Experimental studies of supporting wire disturbances in the near viscous wakes of slender supersonic bodies

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EXPERIMENTAL STUDIES OF SUPPORTING WIRE DISTURBANCES IN THE NEAR VISCOUS WAKES OF SLENDER SUPersonic BODIES

BY

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ABSTRACT

Wires have often been used as a means of mechanically supporting a model so that its wake will be relatively free of support interference. Such support systems have many advantages over stings and are less costly than magnetic suspension systems. Investigations into the disturbances caused by these supporting wires have been carried out with the use of a two-dimensional flat plate and a wire supported slender cone. The tests were conducted in the University of Missouri-Rolla axisymmetric, supersonic wind tunnel at Mach 3.15, and at a Reynolds number of $2.14 \times 10^6$ per inch. Schlieren photography, pitot and static pressure traverses in the near, viscous wake of an 8 degree half-angle wire supported cone were conducted in order to determine the effect of supporting wires on the flow. Additional related data is presented for a two-dimensional, sharp leading edge flat plate with an interference wire used to disturb the plate's wake. Wires were shown to have no effect on the pitot pressures in the viscous wake. Data presented is compared to the previous work of others using supporting wires as a means of model support.
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LEGEND

b: thickness of flat plate
d: diameter of wire
D: diameter of cone base
M: Mach number
M_D: design nozzle Mach number (3.0)
P: static pressure
P_w: test section wall static pressure
P_∞: supersonic freestream static pressure
P_d: design freestream static pressure at nozzle exit plane
P_t1': settling chamber stagnation chamber
P_t2': test section pitot pressure
R: ratio of support wire diameter to model base diameter
R_e: Reynolds number
X: horizontal direction parallel to tunnel centerline (positive in downstream sense)
Y: vertical direction normal to tunnel centerline (positive up)
Z: horizontal direction normal to tunnel centerline (positive to right viewed downstream)
I. INTRODUCTION

A. Problem Description

The identification of high speed vehicles entering the earth's atmosphere is normally accomplished by observation of the particular vehicle's radar signature, a function of the vehicle's near and far wake characteristics. The wake characteristics also have an effect on communications between the vehicle and some other transmitter or receiver beyond the wake. Because of these problems of discrimination and communication, much interest has been shown in the past to find out exactly what happens in this flow region.

Any attempt to study the wake region in an experimental facility will dictate duplication, as close as possible, of the actual flow properties (scaled by use of non-dimensional similarity parameters) encountered by the vehicle as it passes through the atmosphere. A very basic problem in duplicating the flow field is that of holding the models in such a manner that the supporting structure has a negligible effect on the flow in the model's vicinity. The ideal way to circumvent this problem is to support the model by some means other than mechanical devices. This has been done in the past with magnetic model suspension systems but the high cost of such a support makes it somewhat undesirable for most research budgets.

The three most commonly used mechanical model supports
are front mounted stings, aft mounted stings, and wires. The aft mounted sting cannot be used for near wake investigation since it will obviously interfere with the flow region where the measurements are to be made. Although the front mounted sting support leaves the wake free for measurements, it has a major disadvantage of producing an incorrect model boundary layer due to its long length. Furthermore, the front mounted sting rules out any investigation of the effects of varying model nose radii. In view of these problems of support, many investigators have turned to wire as a convenient method of model support. This is not to say however, that the supporting wires do not alter the flow. Some controversy has arisen in past reports regarding the extent of the wire induced flow alteration. Of course, any type of physical supporting structure will have a particular effect on the flow in the vicinity of the model. The problem is to determine the limits of the flow-support interactions so that meaningful conclusions can be derived from the test data.

As shown in the Review of Literature, Section II, the effects of support wires in the non-viscous wake has been fairly well documented, but little has been explicitly said about the effects in the viscous wake. It is imperative that these viscous flow-support interactions be understood since it is the viscous boundary layer which dominates the wake characteristics for slender bodies. It is the purpose of this report to investigate the viscous wake properties
of slender axisymmetric bodies suspended by wires, and to lay the groundwork for future investigations into the problem of base mass injection.

B. Additional Experimental Requirements

Before the wake problem could be initiated, calibration of a newly fabricated Mach 3 nozzle was needed in order to know as much as possible about the freestream flow properties. Extensive pitot probing of the enclosed free jet resulted in a good knowledge of the Mach number distribution throughout both test regions.

In addition to calibration, some work was needed to determine the type and size of wires to be used for model support. A small diameter wire would result in less flow disturbance than a large diameter wire, but it would also be weaker from a strength viewpoint. A fairly accurate estimate of model drag loading during tunnel start is needed to size the supporting wires so that the models will not be lost due to wire failure.

The results of the calibration and wire studies, as well as those changes in the tunnel system since the initial operational report (Ref. 6), are also included.
C. Acknowledgment

The author wishes to express his appreciation to his advisor Bruce P. Selberg, Associate Professor of Aerospace Engineering and Ronald H. Howell, Associate Professor of Mechanical Engineering for their assistance and guidance in this investigation. Thanks are also due to Mr. Frank D. Statkus for his help in tunnel calibration and particularly to my wife, Angie, for her help in preparation of this manuscript and for her unending patience, understanding, and encouragement during the course of this study.
II. REVIEW OF LITERATURE

In discussing the effects of a wire supported structure, one would ideally compare the supported model's flow properties with a free-flight or magnetically suspended model's at the same scaled conditions. In such an investigation, the true effect of the wire, if any, would become evident. The results could then be compared to theory. Out of all of this would evolve a clear picture of the limits of support wire interference. It is however, beyond the scope of this investigation to make all of the above comparisons. It is felt that the data presented herein will be of use in the comparisons when they are finally made.

An intuitive approach would reason that as the ratio of wire diameter to model base diameter is continually decreased, the disturbance caused by the wire should diminish to the point where it has a negligible effect on the flow. This ratio will be designated as R.

The determination of R is not as important a problem as making use of the correct ratio once it is found. Obviously, if the wire becomes too small it will not be of sufficient strength to sustain the drag load of the model. In such a case, multiple wires are often used. For the multiple wire case, R remains the ratio determined from only one of the supporting wires. An additional problem arises when the wires are all positioned in the
same plane. This would be the case for a vertical wire support. Although the wire is normally pre-tensioned before the run in order to reduce the deflection due to model drag, zero deflection is at best, difficult to obtain. When the tunnel is stopped, a reverse load is experienced by the model, introducing a step change in wire loading. This reverse load will not normally be large enough to cause strength problems but the cyclic nature of the loading will normally cause wire failure at loads below its rated breaking load. A similar type of cyclic loading occurs during tunnel start when the model can undergo loads several times the normal running load. In some instances, especially for a single wire support, the tunnel is started with the model out of the flow field in order to bypass the starting load problem. This is more difficult to do with a multiple wire support structure.

There are then in general, two aspects of a wire support system which cause concern. From a fluid mechanics viewpoint, the wire must cause minimal flow disturbance; from a strength viewpoint, the model must be sustained within the test section.

The findings of others, References 9, 15, 16, 17, and 18, would seem to indicate some disagreement on the extent of wire interaction with the flow. In Ref. 15, Hromas noted effects of the wire support on flowfield static and stagnation pressures and the downstream length that the disturbance was carried. Dayman, in Ref. 16, performed a
qualitive check on wire disturbances with the use of schlieren photography. Ragsdale and Darling in Ref. 9, noted the effect of the size of wire on static pressure, static temperature, wake Mach number, velocity defect, wake width and bow and shock wave positions. Zakkay and Cresci in Ref. 17, discussed the interference of wire in regard to wake profile. Schmidt and Cresci in Ref. 18, remark that the flow disturbances caused by wire supports are non-existant beyond certain distances downstream.

