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FINAL REPORT

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ON

CONTROL OF JET NOISE

(NAG-1-1096)

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**ABSTRACT**

This reports describes experiments conducted at the High-Speed Jet Facility at the University of Southern California on supersonic jets. The goal of the study was to develop methods for controlling the noise emitted from supersonic jets by passive and/or active means.

Work by Seiner et al (1991) indicates that eddy Mach wave radiation is the dominant noise source in a heated high speed jet. Eddy Mach radiation is caused by turbulent eddies traveling at supersonic speed in the shear layer of the jet. The convection velocity of the eddies decays with increasing distance from the nozzle exit due to the mixing of the jet stream with the ambient fluid. Once the convection speed reaches subsonic velocities, eddy Mach wave radiation ceases. To control noise, a rapid decay of the convection velocity is desired. This may be accomplished by enhanced mixing in the jet.

In this study, small aspect ratio rectangular jet nozzles were tested. A flapping mode was noticed in the jets. By amplifying screech components of the jets and destabilizing the jet columns with a collar device, the flapping mode was excited. The result was a rapid decay of the jet velocity. A reduction in eddy Mach radiation in rectangular supersonic jets may be achieved with this device.

## Introduction

Noise pollution remains a significant problem in the design of supersonic civil transports (SST). For jet exhausts with exit velocities exceeding Mach 1, eddy Mach radiation becomes a major source of noise production. It is caused by turbulence eddies traveling at supersonic speed within the shear layer of the jet. These eddies radiate Mach waves into the far field. According to Seiner (1991), the source efficiency of eddy Mach radiation is 0.1% to 1.0%. This is much larger than the source efficiency of turbulent mixing noise. Since eddy Mach radiation decreases with the third power of the convective Mach $M_c$ number and ceases completely when $M_c < 1$, eddy Mach radiation may be reduced by a rapid decay of the convection velocity. However, natural axisymmetric jets show little spreading, i.e. the convective Mach number decays slowly. This is reflected in long core of supersonic circular jets, typically 15 to 20 jet diameters, compared to 4 jet diameters for a subsonic jet. In order to reduce the convective Mach number, an increased growth of the shear layer is desired. The problem of supersonic noise control, thus, becomes that of supersonic mixing enhancement.

Passive and active means have been developed to enhance the mixing in jets. Ho and Gutmark (1984) showed that a low speed elliptical jet of small aspect ratio has improved mixing properties over a circular jet. Increased mixing is achieved by the self induction mechanism of the asymmetrically distributed vorticity in the shear layer. Seiner (1991) applied the elliptical nozzle design to a supersonic jet. The improved mixing of the elliptical nozzle reduced the noise of a heated M=1.5 jet by about 5 dB. Other asymmetric nozzle designs were investigated by Viets (1975), Hill & Greene (1977), Hsia et al. (1988), Wlezien & Kibens (1988), Wlezien (1989), and Raman et al. (1992). Hsia et al. (1988) investigated a supersonic rectangular jet. They observed a low frequency flapping mode of the jet that enhanced mixing in the minor axis of the jet. This mode was excited by the screech tones of the choked jet. A similar flapping mode was utilized by Raman et al. (1992) in a small aspect ratio rectangular jet. Schreck et al. (1992) applied active control to amplify the flapping mode of a small aspect ratio rectangular supersonic jet.

This report describes a study on mixing enhancement in small aspect ratio rectangular jets. Experiments on ideally expanded jets and acoustically self excited jets are reported. It is shown that with the addition of a collar mounted at the nozzle exit, which acts as an acoustic amplifier and Coanda nozzle, the spreading of a supersonic rectangular jet is significantly increased.

## Experimental Setup

The experiments were carried out in the Jet Noise Laboratory of the Department of Aerospace Engineering at the University of Southern California (Figure 1). The settling chamber was positioned within an anechoic chamber, which had dimensions of 7.4m x 4.8m x 3.6m. The low frequency cut-off value was 150 Hz. The jet facility was of the blow-down type, in which air was compressed and stored in five large holding tanks at pressures up to 1800 psi. A manual valve, in conjunction with a separate computer-controlled valve was used to control the pressure in the stagnation chamber of the jet. In order to contain the high pressures associated with supersonic flows, the settling chamber was enclosed within a 300 psi pressure vessel. The pressure within the vessel was equivalent to the pressure inside the settling chamber. A contraction was used to constrict the flow from the circular settling chamber to a square outlet of 5.7cm x 5.7cm. Two rectangular nozzles were tested; one at a design Mach number of 1.45 (M1.45 nozzle); the other was designed for a Mach number of 1.85 (M1.85 nozzle). Both nozzles emphasized a 3:1 aspect ratio and a two-dimensional contraction in the minor axis plane from 5.7cm x 5.7cm to 1.9cm x 5.7cm. The contractions for the respective nozzles were designed using the method of characteristics. The contraction section and a rectangular nozzle are shown in Figure 2.

A collar mixing enhancement device, hereafter referred to as a collar, was designed. The collar features a sudden expansion in the minor axis plane of the jet (Figure 3). The function of the collar is two-fold. It acts as a resonance chamber to amplify the acoustic waves generated in the jet. At the same time low pressure regions are formed between the jet column and both walls, which tend to pull the jet away from its centerline destabilizing the jet column (Coanda effect). To study the effect of the length of the collar on jet mixing, collars of lengths of 1 inch, 1.5 inches, and 2.0 inches were built. The following configurations were tested:

| Configuration | Nozzle | Collar |
|---|---|---|
| 1A | M1.45 | none |
| 1B | M1.45 | 1.0" |
| 1C | M1.45 | 1.5" |
| 1D | M1.45 | 2.0" |
| 2A | M1.85 | none |
| 2B | M1.85 | 1.0" |
| 2C | M1.85 | 1.5" |
| 2D | M1.85 | 2.0" |

Table 1

Velocities in the jet were measured with a total head pressure probe. The probe was mounted on a one-dimensional traversing system to survey the velocity distributions along the jet axes. The pressure at the base of the collar was measured with a Validyne pressure transducer. Two PCB pressure transducers integrated in the two long walls of the collar were used to investigate the high frequency pressure fluctuations present in the self excited jets.

A shadowgraph system was constructed to visualize the jet. Video images were taken using a standard two-mirror system and a continuous light source. Still pictures were recorded onto X10 Kodak TMAX400 film directly exposed to a custom designed spark light source of a discharge time of less than 1 μsec.

## Experimental Results

### Shadowgraph Images

Video images of the jets for the two rectangular nozzles with and without collar were recorded on video tape for a wide range of Mach numbers. First, the nozzles without collars were tested at Mach numbers ranging from 1.1 to 2.0. Subsequently, the collar was attached to the nozzles and the experiments were repeated for collar lengths of 1.0 inches, 1.5 inches, and 2.0 inches. The most dramatic effects of the collar on the development of the jet were observed for configuration 2C (see Table 1). For this configuration, no significant effect of the nozzle on the jet was noticed between Mach 1 and Mach 1.2. Slightly above Mach 1.2, however, the jet column became unstable. The jet started flip-flopping in the minor axis plane. Frequency and amplitude of this flapping motion were small and the motion was erratic. In this regime, the jet sometimes attached to one wall of the collar and did not separate unless the exit velocity was increased. When the Mach number was increased beyond Mach 1.25, the jet resumed its central orientation. At this point distinct screech frequencies were audible. The frequency of the screech tones did not change monotonically with the jet Mach number but showed a discrete behavior, i.e. sudden changes in the frequencies were noticed. Changes in the frequencies were associated with a change in the spreading of the jet. Maximum spreading was observed at Mach 1.45. Since the high frequency oscillations in the jet column could not be resolved with the video camera, still pictures were taken to investigate the structures in the jets. The natural jet ideally expanded at Mach 1.45 is shown in Figure 4. Shock cell structures are visible close to the nozzle. Some expansion waves originate in the nozzle indicating that perfect expansion is not achieved with the two-dimensional nozzle design. At three minor axis diameters downstream of the nozzle, sinuous oscillations are presented in the jet. The wavelength of this flapping mode is about two minor axis diameters. Associated with the flapping mode, large scale structures are observed in the shear layer. Despite the oscillations, the jet column remains intact until about 10 minor axis diameters downstream of the nozzle exit. Figure 5 shows a Mach 1.45 jet exiting the M1.85 nozzle. A Mach cone forms immediately downstream of the nozzle. Four large cell structures are observed before the jet column disintegrates. The amplitude of the flapping mode is larger than that of the ideally expanded jet resulting in an increased spreading of the jet. This beneficial effect of the flapping mode on mixing enhancement is exploited in the collar nozzle design. The M1.85 nozzle with the 1.5 inch collar is shown in Figure 6. The Mach number was with 1.45 identical to that in Figures 4 and 5. A dramatic increase in the mixing of the jet is observed. The large amplitude flapping mode causes the jet to disintegrate within four minor axis diameters. Note turbulent pockets of high contrast within the first four jet diameters. The high contrast indicates a low convection speed.

## Jet Velocities

Centerline velocity profiles were taken to quantify the enhanced mixing properties of the collar. In Figure 7, measured centerline velocities of the ideally expanded jet (Fig. 4) and the jet with the 1.5 inch collar (Fig. 6) at M=1.45 are shown. Since the convective Mach number is directly related to the local jet centerline Mach number (Seiner 1991), the decay of the centerline velocity is a first measure for a potential decrease in eddy Mach radiation. In the ideally expanded jet, the centerline velocity reaches Mach 1 at approximately 20 minor axis diameter downstream of the nozzle. For the collar nozzle, subsonic speeds are already reached after 11 minor axis diameter. This suggests that the effective length of the jet column along which eddy Mach radiation can take place is reduced by a factor of 2 by the collar nozzle. Note the stepwise decay of the centerline velocity for the collar nozzle. A similar velocity distribution was measured by Hill & Greene (1977) in an oscillating subsonic jet. It is speculated that this phenomenon is caused by the long time averaging of the local velocity. When the probe is positioned at a node of the oscillating jet column, the measured velocity changes little with time and is close to the true centerline velocity. Conversely, when the probe is located at an antinode of the oscillation, the jet sweeps across the probe. In the latter case, the local average velocity is less than the true centerline velocity of the jet.

Mechanism of Mixing Enhancement

By visually analyzing video recordings of the jets, it was found that the best results of increased mixing were observed for the M1.85 nozzle with the 1.5 inch long collar (configuration 2C) at about M=1.45 and for the M1.45 nozzle and the 1.0" collar (configuration 1B) at about M=1.25. To investigate the underlying physical mechanism, the pressure at the base of the collar and the pressure fluctuations at the wall of the collar were measured for the different configurations. In Figures 8 to 13, the dominant frequencies in the collar are plotted vs. the exit Mach number for all configuration. Since multiple peaks were observed in the spectra, the three most dominant peaks are plotted. The first component of the natural screech frequency calculated after Tam (1991) is also included in the view graphs. For the configurations 1B and 2C, the measured 2$^{nd}$ modes closely match the calculated screech frequencies in the Mach number range of maximum spreading. This indicates that the jets are exited at their natural screech frequencies. It is speculated that at the point of maximum spreading, the collars act as resonators. To test this hypothesis, the measured frequencies were converted into acoustic wavelengths and normalized by the length of the collars. Results of this operation are shown in Figures 14 to 19 for all configurations. In the Mach number range of maximum spreading, the calculated acoustic wavelengths are about twice the length of the respective collars for the configurations 1B and 2C. The fact that resonance occurs in this Mach number range is reflected in the sound amplitude measured inside the collars. The amplitudes (r.m.s) of the acoustic signal are presented in arbitrary units in Figures 20 and 21. Note the pronounced peak in the amplitude for configuration 1B at M=1.25.

