Any streamsurface of an inviscid flow can be taken to be a solid boundary. Consequently, the streamlines shown in Fig. 3 can be used to generate new lifting body shapes. These shapes are called waveriders as they develop lift because of the shock wave they "ride" upon. By choosing streamlines such as shown in Fig. 3, bodies can be developed which have winglike surfaces that fair smoothly into the rest of the body. Closed aerodynamic shapes can be achieved in a variety of ways. Figure 4 shows sketches of possible shapes that derive from the streamlines in Fig. 3 and planes parallel to the freestream velocity. These waveriders efficiently integrate volumetric, propulsive, and aerodynamic requirements and could be the basis for a new generation of maneuverable supersonic/hypersonic vehicles. The analytical solutions developed herein are particularly attractive in that they allow the effects of Mach number, angle of attack, and cross-sectional shapes to be evaluated in closed form.

Acknowledgments

This work was sponsored by the Air Force Office of Scientific Research under AFOSR Grant 77-3468 and by the Air Force Armament Laboratory under Contract F0 8635-79-C-0017. The author has profited from discussions of this work with D. Daniel and M. Rasmussen.

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AIAA 81-4038

Technique for the Evaluation of Wall Interference at Transonic Speeds

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In recent years, there has been an increased emphasis upon the development of more efficient transport configurations with cruise speeds in the transonic speed regime. This has resulted in a requirement for high quality aerodynamic data on increasingly complex configurations in this speed regime. This requirement for high quality data has revealed some of the shortcomings of existing transonic test facilities.

A limitation of existing transonic wind tunnels is their inability to provide an adequate simulation of full-scale free-flight Reynolds number. It has been proposed[1] that this present inadequacy can be overcome by operating transonic wind tunnels at low total temperatures, i.e., on the order of 80 K. In such test facilities, the maximum values of Reynolds number are obtained at the lowest values of total temperature. Under these conditions, the possibility exists that condensation in the tunnel flow can occur with its attendant effects on the aerodynamic measurements.

A second concern in wind tunnel measurements, cryogenic or not, is the manner in which these measurements are affected by the tunnel boundary. Although significant improvements have been made in the theoretical methods that have been developed to correct for these boundary effects, these methods are not yet in a sufficiently developed state where they can be used to correct the aerodynamic measurements for wall interference effects.

From the foregoing, it clearly is necessary to distinguish between wall interference and condensation effects in the operation of cryogenic transonic wind tunnels. It is the purpose of this Note to suggest that some aspects of these problems can be evaluated using existing free-flight sphere drag data, although additional measurements at lower Mach numbers and high Reynolds numbers would be highly desirable.

To properly calibrate a wind tunnel in the transonic region, a known configuration with sufficient real free-flight data is required. The obvious shape is the sphere, since projectile or other shapes require duplicating in the tunnel the complicated yaw, spin, and orientation dependence on M_∞ of free-flight conditions.

In our context, three types of sphere drag data need to be considered. These are 1) actual free-flight data (ff) from firings in aerodynamic ranges; 2) force balance measurements in a wind tunnel (t) using stings; and 3) free-flight firings through a wind tunnel (tff). An equivalent to 3 is the sting-free magnetic suspension technique (tsf) in a wind tunnel. As will be seen, these data do not appear to yield the same results. Consequently data of type 1 can be used both to calibrate tunnel effects on type 3 data and sting effects on type 2 data.

Jaffe[2] has measured the drag of a sphere in a transonic wind tunnel both with a force balance (t) and also with a free-flight technique (tff). As a result of these measurements (Fig. 1), Jaffe[2] observes that sphere drag measurements are not affected significantly by reasonably sized stings. However, it should be noted that the experimental free-flight drag value at $M_\infty \approx 0.95$ is approximately 10% greater than the corresponding force balance value. To determine whether this difference is a result of sting interference effects at this Mach number would require a further experimental investigation. It should be noted that these measurements were obtained for a model blockage ratio of 0.03%.

Implicit in Jaffe's discussion[2] is the assumption that the tff sphere drag coefficient values are correct. Whether this is in fact true can be determined by comparing these wind tunnel values with those obtained at the same values of Mach and Reynolds number in actual non-tunnel free flight. These wind tunnel sphere drag coefficient values (tff), which were obtained for a Reynolds number of 2.5×10^5, are compared in Fig. 1 with the corresponding true free-flight values derived from an analysis of such measurements by Miller and Bailey.[3]‡ This comparison shows that for $M_\infty \leq 0.98$, the

‡Since the submission of Ref. 3, the work of Giraud[4] has been received. His 20 mm results and the 4 in. data of Zahm[5] (below $M_\infty = 0.6$) have been incorporated with cannon data collected for Ref. 3. These data lead to Fig. 2, which differs only slightly from Fig. 4 of Ref. 3. The most noticeable change is a persistence to higher Mach numbers of the dips at $Re_{\infty d}$ above 5×10^5.

