STING EFFECTS IN HYPERSONIC BA PRESSURE MEASUREMENTS

by

George S. Pick

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Sting interference effects were investigated at nominal Mach numbers of 6.3 and 9.9. Sting mounted and instrumented free flight sharp cone models were used at a unit Reynolds number of about 1×10^6/ft. Measurements showed that the base pressure distribution changes little below $\alpha = 15^\circ$ but becomes highly nonuniform and sensitive to angle of attack changes at high angles of incidence. Sting interference effects are not very severe at $M = 6.3$ when $\alpha < 20^\circ$ but as the angle of attack increases, the flow becomes progressively more distorted. Consequently, the base pressure values of the sting mounted model deviate from the free flight interference free model measurements. Beyond about 40°, due to the severe effects of sting interference, no steady base pressure value could be reached with the sting mounted model in either of the tested Mach numbers. For the free flight model at Mach number 9.9, the magnitude of the measured base pressure ratios at corresponding flow conditions and angles of attack were about 70 percent above the sting mounted model showing how serious sting interference can be.

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NOTATION

d	Sting diameter, inches
D	Base diameter, inches
K	Defined as Equation (3)
ℓ	Sting length, inches
L	Model length, inches
M	Mach number
P	Free-stream static pressure, psia
P_B	Base pressure, psia
P_t	Total pressure, psia
q	Dynamic pressure, psia
Re	Unit Reynolds number/ft
Re_D	Reynolds number based on the base diameter
Re_L	Length Reynolds number
T_o	Total temperature, ^oR
T_w	Wall temperature, ^oR
α	Angle of attack, degrees
$\Delta\alpha$	Corrected angle of attack (see Equation (1))

ABSTRACT

Sting interference effects were investigated at nominal Mach numbers of 6.3 and 9.9. Sting mounted and instrumented free flight sharp cone models were used at a unit Reynolds number of about 1×10^6/ft. Measurements showed that the base pressure distribution changes little below $\alpha = 15^\circ$ but becomes highly nonuniform and sensitive to angle of attack changes at high angles of incidence. Sting interference effects are not very severe at M = 6.3 when $\alpha < 20^\circ$ but as the angle of attack increases, the flow becomes progressively more distorted. Consequently, the base pressure values of the sting mounted model deviate from the free flight interference free model measurements. Beyond about 40° due to the severe effects of sting interference, no steady base pressure value could be reached with the sting mounted model in either of the tested Mach numbers. For the free flight model at Mach number 9.9, the magnitude of the measured base pressure ratios at corresponding flow conditions and angles of attack were about 70 percent above the sting mounted model showing how serious sting interference can be.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

Base flow about the rear of a three-dimensional body submerged in a hypersonic stream depends on several variables, including the body geometry, transition location, Reynolds and Mach numbers and, very importantly, the model support. Much of the published experimental information concerning base flow properties has been clouded by the uncertainty introduced by model support interference. The sting model support system, in common usage in wind tunnels, is bound to distort the flow field to some degree. Consequently, the reliability of the resulting data might be questionable.

Considerable experimental work has been done at zero angle of attack on the problem of support interference in supersonic speeds. It has been confirmed that the base pressure is stronglv influenced by the support interference and can serve as the first indication of flow distortion caused by the presence of model support (see References 1 and 2). Whitfield (Reference 3) showed that the support interference is dependent on the transition location and the length Reynolds number at M = 3.0 to 4.0 over a unit Reymolds number range of 10^5 to 10^6 per inch (corresponding to Re_L from 1×10^6 to 7×10^6). In the measured test envelop the critical sting length to base diameter ratio in the worst case was approximately 5.5. Love (Reference 4) presented a rather complete summary of available information of the early investigations on support interference at transonic and supersonic speeds. Kavanau (References 5 and 6) also investigated the support interference problem at intermediate and very low Reynolds numbers in the neighborhood of M = 3.0. Reller and Hamaker (Reference 7) studied the interference effects during the course of their investigation of the base pressure characteristics of lifting bodies in the shock number range from M = 2.73 to 4.98. Sivier and Bogdonoff (Reference 8) investigated the sting diameter effects at M = 2.97 and at high Reynolds numbers (10 to 40 $\times 10^6$). They found sting diameter interference for all finite stings tested. However, Sieling (Reference 9) who tested at free-stream conditions of M = 3.88 and Re = 15.6 $\times 10^6$/ft found that if $d/D < 0.15$, the base pressure differs less than four percent from the condition where there is no sting interference. He also found that if $\ell/D > 1.3$ no apparent change in base pressure occurred with change in length.