## Mechanism of Jet Column Brake-Down

The shadowgraph image in Figure 6 indicates that small scale turbulence is created rapidly in the flapping jet. Since the flapping mode is primarily a large scale oscillation of the whole jet column, question arise about the mechanism responsible for the generation of small scale turbulence from the large scale instabilities. Video images of the major axis plane (not shown here) show that the initial spreading of the jet in the major axis plane is not significantly effected by the collar. The oscillations are confined to the minor axis plane. The high amplitude distortion created by the collar nozzle, however, creates three-dimensional vorticity on both minor sides of the jet column. Three dimensional vorticity is necessary to transfer energy from the large scale to smaller scales. The three-dimensional vorticity grows rapidly towards the center of the jet disintegrating the jet column (Figure 22). Based on this interpretation of the video images, it is speculated that small aspect ratio jets may provide better mixing than large aspect ratio jet, since it would take less time for the three-dimensional vorticity to grow from the ends to the center of the jet.

## Thrust Loss

A major issue hampering the development of noise control devices is the often severe loss in thrust. A first estimate for the thrust loss of the collar nozzle was made using the pressure measurements within the collars. The thrust T is defined as

$T = m\,V + A_e\,(p_e - p_o)$, where
m is the mass flow,
V the exit velocity,
$A_e$ the exit area,
$p_e$ the exit pressure, and
$p_o$ the ambient pressure.

For the ideally expanded rectangular jet at M=1.45, the pressure term is zero and the thrust is given by T= m V. For the nozzles with collars, the pressure term is not zero and may be estimated from the cross sectional area of the collar, times the measured pressure at the base of the collar ($2A_eP_{collar}$). Pressures measured at the base of the collar are shown in Figures 23 and 24 for the M1.45 nozzle and the M1.85 nozzle respectively. The pressures generally decrease with increasing collar length. The ranges of maximum for the configurations 1B and 2C are associated with peak negative pressures in the collar. Because of these negative pressures, the pressure term in the thrust equation is negative and may represent a first estimate of the thrust loss. From the measured values for the pressure within the collar and Mach number, the theoretical thrust for configuration 2C (M1.85 nozzle with 1.5" collar) was calculated and compared with the thrust for ideal expansion ($T_{ideal} = m V$). The resulting first estimate of the thrust loss is presented in Figure 25. The calculated thrust loss is about 6% at M=1.45.

## Conclusions

It has been demonstrated that the natural flapping mode in a small aspect ratio rectangular supersonic jet may be utilized to increase jet mixing. With the use of a resonator (collar device), the screech frequencies associated with the flapping mode of the jet were amplified. The excitation of the natural jet instability waves resulted in a rapid growth of the shear layer and a premature disintegration of the jet column. The convective mach number decayed at twice the rate of the natural jet suggesting a significant reduction in eddy Mach radiation. First calculations indicate that the thrust loss may be acceptable if eddy Mach radiation was significantly reduced.

REFERENCES:


Hill, W. G. & Greene P.R., 1977, Increased turbulent jet mixing rates obtained by self-excited acoustic oscillations, *Journal of Fluid Engineering,* 520-525.

Ho, C.M. & Gutmark, E., 1987 Vortex induction and mass entrainment in a small aspect-ratio elliptical jet. *J. Fluid Mechanics.* **179**, 383-405.

Hsia,Y.C., Krothapalli, A., & Baganoff, D., 1988, Mixing of an underexpanded rectangular jet ejector. *Journal of Propulsion and Power,* **4**, 3, 256-262.

Raman, G., Hailye, M., & Rice, E.J., 1992 The flip flop nozzle extended to supersonic flows. *AIAA Paper 92-2724.*

Schreck, S., Ho, C.M., & Sarmiento, R.S., 1992 Noise radiated from axisymmetric and asymmetric jets. *DGLR/AIAA Paper No. 92-02-044.*

Seiner, J.M., Ponton, M.K., Jansen, B.J., & Lagen, N.T., 1992 The effect of temperature on supersonic jet noise emission. *DGLR/AIAA Paper No. 92-02-046.*

Tam, C.K.W., 1991 Jet noise generated by large-scale coherent motion. *NASA RP-1258, WRDC TR-90-3052,* **1**, 311-390.

Viets, H, 1975 Flip-flop jet nozzle. *AIAA Journal.,* **13** (10), 1375-1379.

Wlezien, R.W. & Kibens, V., 1988 Influence of nozzle asymmetry on supersonic jets. *AIAA Journal.* **26** (1), 27-33.

Wlezien, R.W., 1989 Nozzle geometry effects on supersonic jet interaction. *AIAA Journal.* **27** (10), 1361-1367.

FIGURES:

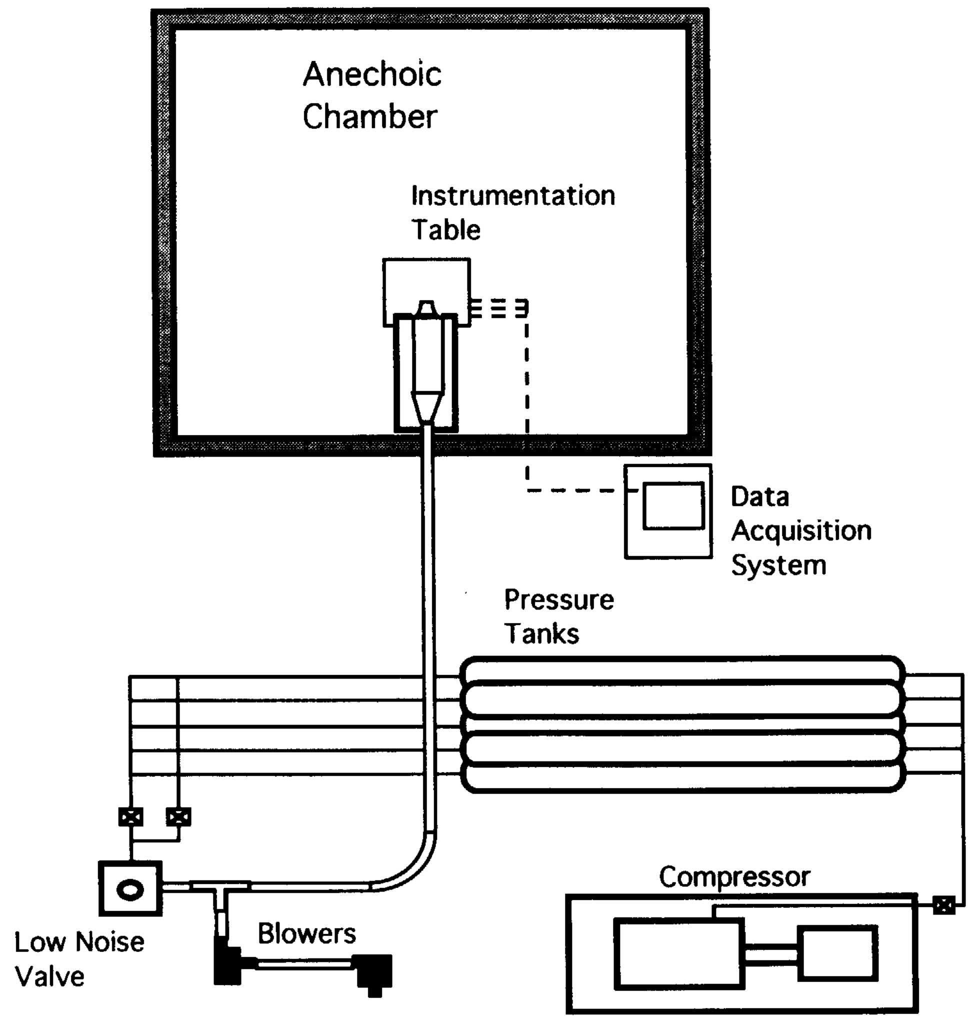

Anechoic
Chamber
Instrumentation
Table
Data
Acquisition
System
Pressure
Tanks
Compressor
Low Noise
Valve
Blowers

