WYLE LABORATORIES - RESEARCH STAFF

TECHNICAL MEMORANDUM 68-5

AN EXPERIMENTAL PROGRAM FOR THE INVESTIGATION OF SHOCK-TURBULENCE INTERACTION PHENOMENA

WYLE LABORATORIES

TESTING DIVISION, HUNTSVILLE FACILITY

research report

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AN EXPERIMENTAL PROGRAM FOR THE INVESTIGATION OF SHOCK-TURBULENCE INTERACTION PHENOMENA

By

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SUMMARY

This report outlines a series of experiments designed to examine the production of acoustic waves in the interaction of a shock wave and a turbulence environment. The approach is divided into five stages: apparatus design; development of instrumentation, in particular, hot wire and fluctuating and static pressure probe systems; a preliminary experiment to observe the interaction and try out the instrumentation; selection of a suitable turbulence generator; and finally conduct of the main experiment. Possible experimental difficulties are discussed. An experiment to observe fluctuating pressures due to expansion-turbulence interaction is also included in the program.

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1.0 INTRODUCTION

The theoretical study of acoustic wave generation in the interaction of a turbulent environment with a shock wave has been pursued by the Research Staff at Wyle Laboratories under Contract Numbers NAS8-11308 and NAS8-21100 (Lowson, Reference 1, and Cuadra, Reference 2). The main area of application for this work is in the prediction of fluctuating pressures on the surface of launch vehicles. In the present report a series of experiments is described, in which the aim is to demonstrate and examine the interaction effects.

In discussing turbulent fields it is usual, for the present circumstances, to follow Kovasznay's assumption of weak interaction (Reference 3) and regard the turbulence as being composed of fluctuating vorticity, entropy and acoustic modes. The interaction of any one of these components with a shock wave will lead to the production of all three in the downstream flow. The present interest is mainly in the production of fluctuating pressures. The generation of acoustic waves from a shock-vortex interaction has been observed by Dosanjh and Weeks (Reference 4), and from shock interaction with entropy spots by Hamernick (Reference 5) in shock tube experiments. For a random turbulence field Lowson (Reference 1) has extended the theoretical work of Ribner (Reference 6) and Moore (Reference 7) by calculating the interaction of the vorticity and acoustic components with shock waves. He has calculated, for the case of an isotropic vorticity field, the root mean square pressure fluctuations in the near and far fields as a function of Mach number normal to the shock. Figure 1 shows the values calculated assuming unit turbulence intensity. Also calculated in Reference 1 is the amplification of plane acoustic disturbances for angles of incidence with the shock front of less than 80 degrees; this result is shown in Figure 2. Cuadra (Reference 2), using Chang's theory (Reference 8), has calculated pressure fluctuations arising from the interaction of plane entropy waves of various orientations to the mean flow direction over a range of Mach numbers and flow deflections. An extension to the theory to allow estimation in the random case is put forward, but as yet no numerical results are available.

During the experimental program on the shock-turbulence interaction it will also be convenient to check some predictions which have been made by Radcliffe (Reference 17) on the fluctuating pressures resulting from expansion-turbulence interaction in a supersonic flow. In this case the pressure fluctuations are considered to arise from rotation of the Prandtl-Meyer expansion fan in response to the Mach number fluctuations in the turbulent stream.

For a turbulence environment with significant contributions from each of the basic modes, an accurate prediction of the acoustic field is a most difficult task, since it involves a knowledge of correlations between the modes. If, however, the turbulence consists mainly of one mode the situation becomes somewhat simplified and a better comparison between experiment and theory is possible.

It can thus be inferred that a fairly precise definition of the interacting turbulent stream is required in order that reliance may be placed on the experimental results.

The primary aim of the experimental program described in this report is therefore to interact a well known stream with a shock wave and to measure pressure fluctuations arising from the interaction at various points in the downstream field. In achieving this goal, it will be necessary to develop and make operational fluctuating static pressure probe and hot wire anemometer systems and their recording apparatus so that the turbulent environment may be examined. Following the stage for design and preparation of the apparatus, this will form the second stage of the experimental program. During this second stage, it will be convenient to study the shock-acoustic wave interaction. In the third stage an experiment will be performed to verify that the generation of acoustic waves from shock-turbulence interaction is observable; for this experiment a turbulence environment created by a boundary layer will be used as the interacting stream, and the plane shock of a wedge in supersonic flow as the shock wave. As well as providing useful results, this experiment will serve to finally test and perfect instrumentation. Also, during this stage it will be convenient to incorporate the expansion-turbulence experiment into the program. This experiment will involve measurement of the turbulence environment upstream of an expansion corner in supersonic flow and of the fluctuating pressures at the wall both upstream and downstream of the corner. The fourth stage of the program is devoted to selection of a turbulence generating device to produce an isotropic turbulence of known mode content and decay features completely filling the cross section of the wind tunnel at the location of the experiment. This examination will rely heavily on the instrumentation developed in the earlier stages. In the fifth, and final, stage of the program an experimental investigation of the shock interaction with a well defined uniform turbulent stream will be conducted. Pressure fluctuations generated in the interaction will be the principal object of measurement, but hot wire anemometer studies will attempt to define changes in the vorticity and entropy composition of the turbulence as it passes across the shock.

In view of the complexity of turbulence and the fact that one mode is in reality always accompanied by the others, it will be extremely difficult to achieve an unambiguous confirmation of existing theories. However, it should be well within the grasp of experiment to illustrate the broad features of the theoretical models, such as the variation of generated noise with Mach number normal to the shock. From the point of view of the prediction of fluctuating pressures at the surface of launch vehicles it will be interesting to make measurements at the surface of the wedge in both the shock-turbulence and expansion-turbulence experiments.

In the next section of this report typical values for the fluctuating pressures generated by the interaction of each mode of the turbulence with the shock wave are estimated. Also given are expected values for fluctuating pressures in the expansion-turbulence interaction. In Section 3.0 features of the experimental program relating to production of the interacting shock wave, design and use of instrumentation, design of turbulence generators and conduct of the preliminary and final experiments in the shock-turbulence study are discussed. The proposed expansion-turbulence investigation is described in Section 4.0. Data recording and reduction is described in Section 5.0. In the next section,the anticipated series of experiments is summarized in approximate order of their execution, the shock-acoustic wave and expansion-turbulence investigations being inserted at suitable points in the program. Finally a preliminary run schedule is given for Stages 2 and 3 of the experimental program.

2.0 FLUCTUATING MAGNITUDES

The relative intensities of the components in any point in a turbulent stream depends both on the turbulence generating mechanism and on the time allowed for dissipation. Vorticity intensities are often defined in terms of axial and lateral velocity fluctuations, and velocity variations of 10 percent of the mean flow velocity are quite commonly encountered in wakes and boundary layers (References 9 and 14). For normal Mach numbers in the range above 1.1, root mean square pressure fluctuations of about 0.25 times the mean dynamic pressure, q, of the flow is predicted in the near field by Figure 1 at this intensity of vorticity. In later experiments q values between 1 and 5 psi will be available, so that acoustic pressures of 159 to 173 dB (re: 0.0002 dynes/cm^2) should be encountered. In the far field the pressure fluctuations are predicted around 0.08 q, yielding 149 to 163 dB. Pressure fluctuations of these magnitudes are easily detectable.

Cuadra's report contains a discussion of typical entropy fluctuation magnitudes in jets, wakes and boundary layers. Referenced to total temperature, it appears that 5 percent is a reasonable upper limit to temperature fluctuations generated in wakes and boundary layers at these Mach numbers. Thus, for a Mach 3 stream and flow deflection of 20 degrees, the maximum pressure fluctuation generated would be (from Reference 2, Figure 29) 0.3 q; for q = 2.5 psi this is 0.75 psi. Although this number represents the accumulation of high values for turbulence, flow inclination etc., and the mean value would probably be much smaller, nevertheless it does stress that the entropy interaction can be quite significant.

In the description of turbulent environments it is most usual to neglect the acoustic component in comparison to the other two (for example, Kistler, Reference 9); this does not mean to say, of course, that it is negligible in the usual scale of intensities. In the shock-acoustic wave experiments to be proposed amplifications of 5 to 10 dB should be encountered.

The existence of fluctuating hydrodynamic pressures just behind a sharp shoulder in a turbulent supersonic flow has been predicted by an expansion fan rotation mechanism proposed by Radcliffe (Reference 17). At Mach 1.99 in the wind tunnel, Figure 6 of that report yields an estimate of about 143 dB for the rms fluctuating pressures due to 10 percent amplitude velocity variation over a 10 degree corner. If the noise of the turbulent stream entering the shock wave is of this order, or smaller, it should be possible to observe the phenomenon.