Based on data from References 4 to 7, it appears that for laminar flow in the $M = 1.5$ to 5.0 range, both critical length and diameter ratios exist but while the length ratio increased from about $\ell/D \approx 3.0$ at $M = 1.5$ to $\ell/D \approx 6.0$ at $M = 5.0$, the critical diameter ratio has a maximum value ($d/D \sim 0.5$ at $M \approx 4.0$) and decreases with both increasing and decreasing Mach number (see Reference 10). Whitfield (Reference 3) states that the sting diameter effects may be important when an attempt is made to correlate data with free flight results.

Peckham (Reference 11) conducted a qualitative exploratory study at $M = 6.8$ where transition occurred upstream of the model base so that a turbulent wake is formed. He found that at $\alpha = 20^{\circ}$, the flow pattern on a delta wing model was not affected by sting diameter in the range of $0.4 < d/D < 0.6$.

There is no information in the literature about sting effects at angle of attack and at hypersonic speeds, so some authors simply compare their data with data obtained in other facilities (see Reference 12). If this comparison yields no major discrepancy, the data is deemed valid. The author of the present paper, however, disagrees with this philosophy and maintains that the only valid comparison between two sets of base pressure data is when in the same facility and in identical free-stream conditions two geometrically similar models are tested. One with support and one free of support interference (free flight model). If that comparison provides identical results then support interference effects can be neglected. It is the objective of this paper to compare base pressure data obtained in the NSRDC hypersonic facility under very similar free-stream conditions using a 9° half angle sting supported sharp cone and a 10° half angle instrumented free flight sharp cone model at varying angles of attack. Free flight measurements show that the base pressure, base flow, and wake characteristics of 9° and 10° sharp cones are nearly identical and therefore discrepancies in the data can mainly be attributed to sting interference effects.

TEST APPARATUS AND EXPERIMENTAL TECHNIQUES

WIND-TUNNEL FACILITY

All of the experiments described herein were conducted in the NSRDC 13.5-inch diameter free jet hypersonic wind tunnel. This facility is equipped with a series of axisymmetric nozzles providing a nominal Mach number range from 5.0 to 10.0 with variable Reynolds number capability. This, in turn, corresponds to the available supply pressures ranging from 15 psia to 600 psia and air temperatures from ambient to 2500°F. Runs of 100 second length are feasible. Further details of the facility may be found in Reference 13.

DESCRIPTION OF MODELS AND INSTRUMENTATION

Sting Mounted Model

The basic model configuration consisted of a 6-inch long 9° half angle sharp cone fabricated from type 416 stainless steel with mirror surface finish and geometric tolerances not exceeding ± 0.001 inch. This model was equipped with two base pressure taps 180° apart at 0.612 inches from the axis. The sting support consisted of a 5/8-inch diameter and 21-inch long stainless steel tube attached to the sector blade. Figure 1 shows the sting mounted cone in the test section.

Free Flight Model

The free flight model was designed to be injected into the flow field and at predetermined angles of attack and roll and released to fall freely through the hypersonic test section. The basic configuration consisted of a 6-inch long cone having a half-angle of 10° and a nose radius of 0.003 inches maximum. The skin was machined from corrosion resistant steel polished and chrome plated to provide abrasion resistance. The model is instrumented to measure base pressure distribution at various roll angles, angles of attack, Reynolds and Mach numbers. Figure 2 shows the exploded view of the skin and the instrumentation package.

The design provided for the adjustment of the center of gravity in such a way that the center of pressure and center of gravity coincided causing the model to maintain the initial angle of incidence throughout its flight trajectory.

Instrumentation

Two low pressure, Datametrics type 1014 Electronic Manometer and type 5.1-3 Barocel pressure sensor systems were used for the sting mounted cone base pressure measurements. These systems were capable of measuring pressures between 0 and 1 psia on seven consecutive scales from 0.001 to 1.0 psi full scale with accuracy and linearity of ± 0.05% full scale accuracy. The output signals of the pressure sensors were processed by a high-speed analog to digital acquisition system, designated as Beckman Model 210 and the details of which are discussed in Reference 13. The pressure time response of the system varied between 20 and 50 seconds, depending on the Mach number, after which the measured and actual pressures were within one percent. Since the running time of the facility was in the order of 100 seconds, the pressure measuring system provided measuring accuracy of about 0.5 percent of the actual pressure.

