Mach Number Control of Ludwieg Tubes

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Ludwieg tubes offer a convenient and inexpensive way to provide high Reynolds number test flows; their primary defect is the very short run time available for flow measurement. Even during this period, the test section Mach number is liable to be affected by the boundary-layer growth along charge tube walls and shows gradual increase. In order to decrease this Mach number creep, a Ludwieg tube equipped with a quick-moving choker flap is developed. Through use of the flap the effective area ratio of the test section to the sonic throat is kept essentially constant for some period during the nominal run time. An appreciable time lag is observed between the tunnel start and the establishment of the constant Mach number flow. The finite inertia of the flap and the flap drive mechanism as well as the finite pressure signal propagation speed are the main causes of the delay and several means to eliminate the lag are discussed.

Introduction

RECENT progress in transonic aircraft design technology has created an increasing demand for high Reynolds number transonic wind tunnels.[1] The cryogenic wind tunnel developed at NASA Langley Research Center[2] is one of the optimum facilities for this purpose, but it is too complicated and expensive to use for educational or small-scale basic research purposes.

The Ludwieg tube,[3,4] on the other hand, offers a convenient and inexpensive way of providing high Reynolds number aerodynamic test flows. Several active programs to construct very large-scale Ludwieg tubes had been discussed[5,6] before the cryogenic wind tunnel concept became popular. The Ludwieg tube can still be a convenient transonic high Reynolds number testing apparatus, particularly for small-scale laboratory use, provided its several inherent weaknesses are improved.

The major defect of the Ludwieg tube is its short run time. The duration of steady flows within the Ludwieg tube is restricted by its charge tube length and is of the order of several tens or hundreds of milliseconds when the tube is sized to be housed within an ordinary laboratory area.

To increase the run time, the charge tube length must be made as long as possible. This means, for a given volume of high-pressure charge gas, a combination of a relatively small charge tube diameter and a nozzle with small contraction ratio. With this arrangement, the flow velocity within the charge tube becomes large enough that the temporal growth of the boundary layer along the charge tube wall tends to alter the effective area ratio of the test section to the downstream sonic throat. The basic principle of the Ludwieg tube operation is well described by the inviscid one-dimensional flow analysis made by Ludwieg[3] or Cable and Cox[4] and the steady flow Mach number M within the test section is predicted by a function of the area ratio A/A^* of the test section to the downstream sonic throat, i.e.,

$$M = f(A/A^*) \tag{1}$$

where

$$f^{-1}(M) = \frac{1}{M}\left\{\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right\}^{(\gamma+1)/2(\gamma-1)} \tag{2}$$

A is the cross-sectional area of the test section, A^* that of the sonic throat, and γ the ratio of specific heats in the test gas.

In the real Ludwieg tube, however, the growth of the boundary layer decreases the mass flow across the given cross-sectional area. This can also be expressed equivalently by a decrease in the effective cross-sectional area A_e; i.e., the area covered by the boundary-layer displacement thickness is subtracted from the geometrical cross-sectional area. The ratio of this effective area determines the test section Mach number through Eq. (1). Consequently, the area ratio variation due to boundary-layer growth results in the gradual increase of the test section Mach number during the nominal run time, which may totally destroy the Ludwieg tube's importance as a transonic testing tool. This fatal Mach number creep could be reduced by increasing the charge tube diameter as well as the nozzle contraction ratio, but this would waste the high pressure charge gas and increase the tunnel operating costs. Another way of improving the flow uniformity and steadiness is to insert a settling chamber with honeycombs or screens between the charge tube and the test section; however, this would increase the delay in the tunnel start and decrease the available time for measurement.

The present paper describes an experimental attempt to remove the Mach number creep by introducing a mechanical device with which the test section to sonic throat area ratio is adjusted instantaneously. If the rate of area decrease at the sonic throat can be increased to match the area decrease at the test section, the effective area ratio A_e/A_e^* can be made constant and the test section Mach number can be held essentially constant during the run time. A mechanical sonic throat area adjustment device is described in the next section. If this device works successfully, the limited run time of the Ludwieg tube can be fully exploited. A 100 ms steady flow would be sufficient to take airfoil pressure distributions by applying present-day advanced instrumentation techniques.

