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Stall margin enhancement of a novel casing treatment subjected to circumferential pressure distortion

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A B S T R A C T

This paper presents the stall margin enhancement of a novel casing treatment subjected to circumferential pressure inlet distortion. Experimental results are carried out on a low-speed compressor. Experimental results show that the stall margin of the test compressor is gravely narrowed by circumferential pressure inlet distortion. The stabilization ability of this novel casing treatment and the pre-stall behavior of the compression system under the impacts of circumferential pressure distortion are shown in the present work. Although subjected to the inlet distortion, the stall margin can also be made up by 6%–8% due to the application of this novel casing treatment. Furthermore, the pre-stall dynamic results can indicate that the mechanism of this stabilization method is associated with two main observations, one is the weakening of the unsteady flow perturbations in the compressor, and the other is the delay in of the nonlinear amplification of the stall precursor waves.

1. Introduction

Aircraft engines may be exposed to various inlet distortions, which generally result in detrimental effects on the engine compression systems, reflecting in the decrease of stall margin and overall efficiency. Therefore, how to understand the influence of inlet flow distortions on aeroengine performance has long been a problem of interest. Especially, with the increasing requirement for aircraft reliability and maneuverability, how to control or weaken the impact of inlet distortions on the compressor stall margin and performance has become a main concern of aeroengine application, research and development in the past decade.

It is known that inlet distortions can be categorized as different type, such as static pressure distortion, stagnation temperature distortion and stagnation pressure distortion. In particular, the patterns of non-uniform total pressure inlet distortions can be also summarized as radial inlet distortion, circumferential inlet distortion, rotating inlet distortion and swirl inlet distortion in terms of differences in the origins, positions, profiles and movement characteristics of the distortions.

On the other hand, it is also noted that the generation of the different type of aeroengine inlet distortions corresponds to diverse physical scenario. In fact, non-uniform temperature profiles usually exist in the inlet ducts when the aircraft is in conditions of very short take-off or landing, when hot exhaust gases are ingested to the inlet. For fighters, the ingestion of the hot exhaust gases from missiles can also leads to non-uniform temperature profiles. Besides, for aircraft engine, pressure loss on the windward side of nacelle can be induced by cross-wind and the take-off with high angle of attack, and this type of pressure loss can also generate distorted inlet flow because of large boundary layer growth and possible flow separation at the nacelle lip [1,2]. Currently, it has been revealed that stagnation pressure distortion is the most universal and arresting one [1], which often occurs spontaneously and has detrimental effects. There are two kinds of stagnation pressure distortion, one is the steady pattern which can be radial and circumferential, and the other is the transient pattern containing rotating inlet distortion and swirl inlet distortion.

Among these kinds of inlet distortions, the transient pattern distortion and circumferential stagnation pressure distortion have drawn more attentions due to the application of multi-spool jet engine and the appearance of integral aircraft-engine aerodynamic design. In fact, take-off operation with high angle of attack, cross-winds and nacelle flow separation can bring about circumferential inlet distortion naturally. In addition, in the multi-spools compressor, rotating stall occurring in an upstream stage can induce a kind of rotating inlet distortion on the downstream stages.

As for swirl inlet distortion, side inlet or S pattern inlet duct usually can induce vortexes in the inlet duct and those vortexes may generate pre-swirl flow or counter-swirl flow at the blade tip or hub region. Previous investigations show that rotating inlet dis-