The active measuring elements in the free flight cone test consisted of four differential pressure telemeter transducer packages housed in the interior. The signals from the transducers were intercepted by a complex antenna system completely outside, but surrounding the free-stream flow. The antenna system was connected with appropriate electronic instrumentation for signal processing and analog data output. The model, prior to injection into the stream was guided by a specially constructed drop mechanism which, after injection and during the free flight phase was completely out of the flow stream. Figure 3 is a photograph of the model, drop mechanism, and antenna installation in the hypersonic tunnel. Figure 4 is a block diagram of the instrumentation. Prior to the free flight measurements a detailed systems evaluation program was conducted. The pressure-time response measurement of the transducer system, which was part of the preliminary calibration (Reference 14) showed that under even the worst conditions the time response was less than 5 milliseconds. This represents about 15 to 25 percent of the total free flight duration.

TEST PROGRAM

Prior to actual testing, a rather thorough flow and temperature survey was conducted in the tunnel which showed that non-uniformities in the free stream did not exceed ± 1.7%.

Table I is an outline of the test program and the main parameters investigated within the scope of the present report. Base pressure data for the sting mounted cone were taken at 0.5 second intervals. Figure 5 is a typical example of the pressure-time history of the base pressure. In addition to the base pressures, the wall to total temperature ratios for the sting mounted model were determined by means of thermocouples. At M = 6.24 the average initial wall to total temperature ratio was T_w/T_o = 0.35 and at M = 9.89, T_w/T_o = 0.31.

In the free flight program, four data points were obtained in each drop. For any given flow condition and angle of attack, a series of 12 drops at 30 degree roll angle increments provided good definition of the complete base pressure distribution. The reported data have been extracted from base pressure distributions determined in this way. More than 125 data runs were conducted involving the free-stream conditions covered by the present report.

DATA REDUCTION AND ACCURACY

The base pressure data obtained, using the sting mounted model were reduced by means of a computer program routine. The raw data were corrected for sting deflection using equation

$$\Delta\alpha = 0.00372 \quad \alpha \frac{q}{P_t} \quad P_t \tag{1}$$

The maximum uncertainty associated with the angle of attack measurements is estimated to be no greater than ± 0.10°.

The error due to high temperature and to low pressure at the base was computed according to the method of Howard (Reference 15). According to this calculation, the maximum error at M = 9.89 did not exceed 2.5 percent; the average error, however, is less than 1 percent. The data are not corrected for this error. The overall accuracy due to instrumentation, temperature, and time response errors is estimated to be ± 3 percent.

Data from the free flight model measurements were extracted by manual means since only analog records were available (oscillograph records for the pressure transducer output and high-speed film for the model incidence). Daily calibrations of the transducers were used in the pressure data reduction procedure together with optically corrected data for pitch angle determination. The overall accuracy of the base pressure data was estimated to be ± 5 percent.

RESULTS AND DISCUSSION

Base pressure measurements were made with the sting mounted model at several angles of attack between 0 and 60° for both M = 6.24 and 9.89. Pressures at both measured locations for $\alpha = 0$ were nearly the same. Furthermore, this is true even at moderate angles of attack, as shown in Figures 6 and 7, where the base pressure ratios (nondimensional by the free stream static pressure) are presented as functions of the angle of attack for M = 6.24 and 9.89. This observation, at least for $\alpha = 0$, was confirmed by other investigators who demonstrated that the base pressure distribution on blunt based axisymmetric bodies exhibited a slight maximum in the geometric center with an axially symmetric decrease toward the edge of the base.

In view of the axial symmetry of the base pressure distribution, it is not unreasonable that the obtained data at zero angle of attack show similar values, particularly since the sensing orifices were located at 180° apart and equi-distant from the center axis.

As shown in Figures 6 and 7, the base pressure ratio is nearly constant below about 15° angle of attack and then increases. This was also confirmed, Reference 16, for a 5° cone angle. Beyond about 40°, because of the sting effects, no steady base pressure value could be reached in either of the tested Mach numbers.

A fair amount of confidence in the data obtained for M = 6.24 at $\alpha = 0$ may be gained by comparing it to the work of other investigators. Based on a large number of experimental measurements conducted in the M = 7.7 to 19.0 speed range, both for laminar and turbulent flows, an empirical base pressure correlation was developed for a 10° [illegible]f angle sharp cone at zero angle of attack. The correlation equation may be expressed as:

$$P_B/P = 0.33 \left(M^3/\sqrt{Re_D} \right)^{0.75} \qquad (2)$$

where the base diameter is the characteristic length in the Reynolds number computation. The measured base pressure ratios at $M = 6.24$ and zero angle of attack are apparently close to the predicted value of Equation (2). In our case $M^3/\sqrt{Re_D} = 0.53$ and consequently $P_B/P \approx 0.21$. This is shown in Figure 6.