Experimental Apparatus

In order to verify the proposed Mach number control principle, a small Ludwieg tube is made from an existing shock tube whose length is 7.37 m with a 70×70 mm cross section. A new transonic test section (Fig. 1) is attached to the end of the tube. The tube inside area is contracted to 50×70 mm through a contraction nozzle attached to the test section, which has a porous wall on one side. Downstream of the test

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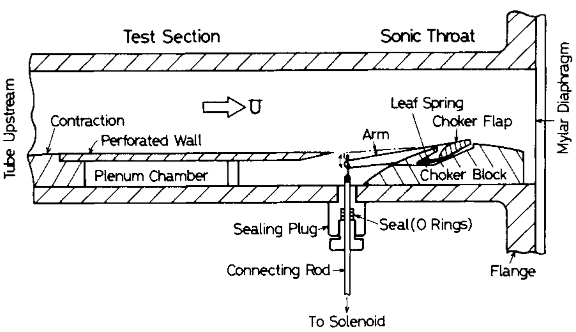

Fig. 1 Details of the test section and the choker flap.

section is a sonic nozzle with a choker block whose maximum height is 25 mm, resulting in a throat of 45×70 mm rectangle. A Mylar diaphragm at the downstream end separates the high-pressure charge gas from the ambient atmosphere. To start the tube, the diaphragm is burned off electrically.

On the top of the choker block, a small choker flap is attached with a leaf spring (Fig. 1). The flap staying flush with the surface of the choker block can be raised up to 2 mm above the choker block through a link by applying electric current to a solenoid. This flap movement reduces the sonic throat area very rapidly, controlling the area ratio. The position of the flap is monitored through a precision linear potentiometer.

Figure 2 is a block diagram of the Ludwieg tube instrumentation. The tube is started by diaphragm rupture and the initial rapid wall pressure decrease is detected by a minicomputer (DEC LSI-11) that subsequently sends trigger pulses to operate the choker flap as well as a xenon light for Schlieren pictures.

A solenoid drive current control circuit is hooked up on a Teledyne-Philbrick Operational Manifold (model 5001). A signal from the linear potentiometer, which shows the current position of the choker flap, and the computer-generated trigger pulse are summed with an adjustable constant offset voltage and fed into a comparator. The latter produces a square pulse whose length can be adjusted by the offset determining the comparator threshold level. This pulse, amplified by a power amplifier, is supplied to the dc solenoid. The movement of the flap can be optimized through the adjustment of the maximum amplitude and the length of the pulse.

The time histories of the flap position signal and the solenoid drive pulse are recorded on the minicomputer with the pressure transducer outputs for future analysis.

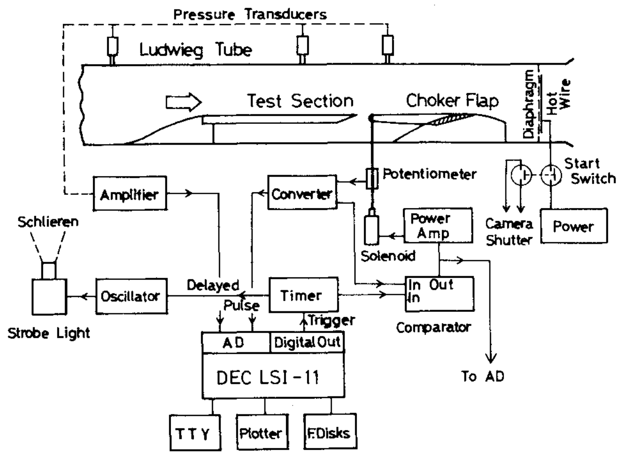

Fig. 2 Block diagram of the instrumentation.

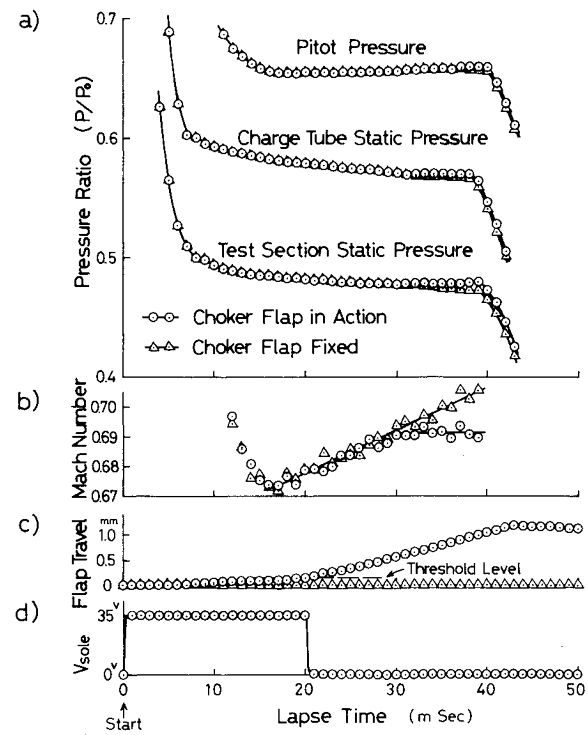

Fig. 3 The Ludwieg tube run time histories: a) nondimensional pressure; b) test section Mach number; c) choker flap upward travel; d) solenoid drive current.

