AIAA 80-1080R

Rarefaction Wave Effects Upon Compressor Performance

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Abstract

THE response of a duct-embedded multistage compressor to downstream generated rarefaction waves and their reflections is discussed. Partial differential equations of flow and work in their hyperbolic form representing the compressor-duct system in unsteady flow were solved using the method of characteristics. Agreement between the analyzed results and an associated experiment was found in terms of the measured frequency of the pulse reflections, amplitude of the first few passes of the waves, and the final operating point of the system.

Contents

The Model

The type of event investigated was that of a rarefaction wave generated downstream of a compressor, simulating, for example, the effects of extinguishing the re-heat in an air-gas turbine engine or the sudden opening of a downstream placed valve in a process plant.

Governing equations of continuity of mass, momentum, and energy were solved in their partial differential form by the method of characteristics. Setting the equations in terms of the independent variables, axial distance x and time t and the dependent variables, speed of sound a, convection velocity C_x, and pressure p, resulted in a hyperbolic form of the equations permitting use of this technique. The flow considered was then inviscid, compressible, unsteady, and homentropic.

The solution, being one-dimensional in space, predicted the passage of planar waves in the axial direction and compressor simulation was confined to high hub-tip ratio machines. Work transfer within a compressor was modeled by using an actuator disk approach.[1-3] Since the compressor had three stages, three actuator disks were set, each at an axially midstage location.

Energy input was dictated by the quasi-steady stage characteristic of every stage and solved simultaneously with the governing equations of mass flow continuity and the polytropic relationship.

For the geometry of the test facility and compressor performance used, the predicted pressure history for a -7.0 mbar pulse is indicated in Fig. 1.

The Test Facility

The facility comprised a three-stage high hub-tip ratio compressor of constant annulus height and 3000 rpm design speed, embedded in long constant area inlet and exhaust annular ducts (Fig. 2).

A pulse generator consisting of a pressure vessel whose contours followed the annulus shape was sited in the hub of the compressor exhaust annulus. The upstream face comprised a bursting diaphragm made of latex stretched almost to its elastic limit. Bursting was accomplished by puncturing with a red hot element operated from a remotely controlled solenoid. The generated wave entered the compressor exhaust flow through a circumferential slot in the annulus hub, moving upstream and downstream as two fronts from the slot. To achieve a rarefaction wave without a related subsequent compression wave experimentally and thus to make the final compressor operating point differ from the original, the downstream face of the pressure vessel was removed and the flow through the compressor exit annulus was restricted by a radial plug. Bursting the diaphragm opened a flow path through the pressure vessel to the exhaust resulting in an instantaneous increase in the exhaust flow area. Adjustment of the plug size allowed for different initial and final

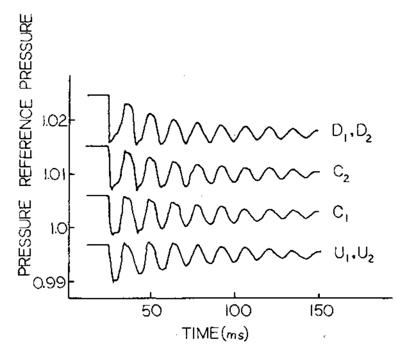

Fig. 1 Predicted pressure history with exit step pulse −7 mbar.

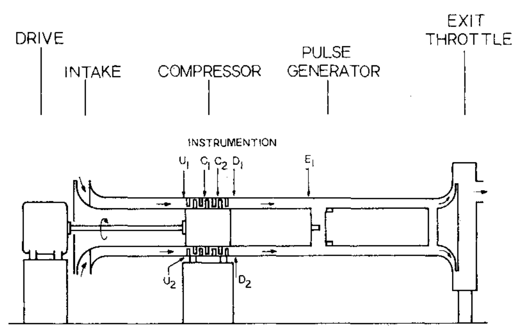

Fig. 2 Layout of compressor facility.

