JOURNAL OF PROPULSION AND POWER
Vol. 25, No. 3, May–June 2009

Flow Characteristics of Tip Injection on Compressor Rotating Spike via Time-Accurate Simulation

Jen-Ping Chen* and Benjamin Johnson†
The Ohio State University, Columbus, Ohio 43021
Michael D. Hathaway‡
U.S. Army Research Laboratory, Cleveland, Ohio 44135
and
Robert S. Webster§
University of Tennessee, Chattanooga, Tennessee 37403

DOI: 10.2514/1.41428

The performance of gas turbine engines is often limited by compressor stall. Steady tip-injection stall control technologies have demonstrated their effectiveness to increase the stable operating range of gas turbine engine compressors. To help understand the fluid mechanic processes of stall with and without stall control and how stall is mitigated by stall control technology, the establishment of a capability to simulate the flow details leading to stall would be extremely helpful. This paper presents results of the simulations of a high-speed single-stage axial compressor. These simulations show the evolution of rotating spikes and range extension as a result of tip injection. The simulations are time-accurate simulations of the three-dimensional Navier–Stokes equations encompassing the full-annulus grid and are executed using high-performance parallel computing. Computed compressor characteristics are compared to experimental data. The general flow features of the compressor with and without tip injection at the onset of stall are presented using time-accurate pressure traces and visualized using a novel disturbance cell concept.

I. Introduction

ROTATING stall control technologies have been demonstrated to extend the stable operating range of axial compressors [1–6]. Upstream of a compressor rotor, high total pressure (relative to the rotor) air is injected at discrete locations through the casing into the rotor tip region. This injected air alters the three-dimensional flowfield above the rotor tip causing the clearance flow to move aft in the rotor passage locally increasing the streamwise momentum (relative to the rotor). This increase in the streamwise momentum is responsible for delaying the onset of rotating stall. Injection not only improves stability margin but also reduces tip losses as the injected jet reduces the blade incidence and therefore partially unloads the rotor tip.

These stability enhancement technologies have been developed through parametric experimental studies. Their effectiveness is based on altering the unsteady flowfield near the compressor blade tips. However, there is a lack of fundamental understanding of the fluid mechanic processes of stall onset and how these stall control technologies mitigate the onset of rotating stall to achieve increased compressor stability. Improved understanding of the stall onset process, with and without tip injection, will guide further development of stall control devices and of compressor blading with increased tolerance to stall, which could lead to an expanded operational envelope of gas turbine engines.

Received 16 October 2008; revision received 8 November 2008; accepted for publication 13 November 2008.

*Associate Professor, Aerospace Engineering, 319B Bolz Hall, 2036 Neil Avenue. Member AIAA.

†Graduate Research Assistant, Aerospace Engineering, 319B Bolz Hall, 2036 Neil Avenue.

‡Aerospace Engineer, Vehicle Technology Directorate, 21000 Brookpark Road, Mail Stop 5-10. Member AIAA.

§Associate Research Professor, UTC SimCenter, 701 East Martin Luther King Boulevard. Member AIAA.

Most of the research on rotating stall has been experimental focusing on understanding its onset. The events leading to rotating stall have been traditionally classified according to two different types of wave disturbances rotating around the annulus: long-length (modal) and short-length (spike) waves [7]. Modal disturbance is associated with the characteristic frequencies of the compression system; the axial length of the disturbance can extend over the entire length of the compressor. Modal disturbances are essentially a two-dimensional phenomenon and they are not an early form of stall cell but instead represent harmonic oscillations of the flowfield. The second form of stall inception is the spike. These are disturbances in which length scale is on the order of a blade passage breadth. Flow instabilities within blade passages initiate the spike disturbances. Spikes can be viewed as embryonic stall cells with flow breakdown in local regions [7]. Spikes are inherently three dimensional whose development depends on the flow structure within the blade passage.

In addition to traditional experimental approaches to understand the development of rotating stall, numerical simulations have been shown to provide another means to shed light on this complicated fluid process. Because of the complex flow structure of the rotating stall, which is characterized by the unsteady, 3-D separated flows, detailed measurement of the flow is difficult if not impossible because of problems with placement and limitation of the measuring devices. Numerical simulation, on the other hand, can provide a higher degree of flow resolution, thus providing deeper insight into the complex flowfield at the onset of stall.

During the last 10 years, steady-flow computational simulations have provided an increasingly accurate prediction of the flow up to the point of compressor stall. Attempts to study stall through unsteady simulations of a subset of the blades in a compressor blade row [8–10] or through reduced-order unsteady flow models [11] have resulted in valuable findings of the flow structure leading to stall. Numerical studies of air injection on compressors were also done with single passage models [1,12,13]. However, because the temporal flowfield variations that occur during stall inception are not necessarily harmonics of blade passing frequency, the unsteady flow in every blade passage within a blade row must be simulated in order to study the transition from a stable flow state to the unstable state at the onset of stall. This is necessary to resolve flow features of the