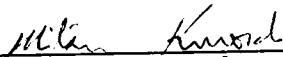
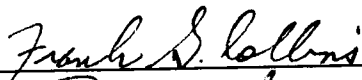
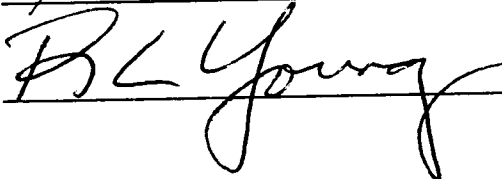


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ENHANCEMENT OF TEMPERATURE DROP BEHIND CYLINDERS
BY ACOUSTIC SYNCHRONIZATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

William C. Riner
August 1985

DEDICATION

This thesis is dedicated to my wife Beth for the sacrifices she has made to allow me to attend graduate school, and to my parents and family for the support they have provided me all my life.

ACKNOWLEDGMENTS

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ABSTRACT

Although the temperature drop behind a cylinder immersed in a flow was discovered in the late 1930s, the exact mechanism of the cooling has remained unresolved. While the shedding of the Kármán vortex street has long been thought to be the cause, this has never been proven conclusively.

Acoustic synchronization--resonance between the cylinder vortex shedding and the normal wind tunnel acoustic modes (the resonance unrelated to structural vibration of the cylinder)--is used as a noninvasive means of intensifying the vortex street and, therefore, the associated temperature drop. Proper design of the physical dimensions of the test apparatus allows this to take place at the low Mach number of 0.21.

At the three lowest resonances, the measured span-wise response of the temperature and pressure at the rear of the cylinder agrees well with the theoretical expectations. The Kármán vortex street is concluded to be indeed the cause of the temperature drop.

Although this investigation is confined to a circular cylinder, the results are expected to be applicable to other bluff bodies since the characteristics of the Kármán vortex street for any body shape are similar.

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LIST OF SYMBOLS

a	Acoustic velocity
C_p	Pressure coefficient
C_{pb}	Base pressure coefficient
$C_{p \text{ kiel}}$	Kiel probe pressure coefficient
$C_p(0^\circ)$	Pressure coefficient at forward stagnation point
d	Cylinder diameter
D	Length of test section side
f_c	Cylinder vibration frequency
f_v	Cylinder vortex shedding frequency
f_{a1}	Fundamental frequency at first lock-in
f_{a2}	Fundamental frequency at second lock-in
f_{a3}	Fundamental frequency at third lock-in
M	Mach number in the test section
m	Number of acoustic pressure nodes in the y-direction
n	Number of acoustic pressure nodes in the z-direction
P	Time-averaged pressure
p'	Acoustic pressure
P_o	Maximum acoustic pressure amplitude
P_t	Time-averaged total pressure
P_s	Time-averaged static pressure
R	Recovery factor, gas constant
R_{kiel}	Kiel probe recovery factor

$R(180^\circ)$	Recovery factor at $\theta = 180$ deg
Re	Reynolds number based on cylinder diameter
SPL	Sound pressure level
St	Strouhal number
T	Time-averaged temperature
T_s	Time-averaged static temperature
T_t	Time-averaged total temperature
$T_t(\theta)$	Cylinder surface temperature
t	Time
U	Velocity in the test section
v'	Acoustic velocity in the y-direction
v_o	Maximum amplitude of acoustic velocity in the y-direction
x,y,z	Cylinder coordinate system
γ	Ratio of specific heats
λ_x	Wavelength in the x-direction
λ_y	Wavelength in the y-direction
λ_z	Wavelength in the z-direction
θ	Cylinder angular position measured from forward stagnation point
ω	Circular frequency of acoustic waves
ρ	Density
∞	Upstream condition

CHAPTER I

INTRODUCTION

In a recent article, Eckert [1]¹ rekindled a general interest in a curious but still unresolved phenomenon, the cooling effect in the wake behind a cylinder. In 1943, Eckert and Weise [2], while measuring the surface temperature around a thermally insulated cylinder placed in air, found that for a cylinder in a crossflow, although the surface temperature at the forward stagnation point expectably attained its upstream stagnation value, at a rearward point, 180 deg from the forward stagnation point, the surface temperature there is found to drop by as much as 20°C, to the extent that it is even lower than the upstream static temperature. In terms of the recovery factor defined as $(T_t(\theta) - T_s) / (T_t - T_s)$ (where $T_t(\theta)$ is the surface or total temperature at an angular position θ measured from the forward stagnation point, T_s upstream static temperature and T_t upstream total temperature), while at the forward stagnation point $\theta = 0$, the recovery factor is equal to 1; at the rearward point $\theta = 180$ deg,

¹Numbers in brackets refer to similarly numbered references in the Bibliography.

it becomes even negative, equal to about -0.1 at the free-stream Mach number of 0.65 .

