Engineering Notes

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A Simple Technique for Sizing Free Jet Facilities

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Introduction

IT has long been recognized that free jet testing facilities offer the possibility of providing substantial test model size benefits in comparison with competitive testing concepts.[1,2] Such facilities are particularly of use for the testing of ramjet inlets in supersonic flight conditions. If optimal use is to be made of such facilities it is important to size the facilities such that minimum mass flow (or maximum model size) can be utilized.

Several physical phenomena limit model sizing. Thus, the model must not create blockage to the extent that the primary nozzle flow cannot "start." Care must be taken not to allow too great a bypass flow area, however, because the facility mass flow requirements can become limiting. A related problem occurs when the backpressure increases, in that the angle of the oblique shock wave at exit to the primary nozzle will change thereby changing the boundaries of the test diamond. In severe cases of high backpressure the oblique shock wave can lead to boundary layer separation with subsequent migration of the shockwave upstream.

In the following, a simple analysis to incorporate these various limitations is developed so that model sizing (and location) can be carried out expeditiously.

Analysis

A schematic diagram of the primary nozzle and test inlet, with related nomenclature, is shown in Fig. 1. As indicated in the figure, the model position is chosen to just intersect the shock wave (or Mach line) emanating from the primary nozzle lip. The choice of this location has two benefits over placing the model further upstream. Thus, when placed in this manner, the area available to bypass the flow prior to nozzle starting (A_s) is maximized, with consequent minimization of by-pass flow once the flow has started. In addition, this furthest downstream location of the model gives maximum optical availability for the inlet flow.

It is assumed that the chamber backpressure will be maintained at a sufficiently low value to retain the shock wave at the nozzle lip. Several methods of estimating the related pressure ratio, $P_a/P_s \equiv \underline{P}$, that must not be exceeded if upstream shock migration is to be prevented are available. Perhaps the simplest of these is that due to Summerfield[3] who suggested that the oblique shock would locate itself where $\underline{P}$ reached some critical value, say 2.8. Thus, if $\underline{P}$ at the exit to the nozzle is kept lower than this value the shock will remain on the nozzle lip.

In order to estimate the required value for the area A_s it is now postulated that this area must be sized so as to just pass all of the air passing through the nozzle exit area, A_e, if a normal shock wave occurs at the nozzle design Mach number, M_D. It is felt that this requirement is somewhat conservative (i.e., leads to a larger A_s than absolutely necessary) because, in fact, prior to nozzle starting the shock system would actually be located at Mach numbers lower than M_D. In addition, the test inlet itself has the capability of passing a portion of the oncoming (subsonic) flow. With the given postulate, the area ratio A_s/A_e would be related by the "Kantrowitz-Donaldson contraction ratio,"[4] thus:

$$\frac{A_s}{A_e} = \left(\frac{2}{\gamma+1}\right)^{1/2} M_D^{-(\gamma+1/\gamma-1)} \left(1+\frac{2\gamma}{\gamma+1}(M_D^2-1)\right)^{1/\gamma-1} \times \left(1+\frac{\gamma-1}{2}M_D^2\right)^{1/2} \tag{1}$$

The ratio of inlet capture area to nozzle exit area follows directly from geometry to give

$$A_c/A_e = 1 - \sin\beta(A_s/A_e) \tag{2}$$

We have also[5]

$$\sin^2\beta = \frac{1}{2\gamma M_D^2}[(\gamma+1)\underline{P}+\gamma-1] \tag{3}$$

Finally, noting $X_s/\Delta r = 1/\tan\beta$ and $\Delta r = (D_e/2)(1-\sqrt{A_c/A_e}$, there is obtained

$$\frac{X_s}{D_e} = \frac{1}{2\tan\beta}\left(1-\sqrt{\frac{A_c}{A_e}}\right) \tag{4}$$

Equations (1-4) allow simple estimation of parameter changes with design variations.

Example Calculations

Figure 2 shows the variation of axial position and required ratio of capture area to nozzle exit area as a function of design Mach number. The virtue of the free jet facility for large Mach numbers becomes evident in that the ratio A_c/A_e approaches unity as M_D approaches infinity. This leads to small by-pass flows at large Mach numbers with consequent easing of pumping requirements. Contrarily, the effects of flow blockage restrictions on nozzle starting are seen to cause severe model sizing and flow pumping penalties at low Mach numbers.

Figure 3 shows the effect upon geometry requirements of increasing the backpressure. As expected, increasing backpressure leads to decreased allowable model size. It is to be noted from Eq. (1) that the ratio A_s/A_e does not change.

