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Final Report

STAGNATION POINT FLUCTUATIONS ON BODIES OF REVOLUTION WITH HEMISPHERICAL NOSES

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SUMMARY

The turbulent fields outside of the boundary layer near the noses of axially symmetric bodies with hemispherical noses have been studied by means of the hot-wire anemometer. Measurements in a low turbulence wind tunnel over a range of Reynolds numbers show that the rms streamwise fluctuations in the nose region are larger than in the free stream. Large negative spatial correlation factors between streamwise fluctuations at $\pm 7^{\circ}$ from the axis at low speeds and in a supersonic tunnel at Mach 2.45 indicate that the fluctuations in the nose region are coupled with a random motion of the stagnation point. The normalized energy spectra of the fluctuations at 7° are found to scale with the free stream wave number n/U_{∞}, where n is the frequency of the fluctuations, over a ten-fold range in model diameter and a forty-fold range in Reynolds number. These normalized spectra also show a shift toward lower frequencies compared with free stream turbulence. Possible connection between these phenomena and heat transfer measurements from bodies as affected by turbulence are pointed out.

ACKNOWLEDGEMENT

Most of the experimental work reported here was supported by the USAF Office of Scientific Research under Contract No. AF 49(638)-336. A few of the measurements and most of the analysis were supported by the US Air Force Research Division, Aeronautical Research Laboratories, under contracts AF 33(616)-6856 and AF 33(616)-7628. Most of the results given are also reported in the PhD Thesis of the third author.[1]

The authors are indebted to C. E. Wooldridge, Ralph Deitrick, and Norman Hawk for some of the experimental results.

INTRODUCTION

Several investigators[2,3,4,5] have reported anomalous effects of stream turbulence on the measured heat transfer near the forward stagnation point of blunt two-dimensional bodies. The integrated heat transfer rates, as well as the local values throughout the region of laminar boundary layer, showed large increases when the turbulence level in the stream was increased, even when the Reynolds number was well below the critical value for the rearward motion of the flow separation point.

A connection has been conjectured[5] between these measurements and the relatively high turbulence level near the stagnation point of a blunt two-dimensional body, as discovered by Piercy and Richardson[6]. They found in a wind tunnel of high turbulence level that the amplitude of the fluctuations near the nose of a streamlined strut reached a value about 4.5 times that in the free stream, and that the region of increased turbulence extended about 1/4 chord ahead of the body.

A detailed study of the boundary layer near the nose of blunt bodies of revolution, particularly with regard to transition at hypersonic speeds, is being undertaken at The University of Michigan. During the course of the preliminary low speed phase of the investigation, it was observed that velocity fluctuations greater in magnitude than those in the main stream occurred near the stagnation point.

Accordingly, the fluctuation field in the vicinity of the nose was studied in some detail. While the measurements of Piercy and Richardson[6] concerned two-dimensional bodies, the measurements reported here represent features of the three-dimensional counterpart of the fluctuation field they observed.

EQUIPMENT

The experimental results were obtained in the 5 x 7 feet low-turbulence tunnel and in the 8 x 13 inch supersonic tunnel at the University of Michigan.

The low-turbulence tunnel is of the closed return type with dimensions shown in Fig. 1. The air speed range is 0-270 ft/sec.

The supersonic tunnel is of the intermittent blow-down type; dry air at atmospheric pressure, stored in a collapsible container, discharges through the test section into manifolded evacuated tanks. The Mach number range is 1.4 to 5 with a maximum run duration of about 20 seconds. The measurements described here were made at a Mach number of 2.44.

Three axially-symmetric bodies, shown in Fig. 2, were used for the subsonic tests. They have hemispherical noses with diameters 20, 11.7, and 2 inches and fineness ratios 5.2, 6.3, and 17, respectively. The nose of the 20 inch model is of aluminum, the 11.7 inch is of wood and the 2 inch is of plastic. The afterbodies were fabricated of sheet metal and wood with steel re-enforcing. For the 20 inch model a heating coil was installed so that the forward 10^{o} could be heated to a few hundred degrees above room temperature.

The supersonic measurements were made with the same 2 inch sphere which had been faired for the subsonic measurements. The sphere was mounted on a sting 0.875 inches in diameter.

A Shapiro and Edwards model 50 four channel hot-wire anemometer system was used throughout the program for measurements of the mean and fluctuating velocities. The amplifier has nearly constant amplification in the range 1 to 20,000 cps.

A low-frequency wave analyzer with frequency range 1.6 to 160 cps, developed by M. S. Uberoi at the University of Michigan, was used for spectrum analysis of the hot-wire signal. For a few of the measurements the equipment was modified to reduce the frequency range by a factor of 10.

The hot-wires used had diameters of 0.0002 to 0.0004 inches and lengths 0.015 to 0.03 inches. Platinum wires were used during the early tests, but because of their short life at the higher subsonic and at the supersonic speeds, tungsten wires were used in the later phases.