3.0 EXPERIMENTAL PROGRAM

This section will describe various aspects of apparatus design and experimental procedure. It is meant to convey the general approach to the practical problems of creating and making measurements in the required environment. From the text it will be apparent that a fair amount of work must be done in leading up to the final experiment. This is a consequence of having to assemble and make operational suitable instrumentation and of the relative lack of knowledge of supersonic turbulence. However, it is anticipated that some useful and interesting results regarding the interaction will be found during the preliminary stages of the experiment.

The experiment will be carried out in the NASA 7 inch by 7 inch Supersonic Wind Tunnel at MSFC. The range of test conditions for this facility are summarized in Figure 3.

3.1 Shock Production

The shock wave of the interaction will be generated by a wedge shaped body inserted into the test section of the tunnel. The general design and mounting of the wedge are illustrated in Figure 4. The support strut is fixed to the removable plate of the wind tunnel. It has vertical slots which allow the adjustment of the wedge and instrument head to any position of interest in the tunnel. The shock generating wedge shown here has an included angle of 10 degrees, but the inclination of its top surface to the flow may be varied over a range of angles. If circumstances require it, another head is easily substituted. The underside of the wedge in this illustration has a ridge which enfolds the projecting ends of instrumentation flush mounted on the upper surface, without causing stand-off of the main shock wave. The wedge will be about 4 inches across so that a good approximation to two-dimensional flow interaction is achieved. In the drawing details of tubing to guide instrument leads outside the tunnel are omitted.

Figure 4 shows the position of the shock wave for a Mach 2 free stream and a wedge of 10 degree half-angle. The turbulence environment, the spillage of an artificially thickened turbulent boundary layer, is created by placing a flat plate on the center plane of the wind tunnel. It would be expected that the point of intercept between the turbulence and the shock would be a sensitive parameter in the noise generated, due to the changing nature of the turbulence. Thus in the experiment it will be possible to vary the distance, A, for a given A to position the point of the wedge suitably for each wedge angle and Mach number. The locus of possible situations for the tip of 5 degree, 10 degree, 15degree and 20 degree half-angle wedges, the anticipated values, is given in Figure 5(a) to (d) respectively. In setting up the tunnel configuration these figures will be used to locate the wedge with respect to the trailing edge of the turbulence generating plate.

For free stream Mach numbers greater than 4 it can be seen that arrangement of the wedge and turbulence would become difficult. The stream Mach number normal to the shock, which is the basic variable, is given for the present range of parameters in Figure 6. The curve for Mach 1.54 nozzle is omitted, since at this Mach number the 15 degree and 20 degree wedges have a detached shock. It will be possible experimentally to cover the range 1.13 to 2.15. If it is desired to have a fixed normal Mach number while varying the nozzle configuration, this may be done by adjusting the wedge angle of incidence to intermediate values.

The instrument head is also attached by an adjustable boom to the mounting plate, and may be located at any point in a large area of the field. The head is hinged and may be tightened to hold any orientation with respect to the flow. Design details of the instrument head are described in Section 3.2.

The interaction is arranged as far as possible to take place within the limits of the optical windows, so that Schlieren and shadowgraph methods may be used. To allow for full development of the turbulence region the zone of interest will normally be near the downstream end of the window.

3.2 Instrumentation

These experiments will require the measurement of mean flow and fluctuating quantities.

The general disposition of shock waves and turbulent regions in the tunnel may be found by shadowgraph or Schlieren techniques, the former being more suitable to shock and Mach wave definition and the latter to turbulence. It is suggested that, say, a shadowgraph of each configuration be taken since information regarding mean flow parameters, uniformity of field, and to a certain extent, origin of acoustic waves (see, for example, Reference 10) may all be gleaned from it. The mean flow Mach number both upstream and downstream of the shock will be defined by pitot-static probe measurements. These techniques are standard in wind tunnel work and need no further description here.

Measurement of fluctuating quantities in the flow will, on the other hand, require a good deal of experimental care and development. The situation is made difficult by the complex nature of turbulence; pressure fluctuations in the flow may be consequences of either or both flow rotation and acoustic waves. In the latter case, the disturbance is moving with the free stream velocity plus the velocity of sound in the medium, whereas in the former, it is convected with the mean stream speed. Further problems arise in interpretation of measurements when it is considered that instruments react to independent variables which are not always the same as the ones of interest; for example, hot wire anemometers respond basically to mass flow and stagnation temperature fluctuations, whereas velocity and static temperature fluctuations are more often sought.

A lower limit to the high frequency response of diagnostic probes and their associated electronics may be gained by the following reasoning. Suppose the largest eddy in the turbulence is 1 inch in diameter; since it is convected past a fixed probe at greater than Mach 2 (1621 ft per sec in this tunnel) a response frequency of 20 k Hz is required for the eddy to be detected. At Mach 4 this limit is 25 k Hz. Diagnostic risetimes of at least 10 microseconds (100 kHz) and preferably 5 microseconds are required for convected and acoustic disturbances. However, from Kistler's paper (Reference 9) it is seen that there is a large energy concentration at lower frequencies (of the order of 1 k Hz) in supersonic turbulent boundary layers. This occurs because the wall and diagnostic are relatively at rest; when the boundary layer has been accelerated to nearer the free stream speed its energy peak will move to higher observed frequencies.

It is proposed that a probe for the measurement of fluctuating pressure in the flow be developed first, and subsequently used in searching for acoustic waves generated in the shock-turbulence interaction. During these initial stages it is proposed to develop a hot wire anemometer system for the examination of velocity and temperature fluctuations. These instruments are described below.

Pressure Probes

The construction of this diagnostic is illustrated in Figure 7. The proposed sensing element is a small diameter (about 0.050 inch) Kulite ultra-miniature pressure sensor having its surface flush with the surface of a small flat plate or the inside wall of a cylinder. It is also suggested that a static pressure orifice be located next to the transducer. The leading edge of the plate or cylinder would be sharp so that an attached shock wave would be formed, and the wedge angle held less than 10 degrees. On the basis of Mach line location from the upstream corners of the wedge over the anticipated Mach number range, a wedge width of 1 inch would be sufficient to keep side influences away from the transducers. Edge effects could also be circumvented using the cylinder configuration, a bore divergence of one or two degrees would prevent blockage. The diameter of the opening is a variable, but it is unlikely that any effect such as acoustic cut-off will occur for wavelengths less than the tube diameter since the flow is supersonic.

The tubing beneath the wedge or cylinder will act both as a support to attach to the instrument boom and as a duct for leads to the pressure gages. Two opposing conditions define the range of locations of the sensing elements with respect to the front edge of the plate. Firstly, the distance must be small enough so that the boundary layer is laminar. Since the transition Reynolds number at Mach 4 is at least 10^6 for supersonic wind tunnels, it is expected that transition would occur about a foot back from the leading edges; this limitation is therefore not restrictive in the present case. Secondly, the stand-off and separation shocks of the underneath support should not encroach forward of the sharp edge. This means that the sensor must be located about two support widths back from the edge; a distance of 1/4 to 3/8 inch would appear reasonable.

The instrument will be tested in two ways before use in the turbulent stream. First, the instrument head will be located in the clean tunnel and the noise floor determined using the Kulite sensor. The probe will then be rotated up to an orientation of about 6 degrees off-axis to examine the change in reading of the static pressure orifice. This will indicate the contribution to be expected from flow angularity when the fluctuating pressure probe intersects a large eddy of about 10 percent velocity fluctuation. Secondly, a loudspeaker will be placed in the reservoir and made to transmit waves down the tunnel in the "air-on" condition; detection of these waves will be examined and the effect of misalignment of the probe will be investigated. Note that, as will be suggested later, the shock-acoustic wave interaction may conveniently be performed at this stage by inserting the shock generating wedge into the stream.

It is also proposed to locate a few static and fluctuating pressure instruments on the surface of the wedge generating the shock wave. The purpose of this is to provide data which is of more direct significance in engineering application than free stream measurements, particularly the case when the wedge intercepts the turbulence. These will be located at various distances from the leading edge and the decay of amplitude of fluctuation with distance determined. The upstream pressure fluctuations will be measured using the mobile instrument head.

