NOISE GENERATION BY SHOCK-TURBULENCE INTERACTION

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GTL Report No. 102 October 1970

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ABSTRACT

The noise produced by convection of turbulence through an oblique shock wave has been measured and compared to theoretical predictions by Ribner and Kerrebrock. There is excellent agreement with the theoretical prediction that, for a fixed turbulent input, the downstream noise pressure (divided by the mean pressure), should first increase very rapidly, and then decrease as the normal Mach number of the shock is increased from unity to values of the order of 1.5. This behavior implies that a part of the noise from supersonic jets should behave similarly, with a sharp increase, then a decrease as the nozzle pressure ratio is raised from unity.

ACKNOWLEDGEMENTS

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INTRODUCTION

It has been recognized for some time that the convection of turbulence through shock waves should lead to the production of sound downstream of the shocks, and that this mechanism might be significant in the overall production of sound by supersonic jets. Lighthill[1] and Ribner[2] carried out linearized calculations of the interaction of a plane shear wave with a shock, and Moore[3] analyzed the interaction of oblique sound and vorticity waves with a shock. Ribner[4] applied the shear wave results to the interaction of turbulence with a normal shock.[4] Kerrebrock[5] carried out interaction computations for entropy and sound disturbances, generalizing the treatment to apply to oblique shocks. Chang has also considered entropy inputs,[6] and Ribner [7] has recently computed the energy flux from shock-turbulence interactions.

In spite of these several predictions of a strong source of noise, no experimental verification of the linearized approach, or of other critical features of the models, has been available. The statistical treatments of Refs. (4) and (5), treat an infinite shock interacting with turbulence which is homogeneous and isotropic. One may well ask to what extent these calculations can be used to estimate noise levels from finite shock systems. The theories predict a rather surprising one fourth power dependence of the downstream sound intensity on the difference between the shock velocity ratio and unity, implying a very rapid increase in sound intensity as the normal Mach number of the shock increases from unity. The goal of this experiment was to provide an experimental test of this result. This has been done by measuring the downstream sound intensity produced by convection through oblique shocks, of turbulence produced by various wire screens.

The experiments bear most directly on shock turbulence interaction, but as we shall see, some information about sound amplification by shocks has also been obtained.

EXPERIMENTAL PROCEDURE

The difficulties of wind tunnel noise measurements are so well known that a rather detailed description of experimental technique seems in order.

We note first that ideally one would like to measure the intensity and the statistical properties of the upstream turbulence field, as well as the intensity and statistical properties of the noise field, and compare the results to theoretical prediction. In view of the difficulty of measurement of turbulence in the supersonic flow, the experiment was limited to a determination of the variation of noise intensity with shock strength alone, for a fixed turbulent input. Thus we do not have the possibility of checking the theoretically predicted sound amplitude in relation to the turbulence intensity, and in this sense the test of the infinite-shock approximation is somewhat unsatisfactory.

Apparatus:

The supersonic wind tunnel of the M.I.T. Gas Turbine Laboratory was used for the experiments. The Mach number 2 test section has a cross section 8 by 8 inches, with a useful flow length of about 12 inches.

A shock generator consisting of a flat plate with a sharp leading edge was mounted in the test section, as shown in Fig. (1). By means of cams, the wedge angle θ between the plate surface and the flow direction could be changed continuously during a run, thus varying the normal Mach number of the oblique shock wave over the range from 1 to 1.5. The shock and wedge angles were measured optically, by means of a projection lamp casting a silhouette of the shock generator and the shock on a translucent ground glass plate. A photograph of this configuration was taken, for each data point, from which the shock and wedge angles were determined.

The intensity of noise downstream of the shock was measured by a Kulite pressure transducer (Model number CQL-070-4), mounted in the shock generator about one inch from its leading edge at mid-span. It was mounted in a metallic sleeve with silicone rubber. The sleeve was then inserted in the plate so that the probe face was flush with that of the shock generator. The leads of the probe were led through concentric silver braided shielding and 1/8" thick rubber tubing to the wind tunnel wall. To stiffen this lead, a thick flexible braided tubing was used to encase the rubber tubing. The output from the probe was first fed to a Dresser transformer which filtered out the low frequency and in particular 60 cps electrical noise. The signals were then passed through an Ithaco amplifier set at a gain of 90 db. The amplified signals were finally filtered by a Kronhite band pass filter with high and low roll-off frequencies set at 10,000 and 1,000 Hz respectively. The output from the band pass filter was then read out on a Flow Corporation root-mean-square meter and wave analyzed by a Tektronix Spectrum Analyzer.

Input Disturbances:

There is of course a fairly high background sound level in the tunnel, produced by the compressor, by turbulent boundary layers on the tunnel walls etc. In order to obtain meaningful measurements of the sound produced by shock turbulence interaction, its amplitude must be large compared to this background. Furthermore it must be large compared to the background disturbances as amplified by the shock. In order to ensure that this was the case, a careful study was made of the noise levels measured on the shock generator in the absence of upstream turbulence, for the full range of shock strengths to be studied.

Turbulence was then induced by a number of methods. Initially, a pair of cylindrical rods was placed across the channel just upstream of the throat ($M = 0.65$). Their diameter was either 5/16 or 5/8 inch, giving two frequencies. There was however, some question about the approach to isotropy of the turbulence produced by these bars. Accordingly they were replaced by wire meshes, with wires of .025 inch diameter. Three mesh arrays were used to produce three different input intensities. The first was a single square mesh of 3/8 inch spacing. The second consisted of two such meshes staggered, and the third was a single mesh of 1/8 inch spacing. Most of the results to be discussed below were obtained with these wire meshes as turbulence producers.

