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Correlation of Transition Reynolds Number with Aerodynamic Noise Levels in a Wind Tunnel at Mach Numbers 2.0-3.0

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THE correlation of model transition Reynolds number in the aeroacoustic environment of a wind tunnel with that which would occur in free flight is a long-sought and elusive goal. The reason is that transition data in wind tunnels have been enshrouded with effects associated with the test facility and not the model. An important advancement to the understanding of facility environmental influence on transition was the work of Pate and Schueler,[1] which supposed a strong effect of radiated aerodynamic noise from the tunnel wall boundary layer in supersonic and hypersonic test facilities. Verification of the existence of this effect was obtained by shielding a model from the tunnel walls with a shroud.

Pate and Schueler were able to correlate transition Reynolds number data from 10 different wind tunnels using an empirical expression containing the tunnel wall skin friction coefficient (C_f) and displacement thickness (δ^*) to characterize the noise. Because the amount of noise reaching the model depends upon radiation laws, the correlation necessarily included a tunnel size parameter, which was based on the test section perimeter (c). Different empirical constants were found when cone and planar model geometries were considered.

Their empirical correlation was demonstrated to hold over a Mach number range of 3.0-8.0 for tunnel sizes ranging from 1.0 ft square to 16 ft square. In the largest tunnel, the AEDC 16 ft supersonic propulsion wind tunnel (PWT16S), data were acquired on a 12-in.-diam hollow cylinder at Mach numbers 2.0, 2.5, and 3.0. The test-section boundary-layer properties were measured at a reference location 69.9 ft from the nozzle throat, which was behind the model and near the middle of the test section. The data at Mach numbers 2.0 and 2.5, although documented in Ref. 1, were not used in the correlation because the transmissibility of turbulence from the stilling chamber through a supersonic nozzle increases greatly as the Mach number is decreased below 3.0.

Subsequent to these tests, additional data have been acquired by PWT personnel in tunnel 16S, including additional documentation of wall boundary-layer skin friction and thickness, direct measurements of noise level in the test section, and turbulence level in the stilling chamber. These data were acquired at various unit Reynolds numbers over the Mach number range of 1.67-3.0. The stilling chamber turbulence level (axial component, $\bar{u}'/U \times 100$) was found to be quite low, 0.2% maximum. Considering the level of turbulence entering the test section after the nozzle contraction, it was concluded from the test section noise measurements that the disturbances in the test section were predominantly acoustic (turbulent boundary-layer radiation) for all Mach numbers from 1.67 to 3.0.

The noise measurements were made using a flush-mounted microphone on the surface of a 10-deg cone. This is the same cone that was used in a transition correlation study which has been carried out primarily in transonic tunnels.[2] The cone model was mounted so that location of the microphone was at a tunnel axial station 58 ft from the throat. The cone had insufficient length to obtain complete transition on the cone within the Reynolds number capability of the tunnel, hence all of the noise measurements were made with the microphone under a laminar boundary layer. The cone tests provided noise measurements that should be fairly representative of the freestream noise level, free from local turbulence, which would have been present from a measurement under a turbulent or transitional boundary layer.

Recent boundary-layer measurements made on different walls of 16S at different tunnel axial stations[3] showed that the variations of boundary-layer characteristics with Mach number and Reynolds number in 16S can be correlated by the method of Winter and Gaudet.[4] Use of this correlation was the basis for extrapolating all of the recent boundary-layer data to the Pate and Schueler reference station of 69.9 ft. The extrapolated boundary-layer characteristics were correlated (in particular, the skin friction) with the hollow cylinder transition data. It was found that the Mach 2.0 and 2.5 data also could be correlated, using Pate and Schueler's method.

Furthermore, after deriving a correlation between the wall boundary-layer properties and the noise data, a direct correlation was found to exist between the Ref. 1 transition data and the noise levels measured on the cone. The purpose of this Note is to present these correlations.

The transition Reynolds number data to be used herein were interpolated at four unit Reynolds numbers from those measured on a hollow cylinder with a leading edge lip bluntness of 0.0015 in. Table 1 gives the values of transition Reynolds numbers obtained.

These data (Re_T) represent the end of transition length Reynolds number based on the peak in pressure measured by four pitot probes traversing axially along the exterior surface of the cylinder, as described in Ref 1. An average of the four simultaneous readings circumferentially spaced 90 deg apart was taken at each test condition to eliminate any flow angularity error. Correlation of the data given in Table 1 with the correlation from other tunnels given in Ref. 1 is shown in Fig. 1. These data, which are correlated using information

Table 1 Transition Reynolds numbers

M_∞	$Re/ft \times 10^{-6}$	$Re_T \times 10^{-6}$
2.0	1.2	3.60
	1.5	4.06
2.5	0.6	2.40
	0.9	2.79
	1.2	3.09
	1.5	3.41
3.0	0.6	2.11
	0.9	2.45
	1.2	2.69

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Index categories: Boundary-Layer Stability and Transition; Supersonic and Hypersonic Flow.