Hot Wire Anemometer

The velocity and temperature fluctuations may be inferred from measurements with a hot wire anemometer. This technique, developed by Kovasznay (Reference 3) for measurement in turbulent supersonic flows is the subject of a good review report of Morkovin (Reference 11) and other reports (References 12 to 14) so that further detailing of the method is unnecessary. However, it is apparent that extreme experimental finesse will be required in the usage and handling of these instruments, due mainly to their fragile nature; techniques will have to be developed in order to minimize the destructive effect of tunnel start-up and close-down which in the present case will be occurring every few minutes. Steps will also have to be taken to clear the stream of dust particles. It is felt that discussion on these problems is superfluous here since practical experience will suggest its own remedies. The best approach is to begin development of this system early in the program, mounting it on the instrument boom and testing it out in uniform streams before subjecting it to the high shear loading of turbulence.

Laufer and McClellan (Reference 15) and Kistler (Reference 9) present some useful guidelines in acquiring meaningful hot wire data at the present Mach numbers. The hot wire sensor will have a diameter large enough that the Reynolds number based on diameter of the flow behind the bow shock is greater than about 20; in this instance the diameter will not be less than 0.0002 inches. Since a Mach 4 flow is to be examined, the vorticity fluctuation diagram (Reference 3) indicates that sensitivity ratios up to at least 1.5 must be attained to cover the β point. For tungsten wires the sensitivity and overheat ratio are approximately equal; the upper temperature limit of the wire is thus about 400° C. Mode distinction will require operating the wire over the range of temperatures up to this value.

When the system is operational the first objective will be to define the temperature and velocity fluctuations and decay of the turbulent field just ahead of the shock wave in the turbulence configuration of the preliminary experiment. Later it will be used to evaluate the same characteristics in the turbulence created by the proposed generator designs.

3.3 Preliminary Experiment (Stage 3)

In order to provide a real testing ground for the instrumentation and to confirm that the shock-turbulence production of acoustic waves is observable, a preliminary experimental configuration will be used. It is shown in Figure 4.

Although its unsteady characteristics will not have been defined during the early part of the experiment, the boundary layer-wake system trailing a flat plate mounted on the symmetry plane of the nozzle will be used as the turbulent stream. It is intuitively expected that the character of the wake will be rapidly changing as it leaves the plate, the center portion being rapidly accelerated towards mean stream speed and becoming colder due to removal of the wall heating effect.

The plate will extend fully across the tunnel and be supported at the side walls upstream of the optical windows. The plate will be gritted on both top and undersides to trip and thicken the boundary layer; turbulence layer thicknesses of about 2 inches should be obtainable. The plate will be run in two configurations, one with the leading edge in the test section and the other with the plate running through the throat. The main purpose of this is to examine shock and Mach wave formation in the test-section, an important consideration since hot wires are very sensitive to nearly stationary shock waves (Reference 3).

As a first step a shadowgraph will be taken of the flow with the Mach 3.0 nozzle, plate and wedge in position. The transverses of the fluctuating pressure probe along the mean flow streamline inside the wake and outside the wake will be made. On the spot decisions will be made about whether any effect is being observed and appropriate action taken. For these exploratory experiments an oscilloscope and camera combination is most versatile as a recording system. If an effect is observed, wedge angle, Mach number, and interaction distance, A, will be varied to find the general trends. Subsequently, the wedge will be made to intercept the turbulent stream and some values of fluctuating pressures at its surface determined. By this time the hot-wire anemometer should be reasonably advanced and ready for trial in determining the nature and development of the wake.

This experiment, although of a distinctly exploratory kind, should yield some interesting results. Most importantly, however, it will give useful background experience in the use of the diagnostics before the trouble is spent on selecting a suitable generator of isotropic turbulence.

3.4 Turbulence Generators (Stage 4)

The ultimate aim of the experimental series is to interact a shock wave with a known isotropic turbulent stream which uniformly fills the tunnel. The generation of a suitable turbulence environment is at the same time one of the most important and imponderable problems in this experiment. Part of the difficulty arises from a lack of knowledge about the behavior of grids in supersonic flows. Although wakes and boundary layers have been investigated in some detail, these provide only limited regions of non-isotropic turbulence, and their behavior when the generating bodies are combined to form an array is by no means certain. It seems that some effort will have to be expended in determining the performance of some likely designs, examining particularly mode content, decay characteristics and the intensity of stationary shock waves which will also be generated in the stream. Some candidates are described below.

The first generator, which has been suggested for use in the preliminary experiment, but which does not uniformly fill the test section with turbulence, consists of a thin flat plate laid along the axis plane of the nozzle. The turbulent boundary layers on each face would be tripped and thickened by gritting the plate. The two boundary layers peeling off the end of the plate would form the turbulent stream, and the wedge shock would be positioned to intercept the stream at any desired point. Kistler (Reference 9) has shown that Mach number fluctuations of greater than 10 percent are obtained in the boundary layer, so that the required magnitude of disturbances are created by the device; whether these levels are maintained after the flow passes the end of the plate will be determined experimentally. The plate generator should possess two advantages over the wake generator of Kovasznay (Reference 14) in that it should have weaker stationary shocks and that the turbulence channel should be better defined.

Depending on the performance of the flat plate generator, a honeycomb arrangement will be considered: it is illustrated in Figure 8, with tentative dimensions written in. The vertical plates are parallel to the side walls of the tunnel, and the cross plates are contoured to the streamlines of, say, the Mach 3.00 nozzle. The generator will be installed in the downstream region of the nozzle. More precise definition of the geometry of the device will be possible after experience with the flat plates.

Grid geometries will also be considered. These are commonly in use for incompressible flows and an experimental evaluation of various geometries in this case is available in Reference 16, for example. However, a brief literature search of major publications from 1965 revealed no suitable references for the supersonic case. It is anticipated that grid geometry will be decided on the basis of incompressible behavior. There are two possible locations for a grid, either in the supersonic part of the nozzle or in the high speed region of the stilling chamber. In the first instance, strong shocks will probably cross the flow and in the second, there may be attenuation of the disturbance during its passage through the throat.

Other generating mechanisms using modulated air jets exhausting into the stream may be possible, but these incur significant mechanical complication, and consideration of them will be left to a later stage.

3.5 Main Experiment (Stage 5)

By this stage, experience in operating all the diagnostic equipment will have been gained and the features of the turbulent field ahead of the shock determined. The experiment is then merely to use the wedge for creation of shocks across this field, and to measure the turbulence properties downstream of the shock, in particular fluctuating pressures in the flow and on the surface of the wedge. Variation of the downstream field properties with Mach number normal to the shock and free stream Mach number will be determined and the results compared as far as possible with theoretical predictions.

4.0 EXPANSION-TURBULENCE INTERACTION

Experimentally an arrangement similar to Figure 9 would be used. The wedge-corner system would be mounted on the wedge arm of the above experiments and configurations corresponding to 5 degree, 10 degree, and 20 degree corners used. Pressure transducers would be located both upstream and downstream of the corner as indicated. The experiments could most conveniently be carried out during the preliminary experiment of the shock-turbulence series of experiments since the phenomenon is only concerned with the effects of large eddies near to the wedge surface. With the present tunnel it will not be possible to examine the interesting dip in generated fluctuating pressures around Mach 1.3 since the lowest nozzle has a Mach number of 1.54; however, the general trend of the curves above this Mach number should be observable.

5.0 DATA REDUCTION

The general geometrical features of the flow field will be examined by Schlieren and shadowgraphic techniques. Inspection of these photographic records will indicate:

(i) The location and angle of shock waves in the flow. The inclination of shock waves will yield an estimate of the flow Mach number ahead of the shock.

(ii) The extent of turbulence regions; for example, in Stage 3 an idea of the width of the turbulent stream will be gained.

(iii) The strong acoustic waves, in the case of the shadowgraph technique, so that it may be possible to locate their origin.

More accurate knowledge of the mean Mach number at any point in the turbulence will be obtained using the usual pitot-static tube technique. For each of a series of points in the flow field, the mean Mach number will be recorded and an estimate of the mean Mach number at any other point obtained by interpolation.

In the experiments the outputs from the fluctuating pressure probe and the hot wire anemometer will be first examined on an rms voltmeter and an oscilloscope. The importance of this is to provide an on-the-spot indication to the experimenter of the intensity and shape of the energy spectrum and the acoustic vorticity and entropy content of the turbulence. For subsequent analysis the fluctuations will be recorded in the direct mode on magnetic tape and later examined at a reduced tape speed. Reduction of this signal by analog methods will define more accurately the spectral properties. If it is possible to carry out an accurate power spectral density analysis of the fluctuating hot wire and pressure transducer responses, their comparison could firmly define the origin of the acoustic waves. The rms value of fluctuations of frequency outside the range of either the recording or analyzing equipment may be found by filtering out the low frequencies and displaying the signal on an unswept oscilloscope trace. A photograph is taken of the fluctuations over a long time interval and the photograph is then subjected to a photodensitometer analysis in order to determine the distribution and rms value of the fluctuation. This second method, used previously by Kovasznay (Reference 3), is suitable for acoustic, vorticity and entropy separation purposes, but the first method must be employed when spectral characteristics have to be determined.