The question arises, as to what extent the disturbance field of the wires or other obstacles is turbulence, and to what extent sound. The "Aeolian Tones" produced by vortex shedding from the wires could be of such intensity as to mask the sound produced by shock turbulence interaction. To provide at least a partial answer to this question, the rods were inserted part way across the channel, in such a fashion that convected disturbances from them would not be carried through the shocks for small amounts of insertion, whereas for larger amounts they would be, resulting hopefully in a sharp change in intensity with rod immersion. The pressure disturbances, on the other hand, would be expected more or less to fill the channel, giving a more gradual change with rod immersion although, because the dipolar character of the shed vortex field, the sound would not be isotropic. As we shall see, the behavior was nearer the former (convected) case, so we are fairly confident that we have indeed measured shock turbulence interaction.

RESULTS AND DISCUSSION

Background Noise and Sound Input:

The variation of transducer output, amplified 90 db and filtered as noted above, with shock generator angle, in the absence of turbulence producers, is shown in Fig. (2). There is general increase with θ, but superimposed on the general trend is a distinct maximum at $\theta = 10°$. This maximum was quite reproducible, as indicated by the two sets of data taken at different times.

We note first that there are at least two possible explanations for the general trend of increase with θ. One is that the background noise of the tunnel was amplified by the shock. Another is that the probe measured noise produced by the boundary layer on the shock generator.

Consider first the former explanation. Kerrebrock[5] has given a statistical theory of amplification of upstream sound by an oblique shock. His results are given in terms of transfer functions relating the intensity of sound downstream of the shock to the intensities of various disturbances upstream of the shock, the disturbances all being assumed sotropic and homogeneous. Thus

$$\overline{(\frac{p}{P})^2_2} = \overline{(S_p^v)^2}\ \overline{(\frac{U1v}{V})^2_1} + \overline{(S_p^s)^2}\ \overline{(\frac{s}{c_p})^2_1} + \overline{(S_p^p)^2}\ \overline{(\frac{p}{P})^2_1}$$

where 1 denotes the region upstream of the shock and 2 that downstream. Here U and Ulv are the mean and perturbation velocities normal to the shock, and P is the mean pressure. The transfer functions $\overline{(S_p^v)^2}$, $\overline{(S_p^s)^2}$ and $\overline{(S_p^p)^2}$ relating the downstream pressure field to the upstream turbulent, entropy and sound fields are reproduced in Fig. (3). The parameter m is the velocity ratio across the shock. From the value of $(S_p^p)^2$, a theoretical increase in downstream sound intensity due to amplification of upstream sound is predicted as shown in Fig. (4). In plotting this curve the value of $\overline{(p/P)^2}$ was taken as the mean square pressure measured at the plate for $\theta = 0$. The agreement with experiment is good, except for angles near 10°, but this result must be viewed with suspicion. The range of M_n covered by the data encompasses a range of m from 1 to about 2. Over this range, we see[Fig. (3)]that $\overline{(S_p^p)^2}$ ranges from 1 to about 0.7. Thus, the two fold variation of mean square sound pressure shown in Fig. (4) actually corresponds to only about 30 percent variation in the ratio of the pressure perturbation at the plate to mean pressure there.

This suggests the alternative explanation, that the transducer was actually measuring at least in part the pressure fluctuations due to a turbulent boundary layer on the shock generating plate. One would then expect $(p/P)^2$ to be about constant, if the boundary layer were fully turbulent. Such a dependence is shown as the dashed curve on Fig. (4). Although it does not give as good an overall fit as the amplification theory, it fits the slope for $M_n > 1.3$ better. Furthermore the boundary layer noise hypothesis offers an explanation for the maximum at $\theta = 10°$. Supposing that transition occurs between the leading edge and the transducer for $\theta > 12°$, and after the transducer for $\theta < 7°$, the hump may be due to the passage of transition over the transducer as the Reynolds number increases with increasing θ. The Reynolds number at the probe location was 2.5×10^4 for $\theta = 10°$. This is a little low for transition. On the other hand, the leading edge and surface of the plate were somewhat rough. To check this point, the boundary layer was tripped with small strips of tape and by roughening the surface, with the results shown in Fig. (5). The local maximum at $\theta = 10°$ seems to have been removed, and the correspondence with a pressure fluctuation equal to a fixed fraction of the mean pressure is quite good.

On this basis, we tentatively conclude that the data of Figs. (2) and (4) represents shock amplification of upstream sound for $\theta < 7°$ ($M_n < 1.2$) and boundary layer noise for $\theta > 12°$ ($M_n > 1.3$). In the first range, the agreement with the theory of Ref. (5) is satisfactory, but the range of variation is too limited to give a good verification.

A second conclusion is that the noise levels produced by both of the above mechanisms are small compared to those produced by the shock-turbulence interaction.

Turbulent Input Disturbance:

The signal levels found using the various screens as turbulence generators, are given in Fig. (6), with the wedge angle of the shock generator as parameter. We note first that the signal is about twice the largest found in the absence of the turbulence generators. Supposing that this (rms) signal represents the sum (p_t) of the background noise described above (p_p) and the noise produced by shock-turbulence interaction (p_v), and that the two are uncorrelated,

$$(\overline{p_t^{\,2}})^{\frac{1}{2}} = [\overline{(p_v + p_p)^2}]^{\frac{1}{2}} = [\,\overline{p_v^{\,2}} + \overline{p_p^{\,2}}\,]^{\frac{1}{2}} \simeq (\overline{p_v^{\,2}})^{\frac{1}{2}}\,[\,1 + \tfrac{1}{2}\,(\overline{p_p^{\,2}}/\overline{p_v^{\,2}})]$$

Since $\overline{p_p^2} \,/\, \overline{p_v^2} \leq 1/4$, the error made by interpreting the total pressure fluctuation as that due to turbulence is at most about 10 percent.