Theoretical calculation in Reference 17 (showing the effect of cone angle bluntness ratio and Mach number on the base pressure ratio) predicts base pressure ratio values of 0.17 for $M = 6.24$ which is in good agreement with the measured values at $\alpha = 0$, considering all the uncertainties.

Base pressure results for the free flight model for $M = 6.34$ and 9.94 are presented in Figures 8 and 9. Note that the base pressure ratio increases with increasing angle of attack, which is the trend exhibited with the sting mounted cone. The magnitude of the base pressure ratio at $M = 6.34$ below $\alpha = 20^\circ$ is close to the measured values of the sting mounted cone. However, at higher angles of attack the deviation is considerable (about 30 to 70 percent). At $M = 9.94$, base pressure ratios obtained by the free flight model are [illegible]0 percent above the magnitude of the values obtained with the sting mounted model for the same α and flow conditions. At angles of attack the base pressure distribution becomes highly nonuniform. A measure of the sting interference effect may be defined as:

$$K = \frac{(P_B/P)_{\text{free flight}}}{(P_B/P)_{\text{sting mounted}}} = f(\alpha) \qquad (3)$$

K as function of the angle of attack is shown in Figure 10. It is evident that as the angle of attack increases the sting interference effect becomes more severe. The interference effect is worst at higher Mach numbers.

CONCLUSIONS

Sting interference effects were investigated at M = 6.3 and 9.9 with a unit Reynolds number of about 1×10^6/ft. A 9° half angle sting mounted and a 10° half angle instrumented sharp cone model was utilized. Measurements showed that:

(a) At $\alpha < 15$ degrees the base pressure distribution changed very little with angle of incidence at both Mach numbers. As the angle of attack increased base pressure increased also.

(b) Sting interference was not very severe at M = 6.3 and $\alpha < 15$ degrees, but at higher angle of attack the flow became progressively more distorted and K increased to 1.

(c) At M = 9.9, K was approximately 2.2 at $\alpha = 0$, showing the severity of the sting interference.

TABLE I

Outline of Test Program

Model Description	Nominal Angle of Attack Range	Free-Stream Mach Number	Reynolds Number per ft	Remarks
Sting Mounted 9° Cone	0° - 60°	6.24 ± 0.13	$1.0 \times 10^{6} \pm 2\%$	Base pressure measured in two locations. Model also rolled 90°.
	0° - 60°	9.89 ± 0.15	$1.0 \times 10^{6} \pm 3\%$	
Free Flight 10° Cone	0° - 40°	6.34 ± 0.11	$1.1 \times 10^{6} \pm 5\%$	Base pressure measured in four locations. Model rolled 360°.
	0° - 40°	9.94 ± 0.16	$1.1 \times 10^{6} \pm 4\%$	