6.0 SUMMARY OF EXPERIMENTS

This section summarizes the main tasks of the program in approximate order of their execution. The side experiments which appear during Stages 2 and 3 are expected to yield interesting results and experience with the apparatus, and not to delay significantly progress toward the final experiment.

Stage 1: Preparation of Apparatus.

(a) Design and construct wedges, turbulence plate, and supporting mechanisms.

(b) Design and construct fluctuating static pressure probe.

(c) Design hot-wire setup.

(d) Assemble optical and mean flow measuring equipment.

Stage 2: Development of Instrumentation.

(a) Develop first the fluctuating and static probe instrument head, examining effects of orientation with respect to mean flow, its response to acoustic waves in a clean tunnel, and its response near to and in the turbulent boundary layer.

(b) Take Schlieren/shadowgraph pictures of the boundary layer - wake system spilling off the plate, in order to define its extent. Examine acoustic field.

(c) Carry out acoustic wave - shock interaction experiment using the fluctuating pressure static probe. Examine amplification for various shock strengths.

(d) Begin experimentation in free stream and in wake of plate with the hot-wire system.

(e) Begin design and construction of grids in prepration for Stage 4.

Stage 3: Preliminary Experiments.

(a) Interact shock wave and turbulent region and search for acoustic generation with the fluctuating static probe device. Measure fluctuating pressures at the surface of the wedge.

(b) Vary wedge position examining general trend with Mach number normal to shock. Alter turbulence by changing stream Mach number and interaction distance, A.

(c) Carry out expansion-turbulence experiment, measuring increase in fluctuations observed at the wedge surface for various mean stream Mach numbers.

(d) During the series experimentation with hot wires will continue and measurements of the turbulence and entropy content of the turbulence from the plate will be examined. The hot-wire system must be fully operational in preparation for the next stage.

Stage 4: Using hot wires, etc., determine mean flow characteristics, mode content, decay parameters and field isotropy of the various grid configurations which have been designed from boundary layer and wake concepts. Select a suitable generator on the basis of the parameters just listed.

Stage 5: Interact shock waves of varying strength with a uniform isotropic turbulence, mapping out the field of fluctuating pressures. At all stages in the series data will be analyzed immediately and results will be compared with theory.

The experimental program outlined above is quite lengthy, but useful results will be obtained at an early stage so that, if necessary, the remainder of the program may be changed without too much wasted effort. It is also felt that the results from the preliminary experiment will be useful in indicating some broad features of the theories.

7.0 TEST CONDITIONS AND PRELIMINARY SCHEDULE

The major part of the experimental work will be carried out with the Mach 1.99, 3.00, 4.00 nozzles, but the intermediate nozzles of Mach 2.44 and 3.26 will be used if it is necessary to examine any effect more closely. The upper and lower limits of nozzle Mach number are set, on the lower side by the detachment of the wedge shock from the wedge, and on the upper side by the geometrical convenience of arranging the wedge with respect to the turbulence plate (see Figure 5): as the free stream Mach number is increased the generating wedge and instrument head have to be located closer to the tunnel centerline.

A preliminary run schedule for Stages 2 and 3 is given below. It is anticipated that completion of the entire program, including the final stages, will require visits to the wind tunnel facility over a period of time, mainly because development work on some of the apparatus, such as the turbulence generators, will depend on information gained during the preliminary experiments.

The range of various parameters and their coding in the schedule are as follows:

Mach Number: refers to nozzle Mach number and has values 1.99, 3.00, 4.00.

Wedge: refers to shock generating wedge and causes mean flow deflection of 5, 10, 15 and 20 degrees due to its attached shock wave. For the expansion-turbulence interaction, it causes 5, 10 and 20 degree deflection of the mean flow direction by expansion.

Diagnostic: refers to technique employed during the run to investigate the flow. The following coding is employed:

A - Schlieren/shadowgraph

B - Pitot-static probe for definition of mean Mach number

C - Fluctuating and static pressure probes on instrument head

D - Hot wire anemometer mounted on instrument head

E - Fluctuating and static pressure probes mounted either on shock generating or expansion generating wedge

Turbulence: refers to turbulence generating device. Three configurations are:

A - Gritted plate with leading edge upstream of nozzle throat

B - Gritted plate with leading edge downstream of nozzle throat

C - Either configuration A or B or other location of plate giving least shock perturbation of its own turbulence.

Location: refers to location of diagnostic during the run. Four general locations:

A - Upstream of wedge generated shock outside the turbulence

B - Downstream of shock outside turbulence

C - Upstream of shock within turbulence

D - Downstream of shock within turbulence

Acoustic: refers to generation of acoustic waves by a loudspeaker located in the reservoir. Sinusoidal waves of low frequency (about 1 kHz; code LO), intermediate frequency (about 10 kHz, code MED) and high frequency (code HI) will be generated.

Head: refers to orientation of surface of instrument head with respect to the local mean flow direction. Settings to 0°, 3°, and 6°.

Stage 2

Run No.	Mach No.	Wedge	Acoustic	Turbulence	Diagnostic	Location	Head
1-9	1.99,3.0,4.0	No	OFF	No	A,C	A	$0^\circ,3^\circ,6^\circ$
10-36	1.99,3.0,4.0	No	LO,MED,HI	No	C	A	$0^\circ,3^\circ,6^\circ$
37-48	1.99,3.0,4.0	$5^\circ,10^\circ,15^\circ,20^\circ$	MED	No	A,C	B	0°
49-54	1.99,3.0,4.0	No	OFF	A,B	A	-	-
55-63	1.99,3.0,4.0	No	OFF	C	B	-	-
64-81	1.99,3.0,4.0	No	OFF	C	C	A,C	0°
82-90	3.0	No	OFF	C	D	A,C	0°

Notes on Stage 2

Runs

1-9 Observe tunnel background noise. Observe effect of static probe orientation to mean flow on its response. Diagnostic A observes shock field around instrument head.

10-36 Observe acoustic disturbances at low, intermediate, and high frequencies with fluctuating pressure probe. Observe effect of misalignment of head with mean flow on acoustic pickup. Measure with rms voltmeter and oscilloscope.

37-48 Shock-acoustic wave interaction at frequency giving maximum signal-to-noise ratio.

49-54 Optical examination of turbulence generated by plate in each of A and B configurations. On basis of shock pattern in the tunnel select optimum configuration, C.

55-63 Using pitot-static rake examine mean Mach number profile at three values of interaction distance, A.

64-81 Observe the fluctuating pressures recorded by the fluctuating pressure probe when instrument head is inside and outside turbulence environment and located at the same values of A as the 55-63 run series.

82-90 Preliminary experiments with hot wire inside and outside turbulence environment.

Stage 3

Run	Mach No.	Wedge	Diagnostic	Location
91-100	3.00	20°	A,C,	A,B
101-124	1.99,3.00,4.00	$5^\circ, 10^\circ, 15^\circ, 20^\circ$	C	B
125-144	3.00	No	D	C
145-153	1.99,3.00,4.00	$5^\circ, 10^\circ, 20^\circ$ Expansions	A,C	Wedge
154-160	3.00	No	D	A

Notes on Stage 3

Runs

91-100	Define mean field with optical techniques. Search for acoustic waves generated in the interaction.
101-124	Examine acoustic generation variation with shock strength and mean flow Mach number at two interaction distances, A.
125-144	Use hot wires attempt to define velocity and temperature fluctuations in upstream turbulence. Allowing 10 overheat ratios and examining at the two interaction distances used in previous set of runs.
145-153	Expansion-turbulence investigation with fluctuating pressure sensors flush mounted with walls of expansion wedge. These wedge angles used, giving $5^{\circ}, 10^{\circ}$ and 20° expansions.
154-160	Hot wire development runs to prepare for Stage 4.