These findings of Eckert and Weise were later confirmed by Ryan [3]. Even for bluff bodies other than a cylinder, Ryan found the presence of lowered temperature and in addition recorded a particularly noteworthy observation: at the Mach number of about 0.7 , a whistling noise was suddenly heard emanating from the wind tunnel within which the model was tested and at that instant a drop in the recovery factor was noticed. Although it led Ryan to presume that tunnel resonance was somehow involved in this, unfortunately this speculation was not pursued further. As to the general cause of the lowered temperature, Ryan also postulated, as had Eckert, that the Kármán vortex street shed by bluff bodies might somehow be responsible.

Subsequently, Thomann [4] did show that the attachment of a splitter plate behind a wedge raises the recovery factor while suppressing the Kármán vortex street, the latter being an effect initially found by Roshko [5]. Although it is not entirely unreasonable to assume from this that the Kármán vortex may be an apparent cause of the cooling, the insertion of such a physical object as a splitter plate obviously presents an unfortunate drawback: it alters the body geometry in general, a sensitive near

wake body shape in particular. Furthermore, when the effect is forcibly suppressed and removed, one can no longer hope to investigate the explicit process of the temperature drop. Thus, the mechanism of the cooling effect in the wake has remained, as Eckert's article [1] states, an unresolved issue.

In the present investigation, instead of suppressing the vortex street shed from a cylinder, the Kármán vortex is intensified by the use of a noninvasive means and it is seen whether one could further lower the wake temperature by it. Once confirmed, from such a demonstration, which does not involve any alteration to the body shape, one could conclude that the Kármán vortex is indeed the cause of the cooling effect; furthermore, by elevating the vortex street to its excited state and by examining its robust behavior, perhaps some insight may be gleaned into the very mechanism of the cooling.

As a nonintrusive means of excitation, use is made of wind tunnel acoustic resonance: synchronization between the frequency of vortex shedding from a cylinder and that of a transversely standing acoustic wave, the latter being latently present in a wind tunnel. In the normal operation of a wind tunnel, one avoids the condition of acoustic resonance but here it is exploited deliberately and fully as a simple, noninvasive means of intensifying a Kármán vortex

street. Although vibrating a cylinder could achieve the same goal, acoustic resonance, in its obvious simplicity realizable by the mere presence of wind tunnel walls and walls only, without any additional provision, offers a decisive advantage.

Curiously enough, despite its evident superiority over the method of mechanical vibration of a cylinder, a precedent use of acoustic resonance for the study of vortex shedding from a cylinder has not been found in the literature, although its investigations for a flat plate and cascaded airfoils abound (Parker [6], Whitehead and Cumpsty [7], Hiramoto et al. [8], Taneda et al. [9], and Maull and Young [10]). The only published allusion to acoustic resonance for a cylinder appears to be that of negative results reported earlier in a well-known paper by Parker [6] and Blevins [11]. There for a single cylinder, contrary to the case of an array of flat plates, Parker failed to detect any acoustic resonance. It can only be surmised that the diameter of the cylinder, 0.0625 inch (1.588 mm), used by Parker might be too small and the flow velocity at acoustic resonance might therefore be too low to excite any significant resonance.² As will be observed

²Bearman and Graham [12], in a report on Euromech 119, cite the results of Welsh, Parker, and Stoneman where they found acoustic resonance even for a cylinder, although the phenomenon is purportedly not so pronounced as for flat plates.

shortly, with a cylinder of 0.5 inch (12.7 mm) diameter, no difficulty was encountered in achieving acoustic resonance, a loud and ringing one indeed, even at the Mach number of 0.2.