Measurements of the turbulence in the nose region were made for the most part by means of a traversing unit shown in Fig. 3. The position of the wire could be adjusted in the radial, meridional, and azimuthal direction. The motion of the wire in the azimuthal direction was limited to about one inch, that in the meridional direction from near 0° to 63°, and that in the radial direction was ± 0.05 inches about a pre-set position.

RESULTS

Pressure Distribution. The pressure distribution was measured in the nose region of the 20" body and compared with that for an inviscid incompressible flow. The plot of the pressure coefficient is shown in Fig. 4.

Turbulence Contours. Contours of constant u'_s/u'_∞ , the ratio of the rms streamwise velocity fluctuations in the nose region of the 20" diameter body to that in the free stream, are shown in Fig. 5 for two Reynolds numbers.

Relatively high fluctuation levels were measured within 1^o of the model axis ahead of the stagnation point. These higher levels close to the axis are believed to have been caused by interference from the probe support. This conclusion is based on the sudden violent change in signal from a supplemental hot-wire located near the model surface at $\phi = -7^o$ when the primary survey hot-wire was brought within $+1^o$ of the model axis. The validity of the data near the axis is therefore considered doubtful and the turbulence contours in this region are shown as dashed lines in Fig. 5.

Turbulence near Surface at $\phi = 7^o$. Measured values of u'_s/U_∞ , the relative rms streamwise fluctuations, the surface of the three bodies at $\phi = 7^o$ are shown in Fig. 6*. The positions of the hot-wires in terms of radius of the body and boundary layer thickness are shown in Table 1.

The normalized energy spectra of the fluctuations at the positions designated in Table 1 and in the free stream are shown in Fig. 7. These were measured by the harmonic analyzer and used a constant bandwidth of 0.8 cps. The spectra at extremely low frequencies were measured with a much narrower band width but were corrected to 0.8 cps

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*These data and some of the spectrum and spatial correlation data given in the following paragraphs have been previously reported in reference 7.

bandwidth. The individual distributions were normalized so that

$$\int_0^\infty j \, d\,(n/U_\infty) = 1 \text{ ft.}^{-1}$$

where the relative energy in a given frequency band per unit n/U_∞ is $j\, {u'_s}^2/U_\infty^{\,2}$, with ${u'_s}^2/U_\infty^2$ given by Fig. 6.

These spectrum measurements were supplemented by measurements of the spatial correlation factors between the speed fluctuations at $\phi = \pm 7^\circ$ with both wires at the radial positions given in Table 1. The results are shown in Table 2 where

$$R = \overline{u_1 u_2}/u_1{}'u_2{}'$$

is the correlation factor. The subscripts refer to the responses of the respective wires. Most of the measurements were made with the frequency band $0.3 < n < 20{,}000$ cps, but for a few of them the upper cut-off was changed to 10, 100, or 1000 cps.

In addition to the subsonic tests, measurements of the correlation factor were made on the 2" sphere at Mach 2.44 in the supersonic tunnel. When the hot-wire response over the range 10 to 20,000 cps was used, the correlation was near zero. However, when those components with frequencies above 50 cps were suppressed, the correlation factor was -0.4. This result is entered in Table 2.

Effects of Model Mounting and of Flow over Afterbody. To determine if the high velocity fluctuation levels at the nose were influenced by the hot-wire support or by the model after-body configuration, a number of changes were made sequentially. Alternate hot-wire supports with widely different interference to the flow over the body gave no significant change in the fluctuation level. For purposes of reference, the 7° station on the 20-inch diameter model (see Table 1) was used for all speed conditions. Fluctuation levels and spectral energy densities of the velocity were measured at this point as changes were made to the model and its support system.

With the model mounting struts attached directly to the wood floor of the tunnel test section, a coupling between the tunnel and the model was first considered a likely cause of the high fluctuation levels near the nose. Therefore, the model mounting system was radically changed. A structure of steel 6" x 6" I-beams was fabricated to serve as the support for the model mounting struts. This I-beam structure was placed beneath the tunnel test section and supported on wood pads laid on the concrete floor of the wind tunnel building. This floor serves as the building foundation and is isolated from the tunnel structure. The streamlined model mounting struts passed from the support structure through holes in the test section floor to the model. The clearance between the struts and the floor was sealed with rubber sheeting.

Additional support was provided the tip of the model tail cone by three cables, one secured to the concrete floor and the other two to the steel beam structure of the wind tunnel building through shock cord links. These cables passed through holes in the test section walls without contact to form a "Y" support structure in a plane normal to the flow direction.

Test runs of the velocity fluctuations at the reference position with the new model mount gave velocity fluctuation levels essentially the same as those with the initial mounting system.

The possibility was next investigated that these fluctuations might be the result of aerodynamic feed-back from turbulent flow over the surface and in the wake of the model to the flow near the nose.

To determine whether the unsteadiness could be caused by unsteadiness of the laminar separation point near $\phi = 80^{\circ}$, fluctuations with the model in the "clean" configuration were compared with those utilizing a boundary layer trip wire extending peripherally around the nose surface at an angle ϕ of 60°. Velocity fluctuations were not significantly affected.

