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A new approach of casing treatment design for high speed compressors running at partial speeds with low speed large scale test

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ABSTRACT

The instability problems tend to be more severe when high speed compressors operate at partial speeds. This paper proposes an economic approach for casing treatment design that suitable to this situation. Aiming at reducing the expensive and time-consuming high-speed casing treatment experiments, the idea of low-speed similitude of high-speed compressors, which was originally practiced in mid-1980 with the purpose of loss reduction, is now extended to simulate the stability enhancement with casing treatment in this paper. The core idea of this approach is to replace a large portion of design processes for the high-speed compressors (the Prototype) with their equivalent large scale model compressors (the Model). Two different transonic rotors with skewed slots and circumferential grooves casing treatments are conducted as examples to demonstrate this approach. Following the selected similarity rules, the Model is firstly acquired by modeling the near stall point of the Prototype. A variety of casing treatments are designed and assessed on the Model. Then a few more promising configurations can thus be selected via low speed experiments. They are believed to have similar tendency on stall margin improvement on the Prototype. Finally, the selected configurations are converted back to the Prototype with based on the rule of similarity and validated by experimental data. In this paper, principles that guarantee the similitude of the flow field at near stall condition and the effectiveness of the casing treatment are discussed.

1. Introduction

When high speed compressors run with partial loadings, instability problems are often be exacerbated because the operation line of gas turbines may cross over the compressor part-speed characteristic at points beyond the stability limit. Casing treatment (CT) is a remedy to this situation with no need to redesign the whole compressor. Gelmedov et al. [1] measured the performance of a three-stage axial compressor. It was reported that the stall margins were negative when operating with the corrected rotational speeds under 75% design speed. With the use of "annular bypass" slot-type casing treatment, all these unsatisfying stall margins reached higher than 18%. Similar results were reported by experimental studies in other transonic rotors [2] and multi-stage compressors [3].

Over 60 years, the range of applications, effectiveness and mechanism of casing treatments are gradually understood by experimental and numerical efforts [4]. Especially in recent years, numerous of studies are carried out to uncover the mechanisms of casing treatment, most of which are by numerical means [5–7]. However, due to the complexity of stall phenomena, the understandings on CT are still controversial [8]. Up to date, it is difficult to conclude rules or equations that enable the designers to directly select a suitable value of CT geometry. The design of CT remains to be a difficult topic because one can hardly tell the stall margin improvement (SMI) value of a CT before testing it. Despite the great progresses of the numerical methods, the design of CT largely relies on the established database via massive compressor experiments [9], which are considerably expensive and time consuming.

Another unfortunate fact is that for the modern advanced high-speed compressors, the tiny dimension of the tip clearance and the fast rotating speed highly restrict the detailed measurements within the blade passages, not to mention the flow details in regards to the interactions between the main stream and the flow within CT [10]. There is limited experimental data referring to the rotor tip region, with and without CT [11–13]. Therefore, to assess the detailed flow structures are essential to uncover the flow mechanisms and are highly demanded to fully validate the numerical results as well.

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Nomenclature

Abbreviation

NS	Near stall point
SC	Smooth casing
CT	Casing treatment
TLF	Tip leakage flow
SMI	Stall margin improvement

Symbols

M_z	Axial momentum, (m/s)
C_{az}	Tip axial chord, (mm)
V_z	Axial velocity, (m/s)
H	Blade height, (mm)
R_c	Casing radius, (mm)

Greek letters

ρ	Density, (kg/m^3)
g	Tip gap, (mm)
β	Relative flow angle, (°)
η_s	Isentropic efficiency
η	Torque efficiency $\eta = \frac{\dot{m}\frac{k}{k-1}RT_e[(\pi^*)^{\frac{k-1}{k}}-1]}{\eta_m T_q \omega}$
φ	Mass flow coefficient $\varphi = \frac{V_z}{U_m}$ V_z: Inlet flow velocity, (m/s) U_m: Mid span rotating speed, (m/s)
ψ	Pressure rise coefficient $\Psi = \frac{P_{2,s}-P_{1,t}}{\frac{1}{2}\rho U_m^2}$ $P_{1,t}$: Total pressure at inlet, (Pa) $P_{2,s}$: Static pressure at outlet, (Pa)

To investigate such kind of complex flow physics, large-scale model compressor can be a powerful tool, which is originally proposed with the purpose of loss reduction in the 1980s [14]. Later, large-scale compressors also showed great potential on investigating the flow mechanisms of rotating stall [15] and casing treatments [16–19] for axial compressors.

