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Development of an Experimental Data Base to Validate Compressor-Face Boundary Conditions Used in Unsteady Inlet Flow Computations

Dr. Miklos Sajben
Dr. Donald D. Freund

Department of Aerospace Engineering and Engineering Mechanics
University of Cincinnati

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Preface

This report summarizes an experimental research program performed by the Department of the Aerospace Engineering and Engineering Mechanics (AsE/EM) of the University of Cincinnati (UC). The experimental activity was carried out in the Fluid Mechanics and Propulsion Laboratory of AsE/EM, located on the main campus of UC, in Cincinnati, OH.

The program originally started by internal university funding in 1995 and was completed under the present grant from NASA Lewis Research Center (Number NAG3-2003). The period of performance of the NASA grant was January 1, 1997 to December 31, 1997. The grant amount was $ 69,888.00.

The principal investigator was Dr. Miklos Sajben, Professor. The research constituted the Ph.D. dissertation topic of Dr. Donald D. Freund, who did most of the laboratory work. Dr. Freund received his Ph.D. degree in November, 1997. The NASA Technical Officer was Mr. Gary L. Cole.

Introduction

The ability to predict the dynamics of integrated inlet/compressor systems is an important part of designing high-speed propulsion systems. The boundaries of the performance envelope are often defined by undesirable transient phenomena in the inlet (unstart, buzz, etc.) in response to disturbances originated either in the engine or in the atmosphere. Stability margins used to compensate for the inability to accurately predict such processes lead to weight and performance penalties, which translate into a reduction in vehicle range. The prediction of transients in an inlet/compressor system requires either the coupling of two complex, unsteady codes (one for the inlet and one for the engine) or else a reliable characterization of the inlet/compressor interface, by specifying a boundary condition. In the context of engineering development programs, only the second option is viable economically.

Computations of unsteady inlet flows invariably rely on simple compressor-face boundary conditions (CFBC's). Currently customary conditions include choked flow, constant static pressure, constant axial velocity, constant Mach number or constant mass flow per unit area. These conditions are straightforward extensions of practices that are valid for and work well with steady inlet flows. Unfortunately, it is not at all likely that any flow property would stay constant during a complex system transient.

At the start of this effort, no experimental observation existed that could be used to formulate of verify any of the CFBC's. This lack of hard information represented a risk for a development program that has been recognized to be unacceptably large. The goal of the present effort was to generate such data.

Disturbances reaching the compressor face in flight may have complex spatial structures and temporal histories. Small amplitude disturbances may be decomposed into acoustic, vorticity and entropy contributions, that are uncoupled if the undisturbed flow is uniform. This study is focused on the response of an inlet/compressor system to acoustic disturbances.

From the viewpoint of inlet computations, acoustic disturbances are clearly the most important, since they are the only ones capable of moving upstream. Convective and entropy disturbances may also produce upstream-moving acoustic waves, but such processes are outside the scope of the present study.

Concept of the Experiment

The reflection of solitary, planar, short-duration acoustic pulses from the compressor face has been selected as the most appropriate process to provide useful validation data. The advantage of using pulses (rather than periodic perturbations, as done by some investigators in the past) is that the investigated processes are confined to the immediate vicinity of the compressor face and are independent of events occurring elsewhere in the system. Furthermore, the reflection coefficients determined in the study fully define the acoustic impedance of the compressor face, a quantity that provides a well established characterization of acoustic behavior. Similar techniques ("impulse methods") have been widely used in acoustic technology to find the response characteristics of many types of duct terminations, including nozzles, orifice plates and mufflers.

The pulse has to satisfy several stringent requirements to be applicable for this study. It has to be short in duration, to ensure that the reflection process is completed before reverberations from other parts of the system could return to the engine face. The amplitude has to be large, in order to distinguish the processes of interest from engine noise (dominated by the first stage blade passing frequency). Finally, the pulse has to be planar and free of higher order modes to permit straightforward interpretation of the results.