In fact, it was found that acoustic resonance with a cylinder can cause transversely standing acoustic waves to materialize not only with ease but in form strikingly close to idealized normal modes; this occurs not only for the fundamental mode but also for higher modes as well. Therefore, in this regard, wind-tunnel acoustic resonance appears to excel over other excitation methods such as synchronization by speakers.

As the vortex shedding frequency increases proportionally with the flow velocity, the vortex shedding frequency, f_v , is expected to become locked to the frequency of the transverse acoustic mode. This lock-in regime occurs over a certain range of Mach numbers and the vortex shedding frequency remains at a constant value during the lock-in. At these lock-ins, the strength of the Kármán vortex street becomes intensified but, as will be seen later, the spanwise response of the Kármán vortex street will vary according to the position of the loops and nodes of the first three lock-ins.

The results indeed fulfill all these expectations.

Although the results presented in this study are for a circular cylinder, the general trends are expected to be representative of bodies having other cross-sectional shapes which develop a Kármán vortex street since the vortex street scales with the free-stream velocity and is generally independent of the body shape. Each shape, however, will have its own characteristic Strouhal number and Reynolds number dependence. This generalization has been verified by Ryan [3] who investigated not only circular cylinders but also a variety of other cylindrical bodies, half-bodies, and ellipses.

CHAPTER II

TEST APPARATUS

In order to achieve resonance between the shedding frequency of Kármán vortex and natural frequency of standing acoustic mode in the wind tunnel, it is of course necessary to minimize any extraneous background noise. For this, a special, low-noise University of Tennessee Space Institute (UTSI) wind tunnel has been designed and built. As shown in Figure 1, the interior of a settling tank, 20 inches (0.508 m) in diameter and 10 feet (3.050 m) in length, to which compressed air is introduced first, is covered with specially formed acoustic foams: starting from the inlet, the internal surface of acoustic foams is shaped as a diffuser. This provides an effective reduction of background noise to such an extent that in the test section the sound level at $M_\infty = 0.5$ (M_∞ : free-stream Mach number in the test section) is less than 110 db for frequencies over 500 Hz. In addition to acoustic foams, three fine-meshed screens are installed in the settling tank to make the flow uniform.

The cross section of the test section is a square, 6 inches by 6 inches (15.24 cm by 15.24 cm); its size is so chosen that with a cylinder of 0.5 inch (12.7 mm) in diameter placed transverse to the flow, the first lock-in

