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A full engine cycle analysis of a turbofan engine for optimum scheduling of variable guide vanes

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ABSTRACT

This paper proposes a full engine cycle analysis to derive the schedule of variable guide vanes (VGVs) in a multi-stage axial compressor for improving the performance of a turbofan engine with required surge margin. Most researchers assumed the operating line of a compressor in process of scheduling of VGVs. However, it has been known that the performance of a compressor is influenced by the angle of VGVs. As a result, the performance variation of a compressor can affect an engine. Therefore, a full engine cycle analysis is conducted to consider the effect of VGVs on a turbofan engine. The VGVs are applied to the front stages of the high pressure compressor in the low-bypass ratio turbofan engine. The compressor of the front stages is transonic three-stage axial flow compressor. The commercial engine simulation program, NPSS^{TM} is employed to analyze the on- and off-design performance of the turbofan engine. 1D meanline analysis is used for performance prediction of a multi-stage axial flow compressor with VGVs. The engine simulation program is coupled with the compressor performance prediction tool to consider the engine performance variation with application of the VGVs. The proposed scheduling algorithm of the inlet guide vane (IGV) and stator vanes (SV) is adjusting the vanes angle to have the minimum loss incidence angle at all rotor blades and to satisfy the required surge margin at off-design condition. The result shows that the proposed algorithm can obtain the scheduling of the IGV, 1st and 2nd SVs angle with stable operation and improved specific fuel consumption of the engine.

1. Introduction

When the compressor rotating speed and pressure ratio are reduced, the axial velocity of the front stages of the compressor is decreasing more rapidly than the blade speed. This characteristics cause the high incidence angle of the air onto the blades. As a result, the operating point is pushed to the surge line which will bring about the stall and surge in the compressor. The compressor surge causes the blade vibration and can create rapid blade failure and the compressor flow breaks down [1]. There are several methods [2] to vary the engine cycle to avoid surge on the compressor. Typical approaches use the bleed values or variable exhaust nozzles. Especially, the variable inlet guide vane (IGV) and stator vane (SV) in an axial compressor are generally used to avoid the unstable region. By adapting the variable guide vane (VGV) at low speed, the large incidence angle of the airflow onto the front stage rotor blades is reduced to have stable incidence angle. Moreover the VGVs can accomplish accurate matching of the stages, which is crucially important to achieve low losses and stable operation over on- and off-design conditions.

Turbojet-to-ramjet transition is very important for the operation of the turbine-based combined cycle engine for the hypersonic flight propulsion system [3,4]. It can operate as turbo mode for low speed range (Mach number 0–3), then changes into ramjet model for higher speed range (Mach number 2.5–5) [5]. However, it has been known that additional difficulties arise in attempting to produce a turbojet which worked well throughout such a wide speed rage. With fixed geometry compressors, turbojets ceased to act as pressure amplifiers beyond Mach number 2.7. The addition of VGVs can raise the limit slightly beyond Mach number 3 [6].

There are numerous studies on investigating the performance and effectiveness of a compressor with VGVs. Mallett and Groesbeck [7] investigated the effects of a compressor interstage bleed and two-position inlet guide vanes to determine their effectiveness in alleviating the part speed stall margin of the J71-A2(X-29)

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Nomenclature

1D	one-dimensional
HPC	high pressure compressor
HPT	high pressure turbine
IGV	inlet guide vane
LPC	low pressure compressor
LPT	low pressure turbine
m	mass flow rate (kg/s)
N	rotating speed (rpm)
P	pressure (kPa)
PR	pressure ratio
SF	scaling factor
SM	surge margin
SV	stator vane
SFC	specific fuel consumption
T	temperature (K)
VGV	variable guide vane
η	efficiency
ϕ	angle of rotation – IGV and SV settings

