III. Concluding Remarks

Approximate expressions for ζ_D^N are given by Eqs. (44) of Ref. 4. For a HF laser with laminar flows and a helium diluent

$$\zeta_D^{1/2} = 3.27 \frac{p(\mathrm{Torr})w(\mathrm{cm})}{(p/p_F)^{1/2}} \left[\frac{2}{A} \left(\frac{400}{T} \right)^{1.385} \right] \tag{11a}$$

where p is the static pressure, and p_F is the partial pressure of the fluorine at the nozzle exit. Equation (11a) neglects the effect of combustion-generated deactivators. For typical flow conditions ($p/p_F = 10$, $T = 400\,K$, $A = 2$)

$$\zeta_D^{1/2} = p(\mathrm{Torr})w(\mathrm{cm}) \tag{11b}$$

For this flow condition, a saturated laser, $K_I \to \infty$, and $pw > 5$ Torr cm, i.e., $\zeta_D^{1/2} > 5$, the axisymmetric nozzle has an output power twice that of a two-dimensional nozzle with the same exit flow conditions and exit width w. In this pw regime, however, the chemical efficiency of the axisymmetric nozzle is 20% or less that of a premixed ($pw = 0$) laser. For $pw = 1$ Torr cm, i.e., $\zeta_D^{1/2} = 1$, the axisymmetric nozzle has about 30% greater output than the corresponding two-dimensional nozzle and a chemical efficiency equal to about 60% that of a premixed laser. For $pw < 0.5$ Torr cm, i.e., $\zeta_D^{1/2} < 0.5$, both nozzles have essentially premixed laser performance. For either nozzle, a reduction in pw results in improved performance (Fig. 3). The effect of $p/p_F \neq 10$ is found in Eq. (11a).

Fabrication and nozzle wall boundary-layer effects also have to be considered when comparing two-dimensional and axisymmetric nozzles. These are beyond the scope of this study.

Acknowledgment

The present study was supported by NAVSEA HEL project PMS-405 through U.S. Air Force Space and Missile System Organization (SAMSO) Contract No. F04701-75-C-0076.

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Review of Wind-Tunnel Freestream Pressure Fluctuations

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Nomenclature

c_f = skin friction coefficient
D = diameter or height of tunnel test section
M = Mach number
p = pressure
$Re_{\infty,D}$ = freestream Reynolds number based on tunnel diameter
δ^* = boundary-layer displacement thickness
γ = specific heat ratio
τ_w = wall shear stress
$(\,)'$ = fluctuating quantity
$<(\,)'>$ = rms value
$(\bar{\,})$ = mean value

Subscripts

∞ = freestream condition
c = model surface condition

Received Dec. 31, 1976.

Index categories: Supersonic and Hypersonic Flow; Nozzle and Channel Flow.

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It is commonly agreed that pressure fluctuations in the freestream of supersonic-hypersonic wind tunnels have a strong influence on boundary-layer transition over aerodynamic models. The pressure fluctuations arise from interaction between the turbulent boundary layer growing on the tunnel sidewalls and the freestream flow, and it is known that the fluctuations become large for $M_\infty \geq 2.5$. In fact, for unheated tunnels with $M_\infty > 3$ the pressure fluctuations completely dominate the freestream disturbance modes. In heated wing tunnels where the other modes, particularly the entropy mode, become active, the pressure fluctuations still represent a significant portion of the total disturbance level and they increase in importance as M_∞ increases. Over a dozen measurements of freestream pressure fluctuations, obtained with both hot wire anemometers and acoustical transducers in a variety of facilities, have been reported.[1-12] So far, attempts to predict freestream noise, which were generally based on theories of sound radiated from a turbulent boundary layer (Refs. 13 and 14), have not been fruitful. On the other hand, several years ago Pate and Schuller[9] demonstrated a relation between transition Reynolds number on wind-tunnel models and radiated pressure disturbances. On the basis of these measurements they were successful in correlating the transition Reynolds number for a large number of wind-tunnel facilities with the parameters believed also to influence sound generation by the turbulent sidewall boundary layer, including wall shear stress, displacement thickness, tunnel size, etc. More recently, Stainback and Rainey[15] presented a correlation for freestream pressure fluctuations in terms of similar parameters. However, while their correlation provided a reasonable fit to most of the data upon which it is based, they treated hot wire data and acoustic measurements separately. More important, they omitted the acoustical measurements of Pate and Schuller[9] and of Dougherty[12] which, as described later, show a marked departure from the behavior exhibited by the bulk of the reported data. This paper presents a further review of the freestream pressure fluctuations and serves to illustrate the significant trends which characterize the existing measurements.