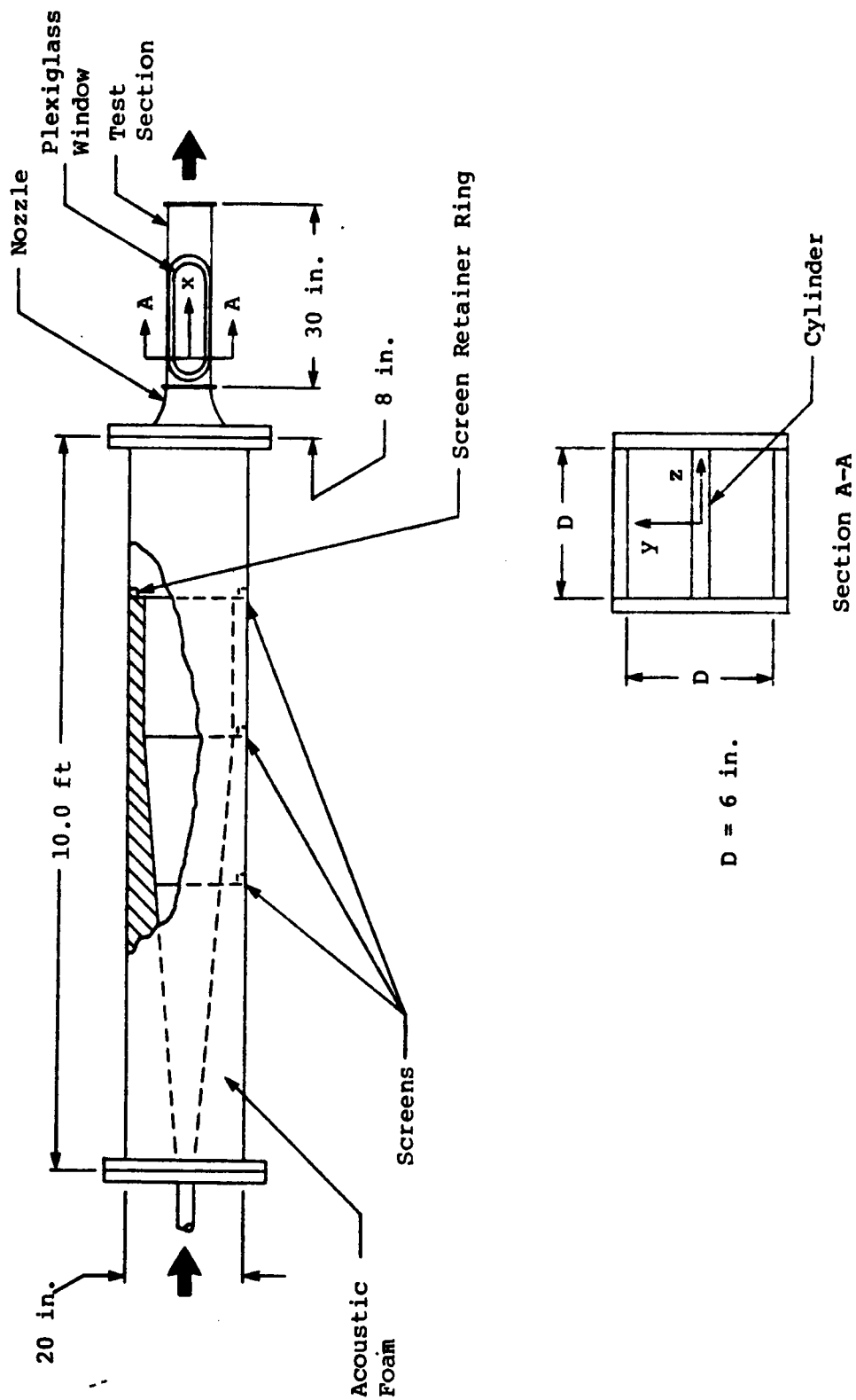


Figure 1. Test Rig Layout.

can take place at the low subsonic Mach number, $M_\infty = 0.21$. The reason for the selection of this low Mach number is as follows. Past investigations on the lowered temperature behind the cylinder were all conducted with high subsonic to supersonic flow: $M_\infty = 0.65$ for Eckert and Weise [2], $M_\infty = 0.4$ to 0.7 for Ryan [3], and $M_\infty = 0.56$ to 3 for Thomann [5]. However, if the Kármán vortex street is indeed the cause, the drop in wake temperature or negative recovery factor should occur even when in this low subsonic flow of $M_\infty = 0.21$.

Within the test section, the uniformity of velocity and temperature profiles outside of the boundary layers is confirmed. Aft of the test section, the air discharges directly to the atmosphere.

With regard to the test cylinder, to meet the objective of sustaining a temperature drop across it, it is necessary to select thermally insulating material; for this, rods of Polyvinyl Chloride (PVC) and Acetal (Delrin) are selected in the preliminary tests. Since both materials are found to yield similar results, the main test is conducted with a PVC rod. As shown in Figure 2, the rod is 0.5 inch (12.7 mm) in diameter and 6 inches (15.24 cm) in its effective length. To increase the thermal response of this thermally insulating material to the air temperature in the test section, the cylinder is