The possibility that fluctuations at the nose were being transmitted through the potential flow from the aft region of the model was explored with a major change to the model configuration. An annular metal shroud with a 12-inch chord and no camber was mounted with its trailing edge 3 inches ahead of the tip of the tail cone (see Fig. 4). Velocity fluctuations at the nose reference position were then measured with the shroud open and also with its annular opening completely closed. The latter configuration gave a bluff body type of wake visually shown by the violent action of wool tufts located on the rear part of the tail cone and the outside surface of the shroud. The effect these configuration changes had on the fluctuation level at the reference position was not significant.

Table 3 summarizes the velocity fluctuation levels for these changes in configuration. The variations in data for all configurations and velocities are within the range of reproducibility of the fluctuation level data.

The spectral energy distribution of the velocity fluctuations was also measured for the various configurations at three nominal free-stream velocities -- 50, 100 and 200 ft/sec. The results, shown in Fig. 8, show close similarity between the spectral distributions for the "clean" model, for the model with boundary layer trip and for the model with the different shroud configurations.

DISCUSSION

The first question to be answered with regard to the velocity fluctuations in the nose region of a body is: To what extent is their origin associated with the model mounting, with unsteadiness of the boundary layer transition point, or with the unsteady wake? The data given in Table 3 and in Fig. 8 demonstrate that the effects of these influences are within the experimental scatter of the hot-wire measurements. We therefore conclude that the characteristics of the turbulence field described by Figs. 5, 6, and 7 and Table 2 depend on the turbulence in the main flow, as influenced by Reynolds number and the nose shape.

Comparison of results given in Fig. 5 for two Reynolds numbers shows that the region in which the turbulence exceeds the free stream value extends considerably farther out from the body for the lower Reynolds number than for the higher.

It is interesting to interpret these regions of relatively high turbulence in terms of boundary layer thicknesses. The calculated boundary layer thicknesses, given by [9] $\delta/R = 2.26\sqrt{\nu/U_\infty D}$ (almost constant over the range $0 < \phi < 25^\circ$) are 0.0022 and 0.00155, respectively, for the lower and higher Reynolds numbers. The magnitude of the turbulence exceeds the free stream value in the layer out to about

$y/R = .04$ at $\phi = 7^{o}$ at both Reynolds numbers. Thus, at $\phi = 7^{o}$ the region of excess turbulence extends to 18δ and 26δ, respectively, at the lower and higher Reynolds numbers. At $\phi = 20^{o}$ the region of excess turbulence extends to 55δ ($y/R = 0.12$) and 40δ ($y/R = .06$), respectively, at the lower and higher Reynolds numbers. This latter comparison is probably significant, but at the 7^{o} position the contours are so close together that the difference between 18δ and 26δ is probably within the experimental error.

The data in Figs. 5 and 6 indicate that the amplitudes of low frequency components near the stagnation point are considerably higher than in the free stream turbulence. Further, the correlation factors given in Table 2 show that the major portion of the turbulent energy at $\phi = 7^{o}$ is identified with a random motion of the stagnation point. Peterson and Horton[10] also identified random motion of the stagnation point on the basis of pressure measurements at the nose.

The coupling of the fluctuations with the motion of the stagnation point was further demonstrated by another observation. When a cruciform arrangement of two perpendicular plates was fitted to the nose, thus fixing the stagnation point, the fluctuations at the 7^{o} position fell to a very low value. However, when new nose shapes, pointed or rounded, were fitted to the region $-2 < \phi < 2^{o}$, the magnitude of the fluctuations at the 7^{o} position was not substantially altered.

The data of Fig. 6 show that the rms value of the streamwise fluctuation at $\phi = 7^{o}$ is a function of the velocity and of model size. The fact that the magnitude of u'_s is greater than u'_∞ for all of the measurements is not significant because the lateral components in the free stream, v'_∞ and w'_∞ are each about twice u'_∞ and, further, near the nose there is a good possibility that energy transferred from v'_∞ and w'_∞ accounts for part of u'_s. For instance, a lateral component, if its scale is large enough, in effect tilts the incident airstream establishing a new stagnation point and thus changing its location relative to the hot wire; in this way energy is transferred from v'_∞ or w'_∞ to u'_s.

The inverse relationship between model size and u'_s shown in Fig. 6 agrees with that expected, since small scale turbulence will influence the flow over small diameter bodies to a greater extent than over large. In other words the flow field over a body of given diameter would be insensitive to small scale eddies in the incident flow but would approach that corresponding to a change in U_∞ for large scale eddies. We find, for instance, that the data given in Fig. 6 can be expressed by the relation

$$\frac{u_s'}{u_\infty'} D^{\frac{1}{4}} = 1.85 \text{ (ins)}^{\frac{1}{4}}$$

with an rms deviation of 4.5%. The scale of the free stream turbulence as shown by the spectra of Fig. 7, is independent of wind speed, and so does not occur in the above expression. More observations with different magnitudes and scales of free stream turbulence will be necessary to identify a quantitative description of the relationship.