Figure 1 - Sting Mounted Model in the Test Section

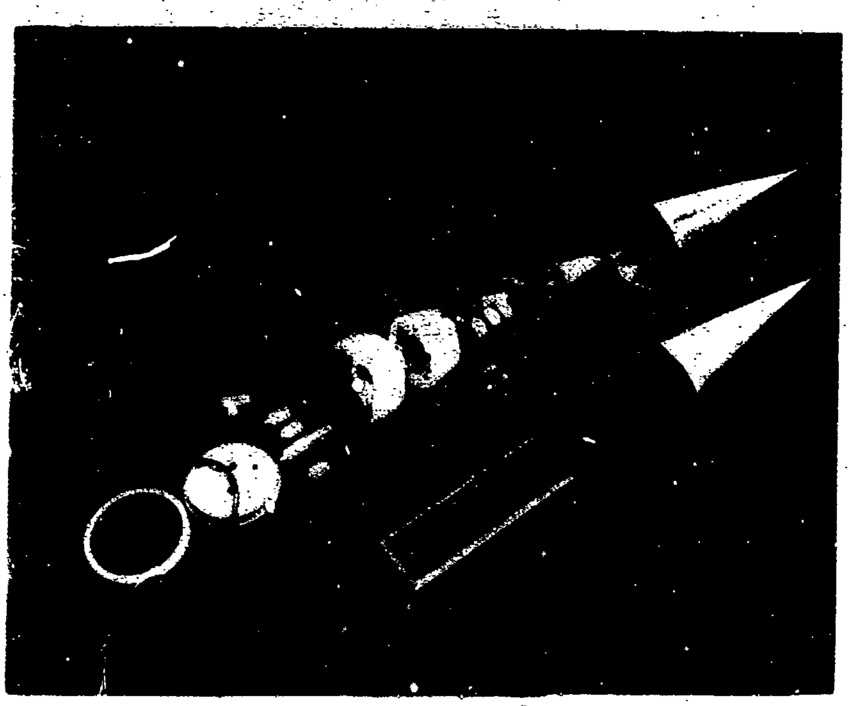

Figure 2 - Exploded View of Instrumented 10° Half Angle Cone Base Pressure Model

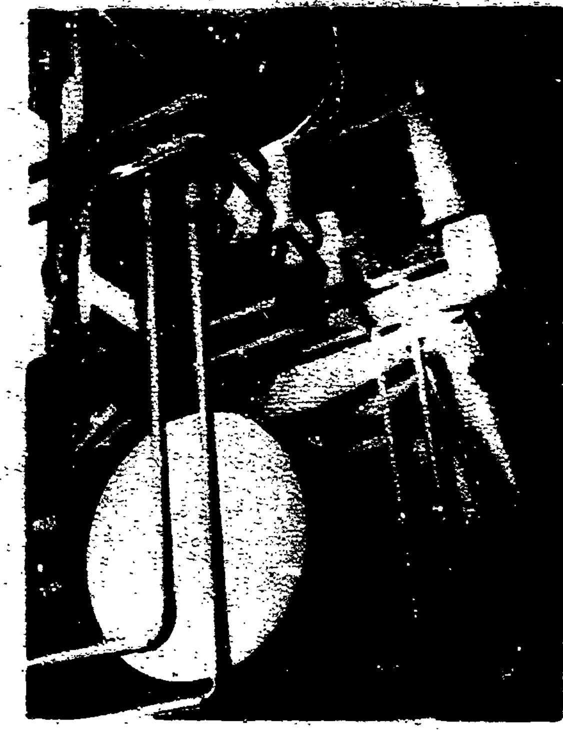

Figure 3 - Instrumented Cone Model and Antenna Installed in Hypersonic Tunnel

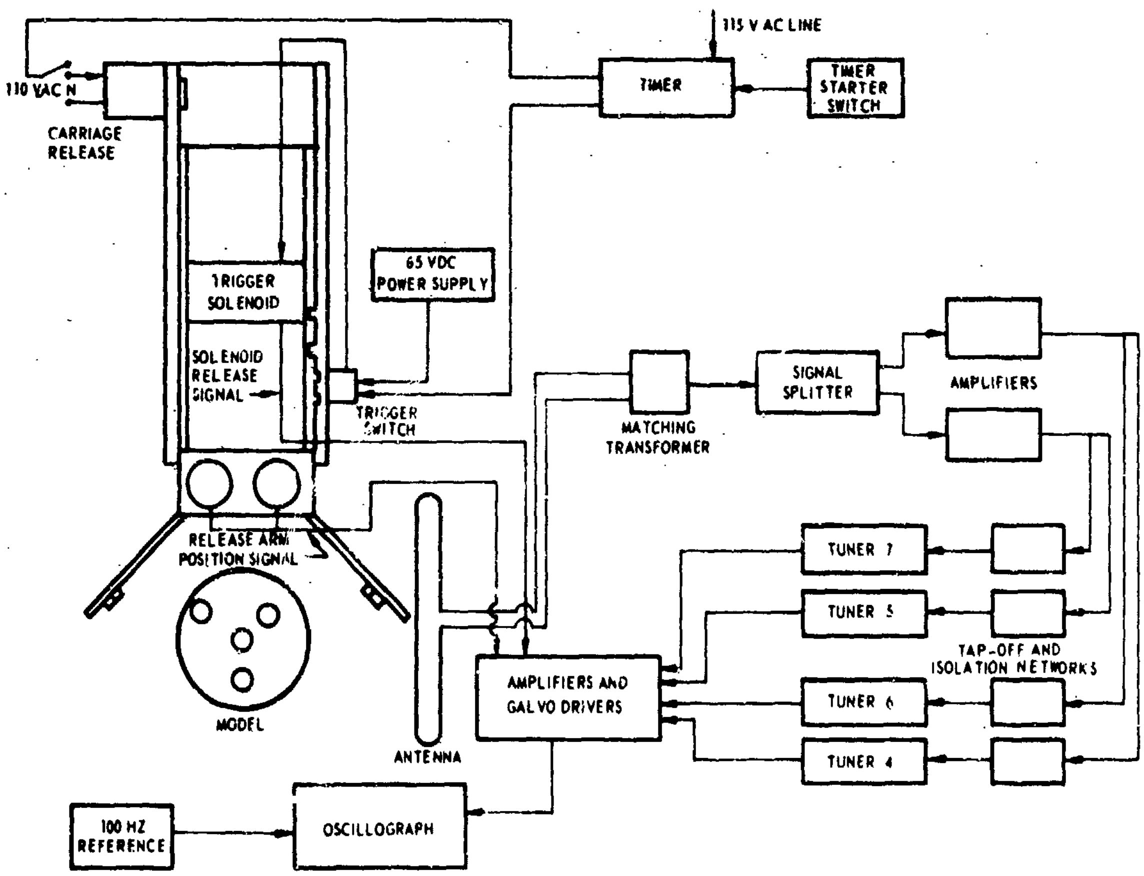