All of these requirements were met by a novel pulse generation technique (called the "collapsing bump" technique) developed at UC under this program. The method is based on making a short segment of the hub inflatable. By appropriate means (involving a shock tube built into the hub), the bump is deflated in less than one ms. The motion of the boundary extracts energy from the flow and initiates two expansion waves, one in each direction. The pulse propagating downstream is then used in the experiment. The success of this design was a key factor in making the characterization of the compressor face possible.

Description of Experiment

The experiments were carried out in a facility combining a constant-area inlet with a multistage compressor (Fig. 1). The pulse generator was located near the midpoint of the inlet. Activation of the generator created a pair of expansion waves, one moving upstream and one moving downstream. Since the inlet area is constant, the waves propagate without appreciably changing their structure. Upon reaching the ends of the inlet, reflections are generated which traverse the inlet in opposite directions. The pulses propagating into and away from the compressor face were monitored with the aid of fast pressure transducers.

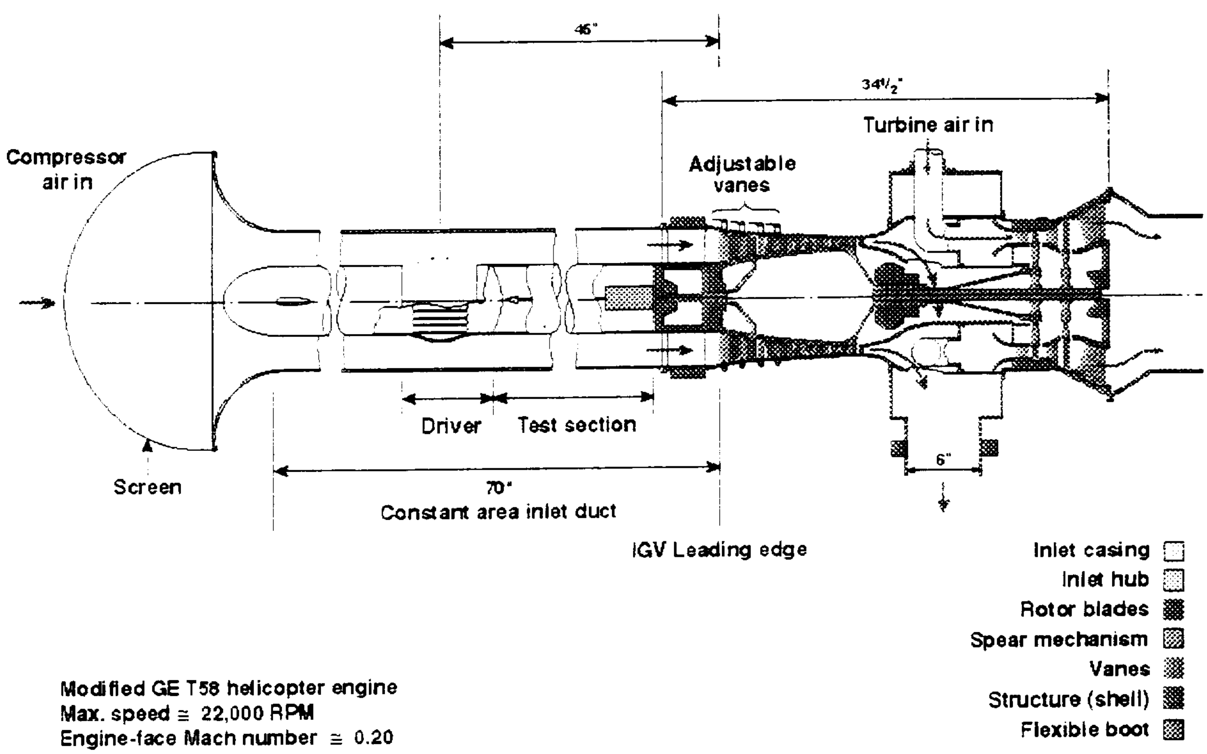

Fig. 1 - Inlet duct and compressor rig. All dimensions in cm.