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Nomenclature

Physical parameter

G	mass flow
ψ	total-to-static pressure rise coefficient
ϕ	flow coefficient
p	pressure
p_H^*	atmosphere pressure
T	*temperature*
η	efficiency
DC	distortion correlation parameter
$\overline{DC}$	time mean distortion correlation parameter
t	time
ρ	density
φ	flow capacity coefficient
φ_k	phase of k mode
k	ratio of specific heat
U_m	tangential speed at mid-span
V_x	inlet axial velocity
A_1	inlet area
$\tilde{\mathbf{F}}$	overall total physical quantity disturbances
$\mathbf{F}_0$	time-averaged physical quantities
$\mathbf{F}'$	physical quantity perturbations
$\tilde{P}_k$	motor power
$\tilde{P}_E$	electrical power
η_E	motor power efficiency
C_k	complex Fourier coefficients for each mode k
N	sample number
u	velocity in x axis
v	velocity in y axis
w	velocity in z axis
x	coordinate of x axis
y	coordinate of y axis
z	coordinate of z axis
e_p	limit error of pressure sensors
e_T	limit error of torquemeter
$\overline{p}$	characteristic pressure
$\Delta\overline{p}$	characteristic pressure variation
$\overline{T}$	characteristic torque
$\overline{U_m}$	characteristic tangent velocity in the mid-span
e_ϕ	uncertainty of mass flow rate
e_ψ	uncertainty of pressure raise rate
e_{q_v}	uncertainty of volume flow rate
e_η	uncertainty of efficiency

Abbreviation

SM	stall margin
CT	with SPS casing treatment
SC	without SPS casing treatment (solid casing)
SPS	stall precursor-suppressed

Subscript

0	time averaged quantity
t	total parameter
s	stall point parameter
d	design point parameter
1	inlet parameter
2	outlet parameter

Superscript

$*$	total parameter

tortion has very multiple effects on the compressor performance, and in some circumstances, can be beneficial to stall margin and efficiency [3–6]. However, circumferential stagnation pressure distortion may be identified as the most serious one and can only lead to impairments in performance, including a decrease in stall margin. Previous research on circumferential inlet distortion has been mainly aimed at assessing the form and impact of the distorted inlet flow using various kinds of experimental methods or mathematical models. For example, Hynes et al. [7] implemented a “first-principle” approach to predicting the stability operation range decrease brought about by distorted inlet, and proposed a strategy for assessing the effects of circumferential pressure inlet distortion on compressor stability. There are some other investigations making similar efforts to evaluate the performance of aircraft engine in the presence of distorted inlet conditions [8,9]. It is no doubt that assessing these effects of inlet distortion is valuable, but the more important issue is that the engine manufacturers are wondering about how to improve the compressor stability in order to guarantee that the engine can still work reliably under inlet distortion. There have been indeed some attempts to enhance compressor stall margin with distorted inlet condition. For example, Van Schalkwyk et al. [10] described the first experimental validation of transfer function modeling and active stabilization for axial compressors with circumferential inlet distortion on a three-stage low-speed axial compressor. They used servo-controlled guide vanes as actuator and regained approximately 40 percent of operation range lost induced by total pressure distortion. This work was a successful attempt to apply system identification and control theory to compressor stability in the presence of circumferential inlet distortion. Thereafter, Spakovszky et al. [11] used active feedback control to stabilize rotating stall in a single-stage transonic axial flow compressor with inlet distortion, and the relating results were very promising for future investigations and applications. Some other investigations making similar efforts to stabilize the compressor system of aircraft engine are also developed through detecting the stall inception [12,13]. Generally, the active feedback control methods are based on a dynamic mathematical model which contains the effect of inlet distortion on the compression system, but the accurate numerical description of inlet distortions and the establishment of quantitative control model are still very challenging issues. It is believed that the practical application of general active feedback control method will speed up once these difficulties being overcame. On the other hand, it is well known that casing treatments are an effective method to improve stall margin. This stabilization method was first proposed by Koch [14], and then Takata et al. [15] investigated the mechanism and effectiveness of casing treatment. The existing studies [16,17] indicate that casing treatment used on modern aero-engines always results in some efficiency loss in exchange for improving the stall margin of both transonic and subsonic compressors. Up to now, very few works have been conducted on the effect of casing treatment under inlet distortion conditions. Madden et al. [18] reported the combined effects of forward sweep and/or rotor casing treatment on a single stage military fan with tip-low total pressure radial inlet distortion. The author thought that the casing treatment can restrain the impact of inlet distortion on triggering stall and surge [18]. They also noted that the application of the casing treatment obviously changed the original performance curves and caused efficiency loss at large mass flow rate. Combining conventional casing treatments with inlet flow distortion may be a valuable attempt to enhance stall margin. However, considering