Figure 4 - Block Diagram of 10° Cone Model and Its Instrumentation in the Hypersonic Wind Tunnel

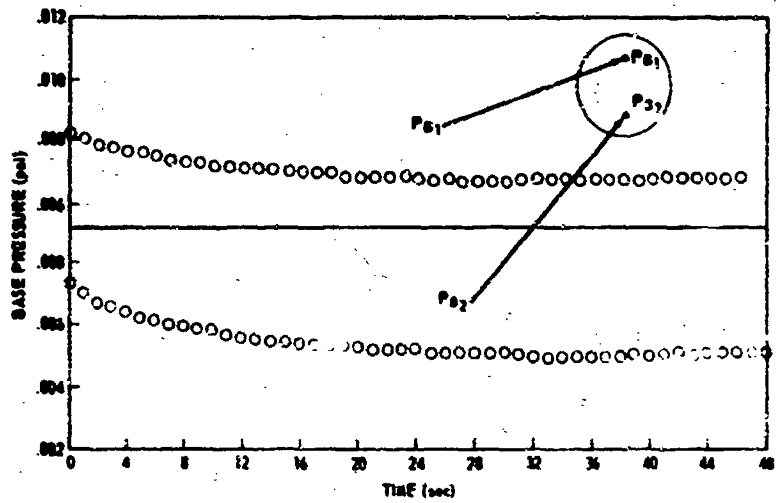

Figure 5 - Base Pressure-Time History at $\alpha = 28^{\circ}$ and $M = 9.89$

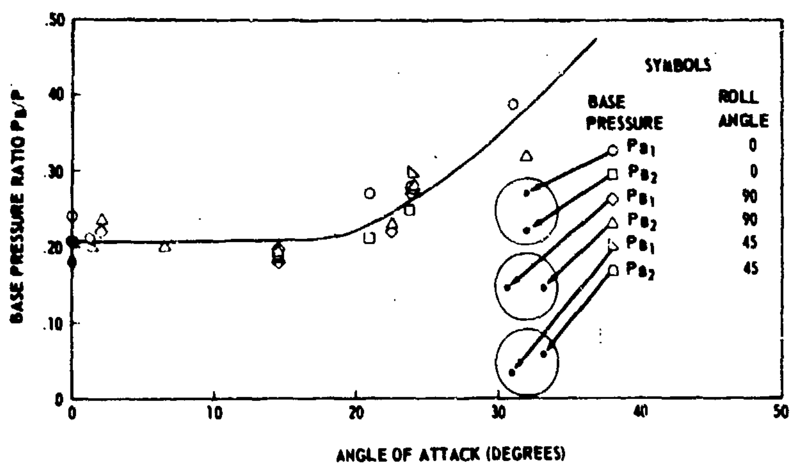

Figure 6 - Base Pressure Ratio as Function of Angle of Attack at $M = 6.24$ (Sting Mounted Cone)