Subscripts

c	corrected
eff	efficiency
op	operating point
rel	relative
surge	surge point
t	total
unscaled	unscaled value at a performance map

turbojet engine. In their study, Mallett and Groesbeck [7] discovered that closing the inlet guide vanes increased the compressor efficiency and slightly raised both the steady-state operating line and stall line in the low-speed range. When the inlet guide vane angle was rotated as +20 degree at design speed, the corrected mass flow rate, total pressure ratio, and efficiency were decreased in 17.9%, 22.8%, and 7.2%, respectively, compared with fixed angle condition. Urasek et al. [8] conducted the performance test of a single stage transonic axial compressor with IGV and SV for stall free operation. Urasek et al. [8] reported that at part speed conditions, the stall points moved to lower flows and correspondingly lower pressure ratio when the guide vanes were closed from their design angles. Steinke [9] performed scheduling of VGVs angle to maximize the efficiency of a three-stage axial compressor on- and off-design condition, a peak efficiency of 0.86 was obtained at design speed near design flow. At part speeds peak efficiency were 0.87 to 0.89 with reset VGVs. Haglind [10] studied the possibility of reducing the formation of contrails by using VGVs for the fan of a high bypass turbofan engine. The author showed that the threshold formation temperature of contrails was reduced by about 1.5 K in the troposphere by employing VGVs for the fan of the engine, corresponding to an altitude of about 300 m. Gallar et al. [11,12] reported the integrated genetic algorithm optimizer within a meanline compressor performance prediction code to maximize the compressor efficiency while keeping an adequate user-defined value of the surge margin. The study assumed that the operating line on the compressor is considered unaffected by the angle of VGVs. The scheduling results for an eight-stage axial compressor in a modern high bypass ratio engine were compared with experimental data from the compressor rig. The result shows that when the schedule of VGVs was applied to the compressor, the efficiencies at highest and lowest total pressure ratio condition were increased in 0.77% and 6.48%, respectively. Abdollah et al. [13] developed an automated optimization tool for scheduling of VGVs in a multi-stage compressor. By using the tool, a ten-stage axial compressor was optimized to maximize its total pressure ratio in off-design conditions. The operating point of a speed line was calculated by surge margin equation with 20% margin. The authors reported that the operating mass flow rate and total pressure ratio were increased in 5.48% and 3.72%, respectively when the compressor used schedule of VGVs. Barbosa et al. [14] carried out the transient study on a small gas turbine performance for different variable IGV angles of a five-stage transonic axial compressor. The authors indicated that simulations needed to study the control strategy. Sun and Elder [15] presented a numerical methodology for optimizing VGVs angle setting in a seven-stage axial compressor to improve the compressor performance at a specific inlet mass flow rate on each speed line. The investigators reported that varying the stagger of the front stages provides a powerful technique to rematch the stages in order to obtain a high overall performance with a wider surge-free flow range. Most authors assumed the operating line of a compressor in process of scheduling of VGVs. However, it has been demonstrated that the steady-state operating line and stall line are changed by adjusting the angle of a guide vane [7]. The operating line on a compressor is calculated by performance a full engine cycle analysis. Therefore, the engine performance analysis with VGVs is needed to consider the realistic condition for scheduling of VGVs.

Therefore, a full engine cycle analysis is conducted to consider the effect of VGVs on a turbofan engine. This study derives the schedule of VGVs of the three-stage axial compressor in the low-bypass ratio turbofan engine by using the full engine cycle analysis. 1D meanline analysis is used to predict the performance of the compressor with VGVs. 1D meanline analysis results are compared with performance test for verification and validation. The commercial engine simulation program, NPSS^{TM} is employed for performance analysis at on and off-design condition. The performance map of the compressor with VGVs is applied to the engine simulation program to predict its impact. The operating line on the performance map of the compressor is calculated by conducting the off-design engine simulation. A scheduling algorithm of the VGVs is suggested to improve both the surge margin and engine SFC at off-design condition. The algorithm takes into account the operating line and the surge margin on the compressor. The engine performance and surge margin with scheduled VGVs are compared with the case of IGV angle only and without VGVs.

2. Engine model

The engine, on which the full engine cycle analysis is tested and presented, is a low bypass ratio mixed flow turbofan engine for military flight application. The engine configuration and design parameters, such as engine SFC, bypass ratio, and specific thrust, are refer to the Honeywell/ITEC F124 engine [16]. A schematic picture of the turbofan engine is shown in Fig. 1. The compression system of the engine consists of a three-stage fan, a three-stage axial compressor and a single stage centrifugal compressor. The fan is divided in to two parts, namely inner fan and outer fan, because the fan pressure ratio and isentropic efficiency is change according to the radial direction [17,18]. For modeling purpose, the high pressure compressor (HPC) is split into two compressors, axial part and radial part of HPC. The air at the exit of the radial part of HPC is drawn to cool the high-pressure turbine (HPT) nozzle and rotor. And the air bleed from the exit of the axial part of HPC is