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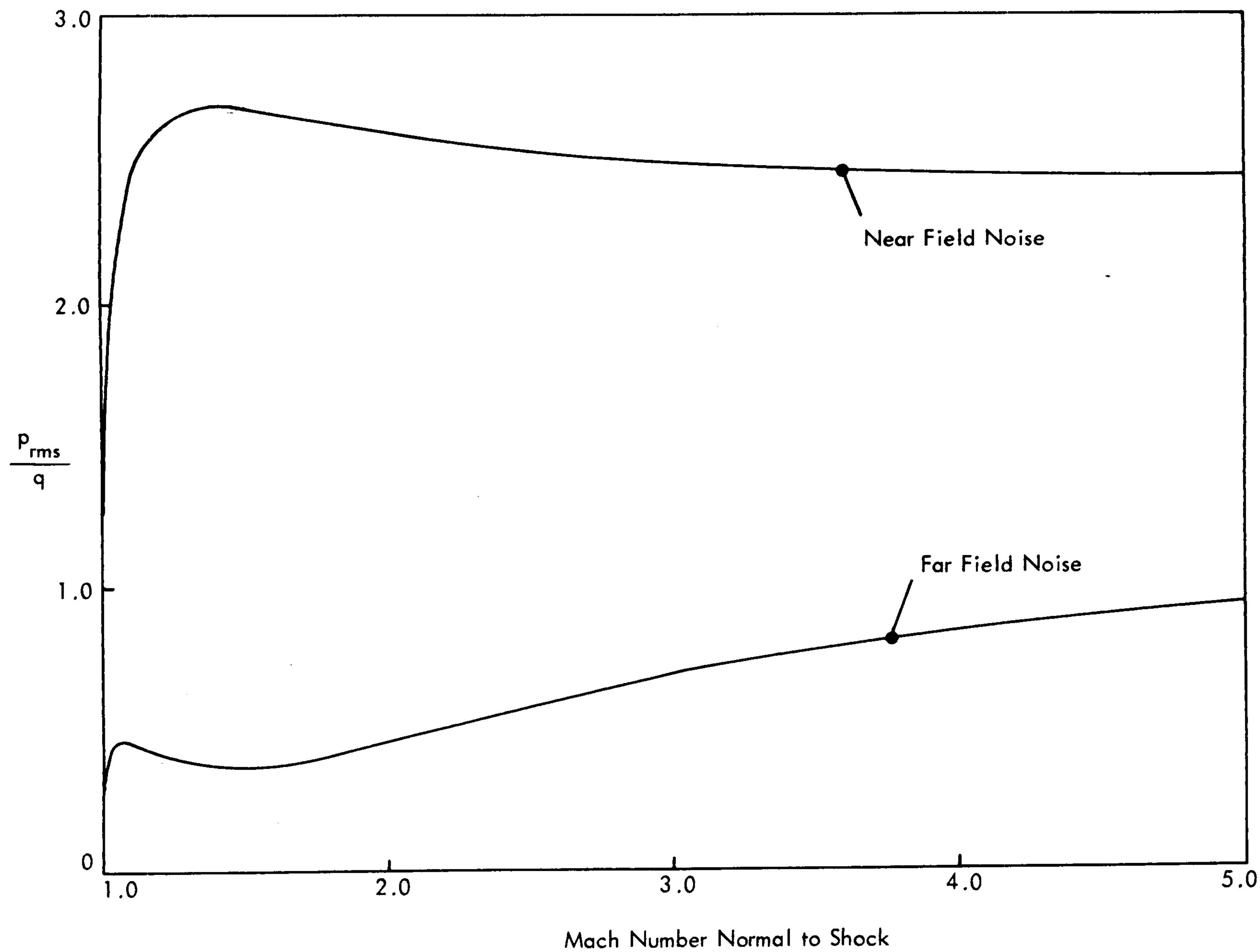


Figure 1. Near and Far Field Sound Level for Shock Interaction With Unit Isotropic Turbulence

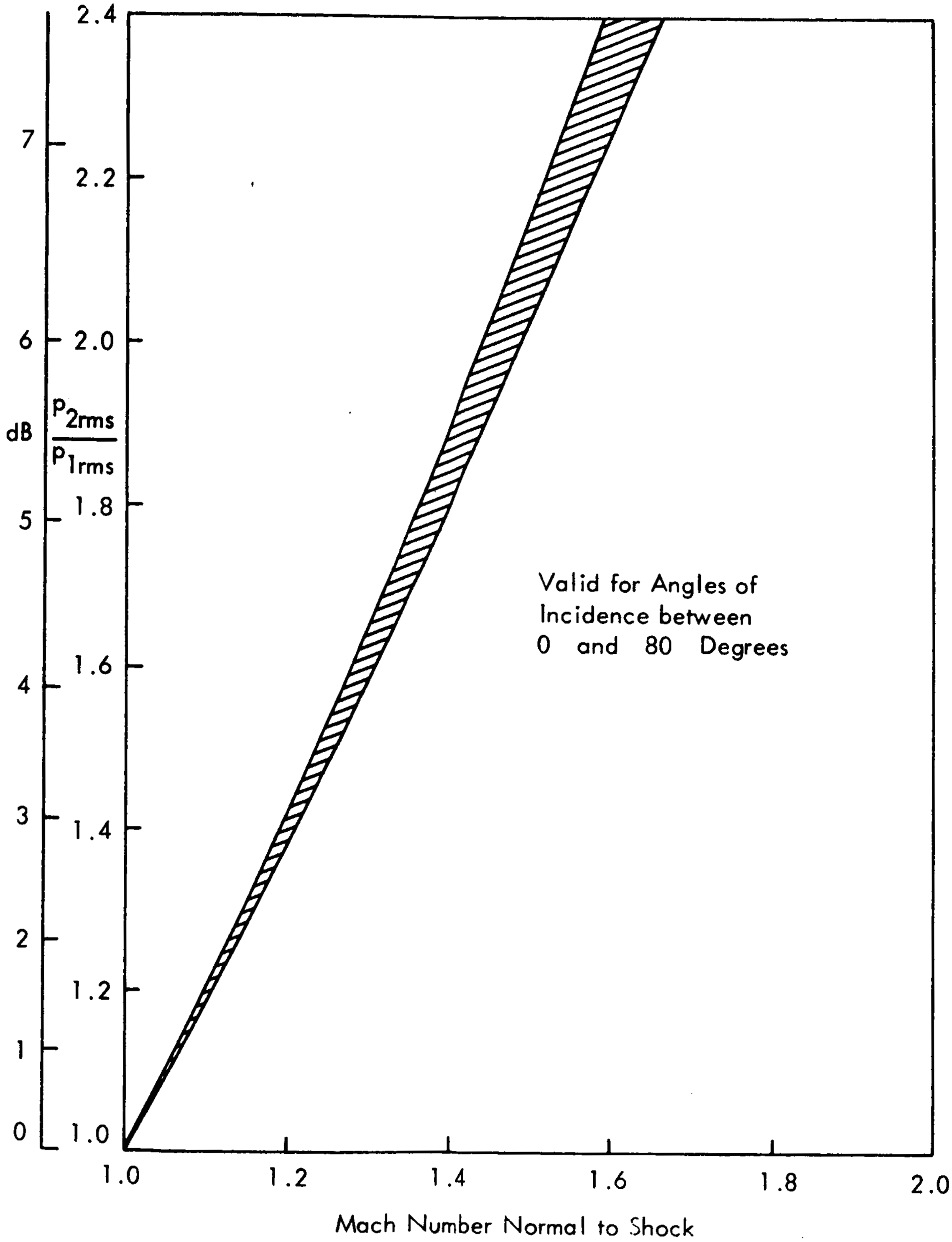


Figure 2. Range of Magnification Factor for Shock Sound Interaction.

Mach No.	1.54	1.99	2.44	3.00	3.26	4.00	5.00
Mass Flow (lb/sec)	13.053	10.030	6.382	3.686	2.802	1.392	0.576
Dynamic Pressure (psi)	6.26	5.29	3.94	2.52	2.03	1.08	0.486
Static Pressure (psi)	3.78	1.91	0.945	0.400	0.272	0.097	0.028
Reynolds No./in.	360,353	305,185	250,000	185,608	163,971	111,306	82,216
Minimum Starting Pressure (psia) (Tunnel Clear)	10.6	9.25	6.55	5.41	5.01	1.65	0.75
Maximum Run Time (sec)	183	210	225	332	378	425	391

Atmospheric Conditions: $P = 14.7$ psia, $T = 90^{o}F$, $\rho = 0.0722\ lb/ft^3$

Figure 3. Table of Aerodynamic Constants for 7 in. by 7 in. Supersonic Wind Tunnel at NASA-MSFC