Schmidt and Cresci report dissipation of the major wire effects at a distance of 250 wire diameter downstream. No data to validate this remark was presented. In striking contrast, Hromas notes "very large effects" at distances of more than 1500 wire diameters downstream.

Hromas continues that the effect of the wire is mainly felt in the plane of the wire support and that useful data can be obtained out of the wire's plane. But Dayman's schlieren analysis would indicate just the opposite, a disturbance (due to bow shocks of the wire) in planes normal to the wire.

Zakkay and Cresci investigated temperature profile asymmetry in the wake of a cone, in which the wire support was located on one side of the model. The diameter of wire was decreased until a symmetric wake profile was obtained. For this analysis the largest value of R was 0.0375 and a symmetric wake was obtained for a range of R between 0.0031 and 0.0062. The value selected for their
tests was $R=0.0047$. Hromas used a value of $R=0.0067$ and Dayman used $R=0.01734$. Schmidt and Cresci's work was performed at $R=0.00375$. Ragsdale and Darling compared the data from three values of $R$: 0.003, 0.006, and 0.012. Although their conclusions concerning the effects of the wire varied, the value of the ratio of wire diameter to model base diameter seemed fairly consistent. It is felt that this consistency arises out of strength considerations; the smallest possible wire was used that could safely contain the model.

Zakkay and Cresci report an additional criteria for the use of wire as a non-disturbing support is that the wires be held to a shallow incline with respect to the model centerline. This seems logical, but no verifying data was given.

In comparing the wakes of wire supported cones with free-flight cones, Dayman noted that above $M=2$, regardless of whether the wake was laminar or turbulent, the noticeable effect of the wire was to move the wake neck toward the model's base. Although Ragsdale and Darling made no comparisons with free-flight wake neck profiles they did note that an increase in $R$ did shift their wake profile toward the base of the cone. This seems to reinforce Dayman's observations. Dayman went on to note that in past tests, normally closed wakes for particular free-flight models became divergent when the same model was supported by wires. Dayman reports that the wake
separation region is not materially altered by wire supports when the model boundary layer is turbulent. Both Hromas, and Ragsdale and Darling were working with turbulent wakes, the separation regions of their wakes were not compared to free-flight data.

Hromas found no effect on flowfield static pressure due to the support. But he did report that due to flow angularity and vorticity in the turbulent wake, the static pressure data could be used only as a qualitative check. Ragsdale and Darling noted no effect on wake static pressure due to a change in wire support size.

Hromas reported that the disturbance due to the wire on measured pitot pressure was mainly confined to the plane of the wire and that no disturbance of pitot pressure occurred where the wire was "shielded" by the base.

In view of the apparent disagreement among the authors of the various reports available for review, one could conclude that the effects of wire interference on viscous wake properties is still a question to be answered. There are definite effects of wire on the flow especially in the non-viscous portion. The exact effect in the viscous wake is far from being completely settled. Much more work is needed in the comparison of wakes of wire supported and free-flight models.
III. RESULTS AND DISCUSSION

A. Experimental Equipment

1. Wind Tunnel and Test Conditions

The experiments presented were conducted in the University of Missouri-Rolla (UMR) supersonic axisymmetric wind tunnel, which is an enclosed free jet, intermittent flow facility. All tests were run with a newly fabricated Mach 3 nozzle at a stagnation temperature averaging about 500 degrees Rankine. The plate tests were run at an operating stagnation pressure of 146 psia; the cone tests at 150 psia. The resulting Reynolds number was $2.14 \times 10^6$ per inch. A more detailed description of the experimental facilities is given in Ref. 6 and in Appendices A, B, and C of this report.

The normal flow-field test area for an enclosed free jet would be in the immediate vicinity of the nozzle exit plane. For a square nozzle, this area could be described by a rhombus; for the axisymmetric nozzle, the test area is conical in nature. Under certain flow conditions, a second test area will exist downstream of the first test area. The flow in the region between these two test areas is nonuniform in nature and should not be used for that reason. However, the type of investigation reported herein made it mandatory to place the models in this nonuniform region. The Mach number distribution for this
model location is shown in Fig. 33. The average centerline Mach number was found to be 3.150, with a maximum deviation from average of 12\% at the cone base, the worst location.

It was desired to study the near wake region of a wire supported cone, a region in the wake from the cone base to four base diameters downstream. For our cone model with a one inch base diameter, this means a length of uniform flow of 7 1/2 inches. The first test region is of sufficient length if the wire supported cone is mounted partially inside the nozzle. However, this would mean attaching the support wires to the nozzle walls and could quite possibly give blockage and starting problems. It was decided that this was not an acceptable solution. The second test area was found to be disturbed by strong compression and expansion waves emanating from the nozzle exit corners due to the test chamber wall pressure being lower than the freestream static pressure. These two static pressures could be equalized by lowering the operating stagnation pressure, thus eliminating the presence of these strong waves. When this was done, the overall quality of flow was reduced as was the free jet diameter.

The obvious solution would be to use a smaller model, thereby affording a shorter length of uniform flow. Time did not permit this answer and the cone was mounted in the region between the two test areas so that only the near wake was in uniform flow. For this reason, the data
presented in this paper is preliminary in nature and should be verified with a smaller model at a later date.

A more complete description of the nature of the flowfield is presented in the calibration appendix of this report.

2. Models

All models used in the experiments were fabricated in the Department of Mechanical and Aerospace Engineering at UMR. The flat plate model was fabricated out of 6061 T6 aluminum, 0.127" thick. One side of the razor sharp leading edge was machined to a 15 degree angle, thus assuring an attached forward shock. The plate length was 3.25" with a 0.018" diameter hole placed 0.503" forward of the trailing edge to accommodate the interference wire.

The cone models were machined from PVC rod, having a 1.0" diameter base and 8 degree half angle. The cone length was 3.25" with a nose radius of 0.047". Five 0.018" diameter holes were drilled normal to the cone centerline to accommodate the support wires. The first two holes were drilled at 2.003" and 1.953" forward of the cone base, respectively, at 90 degree offset. The third and fifth holes were drilled at 0.553" and 0.453" forward of the base, respectively, at 90 degree offset. These two holes were 45 degrees out of line with the first two holes. The fourth hole was drilled at 0.503"
forward of the base and was aligned with the forwardmost hole. Each of the five holes were then shimmed down to 0.010" diameter with stainless steel tubing to accommodate the 0.007" diameter support wires. The first, second, third, and fifth holes were used to support the model while the fourth hole was used only when the instrumentation probe was desired to traverse in a plane aligned with a rear wire. Schematics of the flat plate and cone models are shown in Figures 1 and 2.

3. Model Support

The flat plate was mounted to the wire support jig in such a manner to be a two-dimensional model. The 0.007" diameter wire passing through the plate was used for disturbance investigations only and was not needed for support purposes.