Measurement of freestream pressure fluctuations has been made using either the hot wire anemometer or acoustical transducers (the latter have been mounted flush with the surface of a sharp cone or flat plate and measurements made for conditions producing laminar boundary-layer flow over the model). The measurements considered in this Note are listed in Table 1. The hot wire measurements of Stainback et al.[7] at high hypersonic Mach numbers ($M_\infty \sim 15$ to 20) showed that the ratio $<p'>/\bar{p}$ remains constant across weak oblique shock waves, i.e., that $<p'>/\bar{p}_\infty = <p_c'>/\bar{p}_c$. This suggested, therefore, that acoustic measurements of fluctuating surface pressure could be used to determine the freestream pressure disturbances and, in fact, early measurements by NASA Langley researchers[7] indicated that acoustical measurements of $<p_c'>/\bar{p}_c$ were in accord with hot wire measurements of $<p_\infty'>/\bar{p}_\infty$. However, more recently, the Langley group concluded that acoustic

Table 1 Source of data[a]

Ref	Sym	I.D.	Facility	Test Section Size (inches)	M_∞	Model
			Hot Wire Measurements			
1	○	1,2,3	JPL/SWT	18	3,4,5	–
2	◊	4	AEDC/VKF/D	12	4	–
3	▽	5	AEDC/VKF/B	50	6	–
4	□	6	Ames 3.5	42	7.3	–
5	◁	7	AEDC/VKF/B	50	8	–
6	▷	8	JPL/HWT	21	9.4	–
7	△	9	Langley He	22	~20	–
	⌂	10	Langley He	60	~20	–
			Acoustic Measurements			
8	●	A	Langley HWT	20	6	10° SC
	♦	B	Langley Hi Re	12	6	10° SC
	▼	C	Langley Var Den	18	8	16° SC
9	▲	D,E	AEDC/VKF/A	40	3,5	FP
10	◀	F	Langley Hi Re	12	6	10° SC
4	▶	G	Ames 3.5	42	7.3	10° SC
	☗	H	Langley Var Den	18	7.9	10° SC
11	●	J	NOL HWT	17	5	10° SC
12	⬣	K,L,M	AEDC/PWT-16S	192	2,2.5,3	FP
7	■	N	Langley He	22	~20	16° SC

[a]Note: symbols correspond to data in Figs. 1 and 3. I.D. identifies data in Fig. 2. SC = sharp cone; FP = flat plate.

measurements of $<p_c'>$ may not be a reliable measure of the freestream sound disturbances. Beckwith[10] for example, has presented data acquired simultaneously with two transducers mounted flush with a cone surface, the first located forward on the model where the boundary layer is laminar and the second positioned downstream where the boundary layer has become turbulent. The signals were found to differ by only 10% and this was attributed to amplification of the freestream noise by the laminar boundary layer on the cone (see, for example, the work of Mack[16] and of Kendall[17]). The question is still unresolved and for purposes of this review it was assumed that the acoustic measurements provide an adequate representation of the freestream pressure disturbances. This assumption is justified in part by the data presented in Figs. 1-3. However, the data reported represent "as measured" values and throughout this paper no attempt has been made to account for the fact that the hot wire probe is completely exposed in the wind tunnel and, therefore, is sensitive to sound radiation from the entire sidewall boundary layer, while the acoustic transducer only receives contributions from the boundary layer opposite its sensing diaphragm. This difference will not exceed a factor of two and therefore does not affect the basic conclusions inferred from the data.

The measured pressure fluctuations are summarized in Fig. 1 where $<p'>/\bar{p}$ is plotted versus M_∞. Plotted in this form, the effect of tunnel size is not accounted for and for each facility there is clearly a separation due to unit Reynolds number (listed in the figure adjacent to the plotted points), with $<p'>/\bar{p}$ at a given Mach number decreasing as the unit R_e increases. Below Mach 8 the hot wire and acoustic data tend to overlap with the maximum spread in the data at any Mach number not exceeding a factor of three. A notable exception is the acoustic data of Refs. 9 and 12 which were acquired in the AEDC facilities and are considerably in excess of the remaining measurements. The freestream data of Ref. 9 are, in fact, comparable to the wall measurements at $M_\infty = 9.4$.[6] The high Mach number hot wire data of Stainback, et al.[17] indicates either a peak in $<p'(\bar{p}>$ at some intermediate Mach number or a leveling off in $<p'/\bar{p}>$ above Mach. 8. Whether this is due to a change in the mechanism of sound generation at hypersonic speeds or reflects a difference introduced by the helium test gas (the remaining tests used air as the working fluid) is not known.