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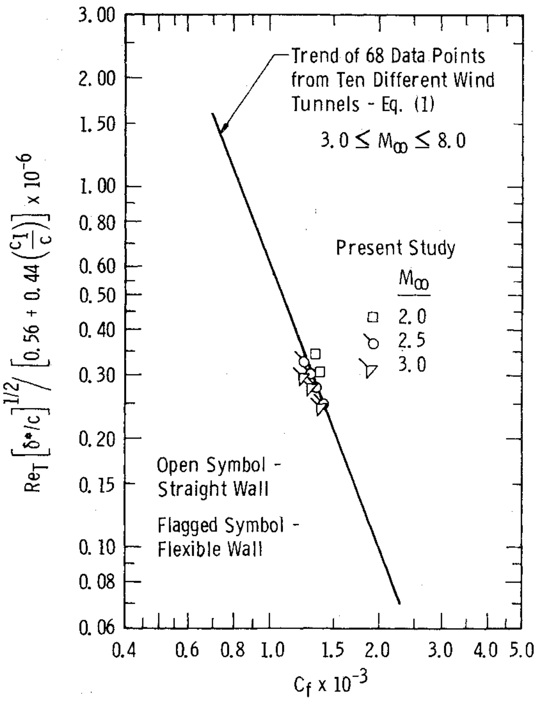

Fig. 1 Hollow cylinder transition data correlation in tunnel 16S (Pate and Schueler[1]).

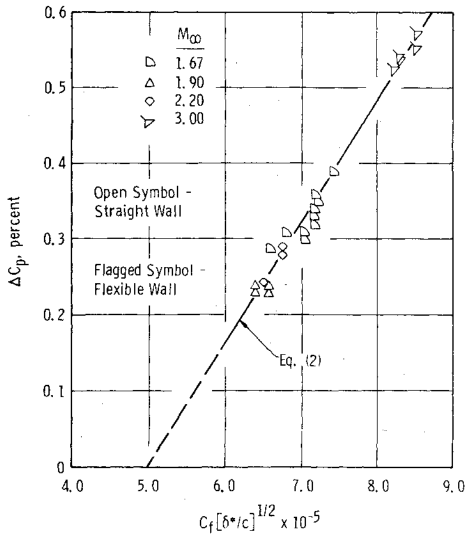

Fig. 2 Correlation of noise levels measured on cone with tunnel wall boundary-layer properties.

from recent boundary-layer measurements, agree very well with the expression given in Ref. 1

$$\mathrm{Re}_T = 0.0141 C_f^{-2.55} [0.56 + 0.44(c_1/c)] / [\delta^*/c]^{1/2} \tag{1}$$

In this expression c is the test-section perimeter in tunnel 16S and c_1 is a reference 4-ft perimeter (1 × 1-ft square test section).

The noise data measured on the cone were correlated with the level generated by the wall boundary-layer source using the parameter $C_f[\delta^*/c]^{1/2}$. This correlation is shown in Fig. 2. The root-mean-square pressure fluctuation amplitude measured by the surface mounted microphone has been non-

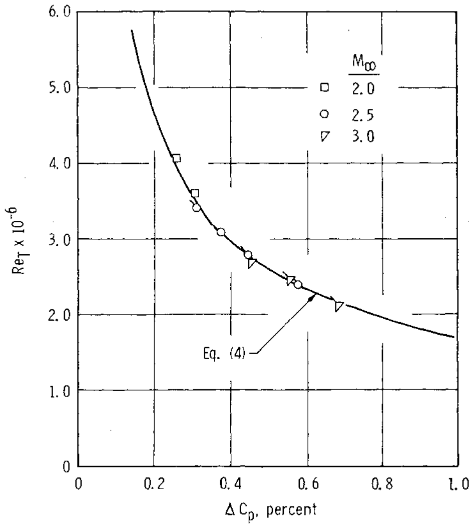

Fig. 3 Correlation of hollow cylinder transition data with noise levels measured on cone.

dimensionalized to a fluctuating pressure coefficient, given in percent (ΔC_p) and defined as follows:

$$\Delta C_p = \tilde{p}'/q_\infty \times 100 \tag{2}$$

where $\tilde{p}'$ has been time-averaged for 3 sec and frequency-integrated from 10 Hz to 10 kHz. The $\tilde{p}'$ spectra were completely random in character with no deterministic components, exemplifying spectra expected from boundary-layer radiation. A simple linear expression

$$\Delta C_p = 0.1613\{C_f[\delta^*/c]^{1/2} \times 10^5 - 5.0\} \tag{3}$$

was fitted to the data in Fig. 2.

Finally, calculation of ΔC_p for the test conditions given in Table 1 using Eq. (3) allowed the variation in Re_T with noise level to be shown directly (Fig. 3). The data exhibit excellent agreement with an empirical trend expressed as

$$\mathrm{Re}_T = 1.695 \times 10^6 (\Delta C_p)^{-0.627} \tag{4}$$

Considering that neither measurements of incident noise level nor the boundary-layer properties at the point of noise origin were available at the locations corresponding to the transition measurements, the actual effect of the noise on transition will differ somewhat from Eq. (4). However, these results do serve to extend the Pate and Schueler hypothesis to Mach numbers as low as 2.0 for flow with low freestream turbulence level and to show that the aerodynamic noise has a profound effect on transition at these Mach numbers.

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