The data of Fig. (6) clearly show the effect of varying the input turbulence level, with the coarser mesh giving the higher level. They have been normalized with respect to their individual levels at $M_n = 1.45$, and plotted versus the normal Mach number in Fig. (7). The theory of Ref. (5), also normalized to fit at $M_n = 1.45$ is presented for comparison.

Apparently the agreement is excellent, for $1.02 < M_n < 1.5$. Bearing in mind that the mean pressure on the plate rises by about a factor of two for $1 < M_n < 1.5$, so that $\overline{(p/P)_2^{\,2}}$ is actually <u>decreasing</u> as the shock strength increases, we take the agreement in the range $1.02 < M_n < 1.5$ as a rather conclusive verification of the theory. There is an apparent disagreement, in that the noise did not drop rapidly to zero (or a low value) for $M_n < 1.02$, as predicted by the theory, but careful observation of the shock structure showed that the shock did not disappear as the wedge angle approached zero, apparently because of imperfections of the leading edge. Nor was it possible to remove the shock by rotating the plate to negative θ, because the resulting blockage of the passage, between the plate and the tunnel wall, generated a shock which passed over the leading edge.

There remains the question, whether the observed noise is due to turbulence or the associated sound produced by the screens. As noted above, it was resolved by partially inserting a pair of rods, as shown in the sketch on Fig. (8). As the inner end of the rod passed into the streamlines which intersected the shock above the transducer, an increase in noise was measured, with the final value, for complete immersion, comparable to those found with the screens. The transition should not be sudden, because the transducer does receive sound from an extended portion of the shock at any one time, but it should not be influenced at all by points of the shock the cone of influence (characteristics) of which do not include the transducer.

CONCLUDING REMARKS

We conclude, then, that the data of Fig. (7) do represent noise produced by shock-turbulence interaction, and that the agreement between theory and experiment gives a conclusive verification of the prediction that the noise should increase sharply for shock normal Mach number very near unity, then remain nearly constant, or in fact decrease if normalized to the mean pressure.

This behavior has important implications for the production of noise by supersonic jets. It suggests that, if shock turbulence interaction is an important noise source, the noise should rise abruptly first as shocks, even though very weak, appear in the jet. The noise from this source should then decrease as the shocks become stronger, and finally increase again for very strong shocks.

Some results of the theory remain unverified. One of the more interesting is that, for a given turbulent input, the frequency of the sound downstream of the shock should initially increase rapidly from zero, as the normal Mach number of the shock is increased from unity, then become nearly constant for strong shocks. As this change occurs in the range $M_n < 1.02$ where the present results were confused by leading edge imperfections, it was not possible to check it here. A quantitative verification of the magnitude of $\overline{S_p^v}$ and $\overline{S_p^s}$ is also needed, but these require measurements of turbulence and entropy in supersonic flows.

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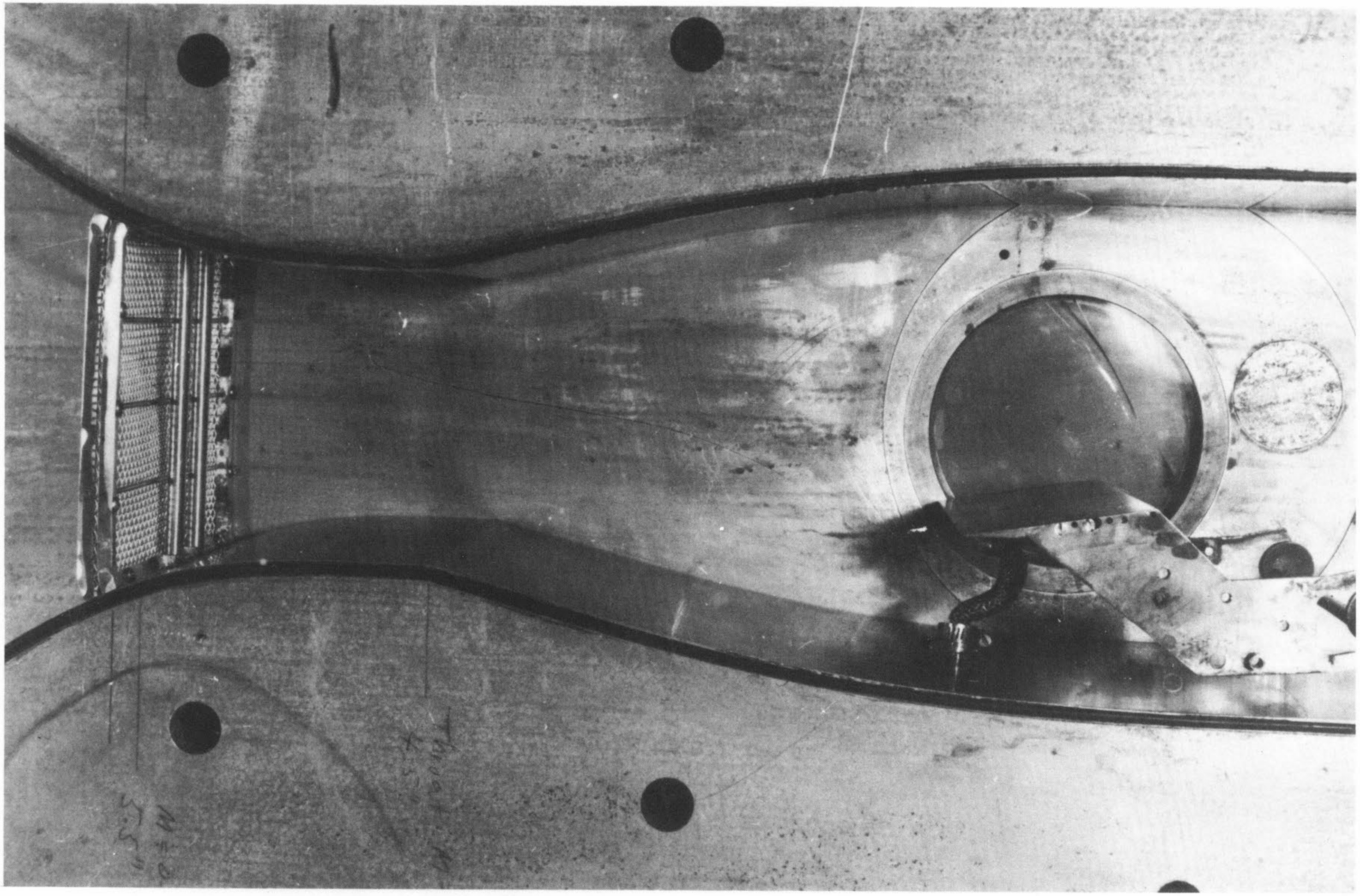