In order to introduce the effect of tunnel size, the data have been replotted in Fig. 2 in the form $(<p'>/\bar{p})/(\gamma M_\infty^2/2)$ versus $Re_{\infty,D}$. For convenience, the hot wire data in Fig. 2 are identified numerically and the acoustic measurements alphabetically as indicated in Table 1. Here again the data separate into three classes: 1) the acoustical data of Pate and Schuller[9] and Dougherty[12] which were acquired in AEDC Tunnels A and PWT16S, and which indicate large values of normalized $<p'>$; 2) the high Mach number hot wire data of Stainback, et al[7,8] which indicate relatively low values of $<p'>$; 3) the remaining data (composed of both acoustical and hot wire measurements) which are grouped together within a factor of 2 show no distinction between the type of measurement, and are intermediate to the data of 1) and 2), above.

It should be pointed out that the hot wire measurements are generally well documented and modal analysis of the data

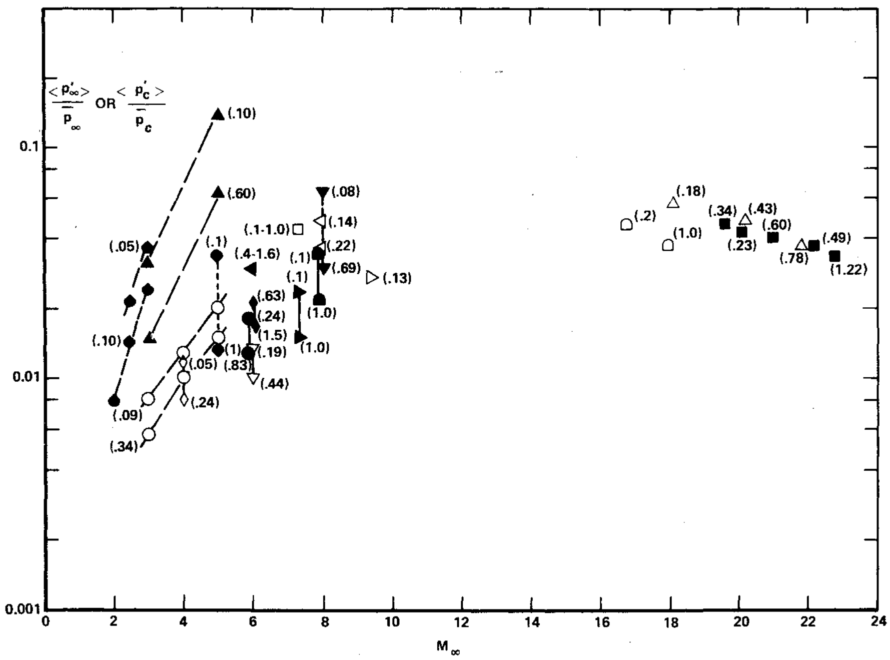

Fig. 1 Rms pressure fluctuation normalized by local mean pressure plotted as a function of freestream Mach number. Symbols identified in Table 1. Number in parentheses adjacent to symbol denotes unit Reynolds number (10^6/in.).

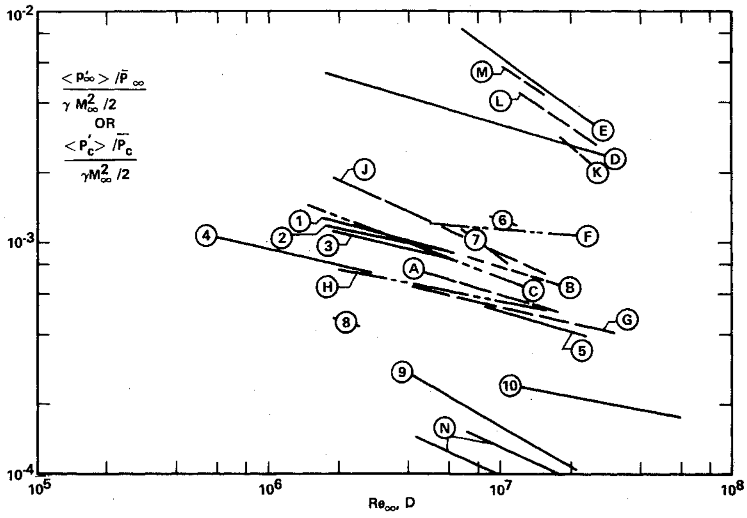

Fig. 2 Rms pressure fluctuation normalized by mean dynamic pressure plotted against freestream Reynolds number based on tunnel test section size. Curves are identified in I.D. column in Table 1.