Fig. 1

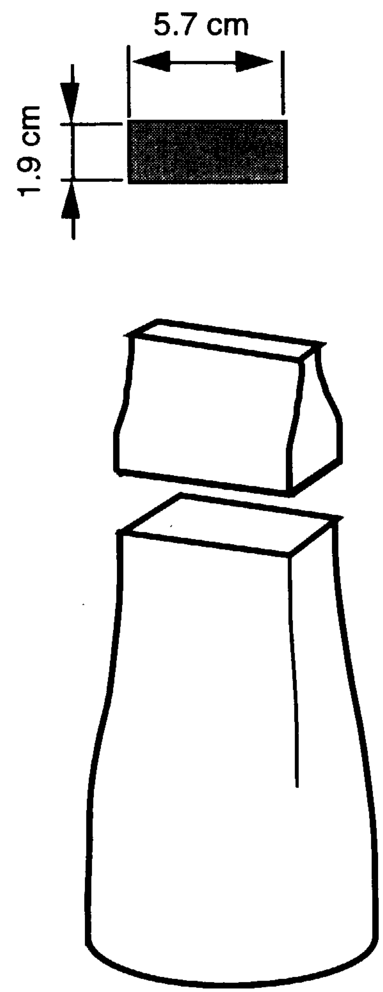



Fig. 2

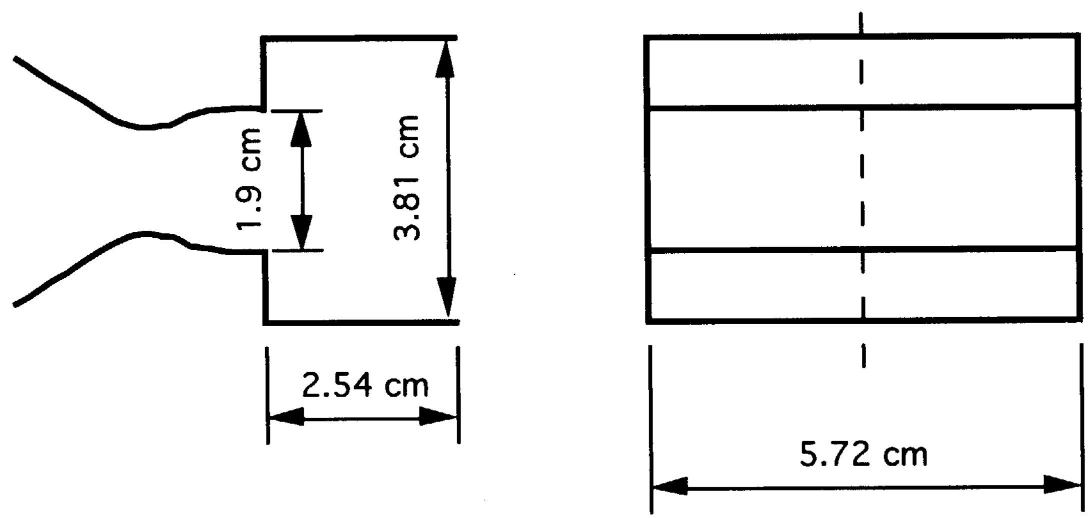



Fig. 3

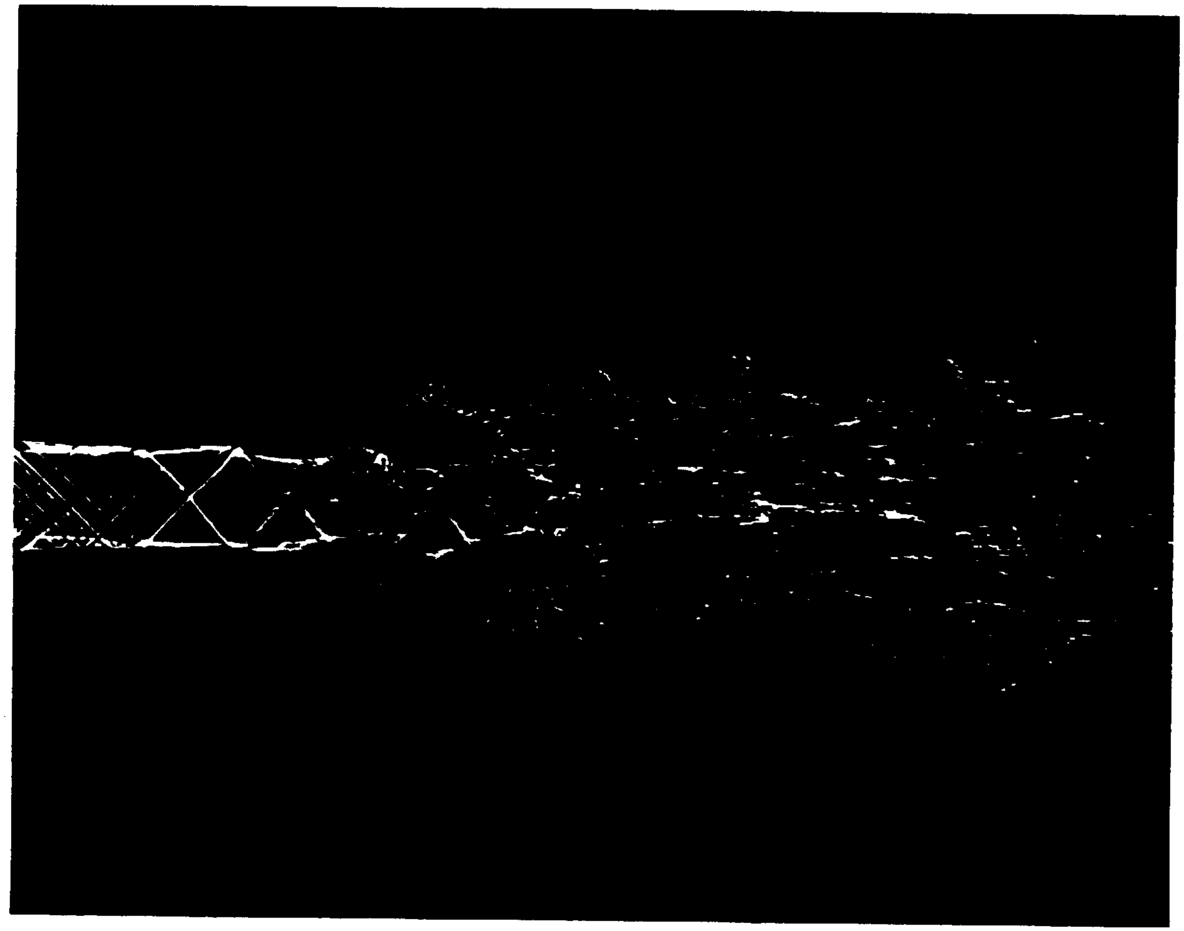


Fig. 4

Fig. 5

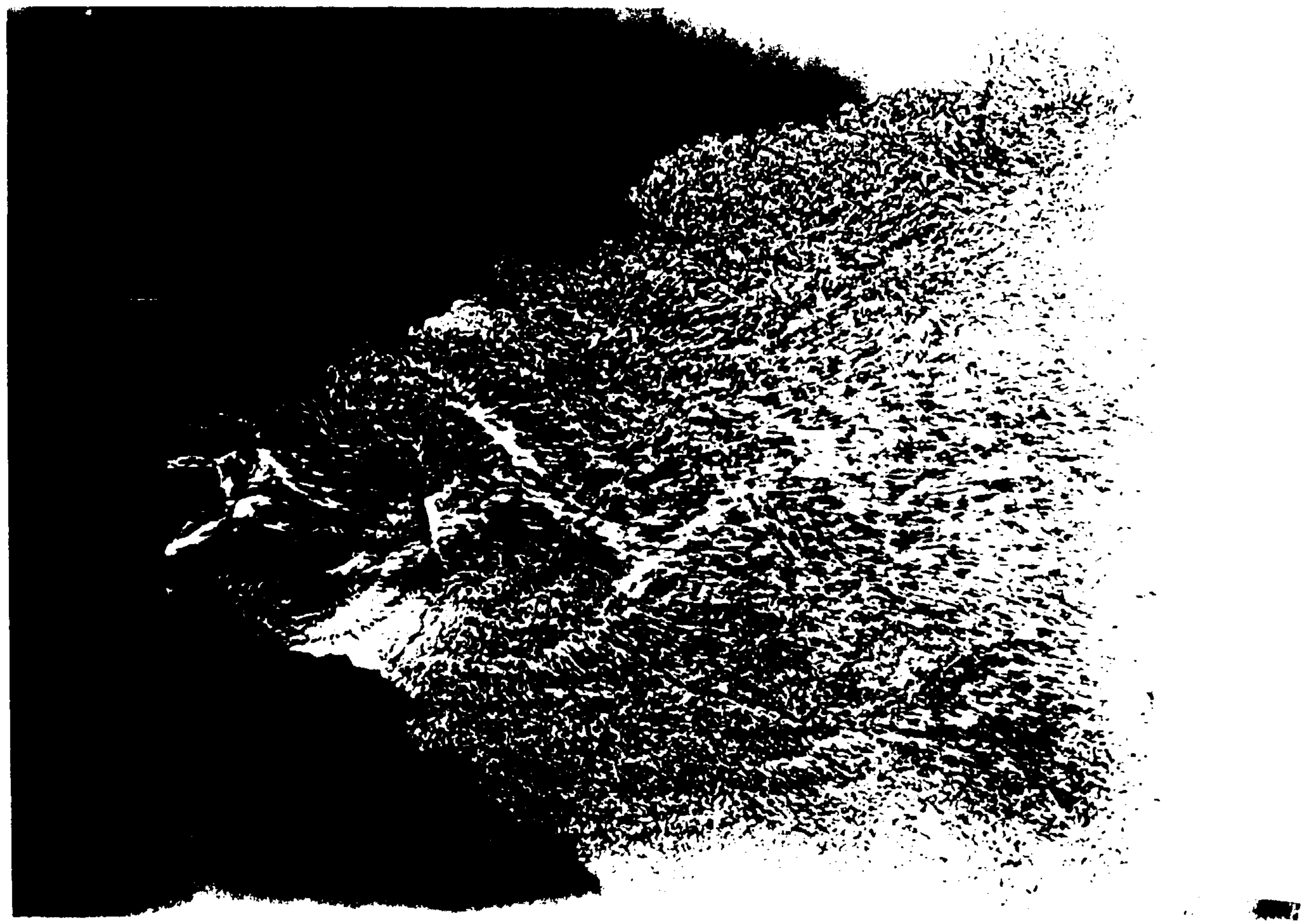
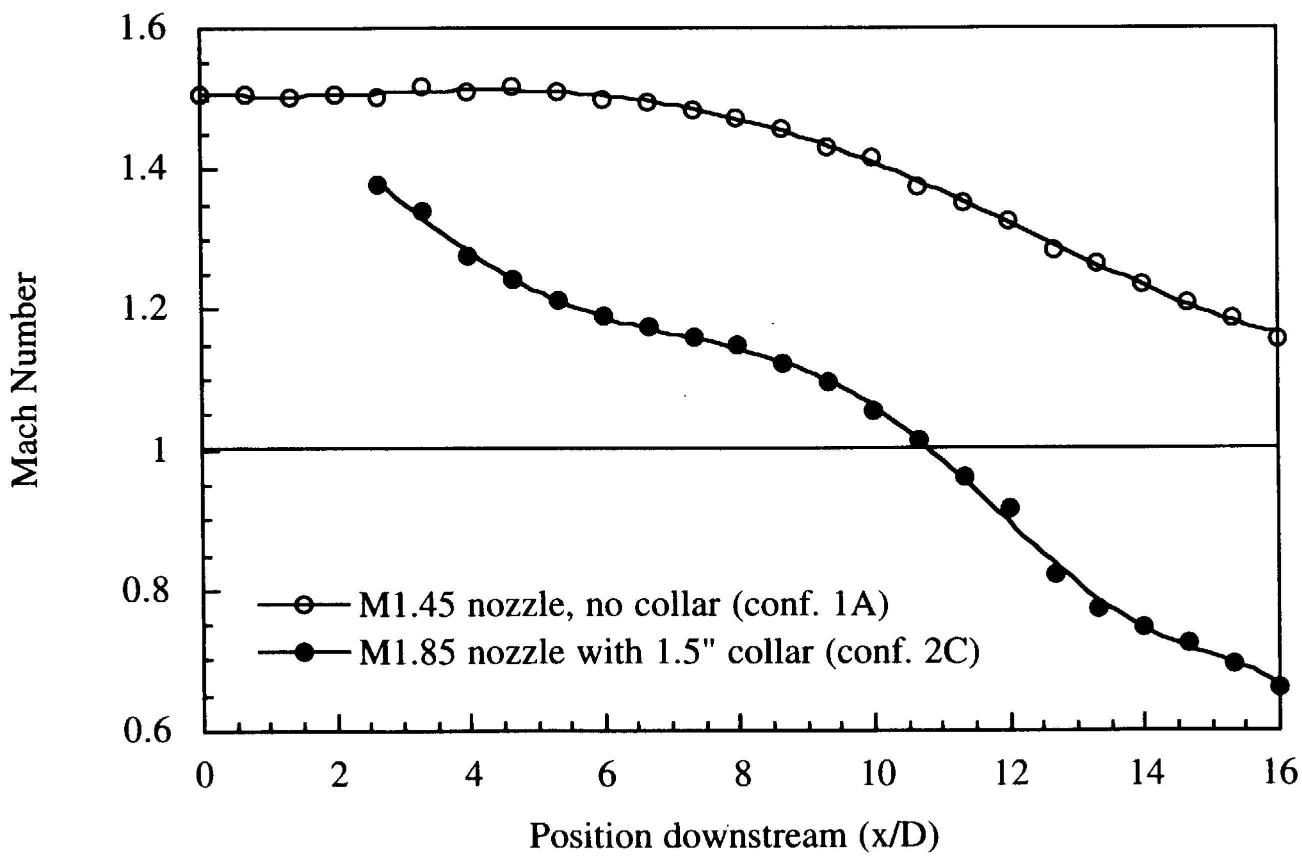
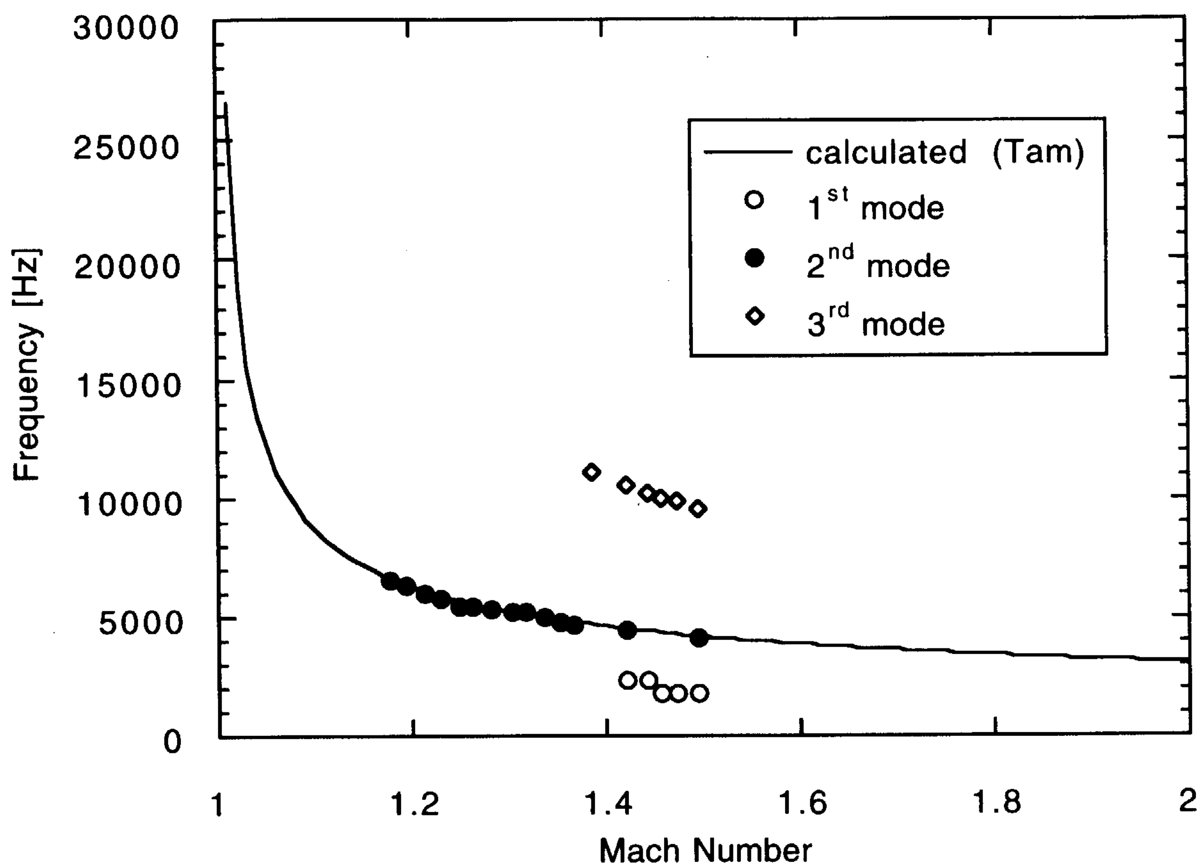