Figure 1

Wind tunnel test section with turbulence producing screen, shock generator, and transducer.

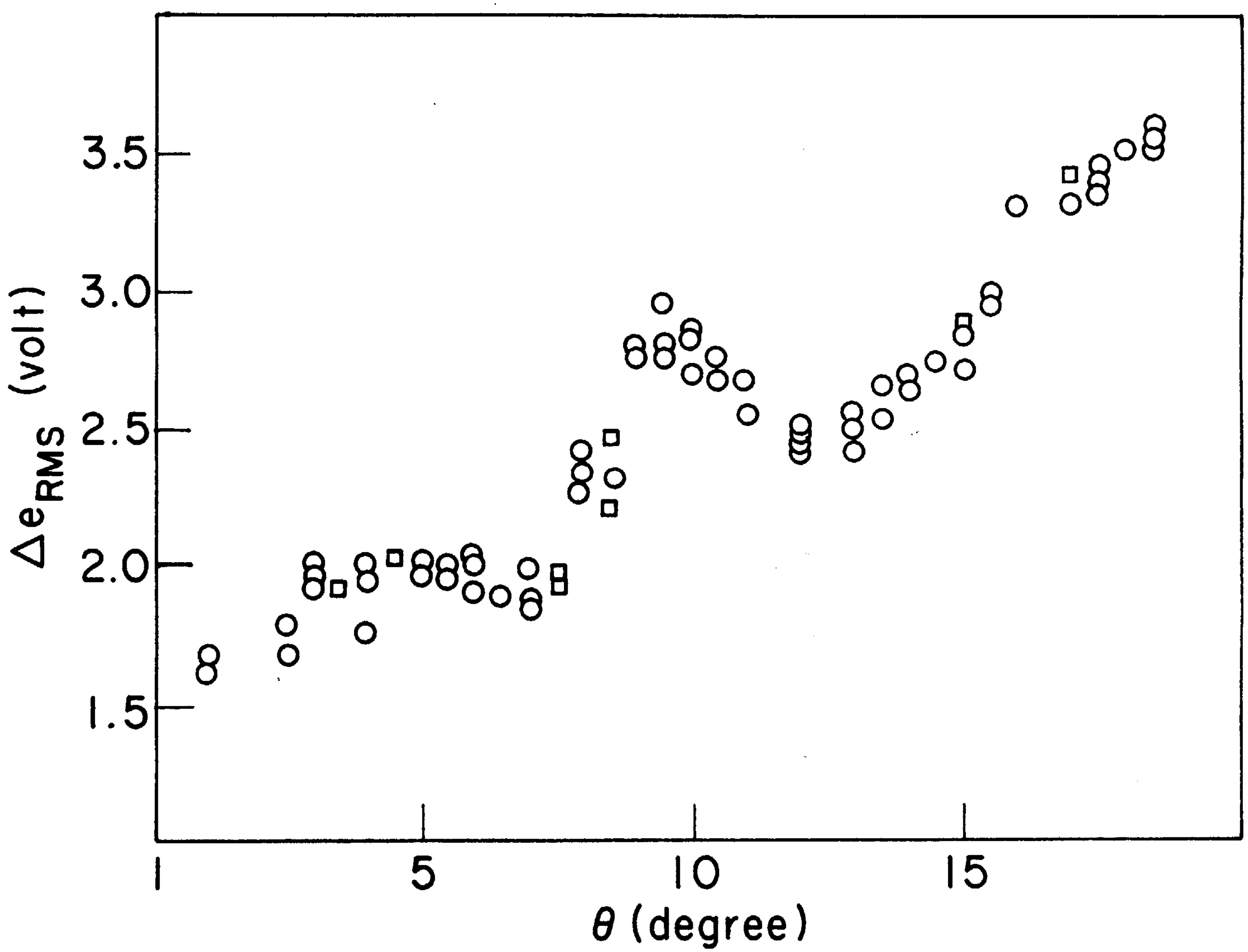

Figure 2

Transducer signal output as a function of wedge angle θ without turbulence.