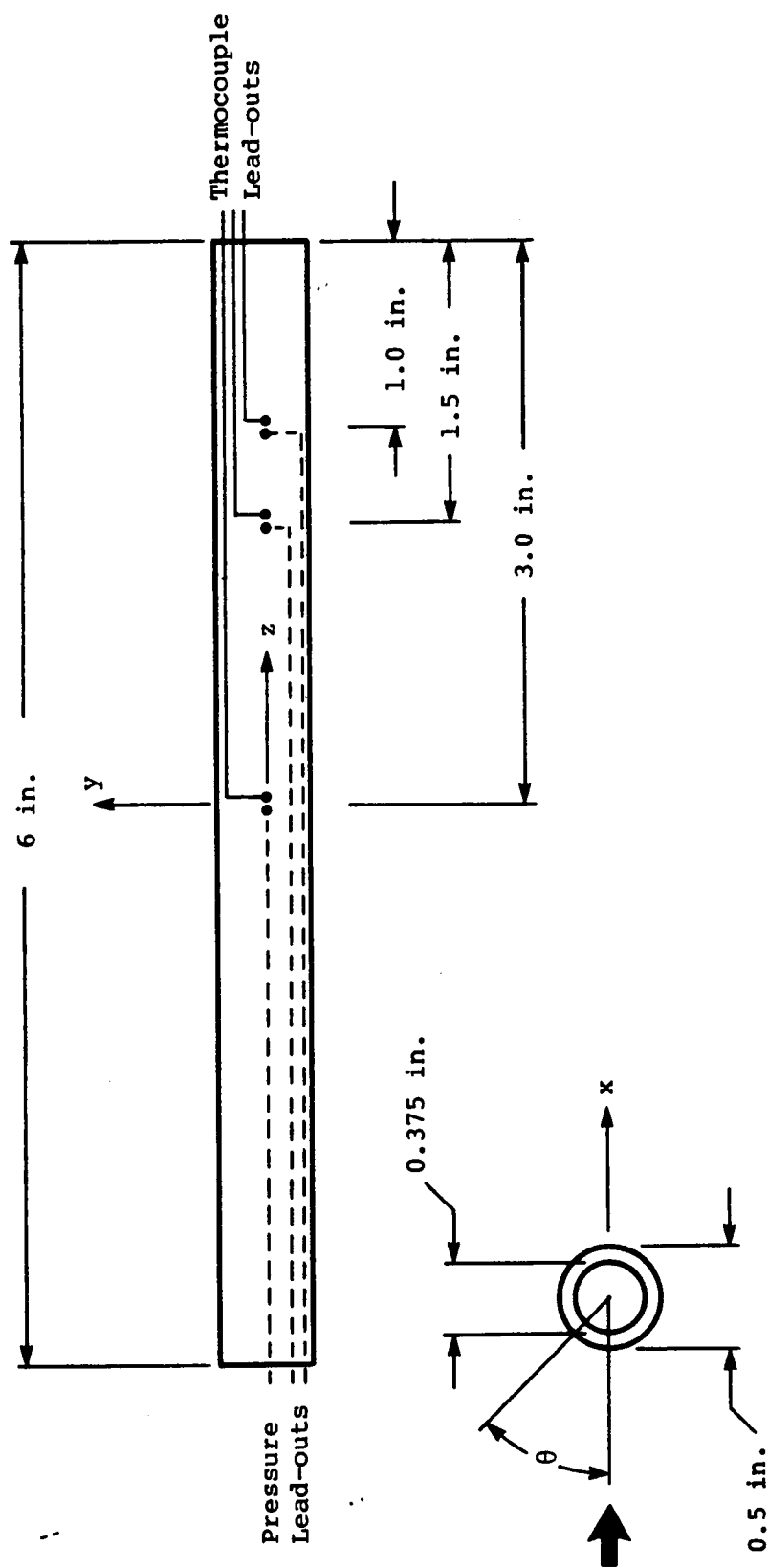


Figure 2. Test Cylinder.

made to be hollow, the inner diameter of the drilled-out cavity being equal to 0.375 inch (9.52 mm), and this inner space is evacuated prior to each test in order to increase the effective thermal diffusivity of the rod by the reduction of air density.

The origin of the x-coordinate, aligned along the free-stream direction, is located at the center of the cylinder, the y- and z-coordinates being, as shown in Figure 2, perpendicular and parallel to the cylinder, respectively.

The cylinder was instrumented with thermocouples and pressure taps. At $\theta = 0$ deg or the forward stagnation point, three pairs of thermocouples and pressure taps were imbedded on the cylinder surface: (1) at the center, (2) at a quarter-point, and (3) at 1 inch (2.54 cm) away from the wall. Also, at $\theta = 180$ deg, the rearward point, three pairs of thermocouples and pressure taps are provided in a similar manner. Thermocouples are of Chromel-Alumel type, 0.005 inch (0.127 mm) in diameter. The grooves to insert them are initially cut on the cylinder surface and later covered with fiberglass fillers so that the cylinder surface remains smooth and circular.

Total temperature is monitored by a thermocouple installed within the settling tank, and the free-stream Mach number by a calibrated total and static pressure

probe (United Sensor, Inc., Part No. YCT-156) inserted in the test section and located upstream of the cylinder, at $x = -2.875$.