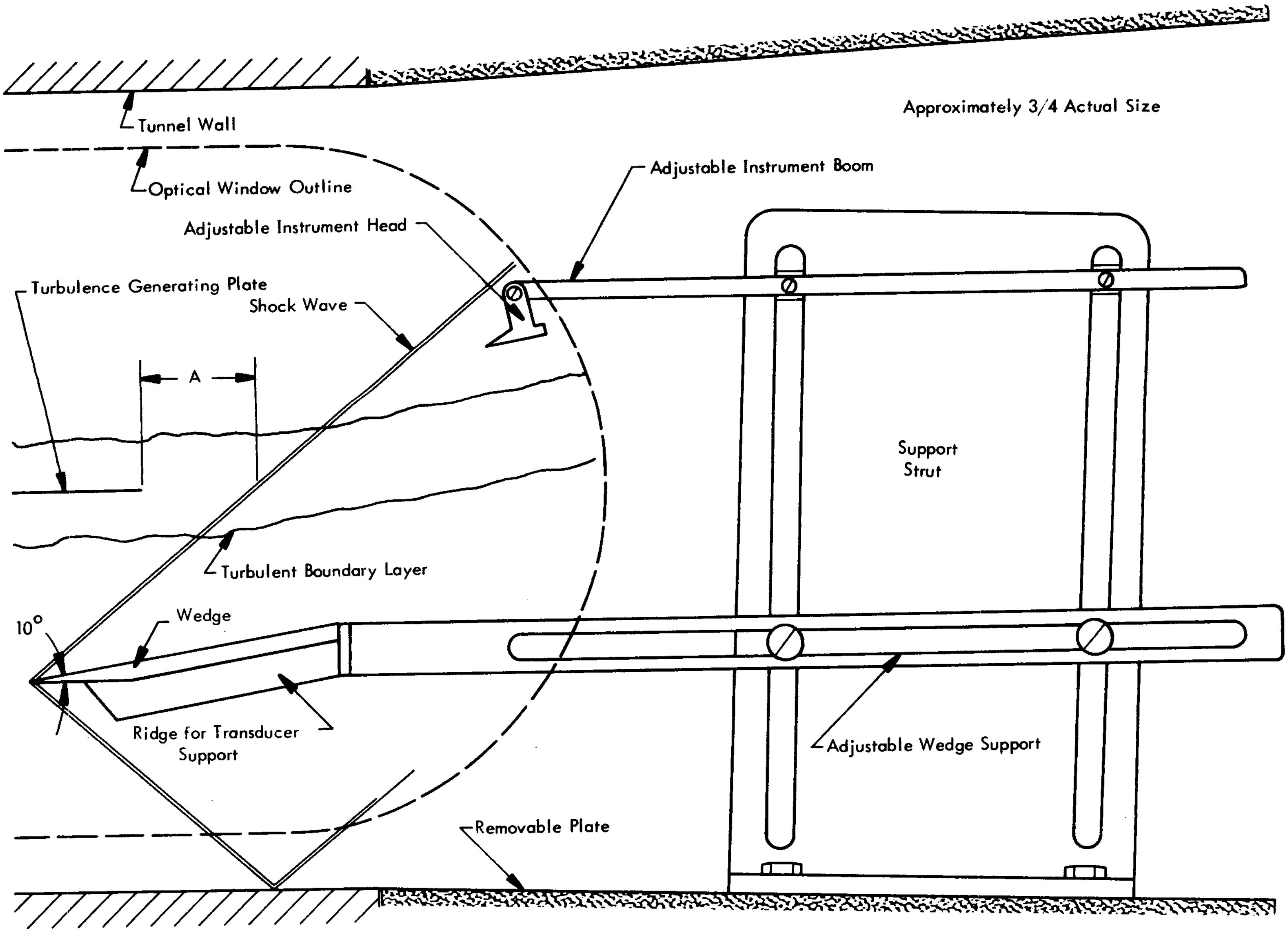
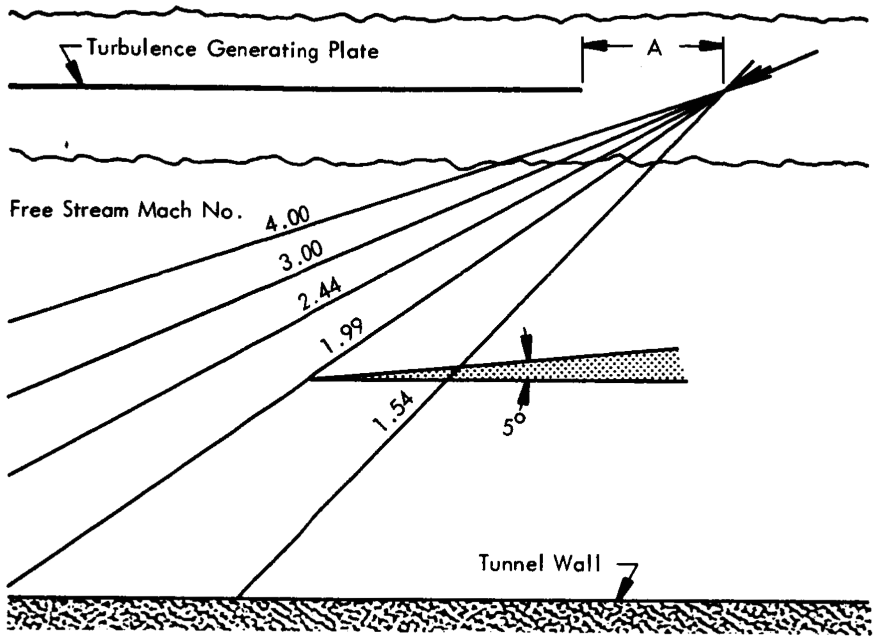


Figure 4. Details of the Experimental Arrangement for the Preliminary Experiments.

(a)



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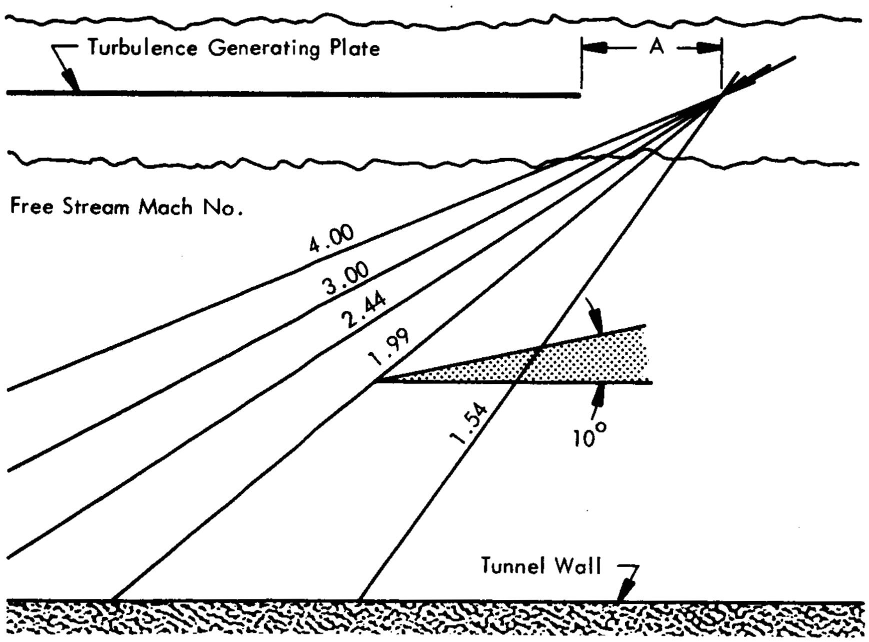
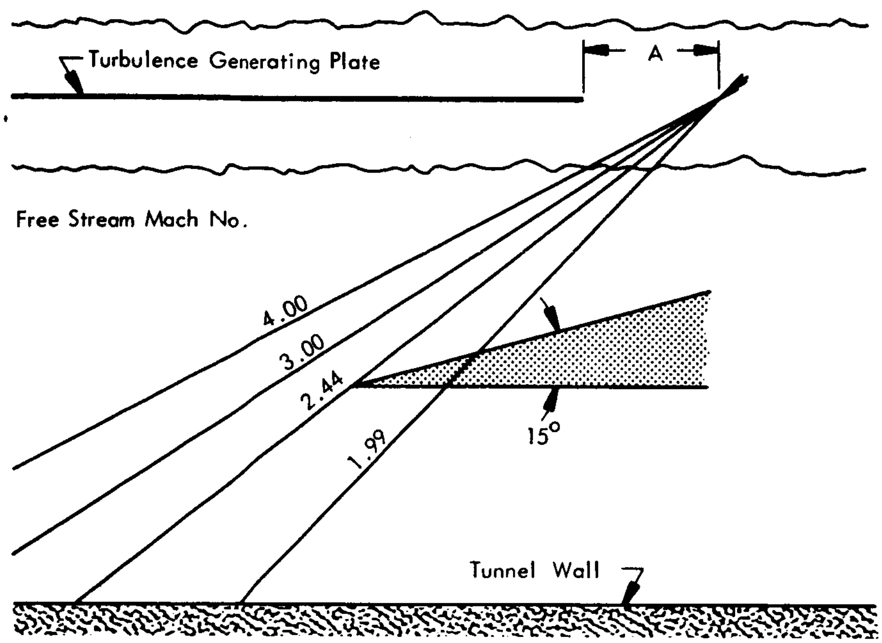


Figure 5. Wedge and Shock Wave Positions at Various Flow Mach Numbers For (a) 5°, (b) 10°, (c) 15°, (d) 20° Flow Deflections. [(c) and (d) overleaf.] Scale: Approximately 3/4 size.