Experimental Results and Discussion

Several trial runs were made and the choker flap movement has been optimized. Figure 3 shows the resulting Ludwieg tube run time histories with fixed and moving flaps. The charge gas was nitrogen and the charge pressure P_0 was 0.3 MPa absolute.

Figures 3c and 3d show the flap upward movement and the solenoid drive pulse, respectively. The drive current is applied during the initial period of the run and, after that, the flap continues to move only through inertia. Several threshold levels, by which the drive pulse length is adjusted, were tested during the trial runs and the one producing a constant test section Mach number has been selected as optimum.

Figure 3a shows the time histories of pressures nondimensionalized with the charge pressure P_0. The total pressure measured at the test section center is not affected significantly by the flap movements. A very slight increase is detected during the final part of the run. The test section static pressure, on the other hand, shows appreciable flap effect. In either case, the effect can be detected with some delay. The test section Mach number can be obtained from these pressure histories and is presented in Fig. 3b. Quasisteady flow is established after 16 ms, but the Mach number continues to rise until the flap movement becomes effective some 30 ms from the start. The Mach number is then almost constant at $M = 0.691 \pm 0.002$.

The Ludwieg tube run time, which is approximately equal to twice the period of the sound wave traveling from one end of the tube to the other, is about 40 ms for the present 7 m tube including the initial transient state. Therefore, Mach number control is established for the final 10 ms only.

The lag time between the solenoid drive current input and the establishment of constant Mach number in the test section results from the following two reasons. First, the finite inertia of the flap and the flap drive mechanism prohibits the flap's catching up with the drive current instantaneous rise. This results in an initial flap movement that is too slow to control the flow. Second, the pressure signal travels upstream from the flap with finite velocity. In the test sec-

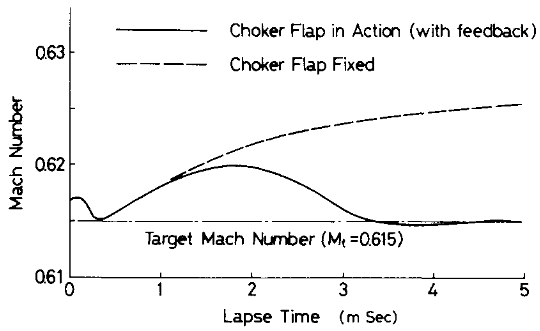

Fig. 4 An example of the numerical simulation of the feedback control.

tion, the mainstream velocity U is transonic with the speed close to the sonic speed c, and the pressure signal upstream propagation speed[4] $c-U$ is low enough to take appreciable time from the flap to the test section. However, the effect of the flap movement also propagates through the plenum chamber, where the average flow speed is much lower than the test section main flow. Therefore, the delay of the flap influence propagation cannot solely be explained from the velocity $c-U$. Even in a sonic or supersonic mainstream, the flap may be able to control the upstream Mach number through the subsonic flow within the plenum chamber.

The lag in flap influence upstream propagation can also be observed in the charge tube static pressure record (Fig. 3a), which is measured at the upstream end of the contraction nozzle. Since this point is further upstream from the test section, the flap influence is detected a few milliseconds later than in the test section.

In order to get constant Mach number flow throughout the nominal run time, the above-mentioned lags must be eliminated or at least be reduced. For this purpose, the flap drive pulse should be supplied to the solenoid in advance of the diaphragm rupture. But this cannot eliminate the lag due to finite velocity pressure signal upstream propagation. The only way to diminish this effect is to make the test section as short as possible and reduce the distance between the choker flap and the test section.

In the present experiment, simple square pulses are used to drive the solenoid; but if a pulse with a much higher initial peak and subsequent gradual decreasing voltage were used, it should be more effective in accelerating the flap and reducing the initial lag. For this purpose, a more powerful power amplifier should be used.