The cone support system likewise utilized the wire support jig with two wires forward and two wires aft of the model center, each wire passing completely through the model centerline. This in effect gave four wires forward and four wires aft. The wires were not rigidly attached to the model and thus allowed the cone to align with the flow during test runs and starting transients. The two forward wires were mounted in a forward facing angle and thus overcame the drag load. The aft wires were in a backward facing angle and were mainly used to sustain model balance and reverse drag during tunnel
stops. Due to the higher drag loading of the forward wires, their angle with respect to the freestream was necessarily smaller than that angle needed for the back wires. For the tests conducted here, two cone locations were used. For the pitot traverses at \( X/D \) of 1/2, 1, 1 1/2, and 2, the cone nose was located 5.25" aft of the nozzle exit plane. For the pitot traverses of \( X/D=3,4 \), and for the static centerline traverse, the cone was moved forward 2.25" to 3" aft of the nozzle exit plane. For the first location, the forward and aft model support wires were at angles of 37.5 and 42 degrees respectively. The interference wire placed through the fourth cone hole was at a forward angle of approximately 50 degrees. In the second model location, the forward and aft support wires were at angles of 49.2 and 32.7 degrees respectively. Figures 3 and 4 are schlieren photographs of the installed models during a test run.

All wires used in this series of tests were 0.007" diameter phosphate finish music spring wire manufactured by the National-Standard Company of Worcester, Massachusetts. Complete data for this wire and various other wires available for use as well as wire support strength limitations are presented in Appendix B of this report.
B. Instrumentation and Measurements

1. Flat Plate

Pitot pressure was measured in one plane, 0.004" aft of the plate base, with the plate at various angles of attack. The inside and outside diameter of the pitot probe tip were 0.010" and 0.018" respectively. The small size of the pitot probe tip was to insure that pitot measurements could be made inside the model boundary layer. After 0.10" of length, the probe was successively shimmed up in 0.625" length steps to 0.25" diameter stainless steel tubing. It was found that 0.10" was the approximate maximum length of the 26 gauge tubing that could be used and still remain rigid in the flow. Connected to the 0.25" stainless tubing was approximately two feet of 0.125" outside diameter tubing which led through the instrumentation port to a Pace variable reluctance pressure transducer located just outside the tunnel wall. An unfortunate result of the changing inside diameter of the pitot probe line was a rather large time constant. Because of this, continuous readings could not be made. The screw driven model support with the steel support block was used to drive the pitot probe, stepwise, in a traverse of the wake. Once a change in position was made, the pressure was monitored until a constant value was reached when the next position change was executed. With this type of operation, one traverse of the viscous wake could be
performed with a full charge of air in the tunnel supply tanks.

With different combinations of angle of attack, the flat plate wake traverse was made in the plane of the interference wire, out of the plane of the wire with the wire still through the plate, and without the wire entirely. The pitot probe location of 0.004" aft of the plate base corresponded to being approximately 72 wire diameters downstream of the interference wire.

In order to determine the precise location of the pitot probe with respect to the plate, position was recorded simultaneously with the pressure on a two channel recorder. The position signal was obtained as a changing voltage across two rectilinear potentiometers, actuated by the steel support block. Position measurements obtained with this method were accurate to ± 0.002".

2. Cone

Pitot pressure was measured in a vertical plane at 1/2, 1, 1 1/2, 2, 3, and 4 base diameter downstream of the cone base. At one-half diameter downstream, measurements were made with and without the interference wire. At all other locations, the interference wire was not used. Static pressure was measured along the wake centerline from 1/2 to 3 1/2 base diameters downstream.

The pitot probe utilized in the cone tests was the same as mentioned earlier for the plate tests. The method
of obtaining readings was also similar. Instead of using two rectilinear potentiometers for position read-out however, an increased stroke, single pot was used.

The static probe used in the wake centerline traverse is of the cone-cylinder type. It has a 12 degree sharp conical tip faired into a 2.5 inch length of 16 gauge hypodermic tubing. A single, 0.024 inch diameter hole is drilled through the 16 gauge tubing at a length of approximately 15 tube diameters downstream of the conical tip shoulder. This hole serves as the static tap. This static pressure probe is used with the aluminum model support block; the position pot is driven by the limit switch carriage mounted exterior to the model support housing. The static pressure probe utilized the same transducer used with the pitot probe.

C. Data Reduction and Analysis

1. Flat Plate

The pitot pressure in psig was read directly from the recorder printout. Atmospheric pressure was then added to obtain total pressure in psia ($P_{t2}$). The settling chamber stagnation pressure ($P_{t1}$) was read from an instrument gauge located on the control panel. The control valve held this value within ±1 psig throughout the length of the run.

When the first few cone wake traverses were made
with the pitot probe, centerline values were found to be identical with those obtained at the lowest point in the plate pitot profile. This discovery, in addition to the rather sharp break in the pitot profile at the lowest values recorded, called for a closer look at the plate data. Both situations were found to arise out of an error in the instrumentation set-up. The zero setting of the recorder (zero psig) was at such a point that the recorder stylus became pinned at a reading of about 8 psia. Hence, any actual pressure below that value would only be recorded as 8 psia. For the cone traverses then, the zero psig setting of the recorder was shifted upwards so that true readings would result.

Since the plate study was not particularly concerned with wake characteristics, and only wire interference effects were desired, the plate data was not rerun. It is felt that although lower pressures indicated in the profile bucket are incorrect, the effects of the interference wire are perfectly valid, as discussed in the results section.

2. Cone

The pitot pressure was reduced in a similar manner to that of the flat plate. An additional problem arose when trying to justify what were felt to be low pitot pressure readings. From Ref. 5, there is a theoretical limit on pitot probe diameters from a continuum consideration. A
low pressure indication could result from a probe diameter being so small as to be measuring pressure in a noncontinuum regime. To be assured of continuum flow it is desired that the characteristic length (probe diameter) be 100 times the molecular mean free path, or from Ref. 5,

\[ \frac{M}{\sqrt{\bar{R}_e}} < 10^{-2}. \]

For the pitot probe used in this study the value of this ratio was \(2.05 \times 10^{-2}\). This value seemed to be on the borderline of slip-flow. It was decided to investigate values of \(M/\sqrt{\bar{R}_e}\) that others had used. In particular, for Hromas, the ratio was \(4.78 \times 10^{-2}\); for Ragsdale and Darling, \(1.29 \times 10^{-2}\); and for M.I.T., \(21.9 \times 10^{-2}\). It was concluded that our probe was not so small as to be in noncontinuum flow. As a final check, a comparison of readings were made at two points in the flow with the pitot probe in question and a larger probe of known accuracy. In both instances, the probes agreed and what had appeared to be low pressures were actual values.

The only static probe presently available for use is the cone-cylinder probe described earlier. Data obtained with this probe was reduced in much the same way as the pitot readings. This probe has certain disadvantages which make it somewhat undesirable for the type of investigations reported here. Probes of this type are quite sensitive to angle of attack, placement of the static taps on the probe itself and viscous interaction. Possibly the best static
probe to use for cone wake studies is the cone static probe. This type of probe has the static holes on the conical tip of the probe itself. Cone static probes were utilized in the works of Hromas in Ref. 15, Ragsdale and Darling in Ref. 9, and M.I.T.'s McLaughlin, Carter, and Finston in Ref. 13.

D. Results

1. Flat Plate

One of the most interesting results of this investigation was the rather significant effect of the angle of attack on the pitot pressure profile at a location of only 0.004" downstream of the plate base. This would correspond to a value of $X/b$ of 0.0315. As the angle of attack changed from +1.4 degrees to -0.6 degrees, the center of the pitot profile bucket moved from 0.035" on the wedge side of the plate to 0.095" on the flat side of the plate respectively. Or, more simply, a bucket center change in $Y/b$ of 1.023 for an angle of attack change of 2 degrees. An offset in pitot profile was expected since the static pressure on the flat side of the plate should be less than that on the wedge side due to the shock on the wedge side of the plate. It is the magnitude of the offset which is interesting. Calculations were made to determine what angle of attack would result in equal static pressures in the inviscid region on both sides of the plate base region.
It was found that at approximately plus one degree angle of attack, the pressures should be equal. This angle of attack should give a symmetric wake profile. This value agrees with the trend shown in Figures 5 through 8.