The spectra of Fig. 7 indicate two interesting features. First, the normalized spectra near the nose scale with n/U_∞ (n is the frequency in cps), that is, with free stream wave number, independent of Reynolds number and relative scale of the turbulence. Second, the observations near the nose at a given U_∞ show a higher relative concentration of energy at low frequencies, compared with the free stream turbulence. The existence of this spectrum shift is consistent with the rationalization given above for the variation of the rms fluctuations with relative scale.

The correlation factor of -0.4 at $\pm 7^\circ$ on the 2" sphere at Mach number 2.44 (Table 2) was measured only after all frequencies above 50 cps were suppressed. This result indicates the presence in the supersonic airstream of relatively high frequency, positively correlated fluctuations, probably pressure waves. The negative correlation indicates that at supersonic as well as at subsonic speeds a random low frequency motion of the stagnation point occurs.

This stagnation point motion could be expected to influence the average heat transfer near the stagnation point. As was pointed out in the Introduction, measurements in several laboratories show that the local heat transfer rate to blunt bodies in supersonic flow reaches a maximum value a short distance from the stagnation point of the main flow[8]. It is to be expected that the rate would be nearly constant on the portion of the surface covering the excursions of the stagnation point, though why it should reach a maximum off the axis is unclear.

RESULTS

1. The turbulent field outside of the boundary layer near the nose of a blunt body in a low turbulence incompressible flow exhibits the following characteristics.

    a) The rms streamwise velocity fluctuations in the nose region are larger than those in the free stream. The region in which the ratio of the two rms values exceeds unity extends many boundary layer thicknesses out from the body. The region extends farther out at Re = 10^6. However, the fact that a Reynolds number based on the scale of the turbulence is different for the two sets of observations prevents a quantitative conclusion.

b) Large negative spatial correlation factors at $\phi = \pm 7^{\circ}$ indicate that the velocity fluctuations near the stagnation point are closely coupled with a random motion of the stagnation point.

c) The expression $D^{\frac{1}{4}} u'_s/u'_{\infty} = 1.85$, with an rms deviation of 4.5%, describes all of the observations. This result agrees qualitatively with the expectation that when the larger scale turbulence elements in the free stream pass over the body, their effect on the flow will be greater than for the smaller scale elements.

d) The normalized energy spectra at $\phi = 7^{\circ}$ scale with the free stream wave number. The observations cover a forty-fold range in Reynolds number and a ten-fold range in body diameter.

e) The normalized spectra of the fluctuations at 7° indicate a shift toward lower frequencies, compared with the free stream turbulence at the same U_{∞}. This shift is in qualitative agreement with the rationalization given under c.

2. A spatial correlation factor of -0.4 at $\phi = \pm 7^{\circ}$ on a sphere in a Mach 2.44 flow indicates a random relatively low frequency motion of the stagnation point similar to that found at low speeds.

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TABLE 1

HOT WIRE POSITIONS FOR

VELOCITY FLUCTUATION MEASUREMENTS

MODEL DIAMETER	ϕ	y	y/R	U_∞	δ(theory)	y/δ	$R_e = \frac{U_\infty D}{\nu}$
INCHES	DEGREES	INCHES	----	Ft/Sec	INCHES	---	x 10^{-5}
2.0	7^o	.034	.034	50	.0100	3.4	.52
				100	.0071	4.8	1.0
				200	.0050	6.8	2.1
11.7	7^o	.10	.017	50	.024	4.2	3.1
				100	.017	5.9	6.1
				200	.012	8.3	12.2
20.0	7^o	.17	.017	50	.031	5.4	5.2
				100	.022	7.6	10.4
				200	.016	10.7	20.9

TABLE 2

VELOCITY CORRELATION FACTORS FOR $\phi = \pm 7^{\circ}$ FROM NOSE

D ins.	U ft/sec	$R(u_1, u_2)$	Band Pass $cps < n < cps$
2.0	125	- .91	$1 < n < 20,000$
	125	- .94	$10 < n < 20,000$
	125	- .90	$100 < n < 20,000$
	125	small but negative	$1,000 < n < 5,000$
	M = 2.44	small but positive	$10 < n < 20,000$
		- .40	$1 < n < 50$
11.7	48.4	- .77	$1 < n < 20,000$
	94.4	- .84	$1 < n < 20,000$
	198	- .65	$1 < n < 20,000$
20	49	- .79	$1 < n < 20,000$
	98	- .65	$1 < n < 20,000$
	206	- .72	$1 < n < 20,000$
	173	- .75	$100 < n < 20,000$

TABLE 3

EFFECT OF CHANGES IN MODEL CONFIGURATION ON THE VELOCITY FLUCTUATION LEVEL, u_s'/U NEAR THE NOSE OF A 20-INCH DIAMETER HEMISPHERICAL NOSED MODEL AT $\phi = 7^o$, $y = 0.17''$.