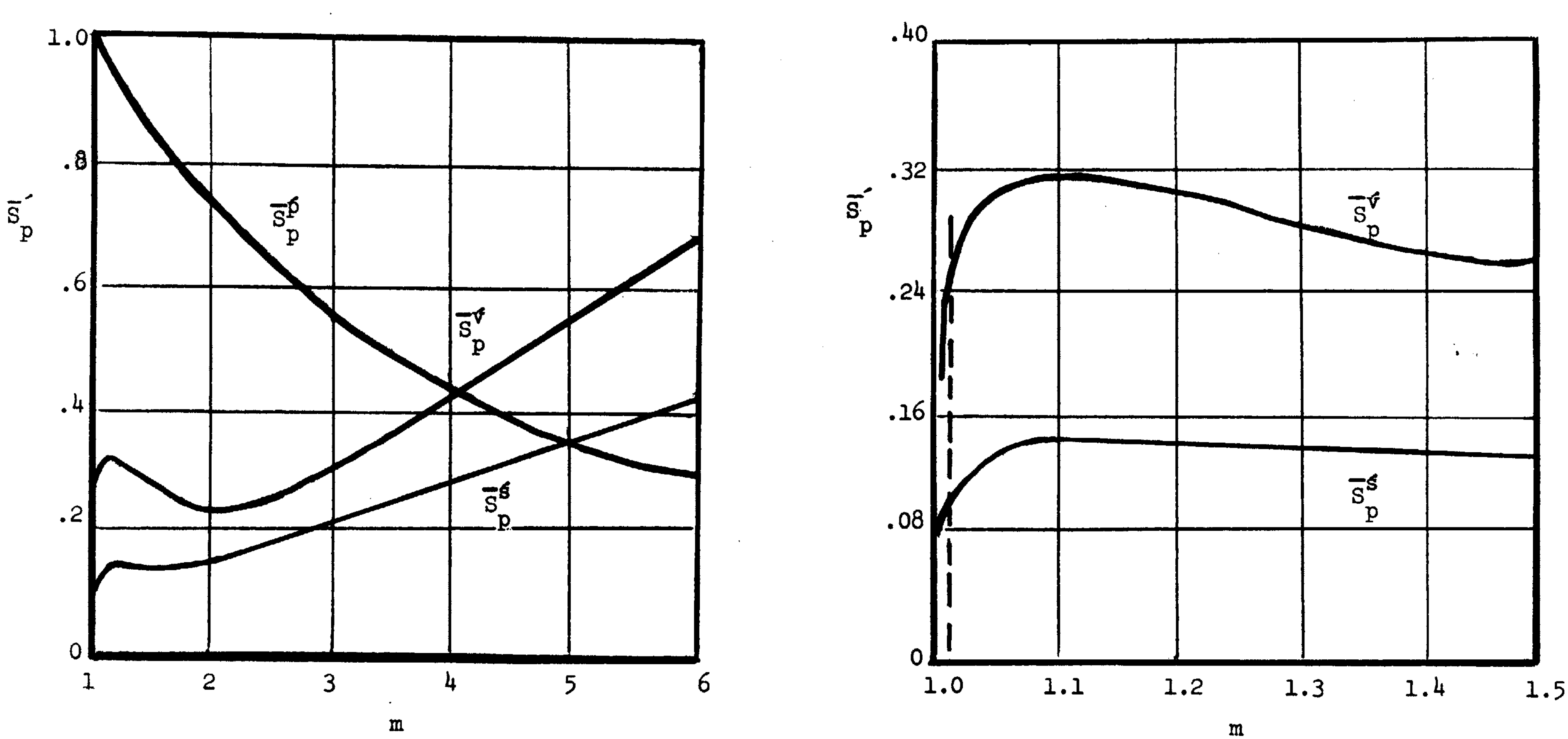

Figure 3

Average transfer functions for downstream sound pressure resulting from interaction of shock wave with pressure, vorticity, and entropy disturbances. Ref.(5).