The pulse duration was typically one ms or less. Pulse amplitudes up to 10% of the mean static pressure could be obtained with the method, but most of the data were obtained with an amplitude near 4%. The reflection amplitudes were found to be linearly proportional to the incoming pulse amplitude, such that the final results are independent of the pulse amplitudes used.

Results

The principal engine related variables were: (1) axial Mach number (equivalent to corrected mass flow for a given engine, varied from 0.10 to 0.18), (2) compressor pressure ratio, varied from 1.28 to 2.04, and (3) the stagger angle of the variable inlet guide vane row, varied from 15 to 32 degrees. In normal operation the stagger angle is set as a function of speed. However, the stagger angle was expected to be an important parameter affecting reflections and mildly off-design settings were also explored.

The results have shown that that

a) *the compressor reflects the incoming pulses in the same sense, i.e. an expansion pulse produces an expansion wave as a reflection,*

b) *the reflection amplitudes are less than half of the incoming amplitude,*

c) *the reflected pulses are substantially longer than the incident pulses.*

These responses are not described by any currently used boundary condition. In particular, the highly popular constant pressure boundary condition leads to entirely different predictions, and is clearly not acceptable for design purposes.

Using frequency domain analysis, these data were used to derive transfer functions that may be thought of as frequency-resolved reflection coefficients. It was demonstrated that the frequency domain methods used to interpret the data also permit the

d) *accurate prediction of reflections produced by the engine in response to incident pulses of arbitrary shape.*

It is believed that this is the first published data set focused on the dynamic characteristics of the inlet/compressor interface, as it affects the inlet. The data are highly appropriate for formulating and validating compressor face boundary conditions.

No inventions were developed during the contract period.

No equipment worth $ 500 or more was purchased under this project.

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Documentation

This research has been documented by several means. The following media have been utilized:

A. Five meeting presentations (and preprints), three of which were published during the period of performance of this grant. The papers are as follows:

Sajben, M., and Freund, D. D. "Experimental Exploration of Compressor-Face Boundary Conditions for Unsteady Flow Computations," AIAA paper 95-2886.

Freund, D. and Sajben, M., "Compressor-Face Boundary Condition Experiment: Generation of Acoustic Pulses in Annular Ducts", AIAA paper 96-2657.

Freund, D. and Sajben, M., "Experimental Investigation of Outflow Boundary Conditions Used in Unsteady Inlet Flow Computations". AIAA paper 97-0610.

Freund, D. and Sajben, M., "Reflection of Large Amplitude Acoustic Pulses from and Axial Compressor," AIAA paper 97-2879.

Sajben, M. and Freund, D., "Unsteady Inlet/Compressor Interaction Experiment to Support the Modeling of Compressor-Face Boundary Conditions," 8^{th} International Symposium on Unsteady Aerodynamics and Aeroelasticity of Turbomachines, Stockholm, Sept. 1997.

B. Freund, D., "Experimental Exploration of Compressor-Face Boundary Conditions for Unsteady Inlet Flow Computations," Ph.D. Dissertation at the University of Cincinnati, November 1997. (This is by far the most detailed account of the work.)

C. Informal communications and transmissions of data files between UC and NASA Lewis representatives.

D. The data files are freely available on UC's anonymous server (**ftp.ase.uc.edu**, directory /**pub/CFBC/acoustic**). A readme.txt file is included to provide information about the content of the files in the directory.

E. An oral presentation of the results and findings was made at NASA Lewis Research Center on October 10, 1997, by Drs. Sajben and Freund.

F. Two journal articles are in preparation.

The public availability of these documents makes it unnecessary to duplicate their contents in this final report.

Acknowledgments

The authors wish to express their thanks to Mr. Gary Cole, the Technical Officer for the grant, for his close attention, interest and encouragement. His parallel efforts based on the LAPIN code were extremely useful in the design of the experiment and in the interpretation of the data. We also wish to thank Dr. Gerald C. Paynter of the Boeing Company for numerous detailed discussions, advice and for providing related theoretical predictions. Mr. Russell G. DiMicco provided invaluable help in the laboratory.