Fig. 6



1.6
1.4
1.2
1
0.8
0.6
Mach Number
M1.45 nozzle, no collar (conf. 1A)
M1.85 nozzle with 1.5" collar (conf. 2C)
0
2
4
6
8
10
12
14
16
Position downstream (x/D)


Fig. 7



calculated (Tam)
1st mode
2nd mode
3rd mode
30000
25000
20000
15000
10000
5000
0
Frequency [Hz]
1
1.2
1.4
1.6
1.8
2
Mach Number


Fig. 8

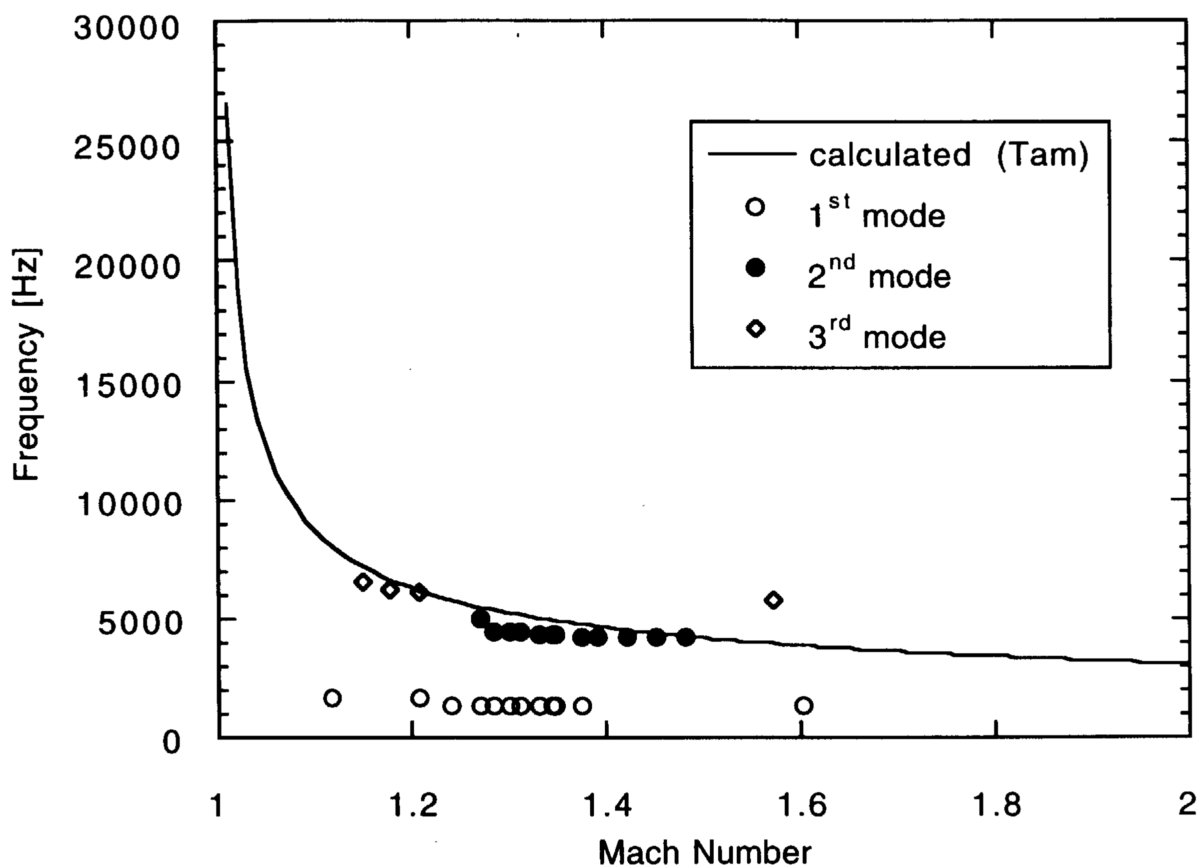

30000
25000
20000
15000
10000
5000
0
Frequency [Hz]
1
1.2
1.4
1.6
1.8
2
Mach Number
calculated (Tam)
1st mode
2nd mode
3rd mode

Fig. 9

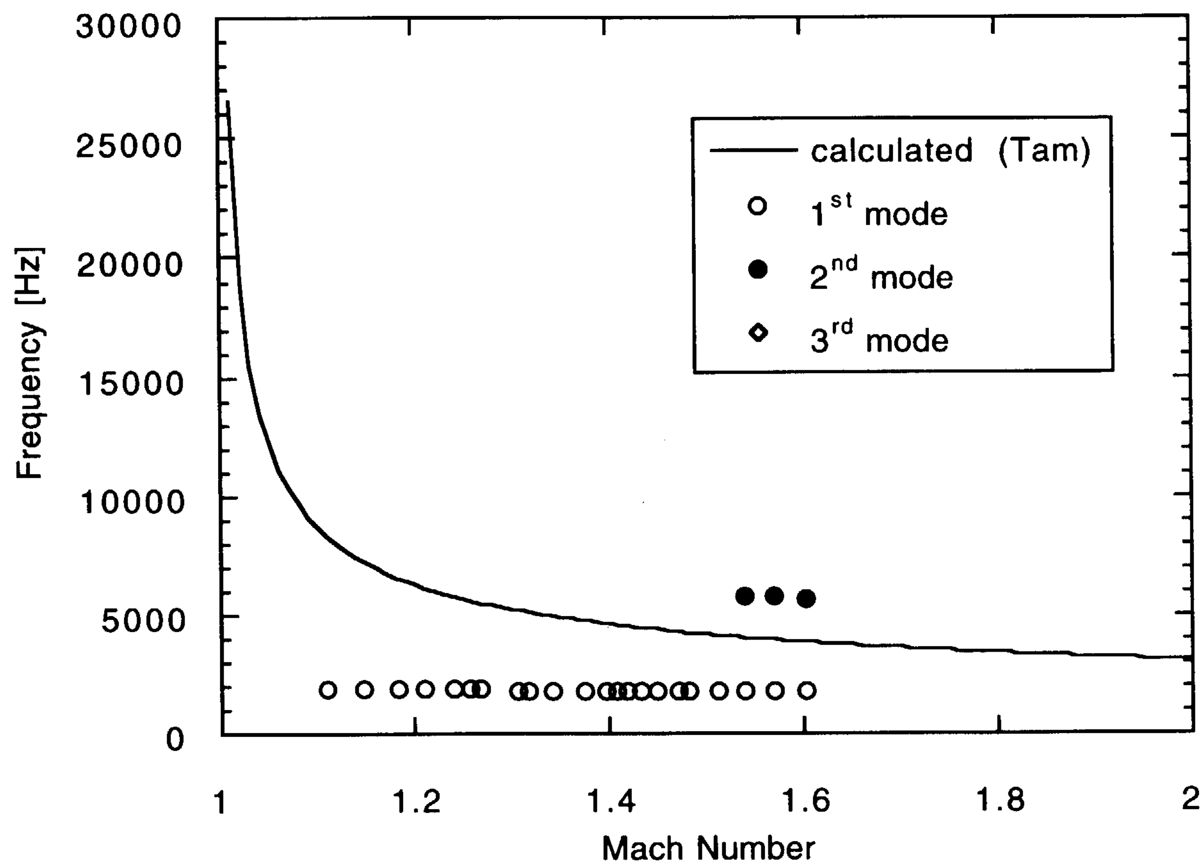

30000
25000
20000
15000
10000
5000
0
Frequency [Hz]
1
1.2
1.4
1.6
1.8
2
Mach Number
calculated (Tam)
1st mode
2nd mode
3rd mode

Fig. 10

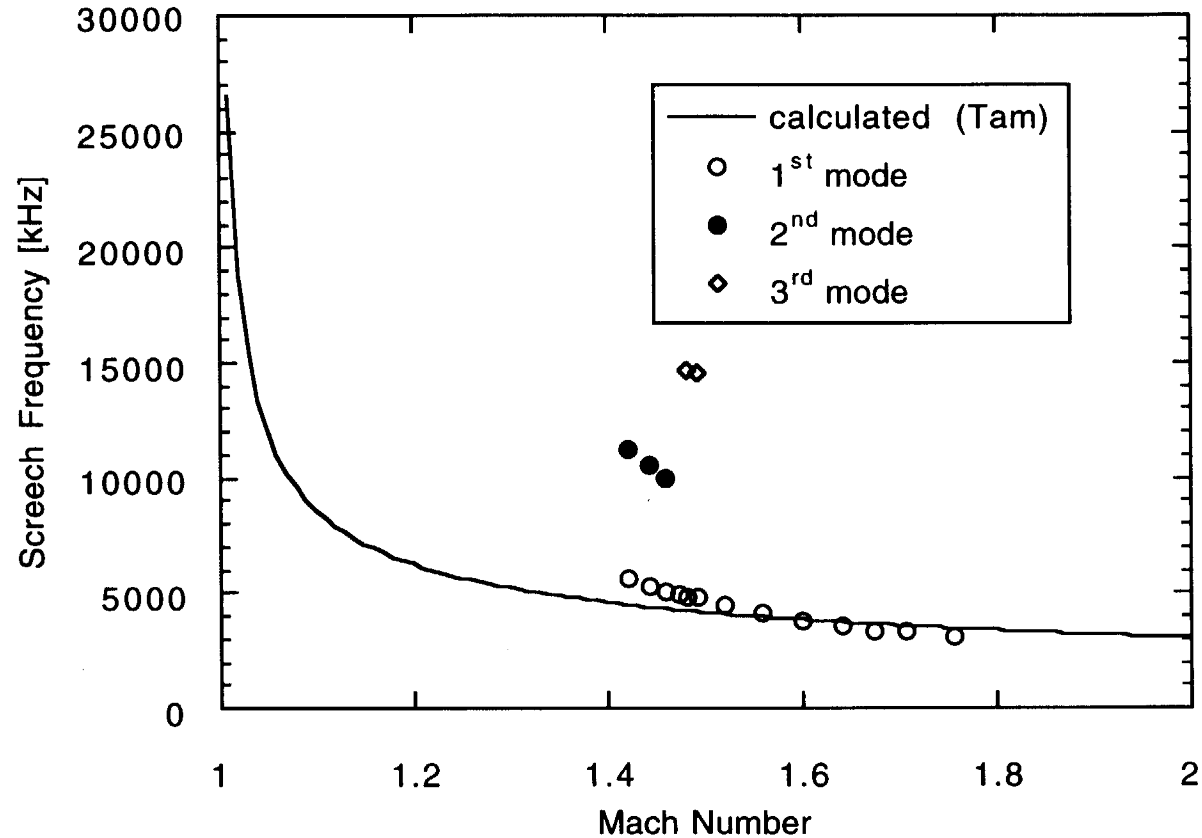

calculated (Tam)
1st mode
2nd mode
3rd mode
Screech Frequency [kHz]
Mach Number
30000
25000
20000
15000
10000
5000
0
1
1.2
1.4
1.6
1.8
2