Moreover, a proper feedback of the temporal variation of the test section pressure to the solenoid drive current supply circuit will produce an ideal pulse for flap acceleration. A theoretical estimation of the proportional feedback effect was made through one-dimensional flow theory using a method of characteristics.[7] The result[8] shows promising acceleration of the control at low Mach numbers, but, at higher Mach numbers, the time lag due to signal propagation introduces some difficulties. These would be reduced if the porous wall effects were taken into account.

Figure 4 is an example of the numerical simulation of the feedback control.[8] In this simulation, the boundary layer is assumed to be turbulent and its thickness increase within expansion waves is estimated through Becker's method,[9] while the thickness increase in steady flow is estimated through Head's method.[10] The effect of the porous wall is not included and the walls are assumed to be solid. The movement of the choker flap has been determined by the following relation:

$$\frac{dy}{dt} = G(M - M_t) \qquad (3)$$

where dy/dt is the speed of the choker flap upward movement, M_t a preassigned target test section Mach number, and G a proportionality constant. In Fig. 4, M_t and G are taken rather arbitrarily equal to 0.615 and 50 mm/s, respectively. The lapse time is measured from the start of flap control actuation, which is about 0.5 ms after the establishment of quasisteady flow within the test section. The observed initial Mach number oscillation around the origin is the result of the unsteady boundary layer's uneven initial growth, which is expected to be reduced if the porous wall effects are included. The test section Mach number converges to the target value in about 3 ms in this particular example. For this active control to be effective, the flap drive mechanism must have both pull and push capabilities, which are hard to realize with the present system using solenoid motors. Further development in the quick drive mechanism is needed to exploit the merits of feedback control.

Conclusions

A Ludwieg tube with a variable-area sonic throat is developed. The test section Mach number of the Ludwieg tube is shown to be kept constant by the action of the choker flap, which compensates the temporal change of the ratio of the test section effective cross-sectional area to the effective sonic throat area. The frequently observed gradual Mach number increase, which is due to the charge tube wall boundary-layer growth, is shown to be partially suppressed with this device and the time available for flow measurement is increased without sacrificing high-pressure charge gas.

To maximize the available time, the time lag between the flap control command and realization of the flap effect must be decreased. For this purpose, further development in the flap control system is needed.

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References

[1]Blackwell, J.A. Jr., "Effect of Reynolds Number and Boundary-Layer Transition Location on Shock-Induced Separation," *Proceedings of AGARD Conference on Transonic Aerodynamics*, AGARD CP 35, Sept. 1968, pp. 21.1-21.10.

[2]Howell, R.R. and McKinney, L.W., "The U.S. 2.5-Meter Cryogenic High Reynolds Number Tunnel," *Proceedings of a Workshop on High Reynolds Number Research*, NASA CP-2009, 1977, pp. 27-51.

[3]Ludwieg, H., "Tube Wind Tunnel—A Special Type of Blowdown Tunnel," AGARD Rept. 143, July 1957.

[4]Cable, A.J. and Cox, R.N., "The Ludwieg Pressure-Tube Supersonic Wind Tunnel," *The Aeronautical Quarterly*, Vol. 14, May 1963, pp. 143-157.

[5]Whitfield, J.D., Schueler, C.J., and Starr, R.F., "High Reynolds Number Transonic Wind Tunnels—Blowdown or Ludwieg Tube?," *Proceedings of AGARD Conference on Facilities and Techniques for Aerodynamic Testing at Transonic Speeds and High Reynolds Number*, AGARD CP-83-71, 1971, Paper 29.

[6]Enkenhus, K.R. and Merritt, D.L., "Evaluation of Two Types of Facilities to Fulfill the Need for High Reynolds Number Transonic Testing," Naval Ordnance Laboratory, Silver Spring, MD, Rept. NOLTR 71-147, July 1971.

[7]Shapiro, A.H., "Unsteady, One-Dimensional Flow with Area Change, Friction, and Heat Transfer or Combustion," *The Dynamics of Compressible Fluid Flow*, 1st ed., Vol. 2, Ronald Press Co., New York, 1954, pp. 972-979.

[8]Taneda, H., "Control of Flow within Ludwieg Tubes by Use of a Quick-Moving Flap," Master's Thesis, University of Tokyo, Japan, March 1983.

[9]von Becker, E., "Das Anwachsen der Grenzschicht in und hinter einer Expansionswelle," *Ingenieur-Archiv*, Band 25, Heft 3, 1957, S. 155-163.

[10]Head, M.R., "Entrainment in the Turbulent Boundary Layers," Aeronautical Research Council, London, ARC R&M 3152, 1958.