direction
Vz	Axial velocity .... m/s
Mz	Axial momentum .... N
C_{az}	Tip axial chord .... mm
Z_{bp}	Normalized axial location of bell curve's peak

Greek letters

ρ	Density .... kg/m^3
φ	Mass flow coefficient $\varphi = \frac{V}{U}$
V	Inlet flow velocity .... m/s
U	Mid span rotating speed .... m/s
ψ	Pressure rise coefficient $\psi = \frac{P_{2,s}-P_{1,t}}{\frac{1}{2}\rho U^2}$
$P_{1,t}$	Total pressure at inlet .... Pa
$P_{2,s}$	Static pressure at outlet .... Pa

Facing this difficulty, the motivation of this paper is to propose a method to quickly assess the effectiveness of various casing treatments. The philosophy of this paper is based on such insightful research results done previously in our research group as well as by others in the community, but NOT to get involved into these flow details this time. Instead, we are trying to develop a method to pre-screen the casing treatments for engineering designers. If the design scope can be quickly narrow down from massive candidates by a low-cost CFD tool without turning into more expensive experimental and CFD approaches, it will be beneficial at the early design stage.

Aiming at quickly pre-screening a variety of groove configurations and providing a few more preferable ones for further detailed test, the authors have previous [7] developed a control volume method to assess the efficacy of the circumferential grooves. Based on the understanding on the stalling mechanism of tip-critical axial compressors is the MF/TLF interface spilling from the leading edge which is determined by the axial momentum distribution of the tip region. The idea of using MF/TLF interface to judge the stability comes from the hypothesis that for tip critical compressors with spike stall inception, the forward spillage of the tip leakage flow is a necessary condition for spike formation [8]. This hypothesis has been studied by many researchers [9] and validated in many experiments [10,11]. Cameron et al. [11] carried out rotor-casing oil flow pattern experiments in a transonic compressor. On a transparent window on the compressor casing, this interface appeared as a straight line in the absolute reference frame, see Fig. 1. Considering this line as the trace of the zero axial wall shear stress, they proposed a 1-D model of the tip gap flow, and pointed out that the MF/TLF interface was driven by the tip axial momentum balance between the main flow and the tip leakage flow. As the compressor approaches to stall, the axial momentum of the main flow decreases and that of the tip leakage flow increases. The zero axial wall shear line moves upstream. Stall happens once this line spills over the rotor leading edge.

From these perspectives, the axial momentum distribution is closely related to the MF/TLF interface, which could be a rational indicator to identify the stability of tip-critical compressor. The core idea for the method proposed in this current approach is to the interface can be down-stream pushed by the effective casing treatment, which can be indicated by a re-distributed axial momentum. To determine the final balance between the main flow and the TLF, the axial momentum of the rotor tip region is acquired by utilizing the control volumes whose depth is deep enough to contain the entire tip leakage effects. The cumulative axial momentum distribution of the tip region named as the bell-shape curve is developed to describe the location of the interface and employed to assess the effectiveness. The bell-shape curve is

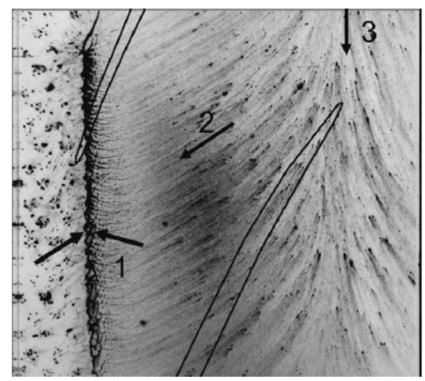

Fig. 1. MF/TLF interface projection viewed as the zero axial wall shear on casing a transonic compressor in Ref. [10].

pushed downstream for the grooved casing compared to the solid wall, which indicates the MF/TLF interface is down-pushed by the grooves and the stalling delays. Rather than predicting the exact stall point for each casing treatment configuration via computation, their effectiveness is compared at the near stall point of the smooth casing using the bell-shaped curves. This method provides a different perspective for quickly assessing the grooves based on the associated flow physical insight.

This integral method provided by the authors is validated to be potential in evaluating the effectiveness of groove type casing treatment. However, to facilitate this integral method for a wider application scope, at least three objectives should be accomplished:

1) Verify this method can be extended into general end-wall treatments, such as slot-type casing treatments and self-injection casing treatments;
2) Discuss the accuracy of this integral control volume method;
3) Preliminary quickly estimate the stall margin improvement (SMI) for the various casing treatments by this current method without simulating the entire performance curves.

This paper is then organized as follows: First, we will introduce the studied examples. A low-speed in-house compressor and three different casing treatment configurations are introduced. After a brief introduction of the control volume setup, the bell-shaped curves and their relation with compressor stability are discussed in detail. Then, the studied casing treatment configurations are evaluated by this method and validated by experiments. It should be noted that if a compressor does not experience forward spillage of tip leakage flow during its stall inception process, the axial mo-