Fig. 11

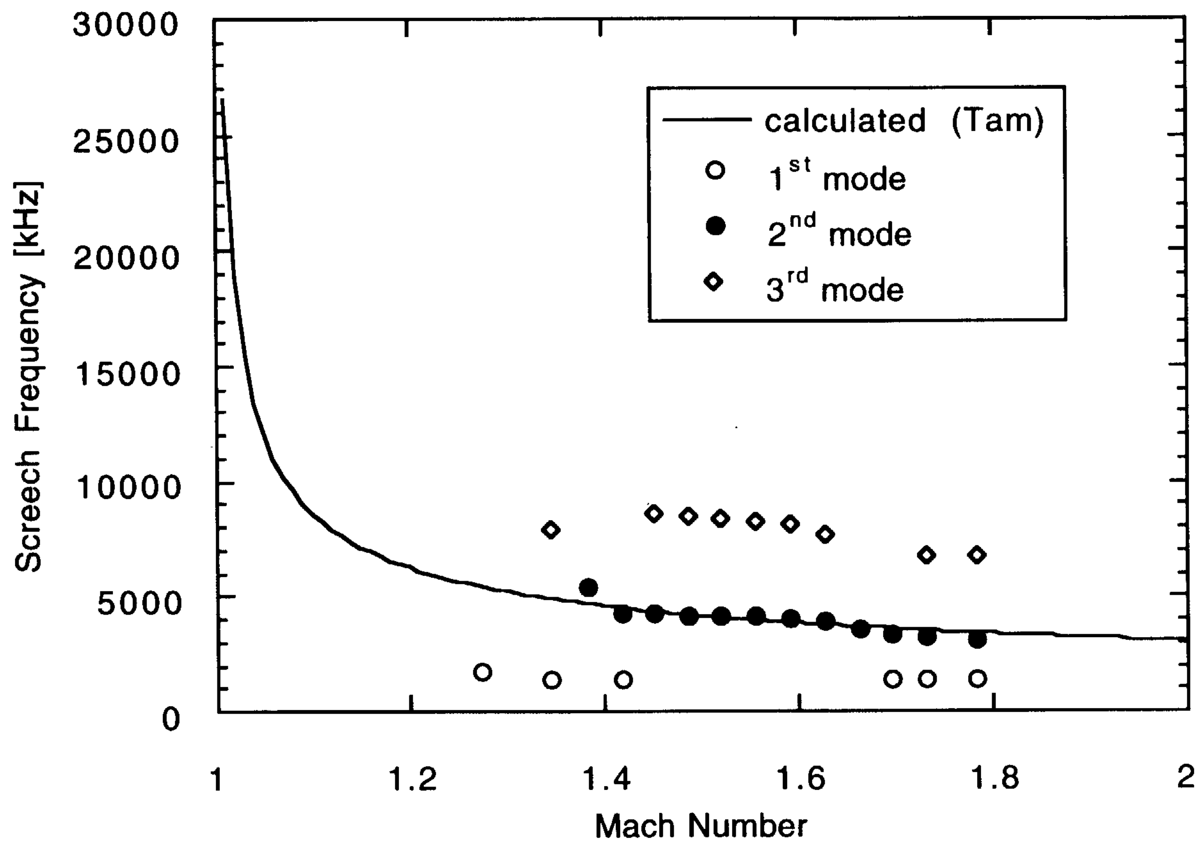

calculated (Tam)
1st mode
2nd mode
3rd mode
Screech Frequency [kHz]
30000
25000
20000
15000
10000
5000
0
1
1.2
1.4
1.6
1.8
2
Mach Number

Fig. 12

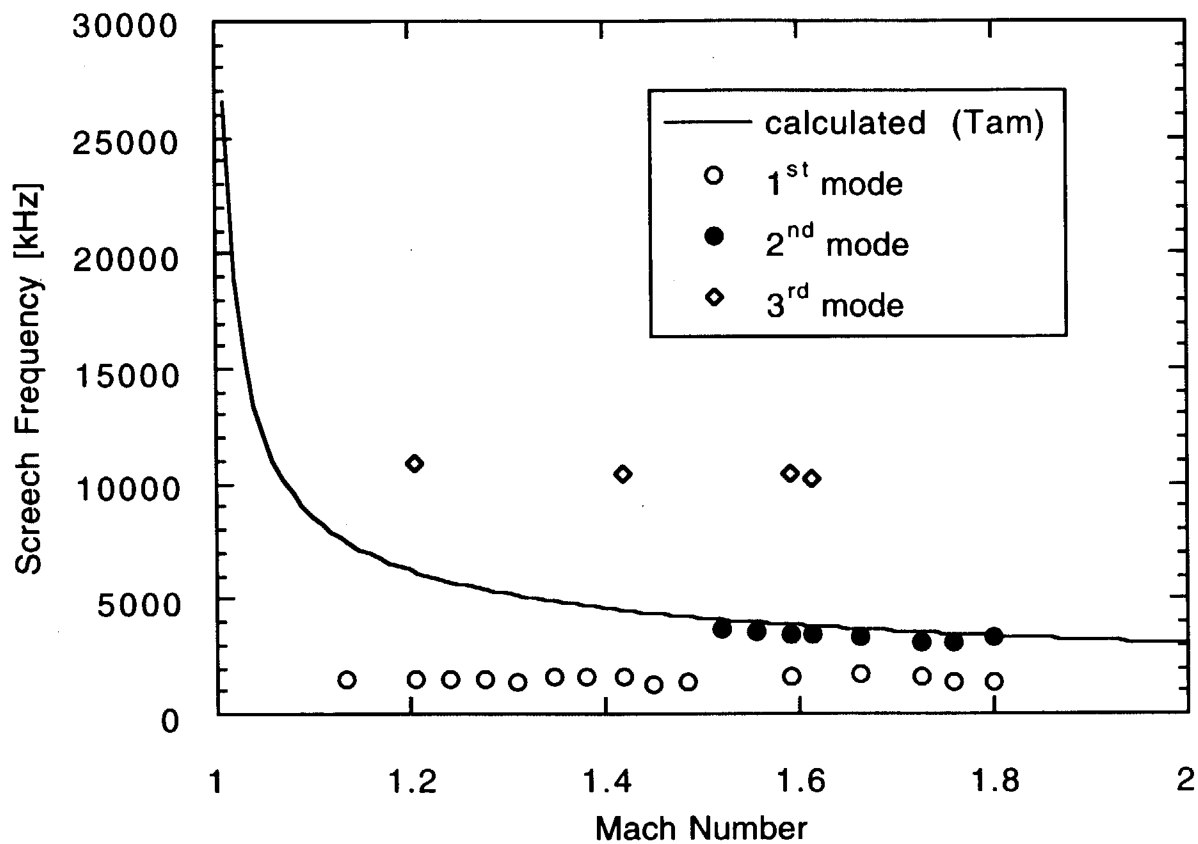

30000
25000
20000
15000
10000
5000
0
Screech Frequency [kHz]
1
1.2
1.4
1.6
1.8
2
Mach Number
calculated (Tam)
1st mode
2nd mode
3rd mode