CHAPTER III

DATA ACQUISITION, MEASUREMENT, AND REDUCTION

Data Acquisition

To enable test data to be acquired and reduced more easily and accurately, an on-line, computer-operated data acquisition system was developed. By on-line, it is meant that the test data are reduced immediately after the test and the results presented in the desired form. Effort was made to enable the system to adapt to differing test setups quickly and with as little effort as possible. A schematic diagram of the system is shown in Figure 3.

The computer, an S-100 bus microcomputer manufactured by CompuPro, Inc., is the main component of the system. Temperature and pressure scanners operate under computer control to measure wind tunnel conditions. At present, the system is capable of reading 80 temperatures and 48 pressures at rates of up to 30 and 20 channels per second, respectively. It is important to minimize the measurement time in a blowdown wind tunnel due to the limited operating time that is available.

Most of the operating software was written using FORTRAN IV, although Z80 assembly language was used to control the scanners. The operating system of the computer is CP/M 2.2 from Microsoft, Inc.

Voltage signals from the thermocouples and pressure transducer are read by an analog-to-digital converter (A/D) (Tecmar TM AD 212) located within the computer. The use of the scanners allows individual temperature or pressure readings to be switched to the A/D and recorded. This is needed because of the limited number of A/D channels available and the large number of inputs. The scanners are controlled by the computer via a serial communications port (RS232). Commands from the computer step the scanners through the thermocouples and pressure taps as the A/D reads the respective voltages. The accuracy of the A/D is 0.05%.

The temperature scanner (John Fluke, Inc., Model 2204A) is equipped with low-level thermocouple input modules. Thermocouples are connected, in groups of 10, to isothermal connector blocks which are allowed to drift with ambient temperature. The maximum temperature difference in any given connector block is 0.09°F (0.162°C). The temperature of the isothermal connector block is read by a separate thermocouple and electronic ice-point and is then used in the conversion process. The output of this scanner is amplified by an instrumentation amplifier (Preston 8300 XWB) and connected to one channel of the A/D. This scanner also contains a relay actuator module

(John Fluke, Inc., 2205A-100) which controls the pressure scanner solenoid controller.

The pressure scanner (Scanivalve Corp., Model J) is capable of sequentially connecting up to 48 pressure lines to a single, internally mounted pressure transducer (Scanivalve Corp., Model PDCR 23D). The pressure transducer is a differential type with a span of ± 5 psi. The scanner is controlled using a solenoid controller (Scanivalve Corp., Model CTRL 2/S2-S6).

The sensitivity of the system was such that a full-scale output occurred at the highest dynamic pressure encountered. This entails the inevitable consequence that pressure readings become less accurate at the lower Mach numbers. No attempt was made to increase the sensitivity of the system at the lower Mach numbers.

The pressure transducer was calibrated using a precision pressure calibrator (MKS, Type 270A with Baratron Pressure Head).

Data Measurement

All voltages from the thermocouples and pressure transducers were converted to engineering units using least-squares polynomial curve fits with maximum errors or less than 0.1°F and 2 psf (0.3%), respectively. These

pressure and temperature measurements are all time-averaged values.

With regard to the measurement of the sound intensity as the overall indicator of acoustic level in the test section, precautions must be exercised not to place a microphone at the node of the standing modes. At higher harmonics, as the spatial separation between nodes becomes narrower, any location of the microphone with its finite size can inevitably infringe on one of the many nodes. The improper installation of the microphone at the node of the fundamental, for instance, would give a falsely lowered level at the lock-in. Therefore, the position of the microphone, which is placed on the side wall of the test section, is nominally chosen to be at $y = 0.75$, $x = 2.0$ inches ($y = 1.905$ cm, $x = 5.08$ cm); though, as seen later, it corresponds to the node of the fourth harmonics at the first lock-in, it is found to serve as a satisfactory, general indicator of the sound level of the fundamental, the second and third harmonics.

A condenser microphone with a head of 0.25 inch (0.635 cm) in diameter (Bruel and Kjaer Type 1435) is used and its output is fed into FFT high-resolution signal analyzers (Bruel and Kjaer Type 2033 for a single-channel operation and Type 2032 for dual channels).

