Energy 119 (2017) 199–210

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Combining effect of optimized axial compressor variable guide vanes and bleed air on the thermodynamic performance of aircraft engine system

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ARTICLE INFO

Article history:
Received 25 August 2016
Received in revised form
9 December 2016
Accepted 19 December 2016

Keywords:
Variable guide vanes
Bleed air
Surge margin
Axial compressor
Turbofan engine
Optimization

ABSTRACT

Aim of this work is to provide evidence of the effectiveness of combined use of the variable guide vanes (VGVs) and bleed air on the thermodynamic performance of aircraft engine system. This paper performed the comparative study to evaluate the overall thermal performance of an aircraft engine with optimized VGVs and bleed air, separately or simultaneously. The low-bypass ratio turbofan engine has been modeled with a 0D/1D modeling approach. The genetic algorithm is employed to find the optimum schedule of VGVs and bleed air. There are four types of design variables: (1) the inlet guide vane (IGV) angle, (2) the IGV and 1st stator vane (SV) angles, (3) bleed air mass flow rate at the exit of the axial compressor, and (4) both type 2 and type 3. The optimization is conducted with surge margin constraints of more than 10% and 15% in the axial compressor. The results show that the additional use of the bleed air increases the efficiency of the compressors. Overall, the percentage reductions of the total fuel consumption for the engine with the IGV, 1st SV and bleed air schedule is 1.63% for 15% surge margin constraints when compared with the engine with the IGV schedule.

1. Introduction

A sudden decrease of rotating speed causes an increase in the relative flow angle at a rotor leading edge. Because the axial velocity generally falls off more rapidly than the rotating speed [1]. Stall and surge occur when the flow angle of attack at the leading edge of blades reaches a value such that boundary layer separation occurs [2]. The stall and surge can start from one blade and propagates around the annulus, causing a high-frequency noise and vibration [2]. There are a number of methods available to the designer to handle this unstable operation in part speed compressor behavior, usually known as multi-spool compressor, bleed air, and variable guide vanes (VGVs). Bleeds achieve an increased mass flow through the front stages of the compressor. As a result, the relative flow angle at rotor leading edge is decreased because of an increase in axial velocity. On the other hand, VGVs redirect the air towards the rotors so that the incidence angles of the rotors have an acceptable range away from the stalling incidence.

Since the mid 1900's various reports have been published the study on the effectiveness of variable guide vanes and bleed air. Constant [3] and Hagen [4] presented general discussions of the problem about stage matching and the effects on stage performance at off-design condition. Hagen [4] demonstrates the compromise which must be made to obtain good engine starting characteristics as well as good design point operation. Finger and Dugan [5] performed analytical study on a stage-matching technique to determine the magnitudes of shift of stage operating points with speed of a single-spool high pressure ratio compressor. This analysis also considered various design point compromises aimed at improved low speed performance of high pressure ratio axial compressor. The results show that if the identity of the single-stage performance were preserved in a multi-stage compressor, there would be no sharp changes in the slop of the surge line with increasing speed. Moreover their study indicated that large improvements in low speed efficiency with some sacrifice in high speed efficiency could be obtained when optimum stage matching was set for speeds below design. Study by Medeiros et al. [6] and Budinger and Serovy [7] shows that the part speed performance of inlet stage can be improved without compromising design speed performance by using variable inlet guide vanes or interstage bleed.

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http://dx.doi.org/10.1016/j.energy.2016.12.076
0360-5442/

Gallar et al. [1] explored the suitability of stochastic approaches to derive the most flow efficient schedule of an axial compressor for a minimum variable user defined value of the surge margin. In this study, the working line position on the compressor map was regarded as unaffected by any re-stagger of the blade rows [1]. Barbosa et al. [8] carried out the transient study for a number of blade settings, using different VGVs scheduling, giving indication that simulations needed to study the control strategy can be easily achieved. Shadaram et al. [9] developed an automated optimization tool for angel of variable stators in multistage compressors and optimized ten-stage axial compressor to maximize its total pressure ratio of operating point in off-design conditions. Sun and Elder [10] presented a numerical methodology for optimizing VGVs angle setting in a multi-stage axial compressor. They used one-dimensional (1D) meanline method and a sequential weight increasing factor technique in optimization process. Reiss [11] conducted the optimization of VGVs to improve the efficiency of a compressor, and investigated the influence of a bleed air on the efficiency. The result showed that the maximum 5.5% improvement of the efficiency at 70% corrected speed. Moreover, the author confirmed that the efficiency can be improved when the bleed air was used in the compressor. Reitenbach et al. [12] presented explains a methodology to optimize VGVs settings of a high pressure compressor. It targets to provide the best solution for the entire engine system in discrete operating points with the use of the preliminary engine design environment and the throughflow tool. The authors conducted the Pareto analysis for SFC and surge margin at cruise condition. The results show that the surge margin can be drastically improved with a modified variable guide vanes setting, whereas the SFC penalty can be simultaneous kept within acceptable limits. Hatami et al. [13] employed the central composite design (CCD) based on design of experiment (DOE) to find optimum design of the vane geometry used for a variable geometry turbine. The results showed that the CCD method was suitable for finding optimum geometry for a variable geometry turbine based on experimental approach. Most authors performed the scheduling for VGVs and bleed air in the component perspective or investigated separately. However, knowledge of the effect of combination of the VGVs and bleed air in the system perspective is still inadequate.