Fig. 13

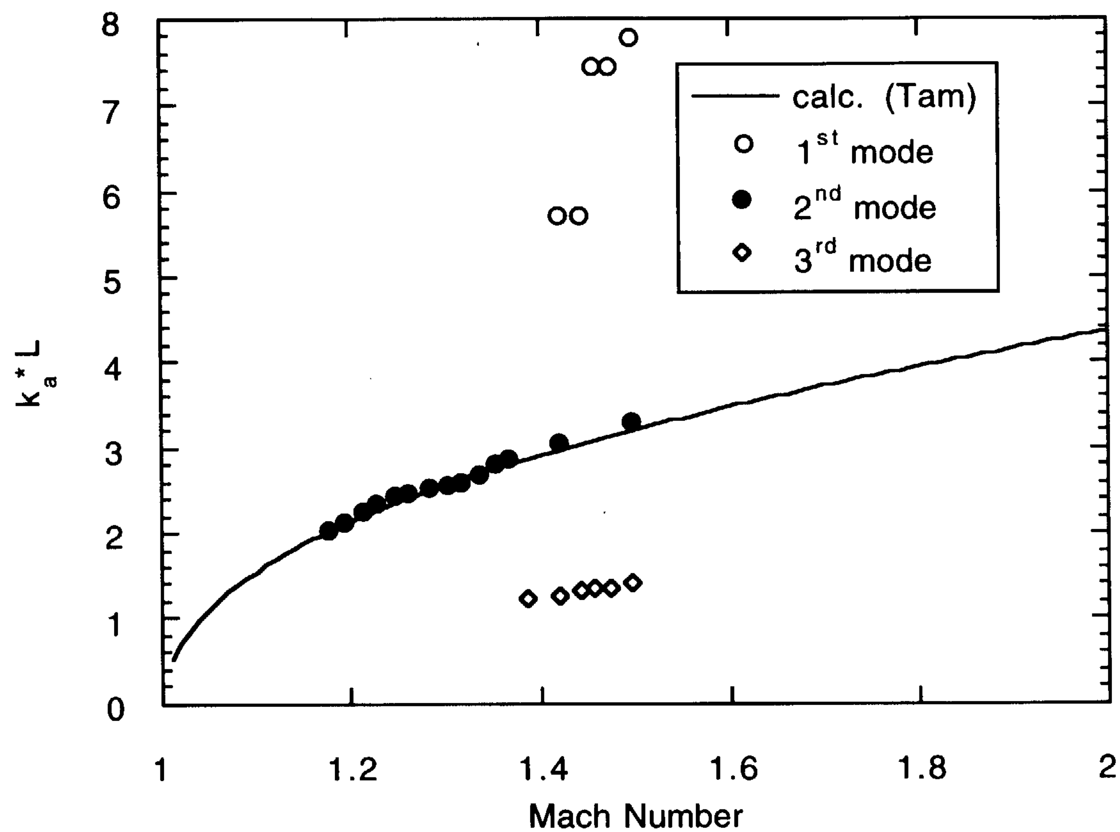
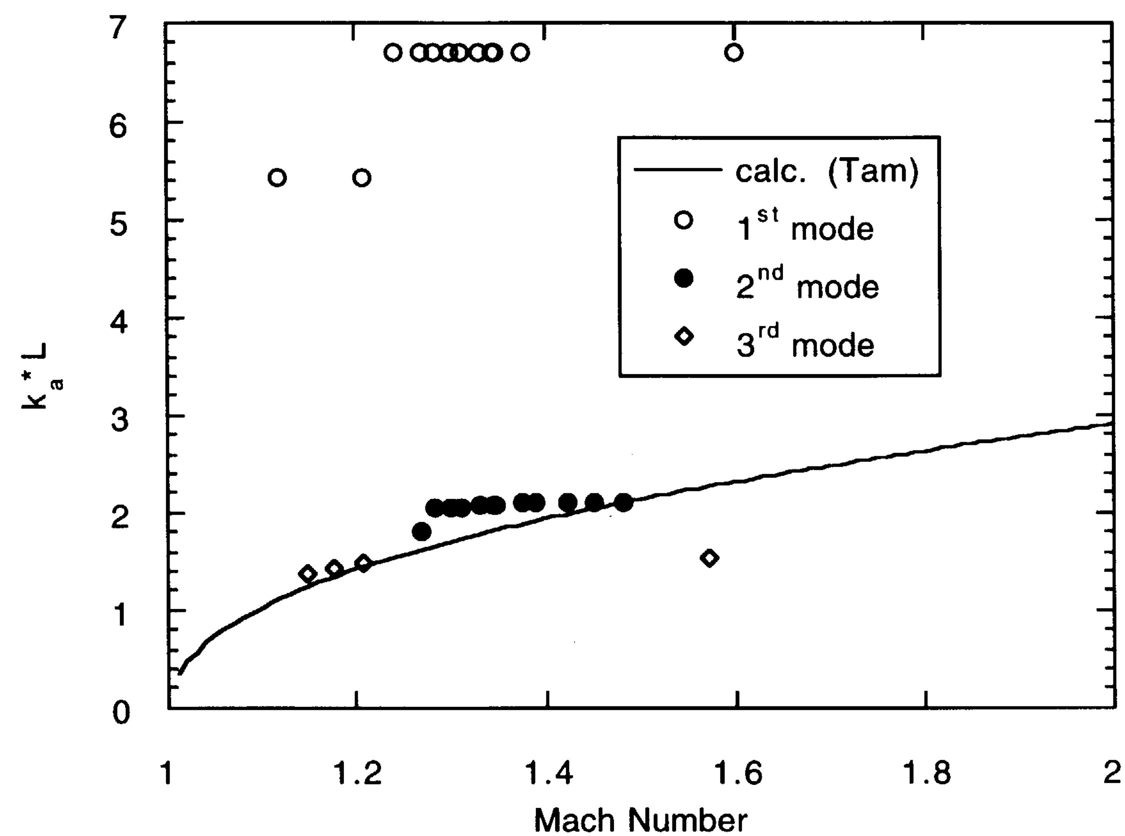
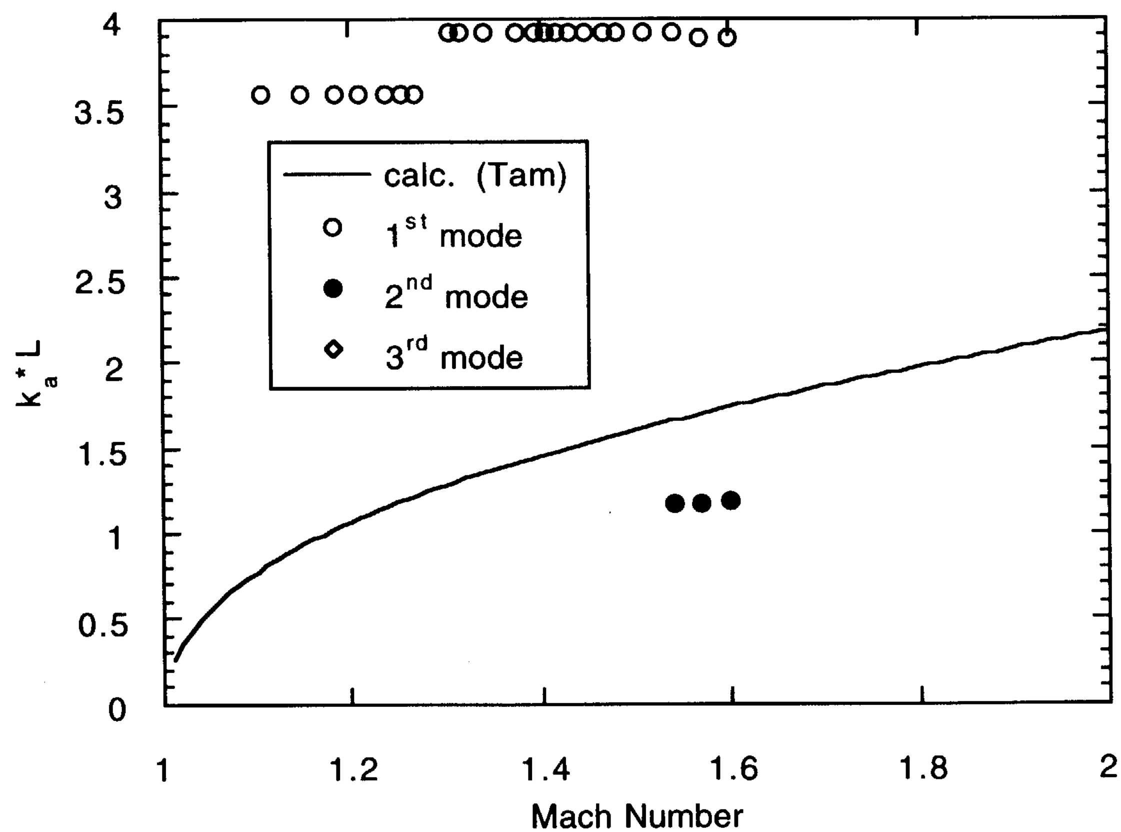

8
7
6
5
4
3
2
1
0
$k_a{}^*L$
calc. (Tam)
1st mode
2nd mode
3rd mode
1
1.2
1.4
1.6
1.8
2
Mach Number

Fig. 14



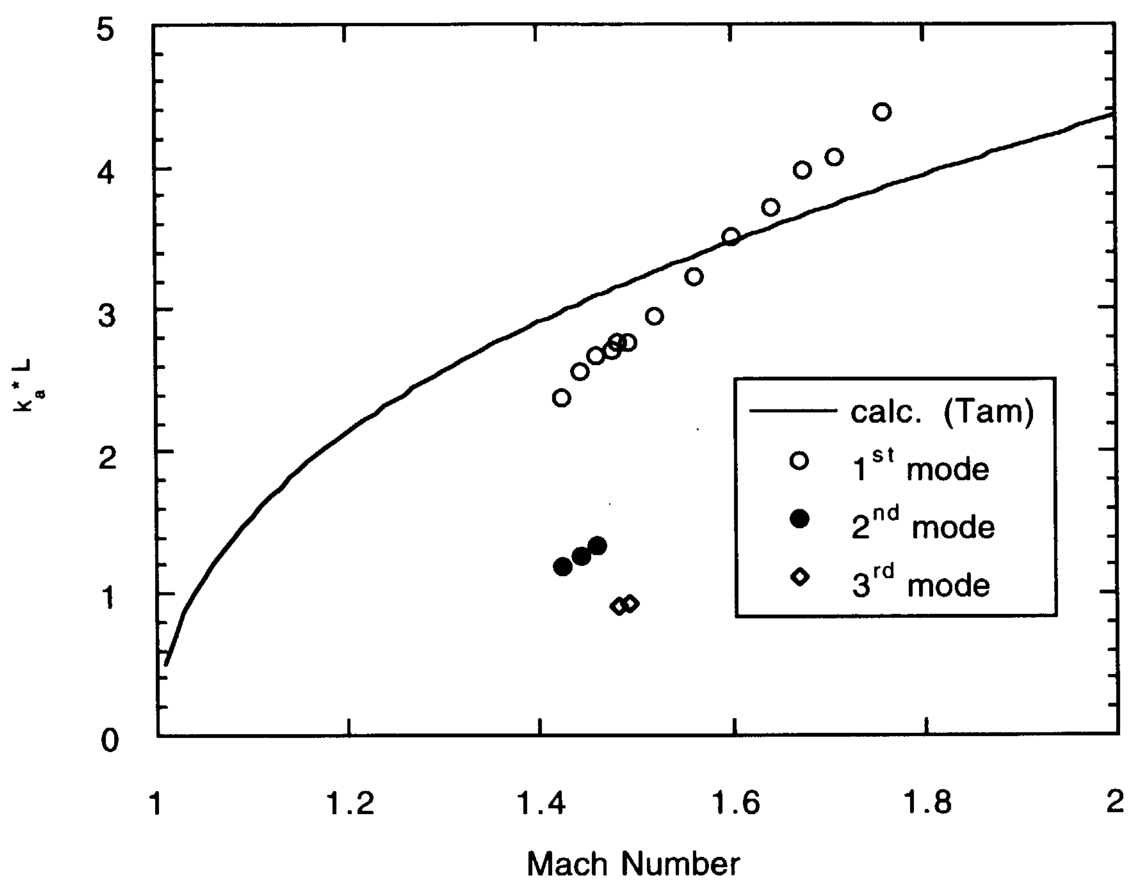
calc. (Tam)
1st mode
2nd mode
3rd mode
k*a L
Mach Number
7
6
5
4
3
2
1
0
1
1.2
1.4
1.6
1.8
2


Fig. 15



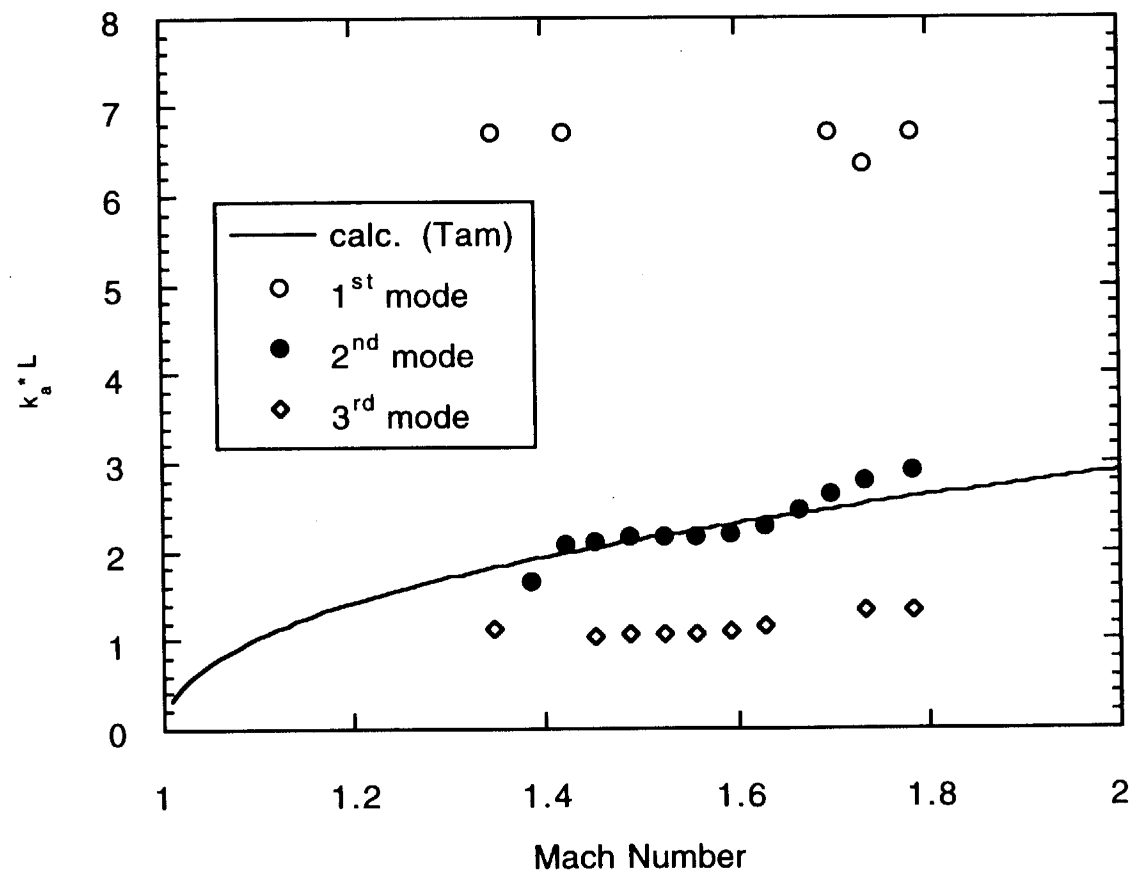
4
3.5
3
2.5
2
1.5
1
0.5
0
k*a L
1
1.2
1.4
1.6
1.8
2
Mach Number
calc. (Tam)
1st mode
2nd mode
3rd mode