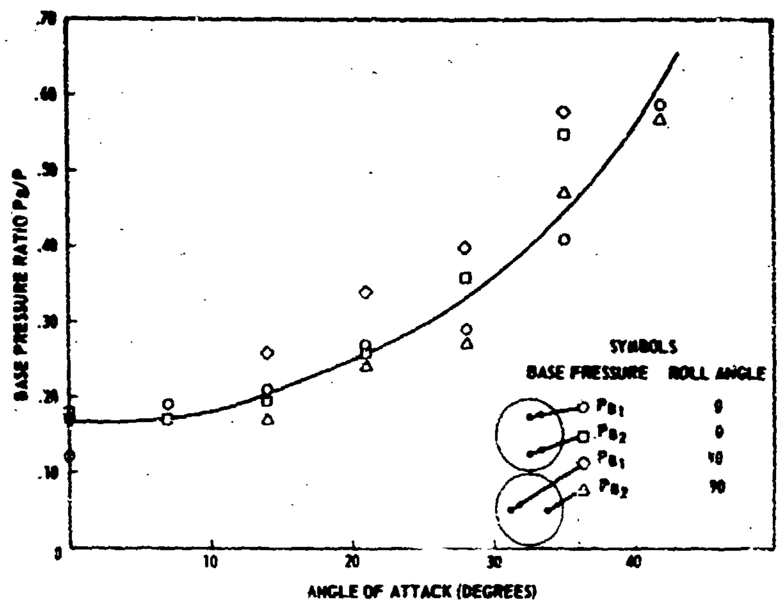

Figure 7 - Base Pressure Ratio as Function of Angle of Attack at M = 9.89 (Sting Mounted Cone)

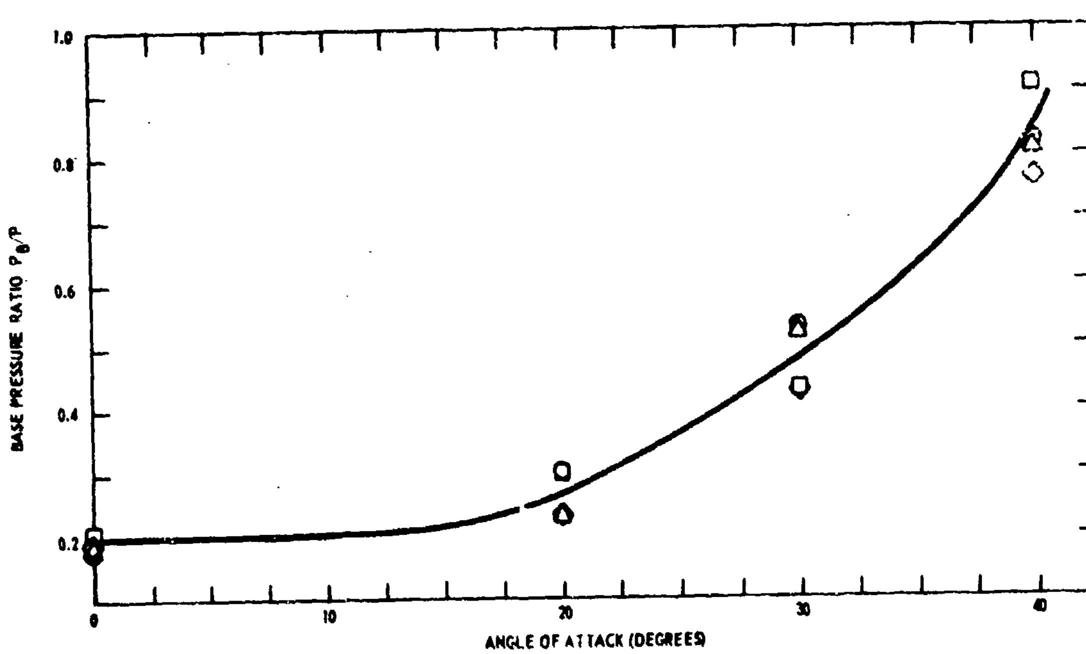

Figure 8 - Base Pressure Ratio as Function of Angle of Attack at M = 6.34 (Free Flight Cone)