NOMINAL FREE STREAM VELOCITY

MODEL CONFIGURATION	50 FPS u_s'/U %	100 FPS u_s'/U %	200 FPS u_s'/U %
CLEAN	.033	.059	.092
	.033	.062	.100
	.037	.064	.110
	.042		
.073-INCH TRIP WIRE at $\phi = 60^o$	----	.051	.102
12-INCH CHORD SHROUD OPEN	.037 .038	.066	.110
12-INCH CHORD SHROUD BLOCKED	.038	.061	.105

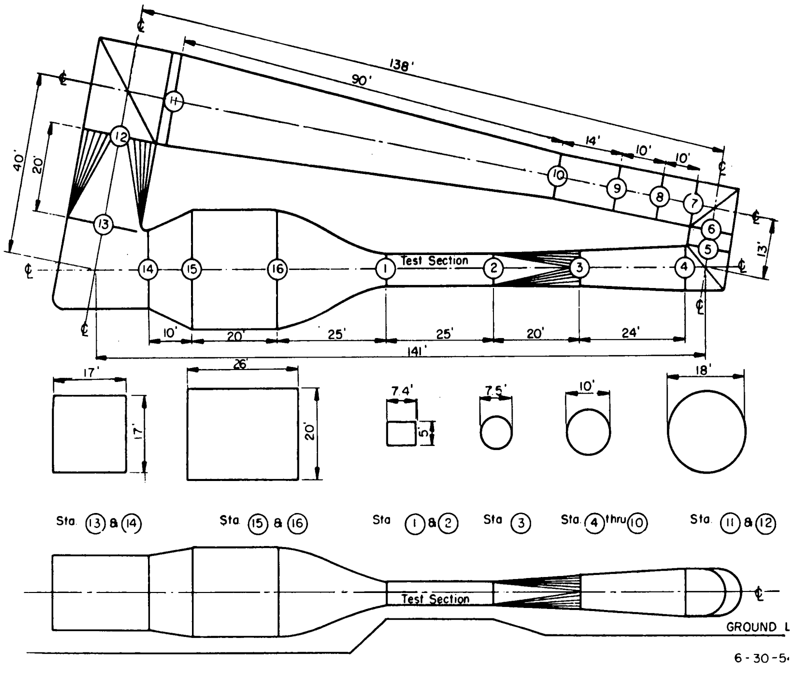

Fig. 1. Drawing of the Low Turbulence Wind Tunnel at the University of Michigan. Six screens are located between stations 14 and 16.

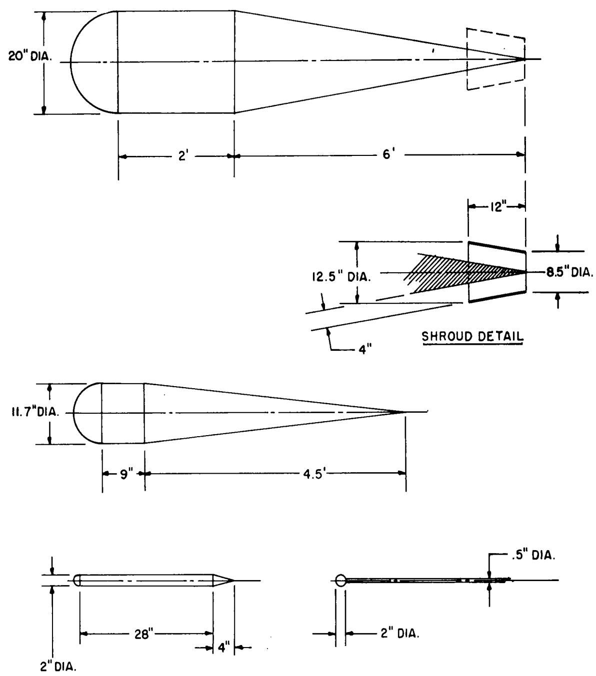

Fig. 2. Bodies of Revolution used in the Investigation. Details of the shroud used in attempt to eliminate or intensify movement of the stagnation point. Model at lower right was used in supersonic test.