Data Reduction

The flow under investigation is assumed to have constant ratio of specific heats. Once the total pressure, static pressure, and total temperature are measured, all the other desired quantities can be calculated from the isentropic relationships:

$$M_{\infty} = \sqrt{\frac{2}{\gamma-1} \left[\left(\frac{P_{t\infty}}{P_{s\infty}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} ,$$

$$T_s = \frac{T_t}{1 + \frac{\gamma-1}{2} M_{\infty}^2} ,$$

$$a_{\infty} = \sqrt{\gamma R T_{s\infty}} ,$$

$$U_{\infty} = M_{\infty} a_{\infty} .$$

Once the vortex shedding frequency, f_v , and the free-stream velocity, U_{∞} , are known, the Strouhal number may be calculated from:

$$St = \frac{f_v d}{U_{\infty}} .$$

The data will be presented in terms of recovery factors and pressure coefficients defined, respectively, as:

$$R = \frac{T_t(\theta) - T_{S\infty}}{T_{t\infty} - T_{S\infty}} ,$$

$$C_p = \frac{P - P_{S\infty}}{\frac{\gamma}{2} M_{\infty}^2 P_{S\infty}} = \frac{P - P_{S\infty}}{\frac{1}{2} \rho_{\infty} U_{\infty}^2} .$$

The reduced test data along with the frequency data are shown in the Appendix.

CHAPTER IV

EXPECTED ACOUSTIC MODES AT THE LOCK-IN

As stated, it is expected, and later confirmed, that the lock-in, where the shedding frequency of Kármán vortex becomes entrained to that of the standing, transverse acoustic wave, the acoustic modes correspond to the standing waves, standing in the y- and z-directions. Such standing waves are governed by

$$(1 - M_{\infty}^2) \frac{\partial^2 p'}{\partial x^2} + \frac{\partial^2 p'}{\partial y^2} + \frac{\partial^2 p'}{\partial z^2} - 2 \frac{U_{\infty}}{a_{\infty}^2} \frac{\partial^2 p'}{\partial x \partial t} - \frac{1}{a_{\infty}^2} \frac{\partial^2 p'}{\partial t^2} = 0 , \quad (1)$$

where p' is the unsteady pressure; U_{∞} , free-stream velocity; a_{∞} , acoustic speed; and t , time. Equation (1) is subject to the boundary conditions of hard walls:

$$\frac{\partial p'}{\partial y} = \frac{\partial p'}{\partial z} = 0 \text{ on walls} . \quad (2)$$

The standing waves, corresponding to a square cross section of the test section with height D , are given, in the absence of the cylinder, by

$$p' = p_0 e^{i\omega t} \cos \frac{m\pi}{D}(y + 1/2 D) \cos \frac{n\pi}{D}(z + 1/2 D) , \quad (3)$$

where ω is given by

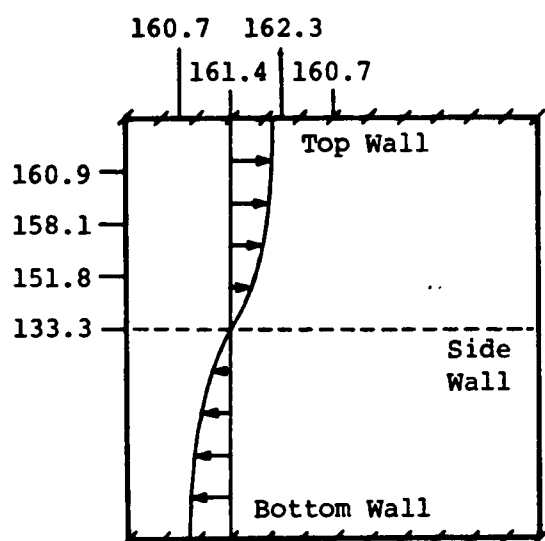
$$\omega = \frac{a_\infty \pi \sqrt{n^2 + m^2}}{D} ; \quad (4)$$