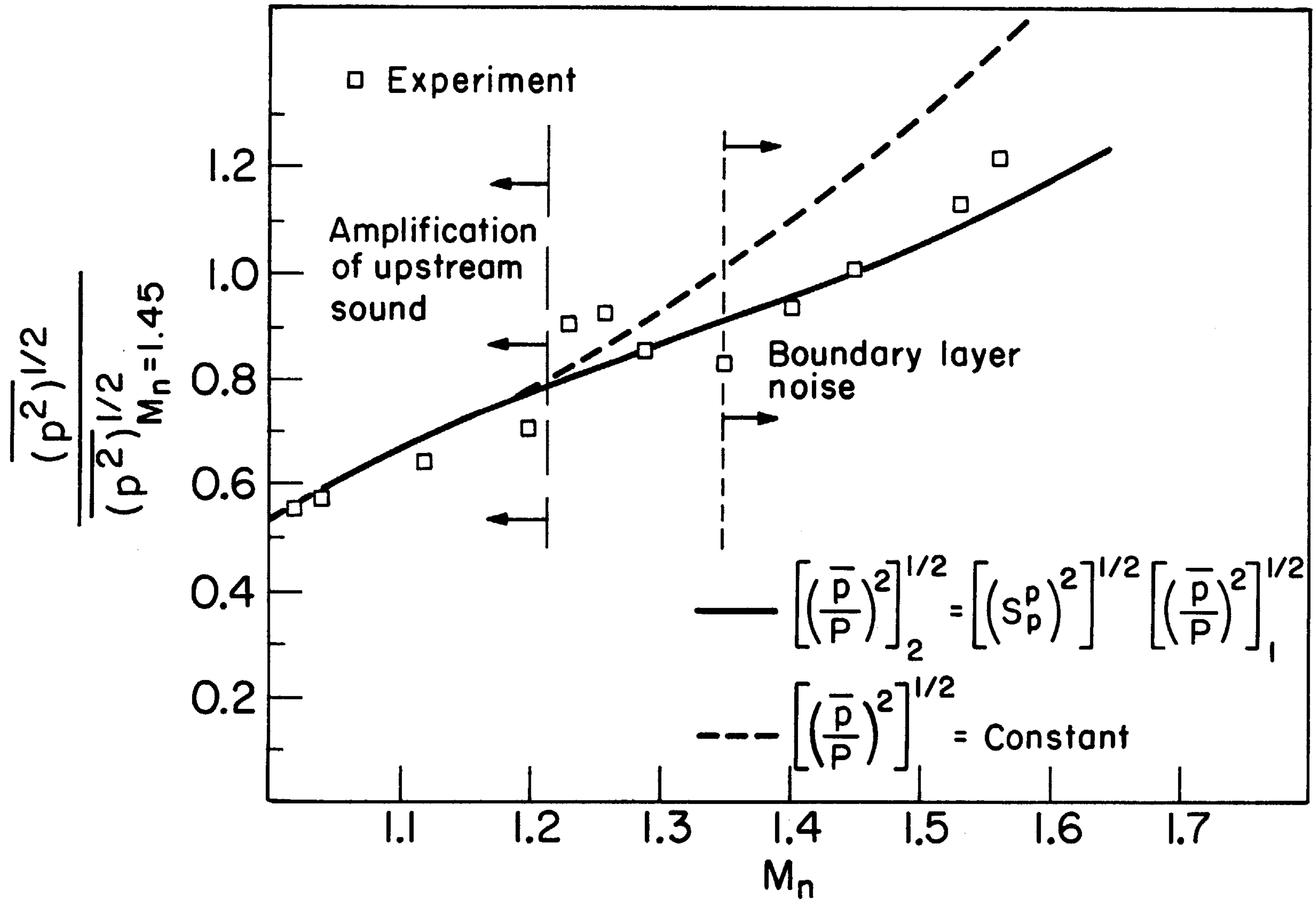

Figure 4

Normalized pressure fluctuation as a function of normal Mach number without turbulence.

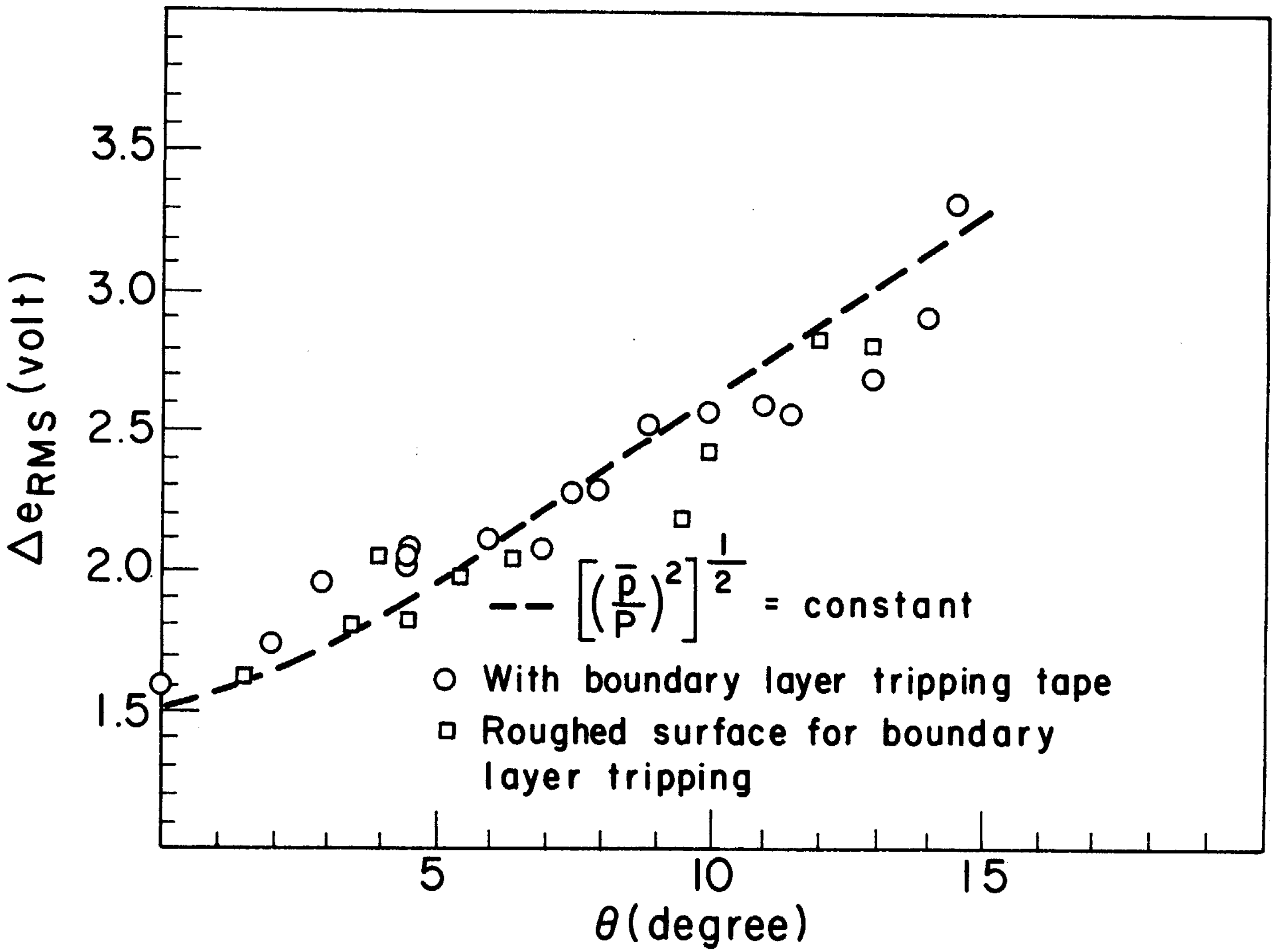

Figure 5

Transducer output as a function of wedge angle θ, with boundary layer tripping ahead of probe.