In the present study, the combining effect of the VGVs and bleed air was investigated on the thermodynamic performance of aircraft engine system. The optimization method was applied to the scheduling of VGVs setting angle and bleed air flow rate in a three-stage axial compressor of a low-bypass ratio turbofan engine to improve the performance of the engine and to meet the required surge margin of the compressor. The commercial cycle analysis program, NPSS™ was used to simulate the engine performance at on- and off-design condition. The performance maps of the compressor with VGVs was generated by using 1D meanline analysis and fed to the engine performance simulation program. The multi-island genetic algorithm (MIGA) was utilized to find the optimum schedule. There are four types of design variables: (1) the IGV of the axial compressor, (2) the IGV and 1st SV angles, (3) bleed air mass flow rate at the exit of the axial compressor, and (4) both type 2 and type 3. The objective function was specific fuel consumption (SFC) of the engine. The optimization was conducted with surge margin constraints of over 10%, and 15%. And the optimized schedule applied to the engine simulation for typical flight mission profile. And the performance results of the engines with optimized schedules were compared with each other quantitatively.

2. System modeling

The low bypass ratio mixed flow turbofan engine was modeled with 0D/1D modeling approach to simulate an aircraft engine system. The engine configuration and design parameters, such as engine SFC, bypass ratio, and specific thrust, were referred to the Honeywell/ITEC F124 engine [14]. Fig. 1 shows the schematics of the engine. The engine consist of a three-stage fan, a three-stage axial compressor with variable IGV and 1st SV, a single-stage radial compressor, an annular combustion chamber, a single-stage high-pressure turbine (HPT), and a single-stage low-pressure turbine (LPT). For modeling purpose, the HPC was split into two, namely an axial part and a radial part of HPCs. Table 1 shows the design parameters of the engine. The engine model and validation were described in detail in our previous study [15].

In this study, NPSS™ was used to predict the performance of an aircraft engine. For validation, simulation results using NPSS™ were compared with the actual engine data [18]. The Pratt and Whitney F100-PW229 turbofan engine was selected as the engine for comparison. This engine is a low-bypass ratio two spool turbofan engine. The engine consists of a three-stage fan, an 11-stage high-pressure compressor, an annular combustor chamber, a two-stage HPT, and a two-stage LPT. The component design performances were based on the study of Lee et al. [19]. For modeling of the performance of the components at off-design conditions, the performance maps of fan and HPC from Lee et al.

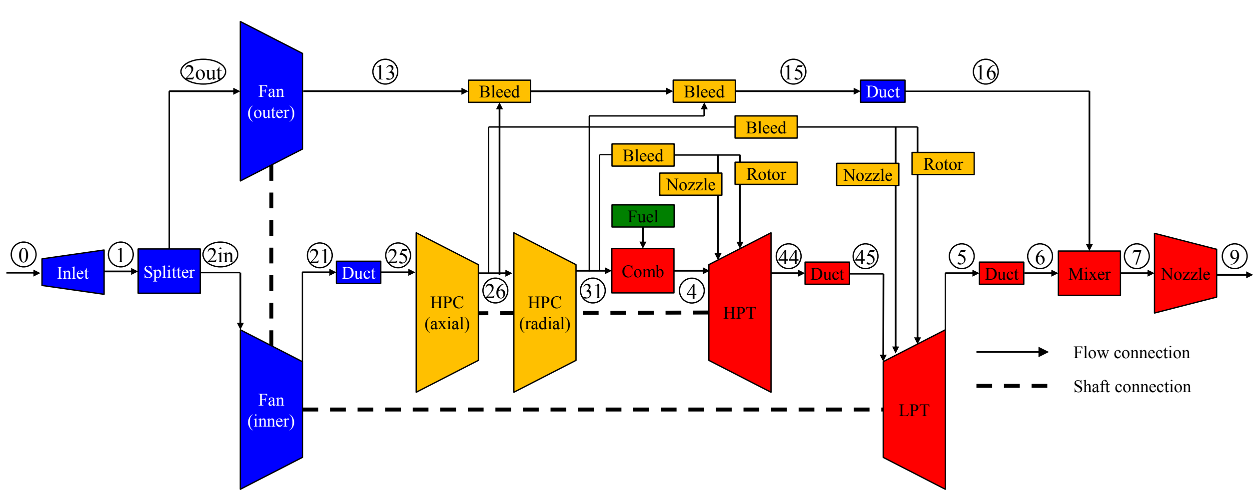

Fig. 1. Block diagram of the engine [15].