Mathematical Model for the Starting Process of a Transonic Ludwieg Tube Wind Tunnel

F. L. Shope*
ARO, Inc., Arnold Air Force Station, Tenn.

Theme

THE critical need for high Reynolds number transonic (HIRT) wind-tunnel testing has required detailed study of the aerodynamics of many different types of transonic wind tunnels. One prime candidate configuration, the Ludwieg tube, has received extensive research and design-oriented attention at the Arnold Engineering Development Center (AEDC). Since the practical Ludwieg tube, essentially a blowdown tunnel with asymptotically constant stagnation conditions, can provide only a few seconds of steady flow from a facility costing $\$10^8$, a major experimental and theoretical effort was mounted at AEDC to minimize the time needed to reach steady flow. Part of this theoretical effort was the development of a mathematical starting model, the subject of this paper, from the large body of experimental data accumulated from the small pilot HIRT facility at AEDC (Fig. 1). The present model, in contrast to the mathematically more sophisticated finite-difference solution of Warmbrod,[1] consists of the simultaneous solution of 19 familiar closed-form equations with differencing in time only. In addition, the present approach models additional tunnel features such as the porous wall of the transonic test section, the plenum chamber, and associated valving.

Contents

The particular Ludwieg tube wind tunnel studied here is illustrated in Fig. 1 and is discussed in detail by Varner et al.[2] Prior to a run, the tunnel is pumped to the desired charge pressure and temperature. A tunnel run is initiated by first opening the main valves downstream of the diffuser. This opening process sends unsteady expansion waves up the tunnel to the supply tube. Were it not for the plenum, the flow in the test section would become steady soon after the trailing edge of the unsteady wave from the valve, initiated by the valve area becoming steady, passed the test section into the supply tube. The test section flow, however, cannot become steady until the plenum volume has been exhausted to the point where the summation of mass flow across the porous wall, through the flaps, and out the plenum exhaust (dumped to atmosphere) becomes zero and allows the plenum pressure to become steady. Since current, state-of-the-art, fast-opening valves easily reach the required flow area in advance of the plenum becoming steady, the plenum is the primary limitation upon how quickly the tunnel can be started and steady flow established in the test section.

The present model assumes that the unsteady expansion wave emanating from the main valves propagates instantaneously to all parts of the wind tunnel and that property variation within the wave at any location in the diffuser, test section, nozzle, or supply tube is controlled totally by the area-time curve of the main valve. Although partially retaining the effect of the unsteady wave, this assumption allows use of the steady continuity equation in the test section, coupled with the well-known exact solution for one-dimensional, variable-area, isentropic flow. Use of these equations at any instant requires a knowledge of stagnation conditions driving the flow, which vary through the nonisentropic expansion wave. Variation of the stagnation properties is computed via the exact solution for a one-dimensional unsteady wave in a variable-area duct.[3] The unsteadiness of the plenum is handled via the unsteady continuity equation by equating the rate of mass accumulation in the plenum to the summation of all the flow rates entering and leaving the plenum. The air in the plenum is assumed to be a calorically perfect gas, and its temperature is assumed either isentropic or equal to the stagnation temperature of the flow in the test section (whichever is greater), an experimentally based assumption. The main valves are treated as one-dimensional sonic orifices driven by the stagnation pressure and temperature of the unsteady wave. The plenum exhaust valves are handled similarly by assuming that the flow in the plenum is stagnant. Flow through the ejector flaps and across the porous wall is computed via an adaptation of the work of Ref. 2, which empirically correlated the flow rates with the pressure drops across these devices. This physical model produces a system of 19 nonlinear equations that must be solved simultaneously at successive time points until the flowfield becomes steady. These equations, along with a description of the numerical procedure and computer program, are given in the backup paper.[4]

The accuracy of the model was verified by comparing theoretical plenum pressure time histories with experimental data from the pilot HIRT. Figure 2 shows this comparison for a subsonic run at nominal tunnel settings. The disagreement

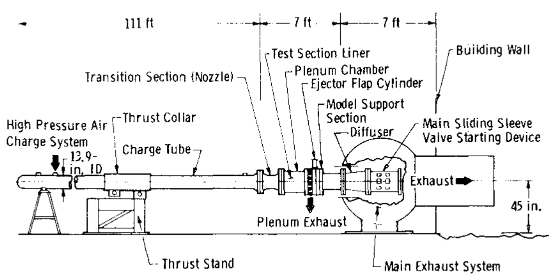

Fig. 1 Pilot HIRT elevation line drawing.

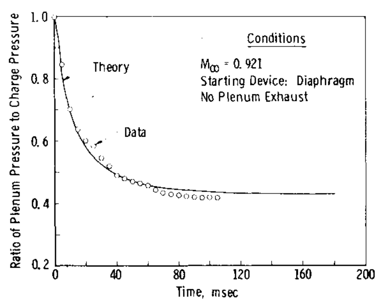

Fig. 2 Plenum pressure vs time for subsonic run with medium plenum volume.

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*Research Engineer, von Karman Facility. Member AIAA.

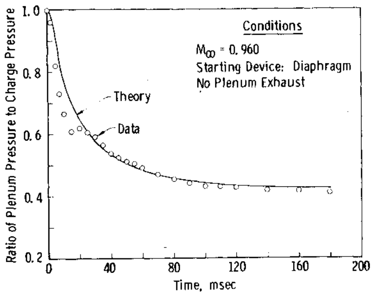

Fig. 3 Plenum pressure vs time for subsonic run with large plenum volume.

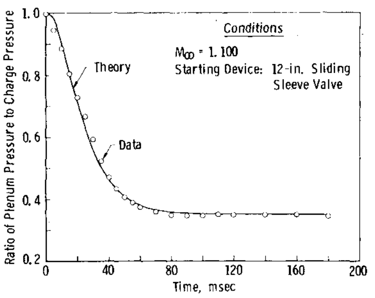

Fig. 4 Plenum pressure vs time for supersonic run with sliding sleeve valve and plenum exhaust.

between 30 and 40 msec results from neglecting wave spreading in the plenum, which is assumed uniform in the model. The disagreement in the asymptotic region is due to neglect of the axial momentum of the test-section flow in modeling the flow through the porous wall of the test section. Figure 3 shows the theoretical and experimental data for a 40% larger planum, which amplifies the wave spreading in the plenum. Figure 4 shows the comparison with a slow-acting, sliding sleeve valve in place of the diaphragm starting device. In addition, this case is supersonic and requires plenum exhaust in order to choke the nozzle exit. The good agreement in these three cases is typical of all cases tested to date, which included other plenum volumes and different settings for the porosity and ejector flaps.

Acknowledgment

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