Fig. 16



$k_a{}^*L$
0
1
2
3
4
5
1
1.2
1.4
1.6
1.8
2
Mach Number
calc. (Tam)
1st mode
2nd mode
3rd mode


Fig. 17



8
7
6
5
4
3
2
1
0
k*L
calc. (Tam)
1st mode
2nd mode
3rd mode
1
1.2
1.4
1.6
1.8
2
Mach Number


Fig. 18

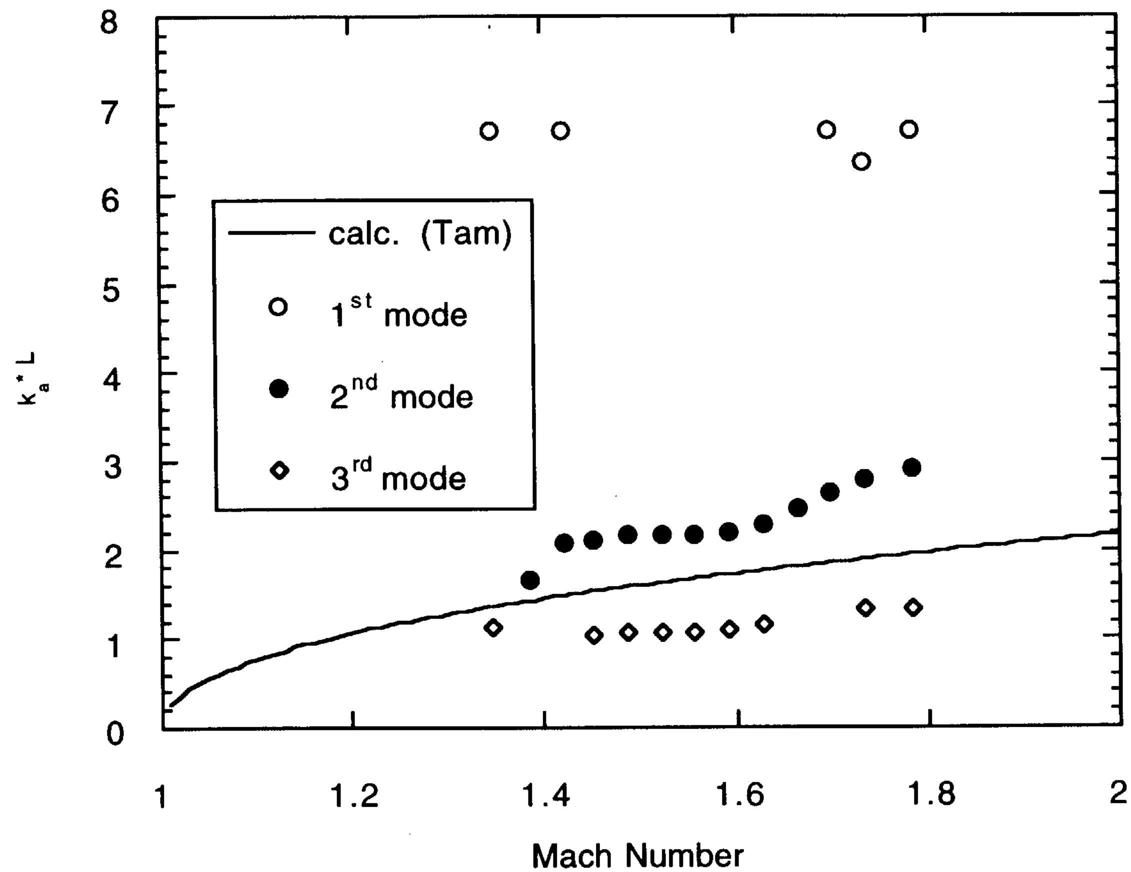
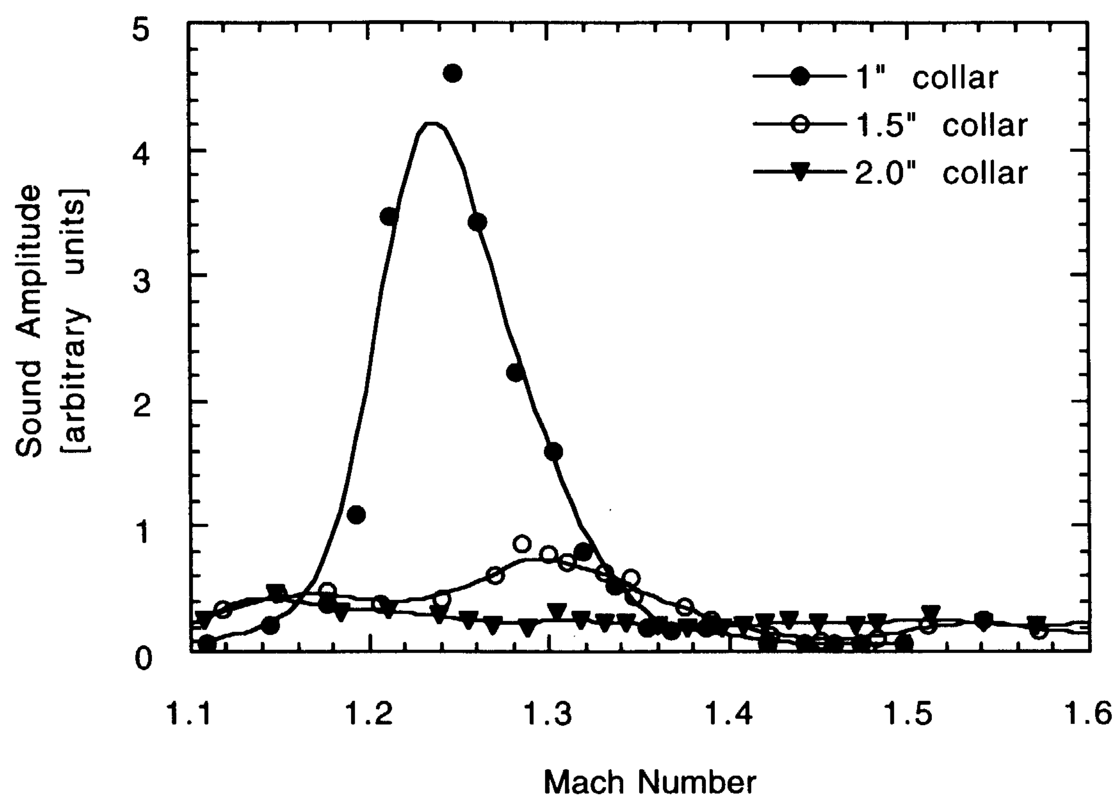

8
7
6
5
4
3
2
1
0
$k_a{}^*L$
calc. (Tam)
1st mode
2nd mode
3rd mode
1
1.2
1.4
1.6
1.8
2
Mach Number

Fig. 19



Sound Amplitude
[arbitrary units]
Mach Number
1" collar
1.5" collar
2.0" collar
0
1
2
3
4
5
1.1
1.2
1.3
1.4
1.5
1.6


Fig. 20

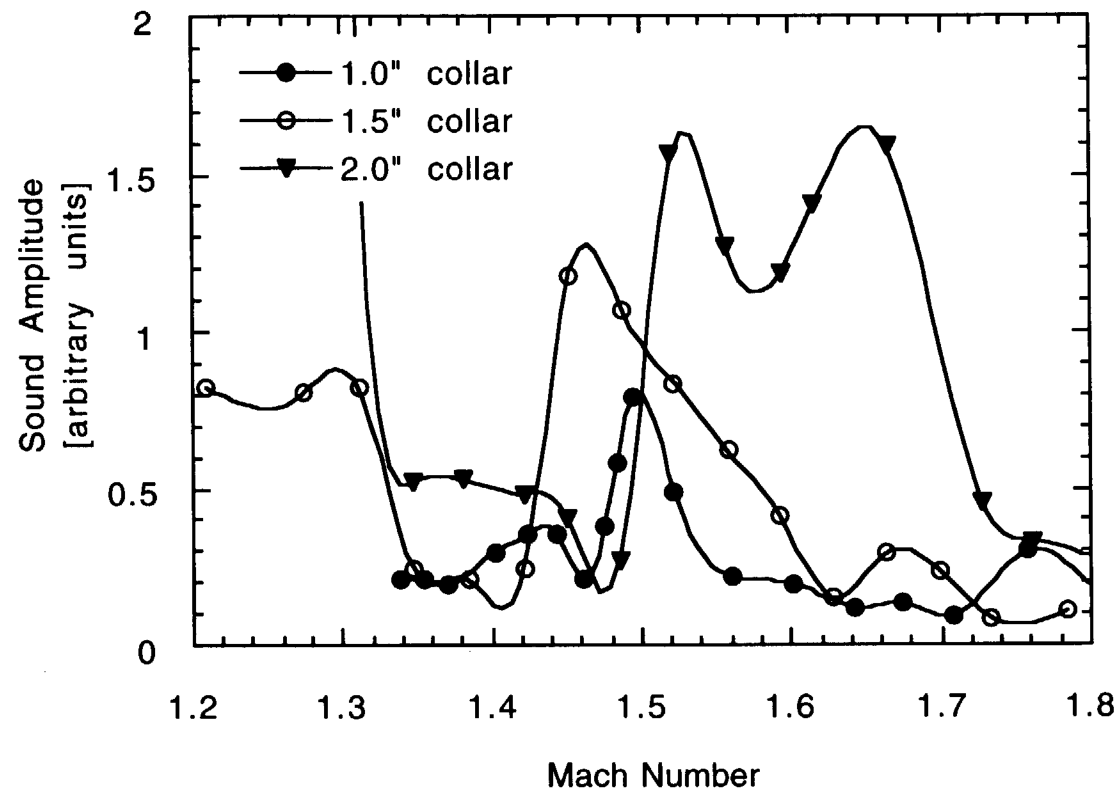

1.0" collar
1.5" collar
2.0" collar
Sound Amplitude
[arbitrary units]
Mach Number
2
1.5
1
0.5
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8

