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Experimental investigation of a high aspect ratio, low speed contra-rotating fan stage with complex inflow distortion

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Abstract This paper focuses on the response of a high aspect ratio, low speed contra-rotating fan with complex inflow distortion. The total pressure at the inlet is artificially distorted by means of two different sets of screens with different porosities to generate a hub-strong complex distortion and a tip-strong complex distortion. Detailed flow analyses were conducted for the design speed of rotor-1 in combination with off design speeds of rotor-2 both for the design and the peak pressure mass flow rates. In order to understand the extent of inlet distortion, the distortion sector was rotated circumferentially at intervals of 15° to cover the entire annulus. Detailed measurements of total pressure, static pressure, velocity components and flow angles were carried out at the inlet of the first rotor, between the two rotors and at the exit of the second rotor using three seven hole probes. The study reveals a few interesting aspects on the effect of complex inflow distortion on the flow behavior of a contra-rotating stage. The presence of a low porosity screen reduces the magnitude of axial velocity and generates higher spread of distortion near the localized region of placement of the screen. The hub-strong complex distortion has a greater effect of presence of this low porosity screen in both circumferential and radial directions. This leads to higher stagnation pressure variation at the inlet. On the other hand, for the tip-strong complex distortion case, the extent of distortion is observed to be higher in the circumferential direction towards the casing rather than radial. The localized improvement in the flow (in tip-strong inflow distortion) near the tip region

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improves the performance both in terms of pressure rise and efficiency of stage compared to hub–strong complex distortion.

1. Introduction

Turbo machines like compressors, turbines and fans are significant components of gas turbine engines. A wider operating margin and high efficiency are important consideration during the design of compressors and fans. At the initial design and development stage, uniform inlet flow assumption has been widely been accepted and used. However, this assumption has seldom been matched by actual operating conditions because of machine inlet configurations or inlet boundary layer, atmospheric turbulence etc. These inflow non-uniformities or distortions can lead to substantial degradation in the engine performance. Distortion is characterized by distributions in the flow parameters of velocity, pressure, temperature, flow angle, which are different from the design intent. The variations of these parameters may have a primary bias in the radial direction, the circumferential direction, or a combination of both the directions. Aero engine compressors exhibit two types of fluid dynamic instabilities, surge or rotating stall. Occurrence of either of these marks the stability boundary beyond which the engine cannot be operated safely. The compressor/fan response to inflow distortions could be different depending upon the nature of the non-uniformities.

The compressor/fan response to inflow distortions could be different depending upon the nature of the non-uniformities. Radial inflow distortion attributes the relative flow field to be axisymmetric and steady. Circumferential inflow distortion poses an additional complication in the flow behavior as the flow relative to a moving blade row is time-dependent or unsteady.

Contra-rotation (rotation of two rotors in opposite directions) in either ducted or un-ducted mode is a serious contender for compact, high performance compressors and turbines. Contra-rotation can enable compact sizes without the need for stators or even higher rotational speeds of the rotor. This concept has been explored by numerous researchers for the past 40 years [1]. There are several interesting, yet not well understood flow features associated with the flow through such turbomachines and is therefore one of the motivations for the present study. Since inlet distortion is an unavoidable phenomenon, its effect on the design of contra-rotating compressors cannot be disregarded. The effect of inflow distortion on a contra-rotating compressor is likely to be more drastic as compared with a conventional compressor/fan. In a conventional rotor-stator arrangement, the presence of the stator downstream of the rotor is likely to reduce the effect of inflow distortion from propagating further.

The effect of inflow distortion on multistage compressors has been extensively investigated since 1950 s both theoretically and experimentally. These studies were continued by several engine designers resulted in improved performance in terms of the operating range and the stability margin. The proven advantage of contra-rotating fans in terms of higher work per length besides an enhanced operating range resulted in several researchers to take up detailed study of the contra-rotating fan stage under distorted inflow conditions (Katz [2]).

A basic understanding of the circumferential variation of inlet flow was given by Pearson and Mckenzie [3] using the "parallel compressor model", which allows description of the compressor behavior in the distorted flow. The general trends of compressor performance with different inlet distortions are illustrated in a series of experiments undertaken by Reid [4]. Distortion index has been found successful in correlating inlet distortion with the compressor performance. The loss in the surge margin has been found to be approximately proportional to the distortion index. One of the simplest ways of defining surge margin has been defined by Cumpsty et al. [5]. The effect of inlet flow distortion on compressors can be broken down into two major areas: 1) the attenuation of the distortion pattern as it passes through the compressor; 2) the resulting change in the compressor performance. Stenning [6] carried out an analysis of a compressor model to predict the effect of circumferential distortion greater than 60° and explained its limitation by negligence of the unsteady effects in the simple parallel compressor model. An analytical and experimental investigation of asymmetric annulus swirling flows in turbomachine annuli was reported by Greitzer et al. [7]. It was mentioned that in a swirling flow, the different types of flow disturbances (pressure and vorticity) are strongly coupled. The magnitude of the flow angle and the static pressure distortion increases with increasing mean swirl angle and/or decreasing hub-tip ratio. Gunn et al. [8] have conducted experiments on a low speed, low aspect ratio axial fan stage operating under 60° sector inlet total pressure distortion to understand fluid mechanics governing the upstream distortion interaction and distortion transfer through the stage. A substantial flow separation near the tip region in the rotor and near the hub region of stator under the influence of distortion was observed. This resulted in significant reduction in the performance of the stage.

There are a few published literatures on the effects of radially distorted inflow on the performance of a single stage axial flow fan. Sandercock and Sanger [9], in their studies on a transonic compressor, reported a decrease in