Calculations were made, in accordance with Ref. 10, to determine a turbulent boundary layer thickness for the flat plate. From both the boundary layer thickness scaled from the schlieren photographs and from the thickness derived from the pitot data were obtained reasonable estimates of the actual value. These values of boundary layer thickness were found to be larger than what the calculations predicted. Thus it was assumed that the boundary layer was fully turbulent from the interference wire location back to the plate base.

Figures 5 and 8 show little effect of the wire in the viscous portion of the wake. For the non-viscous flow however, results vary. In Fig. 5, for the plate at 0.6 degrees, pitot pressures with the interference wire were higher than that recorded without the wire. Just the opposite is seen in Fig. 8. Hromas, in Ref. 15, noted lower pitot pressures in the plane of a support wire than that found outside of the wire plane. This would agree with Fig. 8. If shock waves are formed from the wires, one would expect a rise in pitot pressure due to the lower Mach number behind the shock. Dayman in Ref. 16 did show wire induced shocks in his schlieren analysis. It is difficult to see the absence or presence of shocks due to wires in the schlieren
photographs taken in this investigation. Hromas reported that the supporting wires in his studies did not induce shock waves, but a "quasi-steady, rather complicated vortex pattern in the plane of the wire". The wire can then be seen to have a spurious effect on the pitot pressure in the plane of the wire. This random scatter of data can be seen more clearly in Fig. 6 for a traverse well into the non-viscous region.

Although Hromas had reported an effect on pitot pressure only in the plane of the wire, Fig. 7 shows that the disturbance will carry out of the wire plane. In particular, at 36 wire diameters out of the plane, a spurious nature is seen to start in the non-viscous region (in contrast to the relatively constant profile without wire).

As can be seen best in Fig. 8, in the viscous portion of the wake, the wire has little effect on the pitot pressure.

2. Cone
a. Nature of Boundary Layer on Model

It is not known for sure whether the cone boundary layer was fully turbulent at the location of the interference wire back to the cone base. However, in Fig. 4 a noticeable change in boundary layer thickness can be seen about mid-point on the cone. This is the probable transition point in the boundary layer and thus would assure a fully turbulent nature at the cone base. In addition,
the cone surface was of sufficient roughness to normally trip a laminar boundary layer.

b. Pitot Pressures

In Fig. 9, the addition of the interference wire had little effect on the viscous wake pitot pressure. In the non-viscous wake, pitot pressures measured with the interference wire present were lower than that obtained without the wire.

Figures 10 through 14 show the progressive change in the pitot pressure profile as the downstream distance is increased. The location of the wake shock appears as a sharp break in the pitot profile. Inside the wake shock, the trough or bucket of the curve clearly outlines the turbulent wake region. Outside of the wake shock the generally decreasing nature of the profile is due to the flow expansion behind the cone base.

The data presented in Figures 13 and 14 is questionable in value. For these downstream locations, especially at $X/D$ of 4, the wake shock is being affected by and interacting with the strong nozzle waves present in this second test area.

Figure 15 is an overlay of the near wake profile, i.e., $X/D$ of 0.5 through 2.0. The increasing turbulent wake width and wake shock width can be clearly seen. At approximately $Y/D$ of ±0.5, the pitot pressure changes very little. Inside of these points, the pitot pressure generally increases with downstream length; outside of these points,
the pitot pressure generally decreases, due to the expansion in the wake neck region. The width of both the wake shock and turbulent wake as obtained from the pitot profiles is shown in Fig. 16. The wake shock width values were found to be in very close agreement with values scaled off of the schlieren photographs.

From the pitot pressure data and schlieren photography, the rear stagnation point is estimated to be at approximately 0.8 base diameters downstream of the cone base. In Ref. 9, Ragsdale and Darling found the rear stagnation point of a similar wire supported cone to be at 0.9 base diameters downstream. Their work was performed at \( M = 5 \). Ragsdale and Darling noted that as the value of \( R \) was increased, characteristic wake properties such as the rear stagnation point location were shifted towards the model base. M.I.T. investigators, working with a magnetically suspended cone model at \( M = 4.3 \) had found the rear stagnation point to be 2.5 base diameters downstream of the cone base.

c. Static Pressures

As noted earlier, the cone-cylinder static probe is not the most desirable type of static probe for use, especially in the near wake region. The tip of the probe must be in supersonic flow at zero angle of attack in order to give accurate readings. The data obtained with this probe is presented in Fig. 17 but the values shown are relatively high in comparison to those obtained by
others, References 9, 13, and 15. During the traverse, the static probe vibrated at a relatively high frequency and after the test was found to be bowed approximately 5 degrees. This was due to the long length of the probe. The probe could not be held at zero angle of attack and the high values are attributed to this. In Ref. 13, both cone and cone-cylinder probes were compared. Both probes gave identical readings until the rear stagnation point was passed where their comparative readings diverged. The work of others has been exclusively performed with cone probes and their static pressure results differed significantly from those presented here.

Since both Hromas, in Ref. 15, and Ragsdale and Darling, in Ref. 9, found no effect on flowfield static pressure due to support wires, the loss of this data due to the inherent errors in the cone static probe becomes less significant.
IV. CONCLUSIONS

Schlieren observations plus the measurements of pitot pressures behind a flat plate and both pitot and static pressures behind an axisymmetric cone resulted in these conclusions:

1. In the viscous wake, the presence of support wires has no effect on pitot pressures for ratios of wire to model base diameters equal to or less than 0.007.

2. In the non-viscous flow region, the effect of pitot pressure due to an interference wire is not confined to the plane of the wire.

3. In the non-viscous flow region of the wake, the general trend is a lowering of pitot pressure due to wires.

4. Because of its geometric configuration, a cone-cylinder static probe of the size and type used in this investigation will not give useful wake data.

5. A one inch base diameter cone is too large in relation to our free jet size to allow extended near wake investigations.

6. Schlieren photography was found to agree with pitot measurements of wake shock width.

Although no effect on viscous wake pitot pressure due to support wires was concluded in this study, more work is needed in the viscous wake of slender bodies to determine
support wire effects on turbulence levels, temperature profiles, location of rear stagnation point, and turbulent wake width.
BIBLIOGRAPHY


9. Ragsdale, W.C. and J.A. Darling. An Experimental Study of the Turbulent Wake Behind a Cone at M=5. U.S. Naval Ordance Laboratory, White Oak, Silver Spring, Maryland.


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APPENDICIES
APPENDIX A

Calibration of the Mach 3 Nozzle
1. General Results and Discussion

A detailed calibration of any supersonic wind tunnel would include investigation of Mach number, flow angularity, turbulence levels, influence of dew point, and model blockage effects. Other characteristics and performance parameters such as jet boundary layer growth, optimum free-jet lengths, starting flow behavior, diffuser flow, and starting pressure ratios should also be included.

It was not the purpose of this study to complete such a detailed calibration. The calibration data presented in this report is only a good start, at best, on the above list. Through a series of 52 test runs specifically aimed at calibration, the Mach number distribution throughout two regions were obtained. In the process of carrying out the wire interference studies presented in the main body of this report, additional calibration data was obtained. Flow angularity and turbulence were not studied. The compression system air dryer holds the air dew point at approximately -90 degrees F and hence no attempt was made to study the effects of varying this parameter. No tests specifically aimed at determining blockage were performed.