When the high-speed compressors running at partial speeds, shockwaves are normally absence in the blade passage. Low-speed model testing would be a good solution to CT design. Provided that the similitude of CT can be guaranteed, the design of CT for high-speed compressor running at partial speeds can be derived by using low-speed research model. It can provide at least two benefits: the possibility of low-cost sorting tests and a more measurable experimental environment. Aiming at which, a new CT design procedure is proposed in this paper:

(1) The original high-speed compressor (called the Prototype) will be modeled with a low-speed large-scale model compressor (called the Model) in terms of the near stall point;
(2) The CT tests, including the pre-screening phase and the refining design phase, will be carried out on the Model, in order to obtain the better configurations. A short list of candidates will be selected in this stage;
(3) The resultant configurations from the previous stage will then be transferred back to the Prototype and be tested.

It is understandable that it will be impossible to make the Model exactly replicates the Prototype. Particularly, the value of SMI cannot be exactly equal between the two compressors. However, if the effectiveness for the list of candidates on the Model show similar tendency as their corresponding configurations on the Prototype, this approach is believed to significantly cut down the time and cost in practical design of casing treatment.

However, the blading of the Model in this approach should be differed from those model compressors that addressing design point flow problems. The similarity of flow fields at near stall points for the two compressors should yield a reasonable baseline in order to proceed the following CT study. When a high-speed compressor approaches to stall, the flows of rotor tip region become inherently unsteady and the impact of tip leakage flow is amplified. Hence, the similitude to guarantee the similarity for the Prototype and the Model should be carefully selected. It is hereby introduce the theoretical basis for this current approach, named as “the bell-shaped curve”. It is a method to estimate compressor stability by quantitatively evaluating tip loading and the tip leakage flow (TLF) by numerical means [20]. The forward spillage of the rotor tip leakage flow from the rotor leading edge is considered to be as one criteria of spike inception by Vo et al. [21]. Further, the research group of Univ. of Notre Dame [19] proposed that this interface continually move upstream during the throttling process by observing zero shear on casing with oil pattern experiments. As soon as it reaches leading edge, stall occurs [22]. This movement of the interface is to be driven by the axial momentum ratio between the main incoming flow and the reversed tip leakage flow and validated by the author's group numerically [23].

Based on these studies, the author proposed an integral method to quantitatively identify this three-dimensional complex interface in a time- and spatial-averaged way [24]. By calculating the cumulative axial momentum for the rotor tip region, the final balance between main flow and TLF can be obtained. This distribution resembles a bell and named as “bell-shaped curve”, whose peak indicates the position of time- and spatial-averaged interface. Fig. 1 shows the variation of bell-shaped curves during throttling for an untreated transonic rotor. The peak of the bell-shaped curve shifts towards leading edge as the compressor approaching to stall. If it is compared under one fixed mass flow rate, the more downstream of the peak, the more stable the compressor. The chief advantage of the bell-shaped curve is that it enables a quick judgment on the quality of various CT without expensively pursuing their individual stall points. Meanwhile, the bell-shaped curve evaluates two important flow features in an averaged perspective, the tip loading distribution and the trajectory of TLF lying in the blade passage, which are both essential elements to describe the compressor stability. As a consequence, the bell-shaped curves are taken as the criteria to evaluate the similarity between two flow fields in terms of the stability.

This paper is organized as follows: An in-house large-scale compressor test facility (LSRC) provides the low-speed testing environment for this whole study. Two typical casing treatments: axial slots and circumferential grooves are both involved. At first, a transonic compressor (BHU-TAC) is used to illustrate this approach. Its 65% corrected shaft speed is chosen as the Prototype. After a brief introduction of the experimental facilities and numerical methods, the entire CT similitude design process is introduced, which starts from the blade design for the Model. In particular, the blade geometry is inversely constructed with the target of the near stall point of the Prototype. On the Model, a verity of axial slots are quickly assessed by the bell-shaped curves. A few more potential candidates are selected and tested by experiments. These configurations are then mapped back to the Prototype. The new designed CTs for the Prototype are examined whether their performances are similar as those corresponding configurations on the Model. Unfortunately, the experimental validation on the Prototype was not accomplished due to non-technical reasons. Thus, another example ND-TAC is given as the supplement, in which the open-to-public high-speed test data are available. Its 70% corrected shaft speed

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