Presented as Paper 80-1080 at the AIAA/SAE/ASME 16th Joint Propulsion Conference, Hartford, Conn., June 30-July 2, 1980; received Aug. 8, 1980; revision received May 12, 1981. Full paper available from AIAA Library, 555 W. 57th St., New York, N.Y. 10019, Price: microfiche, $3.00; hard copy, $7.00. **Remittance must accompany order.**

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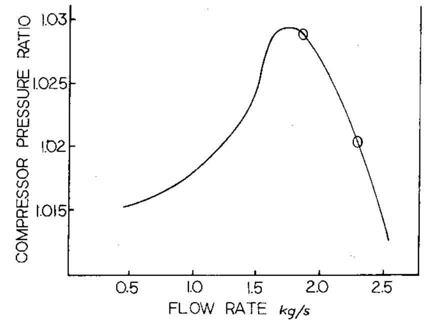

Fig. 3 Compressor operating points across a rarefaction step pulse.

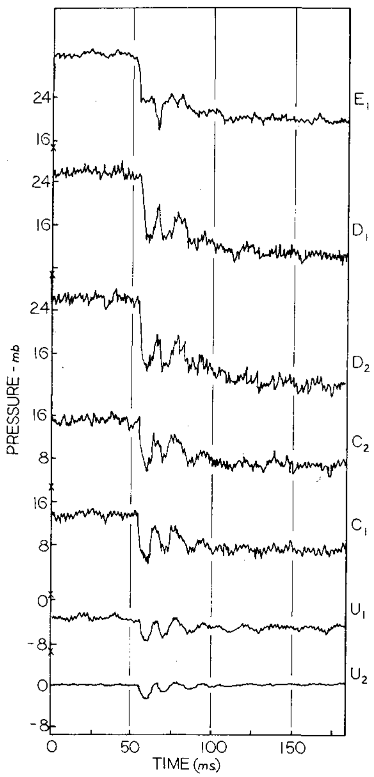

Fig. 4 Measured pressure history with exit step pulse −7 mbar.

operating conditions of the compressor. The resulting passing wave had a ramp time of 1-2 ms.

In addition to steady-state compressor performance instrumentation a series of high response micro-miniature pressure transducers were located as follows: 1) at the compressor inlet in one plane at two locations separated circumferentially by 180 deg (*U*1, *U*2), 2) downstream of the compressor stage 1 (*C*1), 3) downstream of the compressor stage 2 (*C*2), 4) at the compressor exit in one plane at two locations separated circumferentially by 180 deg (*D*1, *D*2), and 5) immediately upstream of the pulse generator slot (*E*1) (Fig. 2).

The Experiment

The compressor operating point was initially set at close to the peak pressure rise condition (Fig. 3). Transducer traces of static pressure taken through the system are indicated in Fig. 4 for the period embracing the pulsed event. In the first 56 ms recorded on this graph stable conditions were evident, small scale ripples being attributed to electrical and aerodynamic noise. From the trace of *E*l it is seen that the diaphragm burst at 56 ms, initiating a sharp drop in static pressure of 7.0 mbar amplitude and 2 ms transition time. This period agrees closely with the time of the bursting sequence recorded by high-speed photography. This rarefaction wave was followed by a second, indicated by the sharp downpeak at 66.2 ms which was a reflection from the plenum chamber of the downstream going compression wave generated with the diaphragm bursting. The initial rarefaction wave was transmitted upstream to plane *D* and then plane *U* with suitable time delays, planarity being shown by *D*1 and *D*2 and then *U*1 and *U*2 changing together and confirmed in cross-correlation of the data, indicating virtually no phase difference. Plane *U* first sensed the pressure wave reflecting from the intake as the upstream boundary and this passed downstream to plane *D* and then plane *E*. Subsequent reflections, rarefaction and then compression, attenuated after two or three more cycles before the final operating point was obtained (Fig. 3).

Comparison with Theory

The pulsed event and subsequent reflections were closely predicted in terms of magnitude and pulsation frequency (Figs. 1, 4). More rapid attenuation of the reflections of the disturbing signal was noticed in practice than predicted by the model which could not account fully for small-scale reflections, viscous interactions, and other nonhomentropic features. Rarefaction waves of short duration but significant magnitude and their reflections could therefore be predicted by the model used and traced in experiment through the system with high response rate instrumentation.

References

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[3] Peacock, R.E. and Eralp, O.C., "Compressor Response to Spatially Repetitive Transients," The ASME Israel Joint Gas Turbine Congress, Haifa, 79-GT-Isr-14, July 1979.