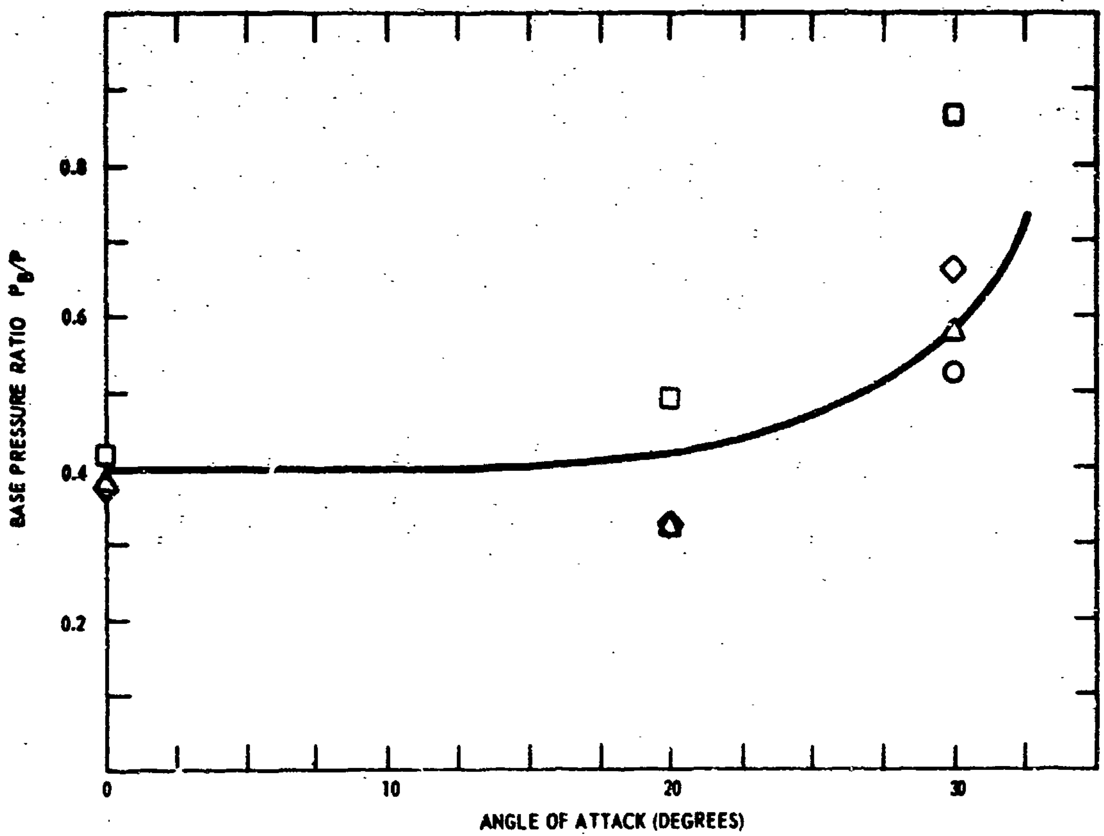

Figure 9 - Base Pressure Ratio as Function of Angle of Attack at M = 9.94 (Free Flight Cone)

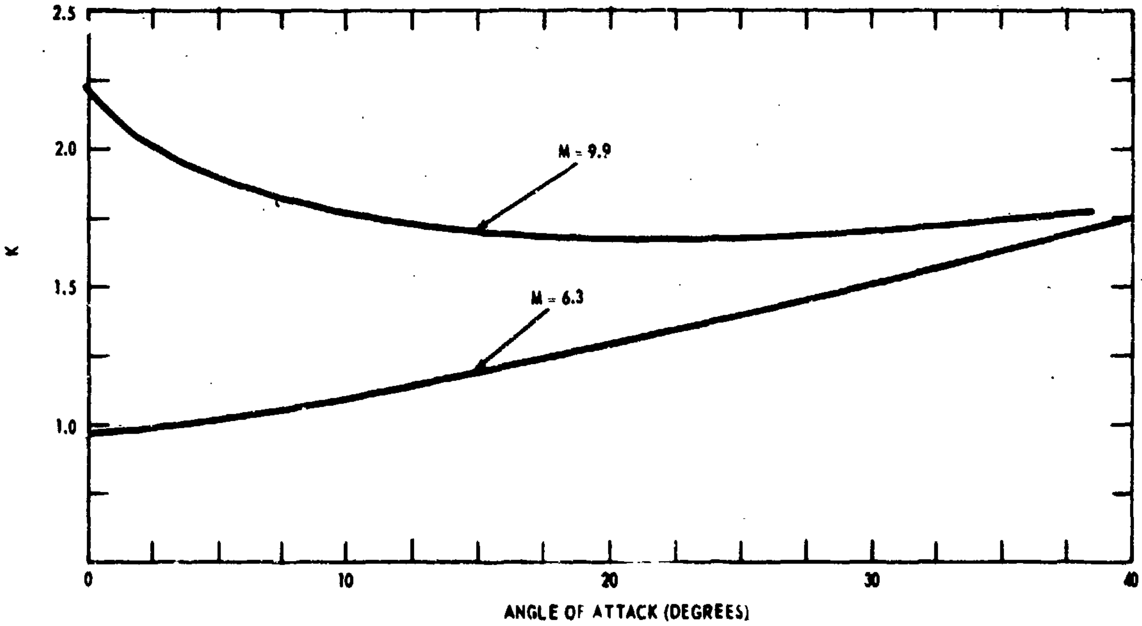

Figure 10 - Sting Interference Effect as Function of Angle of Attack at M = 6.3 and 9.9

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