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New 1-D Method for the Prediction of Axial-Flow Compressors Off-Design Performance

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Abstract

The development of advanced turbomachinery relies heavily on the use of 3-D CFD methods. Fast and efficient 1-D and 2-D methods are used at early design stages in order to explore the design space of a new configuration. A new method has been developed to predict performance characteristics of axial-flow compressors in the following conditions: stable off-design; part-span and full-span rotating stall; reverse flow. The new method is based on the classical empirical 1-D method proposed by L.E. Olshteyn. An empirical model for a stall/unstall hysteresis loop has been developed. The developed method has been implemented in COMPRESSOR_S simulation software. The results for three stage axial compressor have been produced and compared against the experimental data published by Gamache.

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Keywords: axial compressor; off-design; stall; reverse flow

1. Introduction

Gas turbine engines that power both civil and military aircraft are common machines in which axial-flow compressors are found. One of the ongoing trends in aircraft engine design is the substantial reduction of production time and costs. The design process of a modern axial compressor is very complex process, which is divided into many stages and to a large extent is performed using computer simulations. It starts with fairly primitive 1-D and 2-D methods, and ends with sophisticated 3-D simulations with use Computational Fluid Dynamics (CFD). Therefore, design process is heavily dependent on fast and accurate computer programs that can exploit a large design space in

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the shortest time possible. Although, 3-D CFD methods are very efficient, they can only be used on final stages of the design process as it takes a plenty of a computational time for a solution to converge and there is the strong need for a large amount of initial data. Fast and efficient 1-D and 2-D methods at early design stages are used in order to explore the design space of a new configuration. The purpose of the approach being used for performance analysis is modeling of axial-flow compressor based on empirical correlations and classical thermodynamic and aerodynamic laws and the minimization of compressor modelling in CFD software. Finding better correlations and methods on how one can model a compressor will result in less time for fine tuning in advanced CFD programs and a hence time and cost saving.

A performance prediction of axial compressors can be done by a variety of analytical and empirical methods. One of the most popular is the stage-stacking method introduced by A. R. Howell et al. in 1978 [1] and revealed by Jack et al. [2]. Another wide-spread method is a streamline curvature (SLC) throughflow method. It is mainly used at the preliminary design stage for specifying the target aerodynamic performances to be achieved by the blading and gives a first insight of the global component functioning [3]. For over 30 years SLC was a dominant numerical approach and the most important tool for the axial compressor design [4]. Both methods are rather effective, but their effectiveness is limited by empirical models being used in calculation procedures (reference and off-design flow angles, loss models). The development of accurate off-design empirical models is a big problem and new models are being developed to date.

The aim of this work is to develop an integrated axial compressor one-dimensional model being capable of: off-design performance prediction in stable range of operation; stall performance prediction; reverse-flow performance prediction. The will be useful for aero engines stall and surge analysis.

2. Compressor-off design prediction method

An original method for axial flow compressor off-design performance prediction based on compressor stage generalized functions was developed in the P.I. Baranov Central Institute for Aviation Motors (Russia) under scientific supervision of L. E. Ol'shtein. This is a simple meanline method, there is no need for 2-D analysis and spanwise integration of airflow parameters [5-7]. Generalized functions are obtained from a statistical analysis of significant amount of individual compressor stage performance maps.

The method requires a nominal (reference) on a speed line being analyzed. The nominal point for the preferred speed line in Ol'shteyn's method is considered as maximal isentropic efficiency point and is determined by an empirical model. Assume that the angles $\alpha_1 = \alpha_{10}$ (rotor row inlet absolute flow angle) and $\beta_2 = \beta_{20}$ (rotor row outlet relative flow angle) are constant both for the nominal design point and the off-design points (in a wide range of incidence angles up to surge line) [5, 6]. In accordance with the elementary stage velocity diagram the stage loading coefficient for the nominal point and for off-design conditions can be written as

$$\bar{H}_{th0} = 1 - \bar{c}_{a0}\left(ctg\alpha_1 + ctg\beta_2\right),\ \ \bar{H}_{th} = 1 - \bar{c}_a\left(ctg\alpha_1 + ctg\beta_2\right). \tag{1}$$

where $\bar{c}_a$ - is a flow coefficient. The nominal point is indexed 0, off-design point is without an index. The relationship between stage loading, isentropic stage loading, and isentropic efficiency for the design and off-design points can be described by the following equation:

$$\frac{\bar{H}_{th}}{\bar{H}_{th0}} \cong \frac{\bar{H}\eta_0}{\bar{H}_0\eta}. \tag{2}$$

Using equations (1) – (2) two dimensionless groups are obtained:

$$K_1 = \frac{\bar{H}}{\eta} - \frac{\bar{c}_a}{\bar{c}_{a0}}\frac{\bar{H}_0}{\eta_0},\ \ K_2 = \bar{H} - \bar{H}_0\frac{\bar{c}_a}{\bar{c}_{a0}}. \tag{3}$$