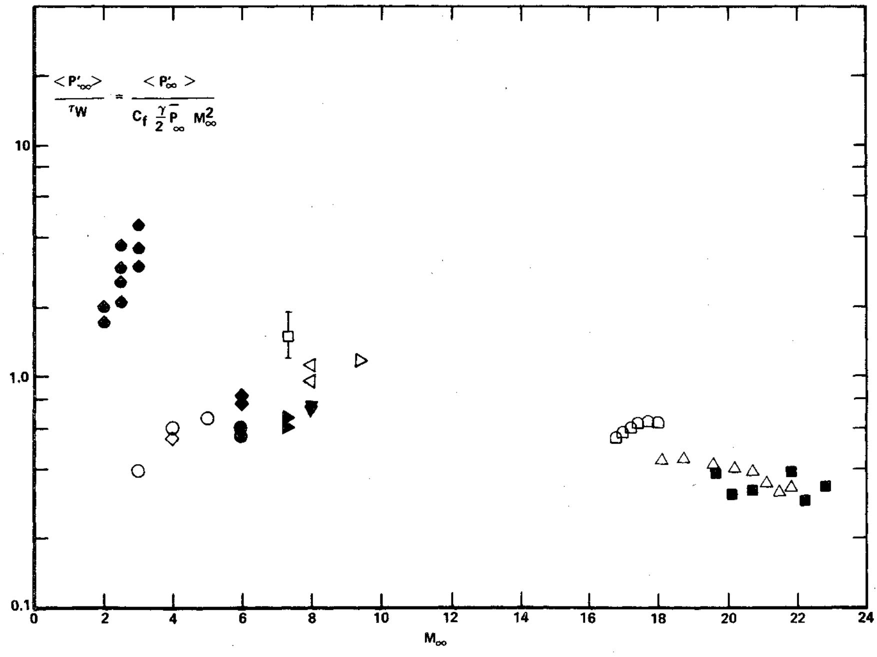

Fig. 3 Rms pressure fluctuation normalized by wall shear stress plotted as a function of Mach number. Symbols identified in Table 1.

yields a clear indication of the $<p'>$ dominance. It should be further noted that as a group the AEDC data of Refs. 9 and 12 indicate excessive freestream disturbances when compared to all other measurements.

Laufer,[18] following the approach of Kistler and Chen[19] and based on Phillips[13] theoretical results, suggested that normalizing $<p'>$ by the wall shear stress τ_w should remove the dependence of the pressure fluctuations on the unit Reynolds number. In Fig. 3 $<p'>/\tau_w$ has been plotted vs M_∞ and the data have been restricted to those cases where information was available on the skin friction coefficient. Thus the data of Pate and Schuller have not been included. However, Figs. 1 and 2 indicate clearly that Pate and Schuller's data are similar in trend to those of Dougherty and it is likely that this similarity would persist when plotted in the coordinates of Fig. 3. Therefore, with the obvious exceptions of Dougherty's and Pate and Schuller's results, which lie a factor of 10 above the remaining data, Fig. 3 demonstrates that the unit Reynolds number dependence vanishes when the pressure fluctuations are normalized by the wall stress and that, for a given Mach number, the scatter in the data is reduced to within a factor of two. The high Mach number data are also well behaved and indicate that $<p'>/\tau_w$ reaches a maximum value somewhere between $M_\infty = 10$ and 16. The Langley data, which were acquired in helium, have not been converted to equivalent air Mach numbers, although this would only shift these data to the right and would not alter the indicated trend.

In summary, the following comments can be offered. First, the pressure fluctuation data of Dougherty and of Pate and Schuller appear to be anomalous. The excessive disturbance levels reported by the latter were first pointed out by Bergstrom and Raghunathorn[20] in an earlier attempt to correlate freestream pressure fluctuations. The discrepancy is considered serious since the data of Pate and Schuller were instrumental in establishing a boundary-layer transition correlation which has found widespread acceptance throughout the industry. Second, while the trend observed in Fig. 3 is encouraging, any firm conclusions would be premature in view of the limited data presented. For this reason, it is recommended that future measurements of $<p'>$ include a complete specification of those parameters known to influence sound generation by shear layers, including c_f, δ^*, D, etc.

Acknowledgments

This work was supported by the United States Air Force, Office of Scientific Research, under Contract No. F44620-75-

C-0016. The author is indebted to P.C. Stainback, NASA Langley Research Center, for supplying a substantial portion of the wall shear stress data used in this Note.

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