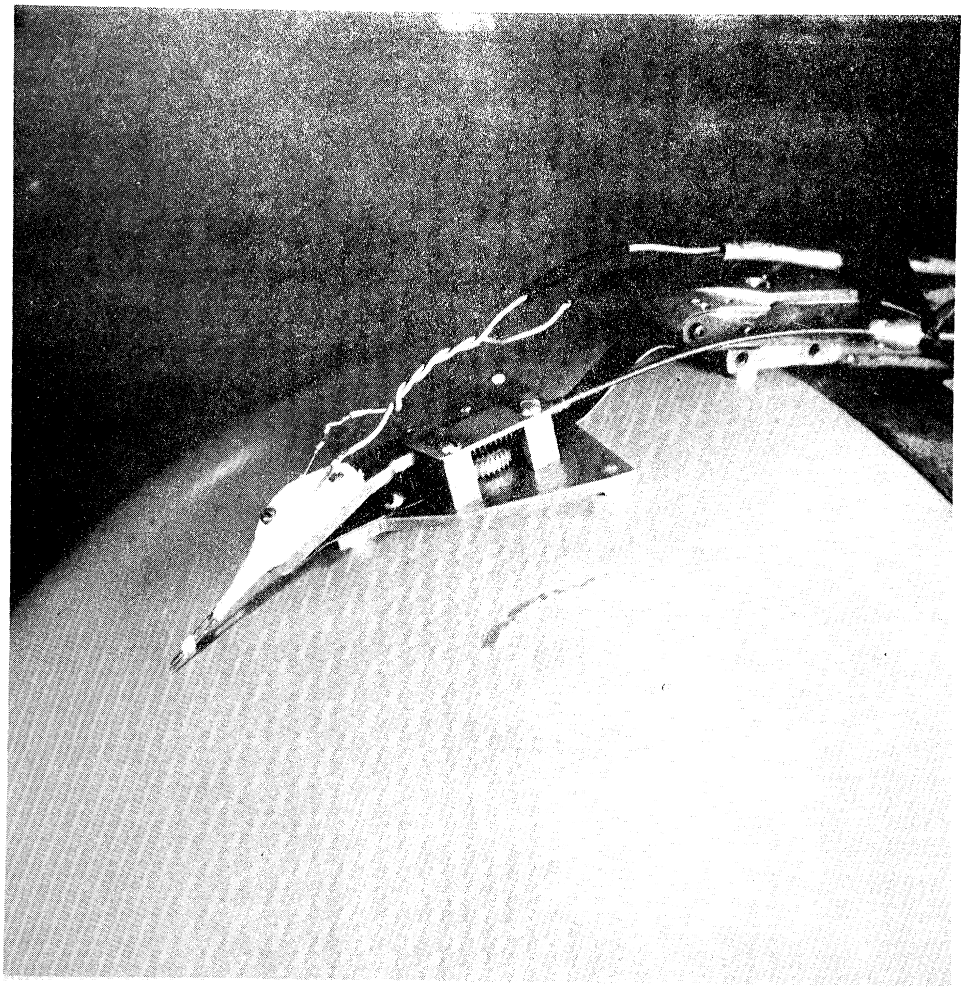

Fig. 3. Photograph of the hot-wire traverse head

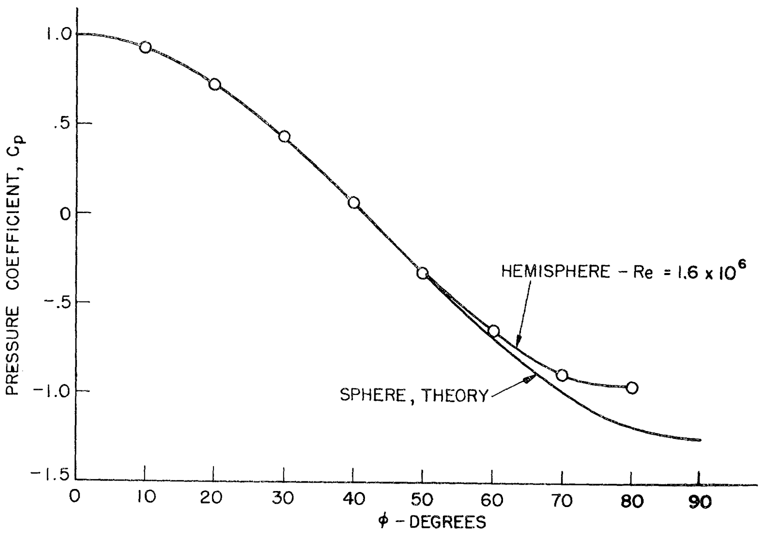

Fig. 4. Pressure distribution over nose of 20" diameter body

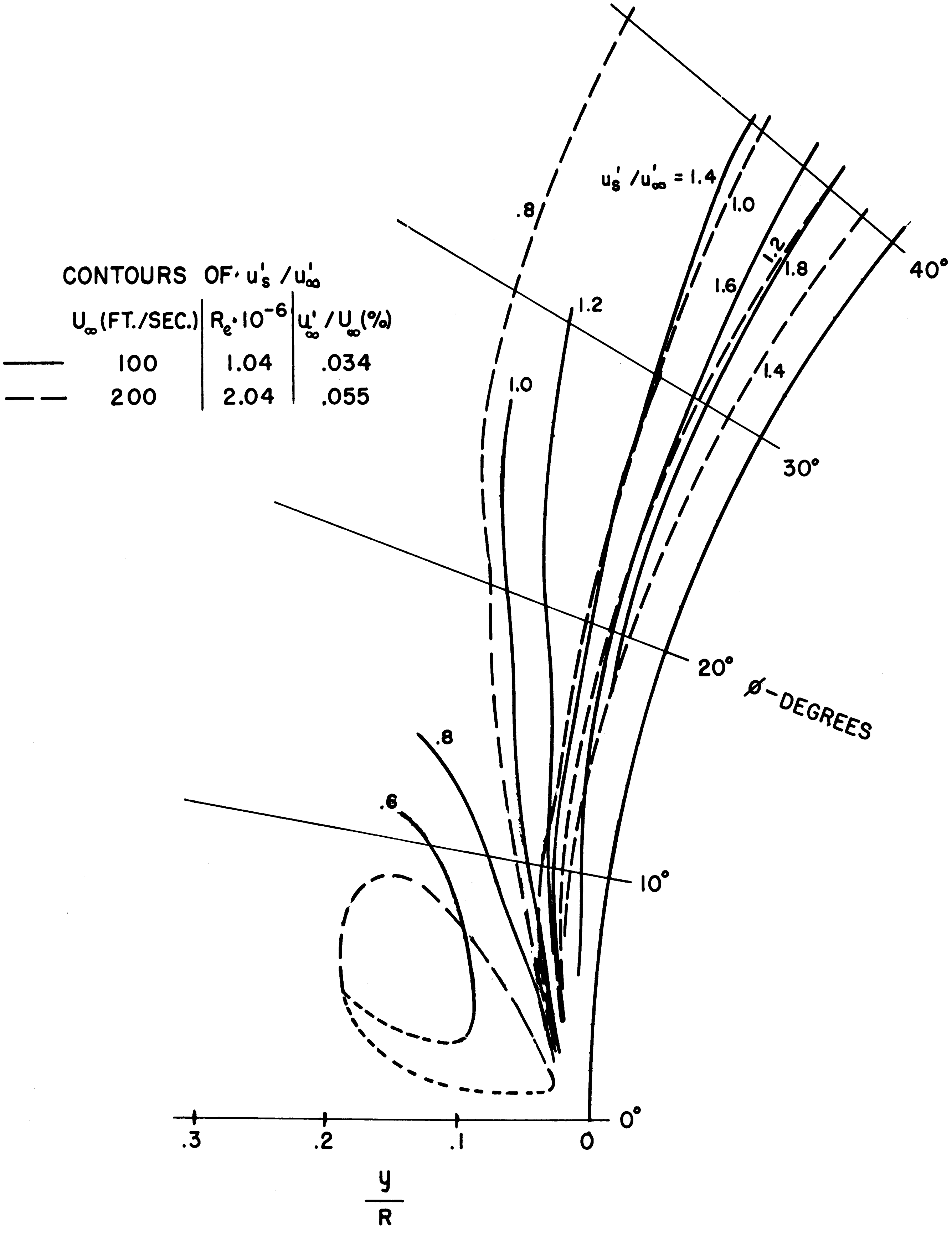

Fig. 5. Contours of equal ratio of local streamwise