The Mach number distribution was determined from a series of pitot pressure measurements made with an 11 probe pitot rake. A majority of measurements were made with the rake in a horizontal position. Additional measurements were
made with the rake in vertical and 45 degree diagonal positions. Measurements were made from the nozzle exit plane (X=0) back every one-half inch to X=5.5 inches. This region comprises what is designated the first test area. A schematic of a typical Mach 3 flow is shown in Fig. 18. Measurements were made in a second test area from X=7 inches back to X=12 inches, in one-half inch measurements. The second test area extends past X=12 but no rake measurements were made beyond this point.

A 30-tube, 60" manometer was used along with a Polaroid camera to record the pitot pressures. A reference pressure of approximately 25 psig was found to be adequate in most cases for a mid-scale reading on the manometer. Pressure check valves located at the inlet of each manometer tube contained the mercury in the tubes until the measured pressure rose high enough to overcome the reference value. Although the check valves are rated at 350 psig, several of the valves malfunctioned, passing mercury into the pitot tubes. However, since only eleven tubes were needed, enough check valves were available for use. The reference pressure was supplied by an air cylinder and regulator, and measured with a 1/4 of 1% accuracy gauge located on the control panel. As soon as the oscillations in the manometer subsided, a picture was taken of the pressure distribution. It was found that the mercury column could be read to the nearest 0.1" from the picture, or 0.04912 psi. This was considered to be of sufficient accuracy for calibration
purposes.

Although a static pressure rake was also available for use, calibration of the Mach 3 nozzle was performed with the pitot rake. Either method would require the assumption of isentropic flow through the nozzle. Ref. 2 indicates that isentropic flow is a valid assumption if condensation is not present. The low dew point of the air satisfies that condition.

There are advantages to using the pitot to stagnation ratio method. For example, a drop in Mach number from $M=3.2$ to 3.0 will result in a pitot pressure rise of about 8 psia but only a 1 psia rise in static pressure. The ratio of pitot pressure (the stagnation pressure behind the normal shock in front of the pitot probe) to the stagnation pressure measured in the settling chamber can be measured more accurately than the static to stagnation ratio. It is a more accurate index of change in Mach number. An additional problem related to making static measurements is in regard to the probe itself. The shock emanating from the conical tip causes a rise in static pressure behind this shock. The pressure orifice then must be located sufficiently downstream of the shoulder of the cone so that the shoulder expansion will lower the pressure back to the free stream condition. But the orifice must not be so far downstream as to be affected by the probe boundary layer. Considering the above, it was felt that the most reliable method of calibration was to make pitot measurements.
This is in agreement with Reference 4, 8, and 7.

The author of Ref. 4 indicates that pitot pressures measured will be affected by low Reynolds numbers (based on the probe diameter) on the order of 1000 or below. The Reynolds number based on the UMR pitot probe diameter is on the order of 100,000 at M=3 (rake probes).

There is an additional method that can be used for calibration and that is measuring pitot and static pressures at the same point in the flow during a particular run. These values can then be used in conjunction with the Rayleigh pitot tube formula to determine the Mach number at that point. The advantage of this method is that the isentropic nozzle flow assumption need not be made. But there are also disadvantages in using this method in the UMR tunnel. The only pitot and static probes available for mounting on a common support are single tube probes and can be traversed in a limited vertical direction. The necessity of making two readings at each point and the limited coverage available makes this method of calibration desirable only as a check on values obtained with the pitot rake. An attempt to make this check was aborted when the plastic tubing connecting the probe to the instrumentation port failed during tunnel start. The force of the jet destroyed this plastic tubing as well as the hypodermic tubing in the pitot probe. This means of checking pitot rake data was not pursued further.

As noted earlier in this report, two "test" regions
were probed. The first area is the typical free jet test area bounded by the final nozzle expansion characteristic and the waves emanating from the nozzle exit. The second test region is bounded by intersecting nozzle exit waves and their downstream reflections. In accordance with Ref. 7, there will be a second test area of uniform flow only if the flow is two-dimensional and if the flow in the first test area is uniform. In regard to the second condition, any non-uniformities in the first test region will be reflected by the boundary layer into the second region, reducing the quality of flow. The restriction of two-dimensional flow was determined from an analytical examination of nozzle boundary expansion waves emitted into an axisymmetric free jet. The analytical examination predicted the nozzle expansion waves would be immediately followed by compression waves. This complex wave system along with jet boundary layer interactions resulted in no second uniform test region. The authors of Ref. 7 proved the predictions correct with a square shaped free jet.

Although the first test region of the UMR Mach 3 nozzle is relatively uniform, the flow is certainly not two-dimensional. And indeed, there are nozzle expansion waves closely followed by compression waves extending into the second test area as can be seen in the schlieren photograph of Fig. 3. There is, however, a region of relatively uniform flow bounded by the nozzle exit waves and this expansion-compression wave system which can be used as a second
test area. It was found that by changing the tunnel operating stagnation pressure, the second test area of uniform flow could be increased or decreased. Use of this fact was made in the wire interference tests. The second test area can be seen in the model-free schlieren photograph of Fig. 46.

It was further found that the presence and strength of the expansion-compression waves could be expressed not only as a function of tunnel operating stagnation pressure, but also as a function of the ratio of test section static wall pressure, $P_{w'}$, to the design free-stream static pressure at the nozzle exit, $P_d$. Although $P_d$ varies only with the operating stagnation pressure, $P_{w'}$ varies with operating stagnation pressure and model size and position. As the model size is increased, blockage is increased causing the free jet to expand more than normal. This jet expansion raises the test chamber pressure. As the larger model is positioned closer to the diffuser inlet, the expanded jet has less of a chance to contract back closer to normal and hence also has the effect of raising the test chamber pressure. The position of the normal shock in the diffuser is a function of the tunnel operating stagnation pressure. As the stagnation pressure is increased, the normal shock is driven farther downstream into the diffuser, lowering the test chamber pressure, $P_{w'}$. The relatively thick boundary layer in the diffuser allows the downstream shock position to affect the upstream
property, $P_w$. Normally, the operating stagnation pressure could be raised enough to drive the normal shock past the diffuser throat and eliminate the shock position effect on the chamber pressure. This was not tried during this set of calibration runs. It is felt that the present diffuser throat is too large to sustain the normal shock downstream of the diffuser throat.

It should be possible to avoid nozzle exit shocks or expansions by setting the operating stagnation pressure and model position in such a combination that $P_{\text{w}}/P_{\text{d}}=1.0$. However, it was found that to obtain a unity ratio, the operating stagnation pressure had to be lowered to the point that stable supersonic flow could not normally be achieved. This was especially true for small pressure probes and models. Fortunately, for the case of the pitot rake in a horizontal position, flow blockage was enough to raise $P_{\text{w}}/P_{\text{d}}$ to approximately unity at higher stagnation pressures. For the horizontal rake data, the range of this ratio was from 0.962 to 1.063.

When the pitot rake was positioned vertically, it aligned with the wedge front of the model support block and blockage was reduced somewhat. Values of $P_{\text{w}}/P_{\text{d}}$ for the horizontal and vertical rake positions are shown in Fig. 19.