Received June 19, 1980.

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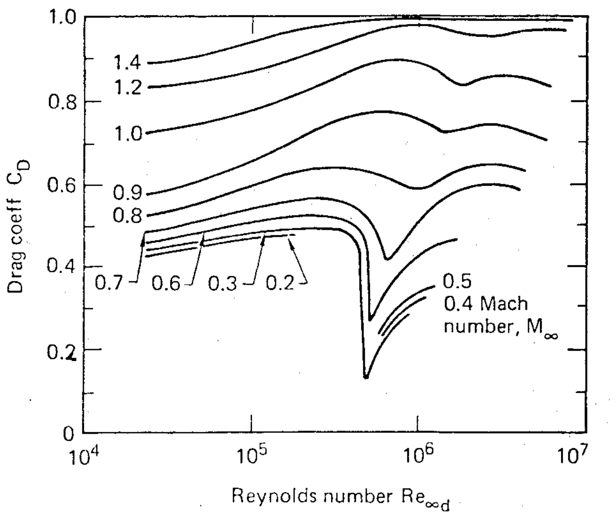

Fig. 1 Comparison of sphere drag from wind tunnel force balance (t) and wind tunnel free flight (tff) measurements with range free flight (ff) measurements.

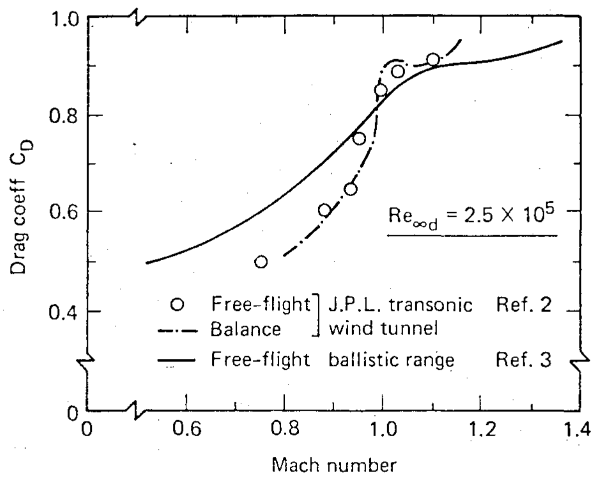

Fig. 2 Summary of sphere drag measurements at high Reynolds numbers in the transonic speed regime.

wind tunnel values of sphere drag coefficient are lower by approximately 15% or more than the free-flight values. It is suggested that this difference indicates that tunnel measurements of sphere drag are affected by wall interference effects. Further verifications of this suggestion could be determined by conducting an additional series of wind tunnel sphere tests using larger and smaller models than those which have already been tested, and comparing the results with existing free-flight data.[3]

It has been shown above that it is possible to use the known value of sphere drag coefficient to evaluate the effect of wall interference on sphere drag measurements in a conventional transonic wind tunnel. In order to apply the same technique to evaluate the performance of a cryogenic transonic wind tunnel it would be necessary 1) to know the variation of sphere drag coefficient in the transonic speed regime for Reynolds numbers on the order of 10^7, and 2) to be able to make sting-free measurements of sphere drag in the tunnel. An analysis of some 19th Century cannon firings by Miller and Bailey[3] has provided values of sphere drag coefficient over much of the required Mach and Reynolds number range of interest (see Fig. 2). Also, Kilgore[1] has indicated that the Langley cryogenic transonic wind tunnel will have a magnetic suspension and balance system which could be used to make the sting-free measurements. Therefore, the possibility does (or will) exist to evaluate the effects of wall interference and/or condensation on sphere drag measurements in a cryogenic transonic wind tunnel.

It should be noted, however, that there are some Mach number-Reynolds number regions which are relevant to wind tunnel calibrations, but which need further experimental exploration. These are the regions on the right-hand portion of Fig. 2 that contains the particularly interesting dips and maxima at high Reynolds number below and near sonic velocity. These striking features deserve a systematic investigation. The appropriate data could be obtained from a relatively modest experimental program using modern equipment.

Acknowledgment

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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AIAA 81-4039

Pressure Fluctuations in Transonic Shock-Induced Separation

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Nomenclature

c	= chord length
f	= frequency, Hz
$F(n)$	= contribution of $\tilde{p}^2/q^2$ in frequency bandwidth Δn
$\sqrt{nF(n)}$	$= \tilde{p}/q(\epsilon)^{1/2}$
h	= height of wind-tunnel test section
ℓ_B	= length of separation bubble
M	= Mach number
M_p	= peak Mach number
n	= frequency parameter based upon test section height, fh/U_∞
$\tilde{p}$	= root mean square of static pressure fluctuations
q	= upstream dynamic pressure, $\frac{1}{2}\rho U_\infty^2$

Received July 7, 1980.

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