(c)



(d)

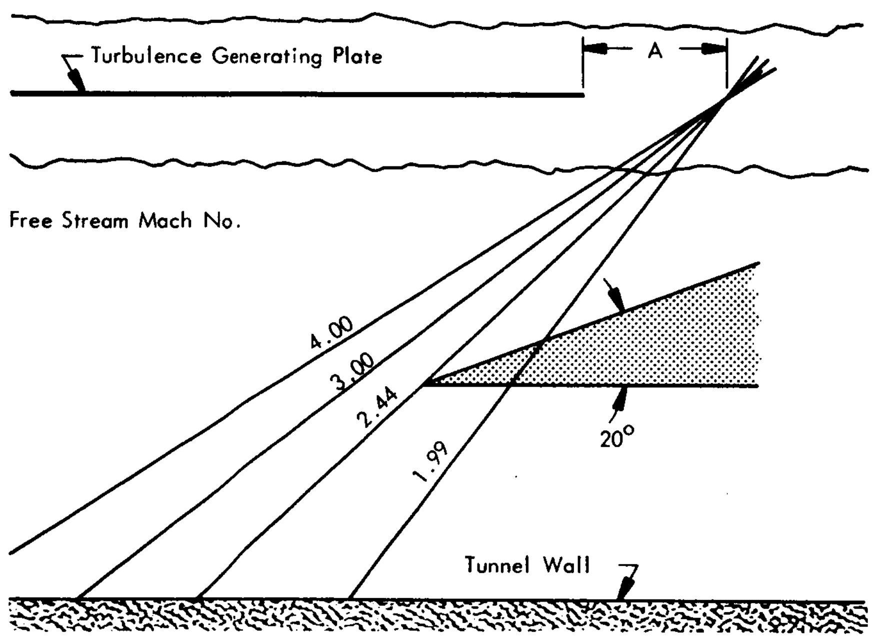


Figure 5. Concluded.

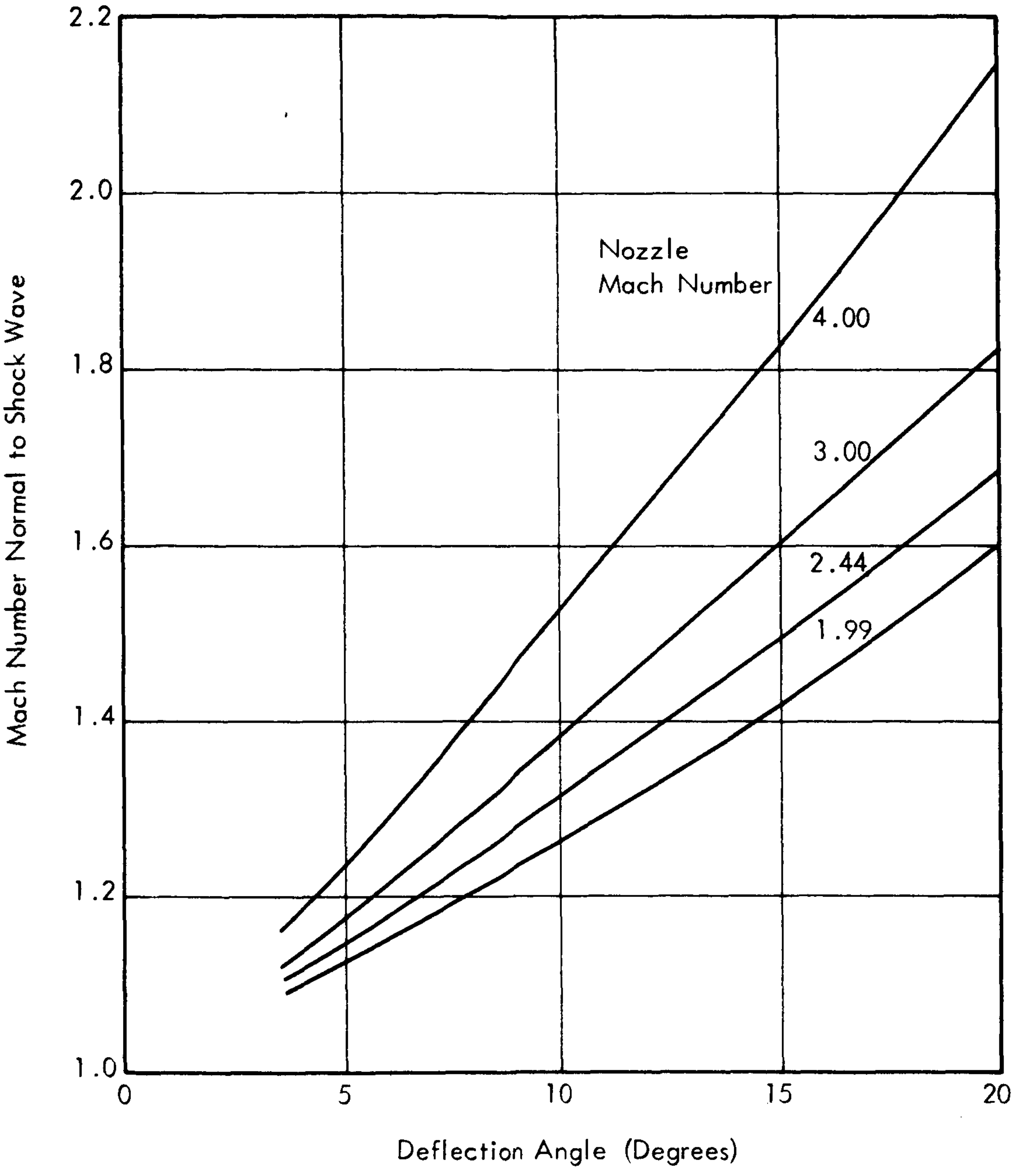


Figure 6. Mach Number Normal to Shock as a Function of Flow Deflection Angle for Various Nozzles.