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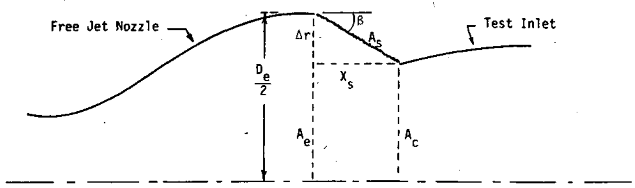

Fig. 1 Free jet test facility nomenclature.

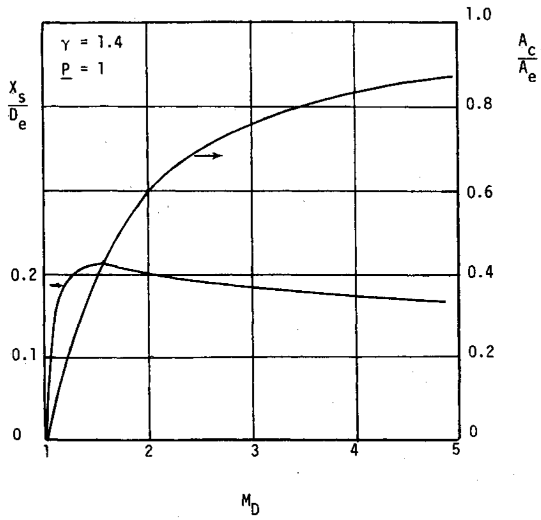

Fig. 2 Axial distance and capture area vs design Mach number.

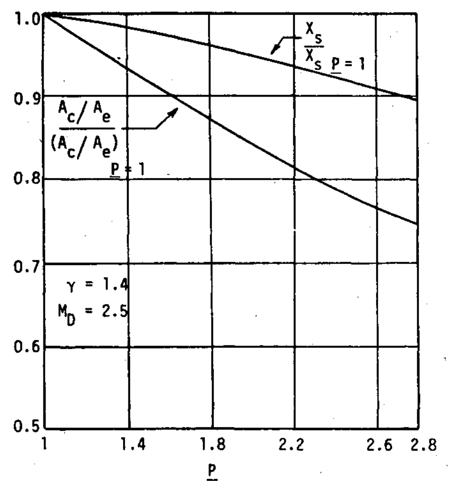

Fig. 3 Axial distance and capture area vs pressure ratio.

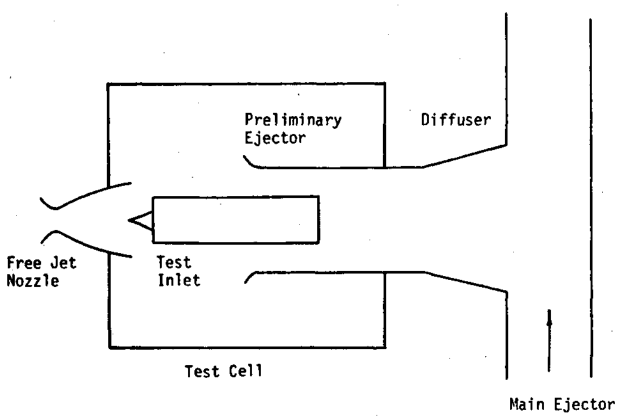

Fig. 4 Schematic diagram of preliminary ejector.

Enhancement of Facility Pumping Capability

The required low backpressure, P_a, must be supplied by the facility pumping capability. This capability is usually supplied by an air or steam[1] driven ejector. In cases where large model sizes are to be tested, facility pumping capability can become limiting, and the requirement to enhance such capability can be imperative. When large test models with high-pressure recovery inlets are utilized, the test model flow itself can have significant pumping capability. Thus, as suggested in Fig. 4, the model exhaust flow can be utilized as the primary flow of a preliminary ejector to raise the pressure at entry to the main ejector. The preceding calculations provide the necessary mass flows in the primary and secondary streams of the preliminary ejector. Estimates of the delivery stagnation pressure from the test model should be available, and it has been found a reasonable lower estimate of the secondary stream stagnation pressure to simply take it equal to the static backpressure, P_a.

With the approximations suggested above, the combined system capability can be estimated in a straight-forward fashion utilizing established theories.[6,7] When high Mach number tests are to be conducted, considerable pumping enhancement occurs when a preliminary ejector is utilized.

References

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[5]Ames Research Staff, "Equations, Tables and Charts for Compressible Flow," NACA Report 1135, 1953 [p. 9, Eq. (128)].

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Effect of Cross-Shafting on Landing Reliability of V/STOL Aircraft

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Introduction

THE desired capability of completing a vertical landing with one core engine inoperative has been a major driver in configuring subsonic V/STOL propulsion systems. The approach generally used to achieve this capability involves the addition of bevel gears and cross-shafting to the engines. In a two-turbofan system, either core can thus drive both fans at a balanced thrust level to allow vertical landing at reduced gross weights.

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