fluctuation in the nose region of the 20 in. diameter body.

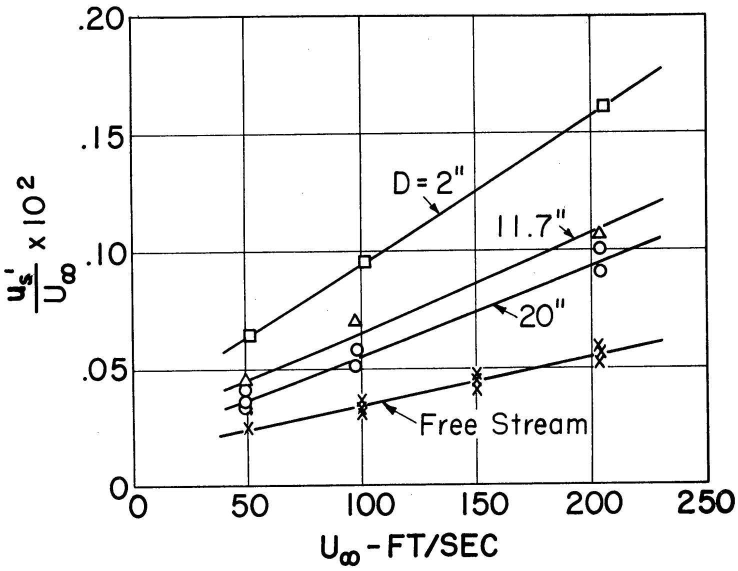

Fig. 6. Root-mean-square streamwise fluctuations at 7° from nose outside of boundary layer as function of body diameter and air speed. See Table 1 for distance of hot-wire from body surface.