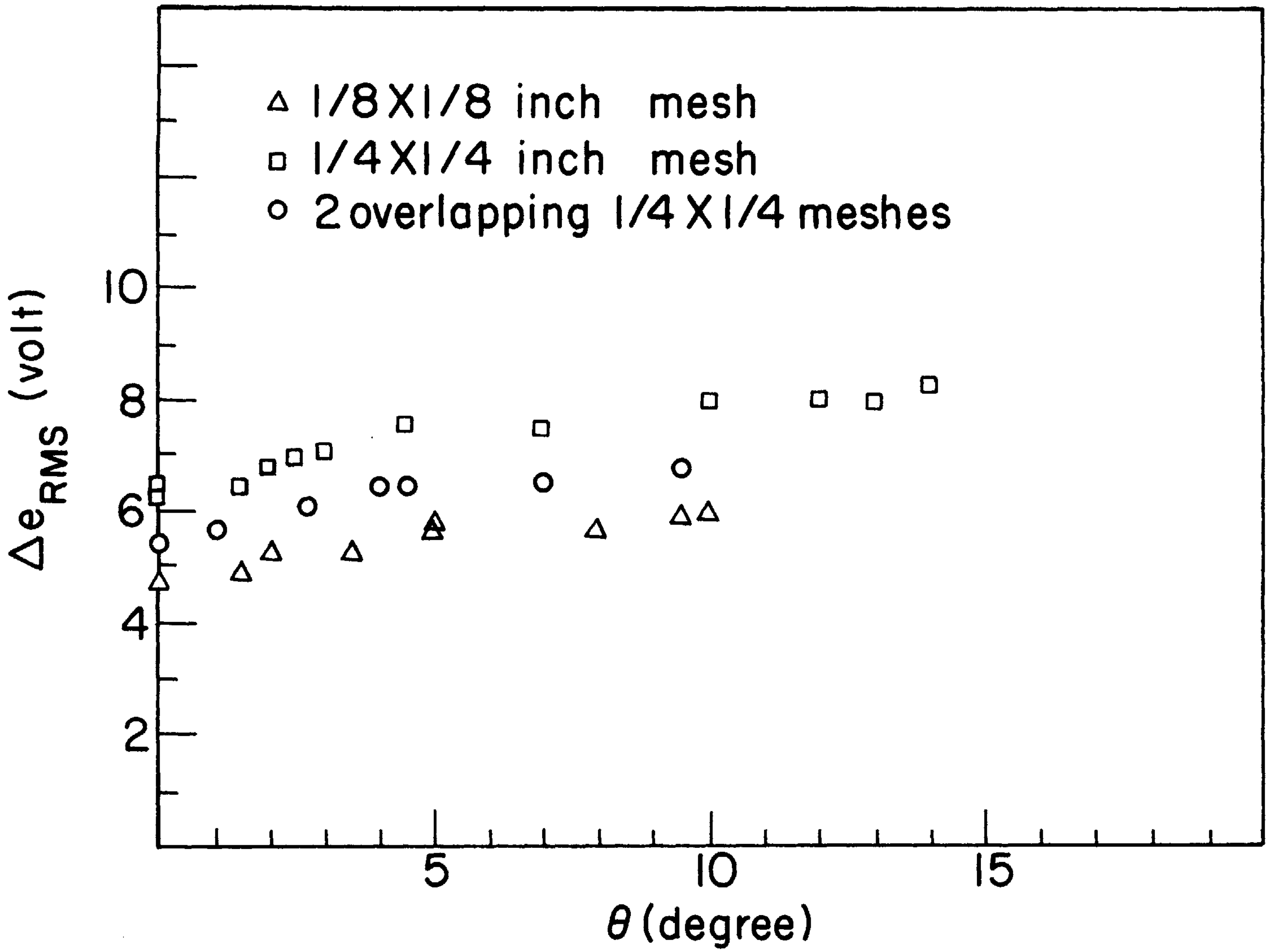

Figure 6

Transducer output as a function of wedge angle θ for turbulent input.

