JOURNAL OF PROPULSION AND POWER
Vol. 9, No. 4, July–Aug. 1993

Blade Row Interaction Effects on Compressor Measurements

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The influence of a downstream stator row on the measurement of compressor rotor performance has been examined using a two-dimensional computational fluid dynamic (CFD) code backed by laser anemometry data on a transonic fan stage. The upstream potential influence of the stator causes unsteady circulation about the rotor blades which is a function of the rotor circumferential position. This, in turn, results in a nonuniform circumferential pattern of time-averaged temperature and pressure in the stationary frame. A relatively fast calculational procedure using a linearized, potential flow approach coupled with an analytical theory relating the temperature and pressure variations to the circulation perturbation is developed and shown to give good agreement with the numerical calculations. The results of a parametric study show that the magnitude of this effect is a strong function of rotor-stator blade row spacing and relative blade counts. The effects range from negligible for large spacings typical of high bypass ratio fans, to several percent of the stage pressure and temperature rise for closely spaced blade rows typical of high compressors. Because the temperature and pressure perturbations are in spatial phase, the net effect on measured rotor efficiency is negligible so long as the pressure and temperature measurements are made in the same location relative to the stators. If they are not, errors of ±1.5% can result. The effects of axial position and stator loading are shown to be relatively small.

Introduction

AERODYNAMIC performance measurements are the most basic of turbomachinery tools required for research, design verification, and development. By performance, we refer to measurements of average temperature and pressure made of the machine inflow and outflow, as well as between the blade rows, used to deduce the turbomachine work and efficiency. It has long been recognized that the interpretation of these measurements is far from straightforward.

Because these turbomachine flowfields are spatially nonuniform and highly unsteady, questions concerned with averaging have received considerable attention. These concerns have started at the probe inlet (how do conventional pitot type probes behave in unsteady flowfields[1-3]) and continue through to measurement interpretation (which averaging technique—time, mass, stream thrust, etc.—most closely represents the thermodynamic quantities of interest[4]). Here, we are concerned with questions of spatial uniformity and spatial averaging.

The best agreements between aerodynamic and shaft torque-based efficiency measurements are generally found when the aerodynamic measurements are made far downstream of the turbomachine in a region of uniform flow. In this case, the fluid mechanics of mixing have homogenized the flow, effectively spatially averaging the temperature and pressure (and incurring a mixing loss in the process, of course). Often, such preferred probe placement is not possible. The probes may be embedded within the blade rows and often, to reduce blockage, within the stators themselves. This is especially true in cases in which the rotor performance is required, in multistage machines when individual stage behavior must be measured, and in small machines in which instrumentation placement is extremely constrained by blockage and access problems.

Any stationary intraturbomachine instrumentation placement is dependent on the presumption that the flow is uniform in the pitchwise direction to the degree that it is adequately sampled by relatively few rakes mounted about the circumference. For stator leading-edge-mounted probes in compressors, e.g., the flow is presumed to be completely azimuthally uniform since only one pitchwise position relative to the stators (e.g., the stator leading edge) is sampled. We know that the flow is not uniform in the case of multistage machines in which upstream stators clearly introduce azimuthal variation. Circumferential traversing of probes and rakes solves this problem but is often not done (especially in compressors) due to access, blockage, or cost considerations. The goal of the work described herein was to examine the importance of probe placement to the measurement of aerodynamic performance in high-speed compressors, and then generate guidelines for probe placement and/or data "correction."

The methodology adopted was to employ a multiblade row, unsteady two-dimensional computational fluid mechanics (CFD) calculation as the basic tool, and compare measurements at various locations as calculated by the code with the true mass-averaged performance of the compressor. The basic fidelity of the calculation was assessed by comparison of the CFD results with laser anemometer measurements where available. A linearized potential theory approach was also developed, which is fast and inexpensive enough for routine use in experiment design and data reduction. The following sections describe the calculational procedure, the compressor examined, the code verification, the calculated spatial variation of aerodynamic performance, a discussion of fluid mechanic mechanisms generating the variations, and the implications and recommendations for the accuracy of performance measurements.

Received July 12, 1991; revision received Jan. 5, 1993; accepted for publication Feb. 15, 1993.

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