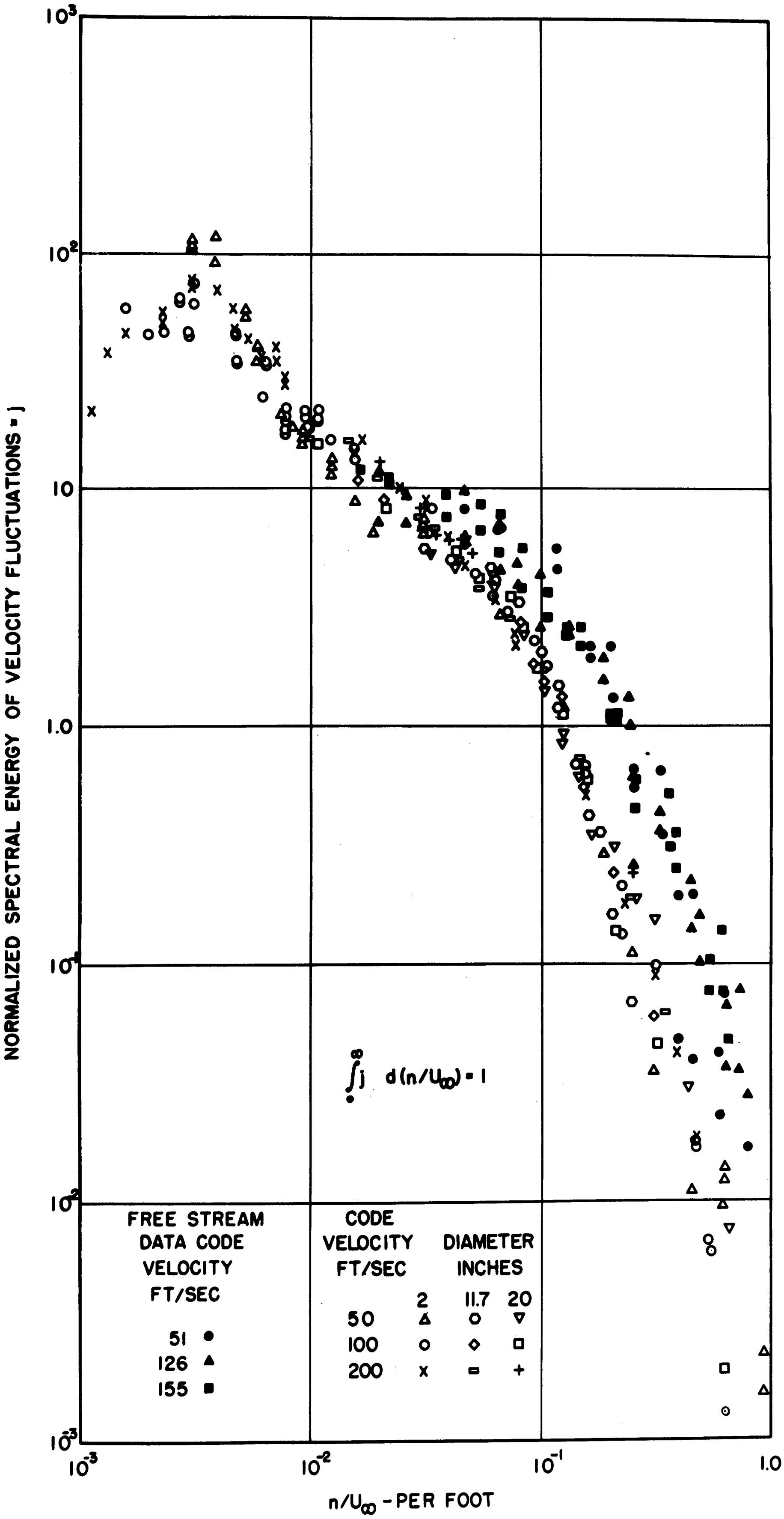

Fig. 7. Normalized spectral energy of velocity fluctuations at 7° from nose.

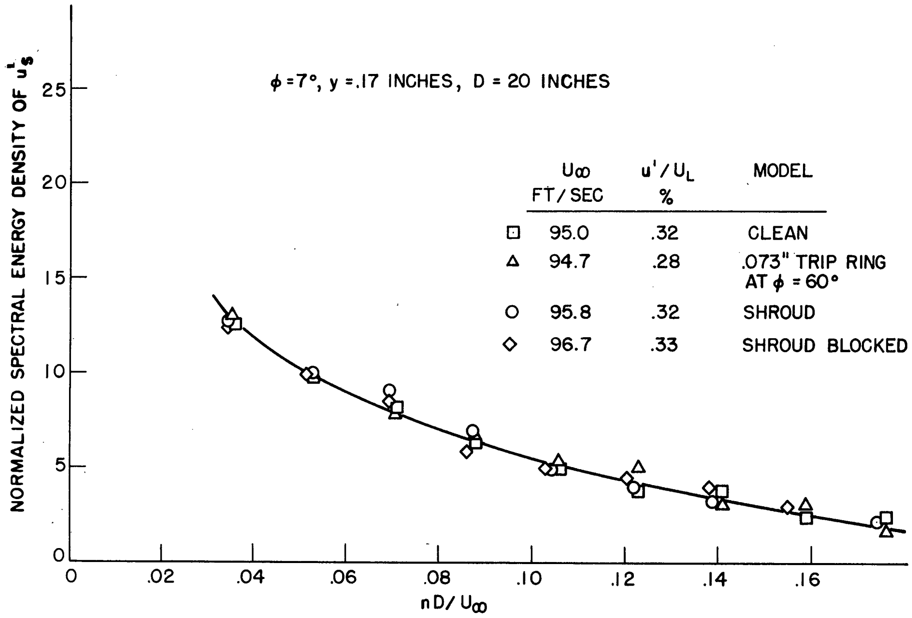

Fig. 8. Normalized spectral energy of velocity fluctuations at 7° from nose on 20 in. diameter body with various flow disturbances.

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