One run was made to try to determine how rapidly $P_{\text{w}}/P_{\text{d}}$ changed with a change in stagnation pressure. For this run a static probe was positioned at $X=8.5$ and was not
moved during the test. At operating stagnation pressures of 122, 143, and 150 psia, the values of $P_{wf}/P_d$ were 1.212, 0.945, and 0.588 respectively. It was found in another run that for model- and probe-free flow, $P_{wf}/P_d = 0.579$. A schlieren photograph of this flow is shown in Fig. 46.

In accordance with Ref. 7, the ratio $P_{wf}/P_d$ along with the ratio of diffuser inlet area to nozzle exit area can be used to determine the tunnel operating efficiency, normally expressed as the ratio of tunnel exit pressure to nozzle exit pitot pressure. Using this method, values of the UMR tunnel efficiency are shown in Fig. 20. These values are expected to be a little high since the friction losses in the tunnel are not included in this method of determining efficiency.

Limitations in axial movement attainable with the model support system necessitates moving the test section with respect to the nozzle to be able to probe different areas of flow. Presently the test section can be positioned in four different locations, each in steps of approximately four inches. This causes changes in free-jet length since the diffuser nozzle is rigidly attached to the test section. In the forwardmost position, the nozzle extends approximately into one-half the viewing area; in the second position, the nozzle exit can be just seen in the viewing area. This is the position used to probe the first test area. In the third position, the second test area can be investigated and it is the setting where the wire interference work was
performed. In the fourth and final position, little work has been done since here the flow is quite nonuniform and unsteady at most normal stagnation pressure settings. For viewing purposes, the schlieren system must be re-aligned each time the test section is moved to a new location. A schlieren photograph of the rake in a vertical orientation is shown in Fig. 21.

Figures 22 and 23 show the Mach number distributions obtained from the pitot rake in a horizontal position for given Z increments. Nozzle exit waves bounding the first test region intersect at about $X=5$ inches. This accounts for the rather large drop in centerline Mach number (from 3.01 at $X=5$ to 2.28 at $X=5.5$ inches). Since this test area is conical in shape, the nozzle wave effect is felt sooner as the distance away from the centerline is increased. These figures show a fair amount of horizontal symmetry in the second test region.

Originally, it was thought that the flow region of $X=9$ and $X=10$ inches would be the best model location for the wire interference tests. Hence a more detailed distribution was desired at that point. At these locations, the rake was aligned horizontally, vertically, and diagonally. These distributions are shown in Figures 24 and 25. The outermost points in the $-Z$ direction are shown with no Mach numbers given. Values for these points were not available due to a leak in this probe of the rake.

Figures 26 through 29 depict the relative changes in
Mach numbers for the horizontal plane in both test regions as the distance from the nozzle exit plane is increased. Tables 2 and 3 indicate average Mach numbers and the station deviations for all probe orientations and the horizontal orientation only. Figures 30 and 31 were obtained from these tables.

Since $P_{w}/P_{d}$ was larger for the horizontal rake position, Mach numbers were found to be slightly higher in the vertical plane than in the horizontal plane. This accounts for the larger overall average in each test region for the composite data than the strictly horizontal data. It is felt that for the second test region, the horizontal data is the best indication of the Mach number distribution since $P_{w}/P_{d}$ approximately equals one.

An indication of the type of flow encountered in the region between the first and second test areas is shown in Figures 32 and 33. This data was obtained with the pitot rake traversing vertically, approximately 1 inch with respect to the flow centerline. Figure 32 is for the test section in the second position with respect to the nozzle; Fig. 33 is with the test section in the third position. Values of $P_{w}/P_{d}$ are also given.

Typical pitot pressure surges on tunnel start and stop are shown in Fig. 34. This particular data was taken on the flow centerline at $X=10.5$ inches.

A typical stagnation temperature versus time relation is shown in Fig. 35. What Murphy, in Ref. 6, had denoted
as "stable operation" was found to actually be after the tunnel was shut down. The plunge in temperature on tunnel shut-down cannot yet be fully explained. Air velocity in the settling chamber should be too low for aerodynamic heating to have any effect (approximately 93 feet per second). Also, for this low speed, the difference between stagnation and static temperatures would not account for the change seen.

2. Conclusions

As a result of the tests specifically aimed at calibration and of the spot calibrations performed in conjunction with the plate and cone investigations, some general remarks concerning the nature of flow in the test section can be made.

The flow in the first test region was found to be relatively constant and independent of test section location with respect to the nozzle. This is the best working location in the tunnel.

A second test area of uniform flow does exist in the UMR axisymmetric jet. However, problems were encountered in this area when the test chamber pressure did not equal the freestream static pressure. For this case, a strong axisymmetric nozzle wave is present in the second test region. More work needs to be performed to determine the best combination of operating stagnation pressure and model size so that chamber and freestream static pressures
are equal. A smaller diffuser throat may be the answer.

As the test section is moved farther back with respect to the nozzle, the free jet length is increased since the diffuser is attached to the test section. For long free jets, the quality of flow in the second test area was found to vary considerably for a small change in operating stagnation pressure.

Increased tunnel efficiency should result from decreasing the diffuser nozzle inlet area and maintaining the ratio of chamber to nozzle exit pressures as close to a value of one as possible.
APPENDIX B

Model and Probe Supports
1. Capabilities of Screw Driven Support

The UMR supersonic wind tunnel model support is in effect a mechanical screw driven device. That part of the support which physically connects the model or probe sting to the positioning mechanism is referred to as the model support block. There are presently two support blocks available for use with the support system, an aluminum and a steel block. The aluminum support block projects into the flow jet, the steel block does not. The screw driven support system was designed for use with the aluminum support block but under normal use, no problems should occur in conjunction with the use of the steel block.

When the aluminum model support shown in Fig. 37, is used, any model or probe with a 3/8" diameter or 1/4" diameter sting may be used, as long as the maximum allowable force is not exceeded. The model support was designed for a maximum drag load of 54 lbf. This is the approximate drag from a 2" diameter, sharp-nosed cone with a 8 degree half angle at M=2. Two values of safety factors were used: S.F.=10 in the determination of nut height to prevent thread shearing during starting loads, and S.F.=4 in determination of the mechanical power requirements to operate the model support during a test run. The nut height on the vertical power screws was chosen to be 0.0625"
with the S.F. of 10 very well satisfied. The increased length of the nuts for the horizontal power screws results in their shearing strength being about eight times larger than that of the vertical screws.

The maximum static load that the support can safely handle will more likely rely on the bending strength of the sting which supports the model. The eleven probe pitot rake used in tunnel calibration has had two different stings fabricated out of 3/8" o.d. stainless steel tubing. Both the thin wall and the thick wall stings have bent during tunnel starts, when the probe was positioned in the maximum forward position.

The safety factor of 4 for the operational mode was, in the end, sacrificed in order to reduce the overall cost of the model support system. The selection of the 1/2 h.p. motors reduced the safety factor for the vertical movements to approximately 2.9; and the selection of the 1/4 h.p. motor reduced the safety factor for the horizontal movement to approximately 2.7. As can be seen from Fig. 38, as the models reduce in size, the larger safety factors are maintained.

One further point should be made in regards to support capabilities, and that is the effect of changing the model angle of attack. To use an extreme case, as goes from 0 degrees to 90 degrees, the projected area for a cone will increase by approximately a factor of 2. Also, typical drag coefficients for a cone can increase by a similar
amount when going from zero to large angles of attack. It is not hard to imagine a somewhat large safety factor being significantly reduced at large angles of attack. The conclusion here is that, neglecting tunnel blockage, a safe precautionary procedure of starting the tunnel at zero angle of attack is recommended.