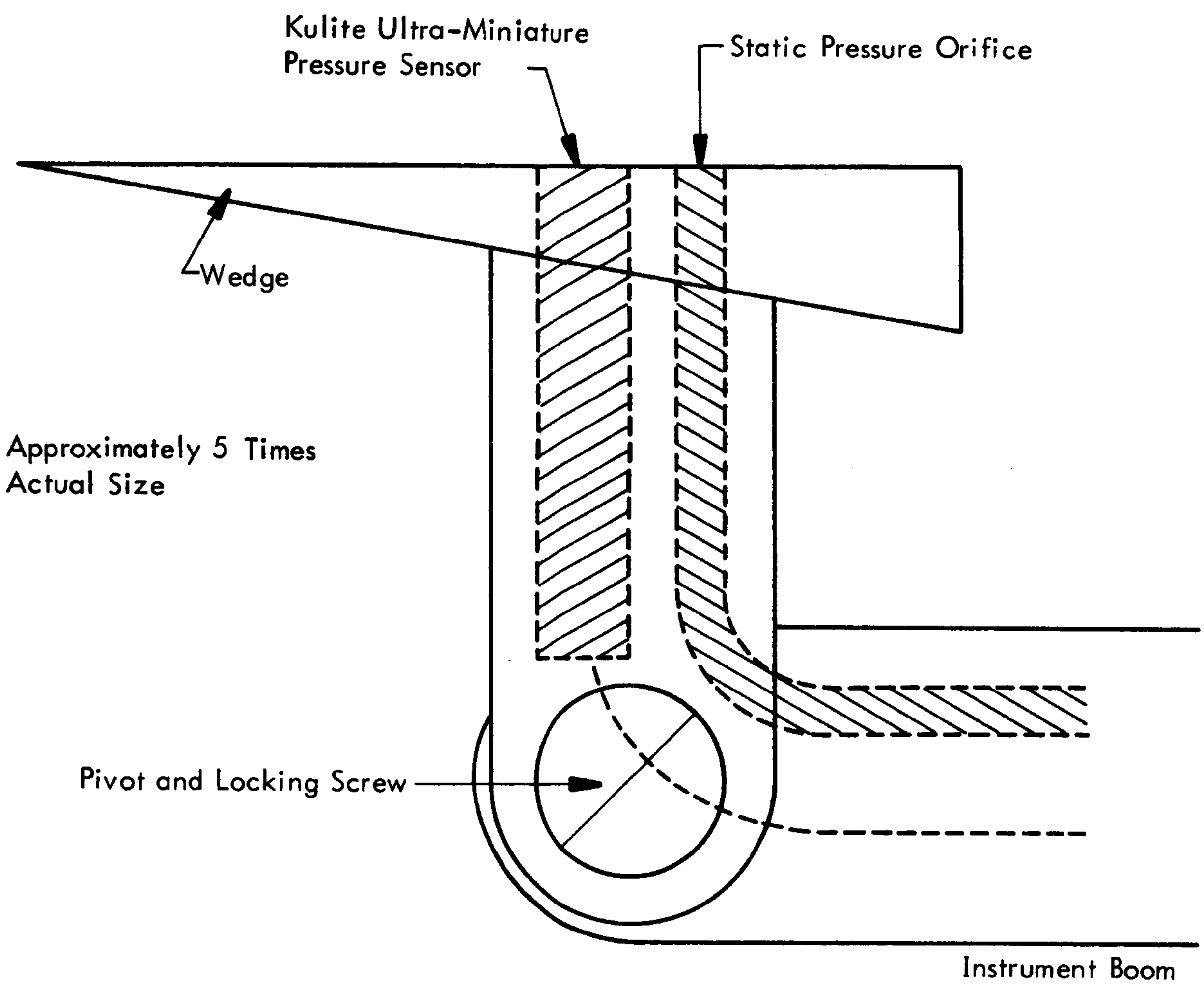


Figure 7. Schematic of Proposed Instrument Head Showing Static and Fluctuating Pressure Sensors. If required it will be possible also to mount the hot wire system with the sensor above the laminar boundary layer.

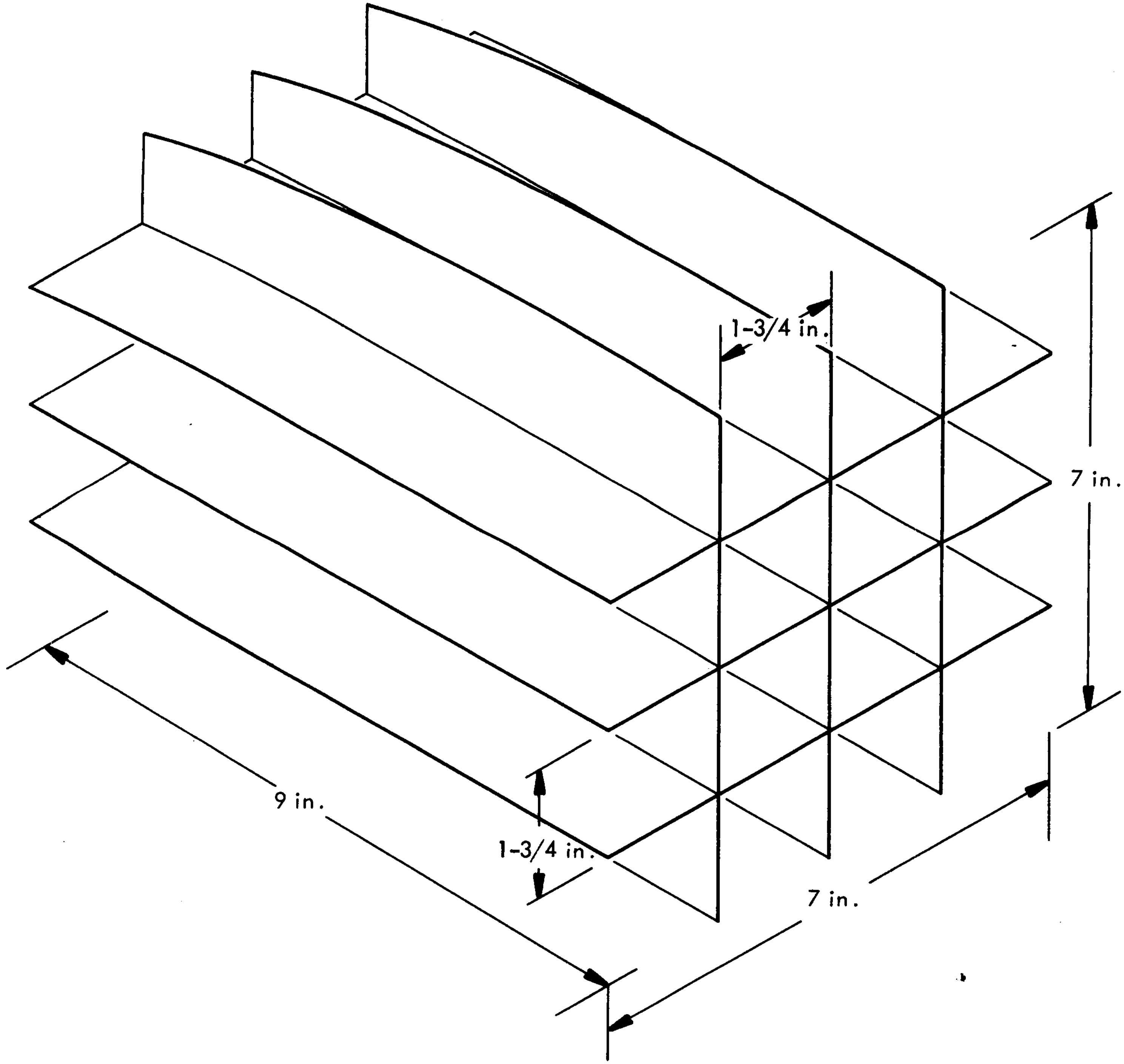


Figure 8. Schematic of Proposed Honeycomb Turbulence Generator.

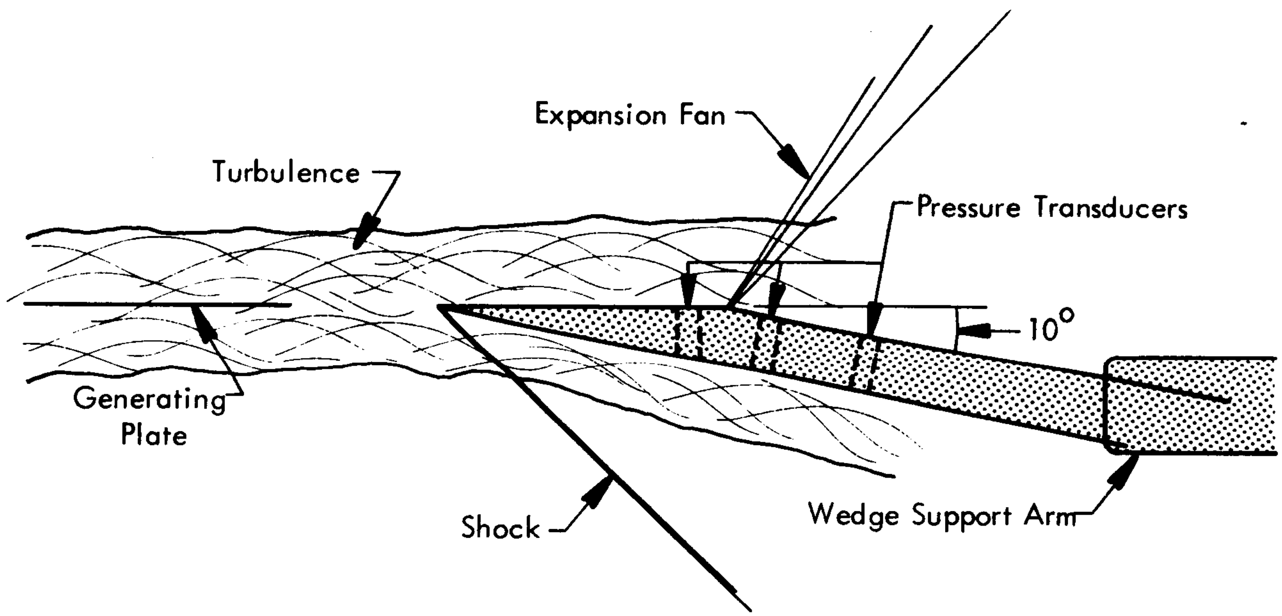


Figure 9. Experimental Arrangement for Observation of Expansion-Turbulence Interaction.