Fig. 21

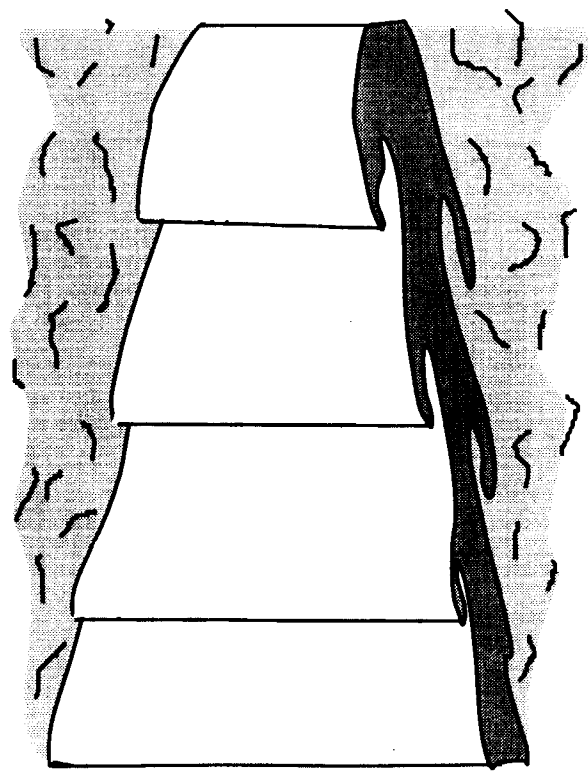


Fig. 22

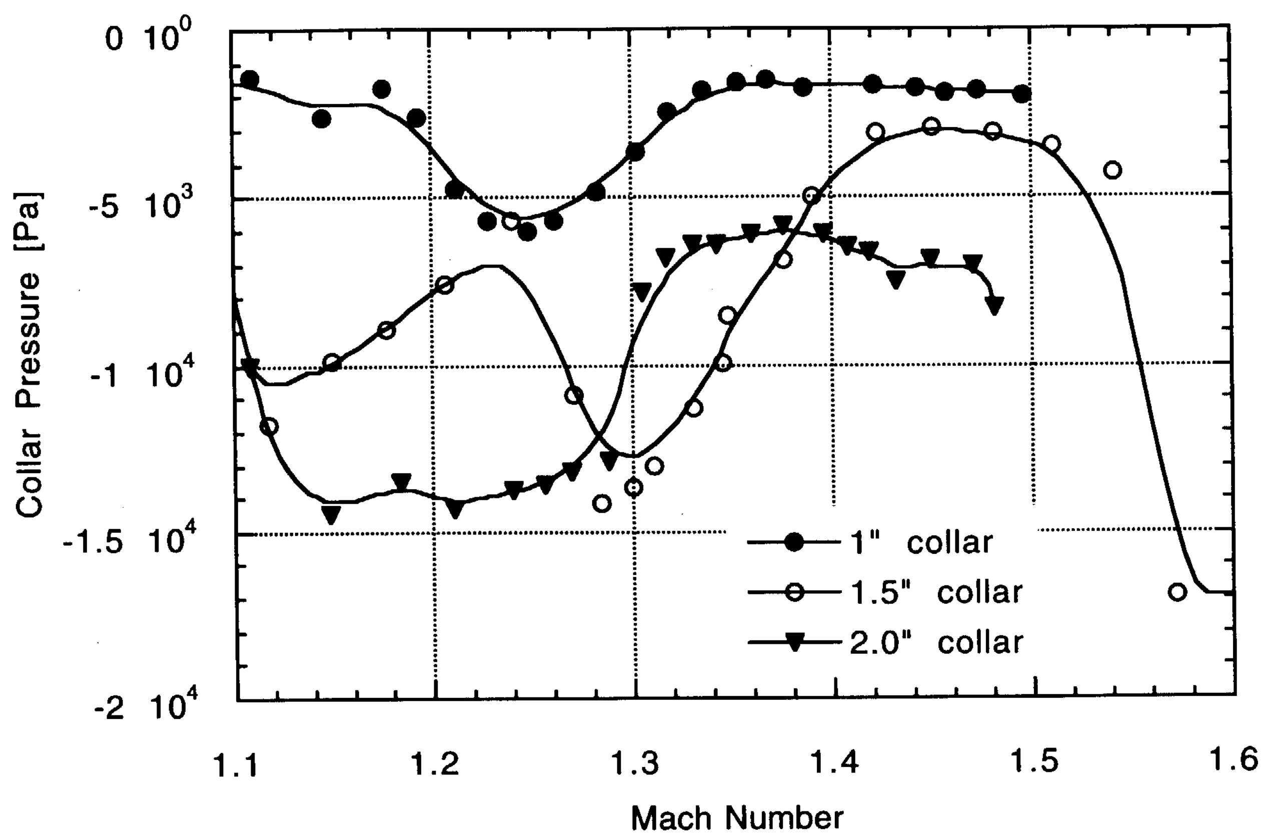
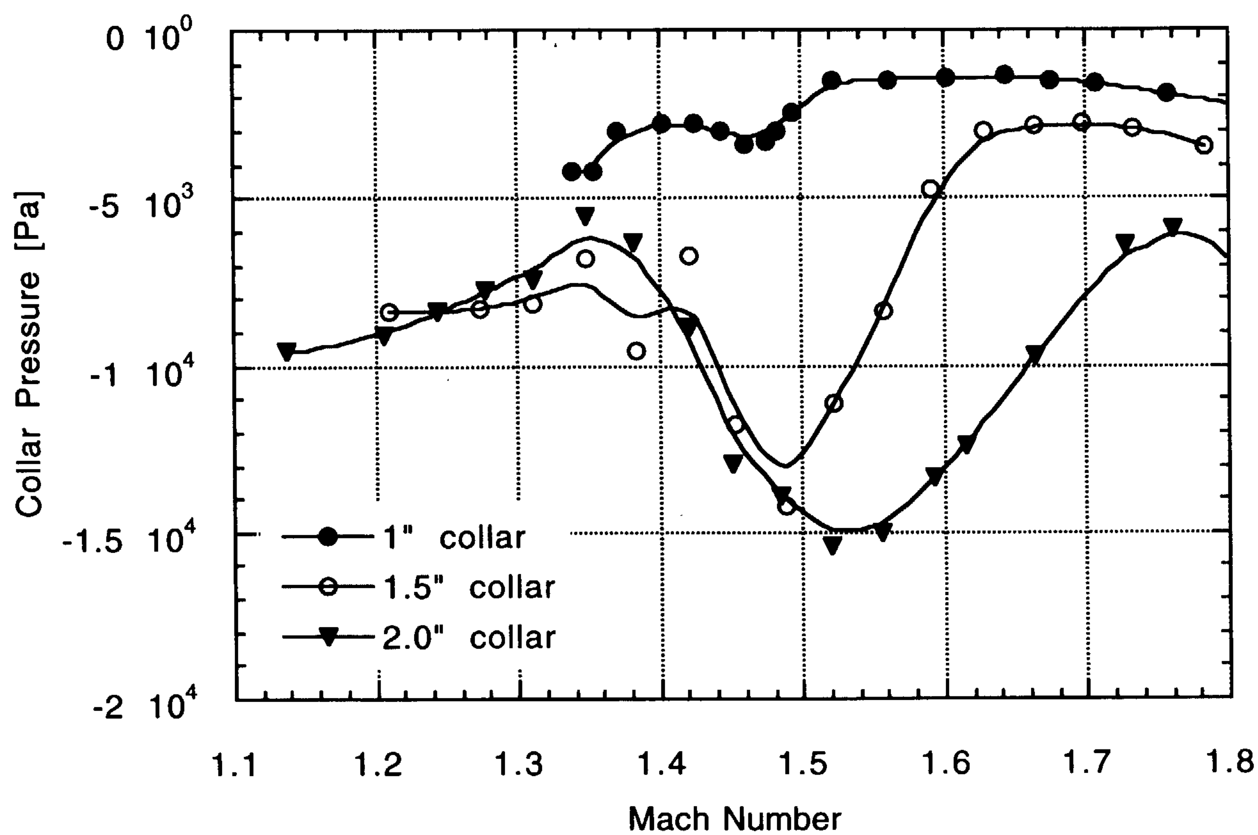

0 10^0
-5 10^3
-1 10^4
-1.5 10^4
-2 10^4
Collar Pressure [Pa]
1.1
1.2
1.3
1.4
1.5
1.6
Mach Number
1" collar
1.5" collar
2.0" collar

Fig. 23



0 10^0
-5 10^3
-1 10^4
-1.5 10^4
-2 10^4
Collar Pressure [Pa]
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Mach Number
1" collar
1.5" collar
2.0" collar


Fig. 24

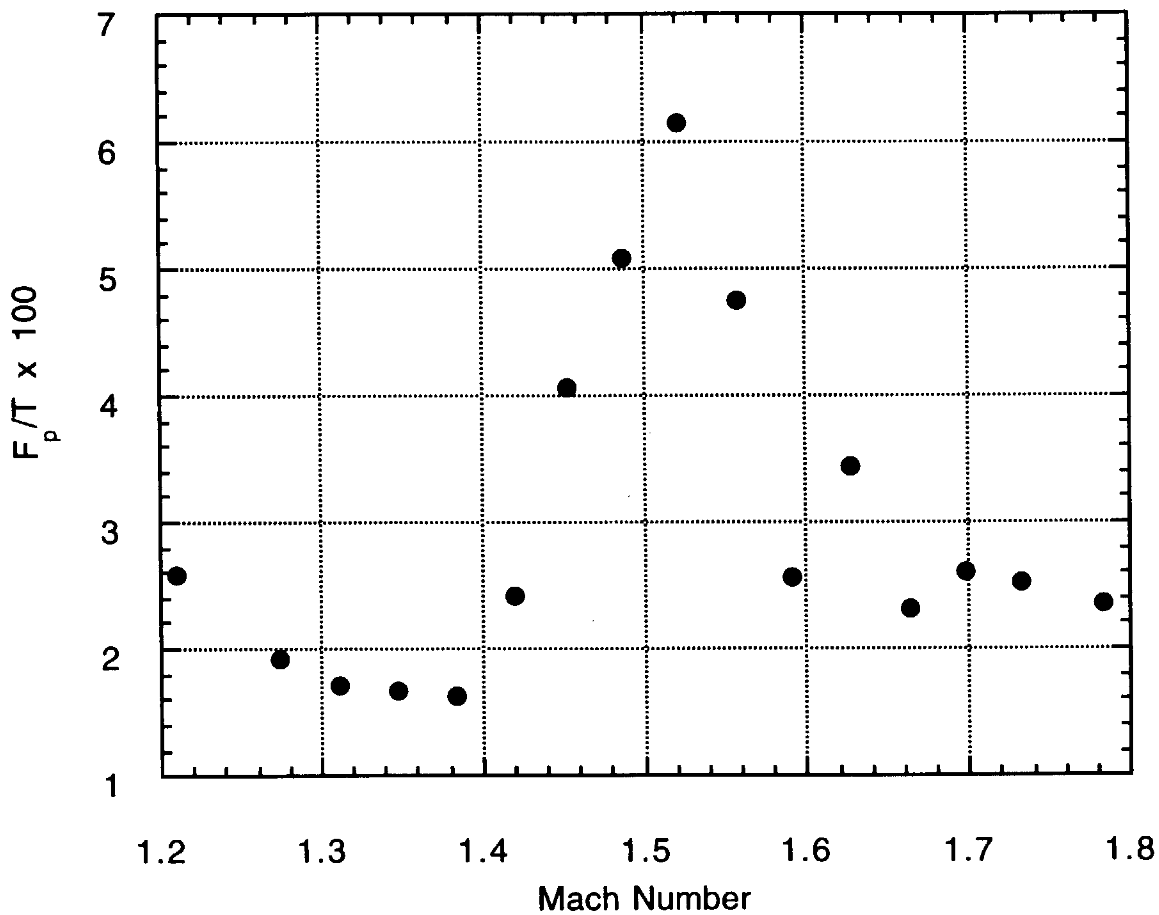



Fig. 25