With the aluminum model support block in use, the maximum drag will then be approximately 54 lbf. The limits of travel are 5" axial translation (at one sting setting), + 0.925" and -1.375" vertical travel w.r.t. the flow centerline, and approximately ± 20 degrees angle of attack. An adjustment of the sting location will supplement the axial movement as well as a movement of the entire test section w.r.t. the nozzle. With the steel probe support shown in Fig. 36 in use, all movement limits remain the same with the exception of vertical travel which increases to ± 2.5" w.r.t. the flow centerline. In addition, the probe top of the steel support block has the capability of ± 30 degrees angular displacement w.r.t. a vertical reference at any axial location. This will allow a maximum side movement of ± 2.125" w.r.t. flow centerline.

2. Description of Screw Driven System

As mentioned above, there are three types of motion attainable when the aluminum support block is used with the screw driven model support. These are axial translation, vertical traversing in a fixed axial location, and change
in angle of attack or more simply, pitching. Fig. 39 shows the mechanical system in a cut-away view. The pitching and vertical traversing are accomplished by twin vertical drive screws driven separately or together. This drive screw arrangement is mounted on a support platform which is driven by two horizontal drive screws to provide the axial translation. All of this is located in the cylindrical housing at the base of the test section. Exterior to the cylindrical housing are located the drive motors and control selsyns on the motor platform. The motor platform is set in a track similar to that of the test section so that it can move away from the settling chamber along with the test section when nozzle changes are required.

The base of the aluminum support block is pinned to the rear vertical drive screw nut and attached to the front drive screw nut through a pin-slot arrangement. The steel support block is attached to the drive system in a similar manner. Unlike the aluminum support block, the steel block can be retracted into the model support housing so that the tunnel may be started with no obstruction in the supersonic jet.

The twin vertical drive screws are independently coupled through 5:1 reduction worm gearing to two horizontal drive shafts. These horizontal drive shafts are each in turn directly coupled to a 1/2 h.p. a.c. motor. These drive shafts are presently directly coupled through a helical gear arrangement located on the motor platform so they can
be driven together from a single motor. No pitching can be accomplished with this set up but the vertical traversing is much easier to control with one motor.

The twin drive horizontal screws which provide the axial translation are mechanically coupled outside of the model support housing. They are in turn coupled through a 3.3:1 chain sprocket reduction to a single 1/4 h.p. a.c. motor. Also coupled to the horizontal drive screws is a limit switch carriage which rides on a single screw of the same thread as the horizontal power screws. Stops are provided so that the maximum axial movement is not exceeded.

Flexible shafts connect a selsyn motor to each of the horizontal shafts and to the limit switch carriage screw. These selsyn motors provide the power to drive the mechanical counters used for position readout located on the control panel. These mechanical counters are 5-place counters with the last row of digits making one complete cycle per shaft revolution. In other words, a one-tenth shaft revolution will register the next number. For example, if the axial readout reads 00405 after an original reading of 00000, the horizontal drive screws have turned 40 1/2 turns or 1.0025", since the screw has 40 threads per inch. The vertical readout counters are not set up to read in a similar manner since these counters are hooked up to the drive shaft and not the screw itself. There is a 5:1 reduction between the counter and the 40 thread vertical screw. If the vertical screw turns 40 1/2 turns, the counter will turn
5 times as much or 202 1/2 turns, giving a reading of 02025 (if the original reading was 00000). The movement would still be 1.0025".

The wiring schematics for the model support controls are shown in Fig. 51 and Fig. 52.

The last item to note in regard to the model support is concerning its deflection under load. An unfortunate effect of the basically cantilevered construction is that it will deflect or bend to a small degree under loading. Fig. 41 shows the deflection at various locations on the model support upper structure. These deflections must be taken into account in order to precisely know the model location in the flowfield.

3. Capabilities of the Wire Support Jig

One additional model support is available for use in the wind tunnel. This is the wire support jig designed by James R. Murphy. This support is for single position mounting only and is not tied into the screw driven support. It is normally used to support a model so that the mechanical driven support system can be used with pressure and temperature probes. The support capabilities of the wire support jig are a function of the mechanical strength of wire used. Once a particular type of wire is chosen, further refinements in the maximum loads possible are obtained by changing the angles of the wire w.r.t. the centerline of the model.
Several types and sizes of wire have been tested for use in this support device: Carbon Steel Music Wire at 0.0105" diameter; Phosphate Finish Music Spring Wire at 0.008" and 0.007" diameter; and Brass Coated Carbon Rocket Wire at 0.006" diameter. All types of wire were manufactured by the National-Standard Company of Worcester, Massachusetts.

The two factors of importance are the wire tensile strength and its elongation under load. An excessive elongation is undesirable especially if the wire remains stretched when the load is removed.

Two methods of testing the wire were used. In the first method, the wire was loaded with progressively larger loads but released to a no-load state between the larger load steps. In this way, elongation could be determined by measuring the length under load and the length after the load was released. The second method consisted of loading the wire continuously to the breaking point. Fig. 42 shows the results of some of these tests. Although the Carbon Rocket wire had a higher ultimate tension strength, it deformed sufficiently under load (both during load and after load was released) to make this type of wire undesirable. The Music Spring wire did elongate under load but returned to its original length when the load was released.

The second consideration is the determination of the strength of wire needed to support the model as it is
subjected to the high starting loads. The starting loads are difficult to precisely determine, and the reader is referred to Ref. 23 for a more complete discussion of their causes. From the use of the drag formula,

\[ D = \frac{1}{2} \rho V^2 AC_d, \]

the one inch base diameter cone is found to have a drag of 3.34 lbf. at test conditions. But in accordance with Ref. 23, the starting drag is much higher, 31.55 lbf. This load must be used in the determination of wire strength needed. Since the conical model is held by four forward wires at some angle, \( \theta \), w.r.t. the flow centerline, the correct wire and mounting angle can be found from the simple relation

\[ 4T \cos \theta = \text{Drag}, \]

where \( T \) is the wire tension load in pounds. If the breaking strength of the wire is used for \( T \), the maximum mounting angle can be determined. For sample D, the maximum angle is 63.2 degrees for the 1" base diameter cone. Fig. 43 shows the effect of changing \( \theta \) on the wire force at various operating pressures (for a particular cone model).

4. Description of Wire Support Jig

The wire support jig consists of a plate bolted to the upstream flange of the test section from which extend 1/2" square rods, spaced every 45 degrees. The wires are attached to these rods by snap swivels. The rear wires
are fixed in their location but the forward drag wires have four possible mounting locations. The length of wire and choice of forward wire swivel location will determine the wire angles with respect to the flow centerline.

The square rods are exterior to the free jet and can be used to support a flat plate or other similar model if two-dimensional studies are desired.
APPENDIX C

UMR Axisymmetric Wind Tunnel Update
In this section, an attempt will be made to bring the reader up to date on the system changes in the UMR supersonic tunnel since the last documented report. (Ref. 6)

1. Nozzles

a. Supersonic Nozzle

The original Mach 3 nozzle fabricated for the UMR tunnel was a sharp-corner nozzle with dimensions calculated by the method of characteristics. The expansion region of such a nozzle is a sharp corner at the throat with the wave cancellation region or so-called straightening section spelling out the nozzle length downstream of the throat. The flow resulting from this nozzle was of sufficiently poor quality, having numerous shocks of fair strength in the test area, that it was decided a second one should be made.