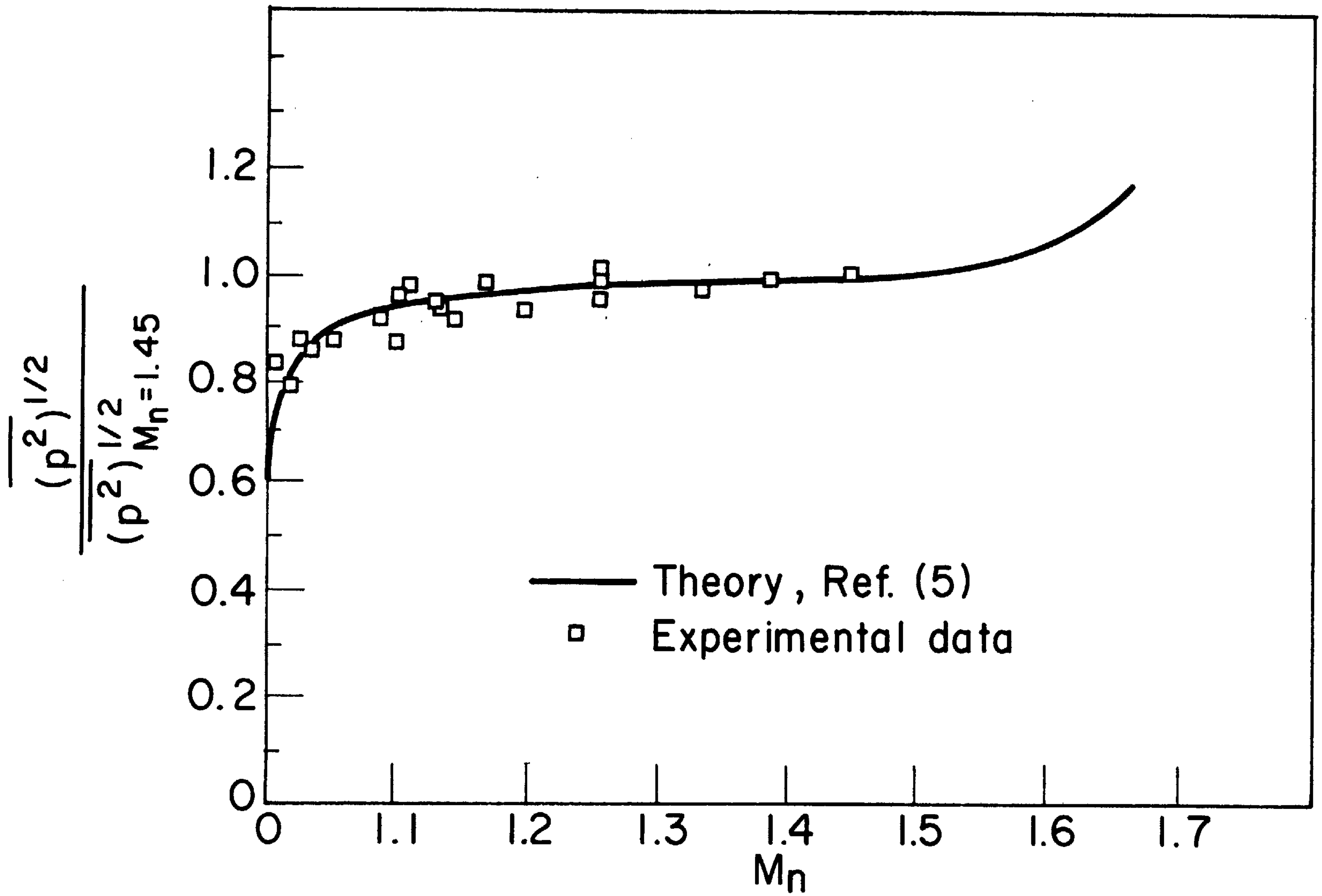

Figure 7

Normalized pressure fluctuations as a function of normal Mach number for turbulent input, compared to the theory of Ref. (5).

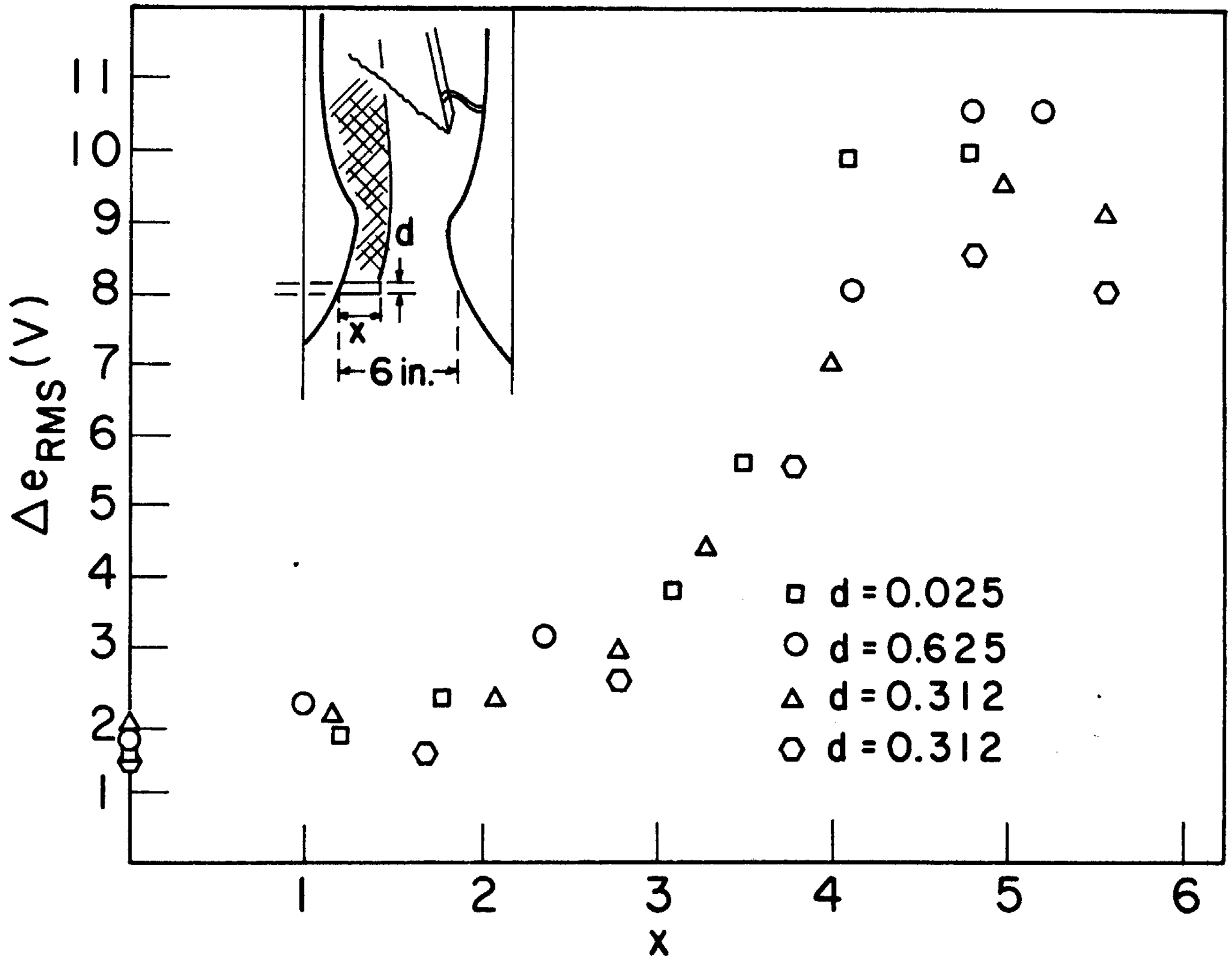

Figure 8

Transducer output as a function of rod immersion.