The present Mach 3 nozzle was manufactured jointly by UMR Technical Services and the McDonnell Douglas Corporation of Saint Louis, Missouri. The flow field for this nozzle was again obtained by the method of characteristics, but has a hyperbolic expansion zone. The use of the hyperbolic zone increased the nozzle length by 3.891 inches compared to the sharp-corner nozzle. In addition to the expansion region the nozzle was further modified by use of
the T. Cebeci method of calculating the turbulent boundary layer with pressure gradient for axisymmetric nozzles. Fig. 44 shows the new nozzle contour with the boundary layer correction. Fig. 45 and Fig. 46 are schlieren photographs of the old and new supersonic flowfields, respectively. The second nozzle shows a very much improved flow field.

b. Diffuser Nozzle

The original diffuser nozzle planned for use in the UMR tunnel had a throat diameter too small to allow shock swallow and hence supersonic operation. Once this diffuser nozzle was removed, supersonic flow could be achieved although this meant operating at a high stagnation pressure. With the installation of a redesigned diffuser shown in Fig. 47, the operating stagnation pressure could be dropped from 180 to 120 psig for the Mach 3 supersonic nozzle. This meant a significant savings in allowable run time versus pumping time.

2. Instrumentation and Controls

The tunnel starting controls were revamped in order to reduce the time needed to acquire a stable supersonic jet at a constant stagnation pressure. When the tunnel is started, the ambient pressure in the stagnation chamber is so much lower than the desired pressure that a full open valve position would normally be required to compensate.
In the original control set-up, the valve did in effect open to a full position. The settling chamber quickly reached its set pressure, and then passed it due to the delayed time response in the control air circuit. This overpressure then caused the valve to close, overcompensating. After considerable oscillation, the valve finally was on-line at the desired stagnation pressure. The time required to reach this pressure varied from approximately 20 to 30 seconds, using up much of the available run time.

Two objectives were desired: quicker on-line time and less oscillation. The result of the below modifications resulted in an on-line time of approximately 5 seconds with minimal oscillation. A 1:1 relay was installed between the supply pressure and the 4160 controller. This relay was delayed in its initial operation by the addition of the delay accumulator. The 1:1 relay gives a one psi output for a one psi pressure change on the relay diaphragm. This relay and delay accumulator combination then replaced the previous step input in supply pressure to the controller with a gradually increasing supply pressure. The overall effect of this change was to reduce the sensitivity of the controller and thereby causing the controller output rate to be smaller. This smaller controller output made the valve respond slower to the initial large difference in actual to desired stagnation pressure.
The controller output originally was sent to the valve positioner which produced the desired relationship between signal and valve position. A further modification was made by replacing the valve positioner with a 1:2 volume booster. The controller output signal was then amplified by an approximate factor of two before reaching the control valve diaphragm actuator. This change made the valve more sensitive, giving a greater stroke for a given input pressure change. The present control air schematic is shown in Fig. 48.

The copper seat of the control valve was replaced by installation of an entirely new throttling plug. An equal percentage plug replaced the original proportional plug. The new plug has a stellited stainless steel seat which at the present leaks air at a similar rate as the original seat. Hand lapping is expected to remedy the problem. At present, the control valve is pressurized on the upstream side only just before runs by keeping the manual valve closed during pumping.

A few controls have been added to the control panel itself. Model support position readout counters, switches and limit lights have been added as well as muffler cap switch and indicator lamp. Main power key switches have been added for safety purposes. The electrical control wiring schematic is shown in Figures 50 through 52. Most of the controls are straightforward enough to not require any instruction in their use. The following exceptions should be noted. The manometer lights cannot be operated
until the Xenon switch is on. The muffler cap control and
the two 1/2 h.p. a.c. motors for the model support are pre­
sently the only load on the Model Support Power key switch.
The 1/4 h.p. a.c. motor for the model support axial control
must be completely stopped before direction is reversed.
For that reason, an adjustable time delay is incorporated
into its control circuit. A time pause, which is set inside
the control panel, automatically takes effect when the
switch is reversed. When the axial limit switches are
thrown, no power can be supplied to the control motor until
the limit switch carriage is reversed manually. This can be
more easily accomplished by installation of an override
momentary switch as shown in the wiring schematic.
APPENDIX D

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Figure 10. Pitot Pressures at One Base Diameter Downstream of Cone Base
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Figure 27. Horizontal Plane Mach Number Distribution for X=3 to X=5
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Figure 36. Steel Model Support Block

Figure 37. Aluminum Model Support Block
Figure 38. Required Operational Torques of the Screw Driven Model Support System
Figure 39. Cut-Away View of Screw-Driven Model Support System
Figure 40. Legend for Figure 39

1. Cap plate for vertical screw housing
2. MRC roller bearings 7300-S
3. Aluminum model support block
4. Vertical drive screws
5. Pinned nut assemblies
6. Vertical screw housing
7. Worm gear housing
8. Boston bronze worm gear DB1600
9. Boston steel worm
10. Shaft bushings (aluminum)
11. Model support housing
12. Translation block
13. Horizontal drive screw
14. Horizontal slotted shaft
Figure 41. Static Load Deflection of the Aluminum Support Block
Figure 42. Typical Wire Elongation in Tension
Figure 43. Wire Tensile Force vs. Location and Operating Stagnation Pressure
$X = AXIAL\ LENGTH$

$R = RADIUS\ FROM\ METHOD\ OF\ CHARACTERISTICS$

$\tilde{R} = RADIUS\ WITH\ B.L.\ CORRECTION$

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Figure 44. UMR Mach 3 Nozzle Contour
Figure 45. Schlieren Photograph of Old Nozzle Flowfield
Figure 46. Schlieren Photograph of Present Nozzle Flowfield
Figure 47. UMR Diffuser Nozzle
Figure 48. UMR Supersonic Wind Tunnel Control Air Schematic
Figure 49. Legend for Figure 48

S1  Asco Solenoid Model 8210C93, Two-Way
S2  Asco Solenoid Model 8210C93, Two-Way
S3  Asco Solenoid Model 8262C2, Two-Way
S4  Asco Solenoid Model 8320A7, Three-Way
S5  Asco Solenoid Model 8342A1, Four-Way

R1  Fisher Regulator Type 67R, Set @ 20 psig
R2  Fisher Regulator Type 67FR, Set @ 22 psig
R3  Fisher Regulator Type 67FR, Set @ 35 psig

1:1  Relay - Fisher Series 2601A
1:2  Booster - Kendal Model 20 Volume Booster
Figure 50. Control Panel Wiring Schematic
Figure 51. Wiring Schematic for Model Support Axial Drive Motor
Figure 52. Wiring Schematic for Model Support Vertical Drive Motors
APPENDIX E

Tables
## Table 1. Breaking Load Data of Support Wires

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>DIAMETER</th>
<th>RATED BREAKING LOAD</th>
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<th>CONTINUOUS BREAKING LOAD</th>
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(1) BASED ON RATING OF NATIONAL STANDARD

(2) BASED ON CYCLIC BREAKING LOAD

(3) DATA NOT AVAILABLE

Samples A and B: Brass coated carbon rocket wire
Sample C: Carbon steel music wire
Samples D and E: Phosphate finish music spring wire
Table 2. Average Mach Numbers and Percent Deviations from the Horizontal Rake Calibration

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<th>X (INCHES)</th>
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<th>MACH NUMBER RANGE</th>
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Table 2. Average Mach Numbers and Percent Deviations from the Horizontal Rake Calibration
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Table 3. Average Mach Numbers and Percent Deviations from All Rake Positions during Calibration