correspondingly, the unsteady velocity in the vertical y-direction is given by

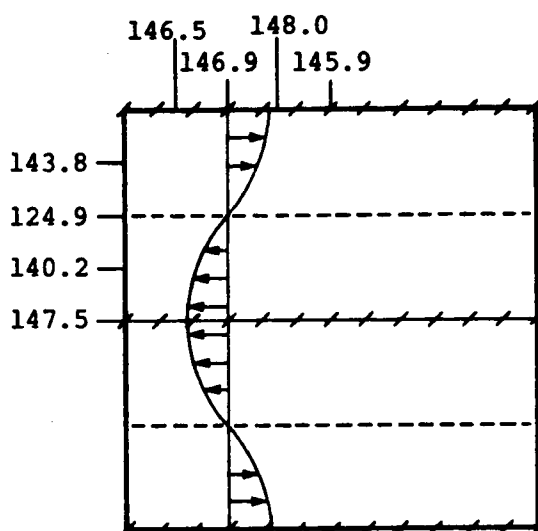
$$v' = v_0 e^{i\omega t} \sin \frac{m\pi}{D}(y + 1/2 D) \cos \frac{n\pi}{D}(z + 1/2 D) . \quad (5)$$

To verify the form of the normal acoustic modes, a microphone was placed around the perimeter of the test section just downstream of the cylinder and the sound level was measured at the wall. As Figures 4 and 5 show, the measured results compare very favorably to idealized modes for the first and second lock-ins. The measured results for the third lock-in do not agree (Figure 6) although, as will be shown later, the frequency calculated with $n = 0$, $m = 2$ is very close to the measured frequency at the third lock-in.

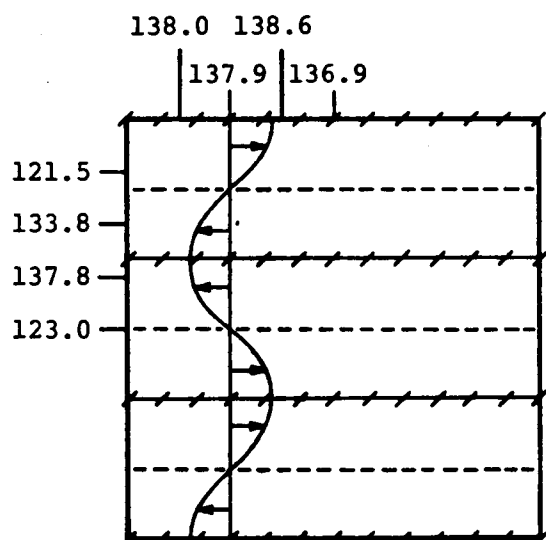
Figure 7, where the loops and nodes are schematically shown, corresponds to the normal modes of v' ; loops are defined as points possessing the maximum attainable amplitude, v_0 , nodes as $v' = 0$. As mentioned, the mode with $n = 0$ and $m = 1$ is expected to correspond to the



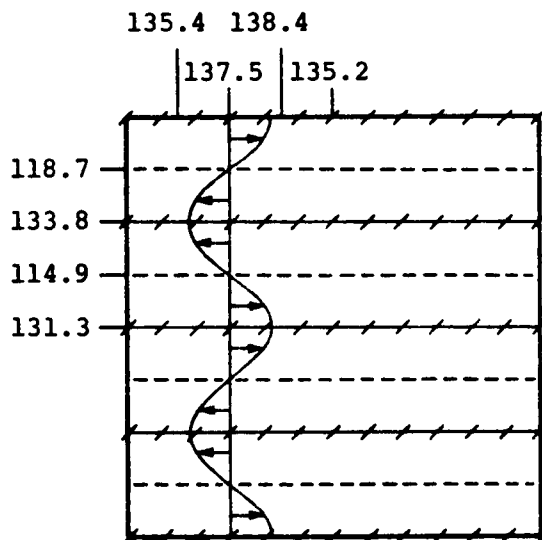
a) Fundamental,
 $n = 0, m = 1$



b) Second harmonics,
 $n = 0, m = 2$



c) Third harmonics,
 $n = 0, m = 3$



d) Fourth harmonics,
 $n = 0, m = 4$

----- Predicted Loop of p'
----- Predicted Node of p'

Figure 4. Comparison of Expected Acoustic Modes for p' and Decibels Measured on the Wall at the First Lock-in, $M_\infty = 0.230$. Numbers in figures denote measured decibels corresponding to a) f_{a1} , b) $2f_{a1}$, c) $3f_{a1}$, and d) $4f_{a1}$.

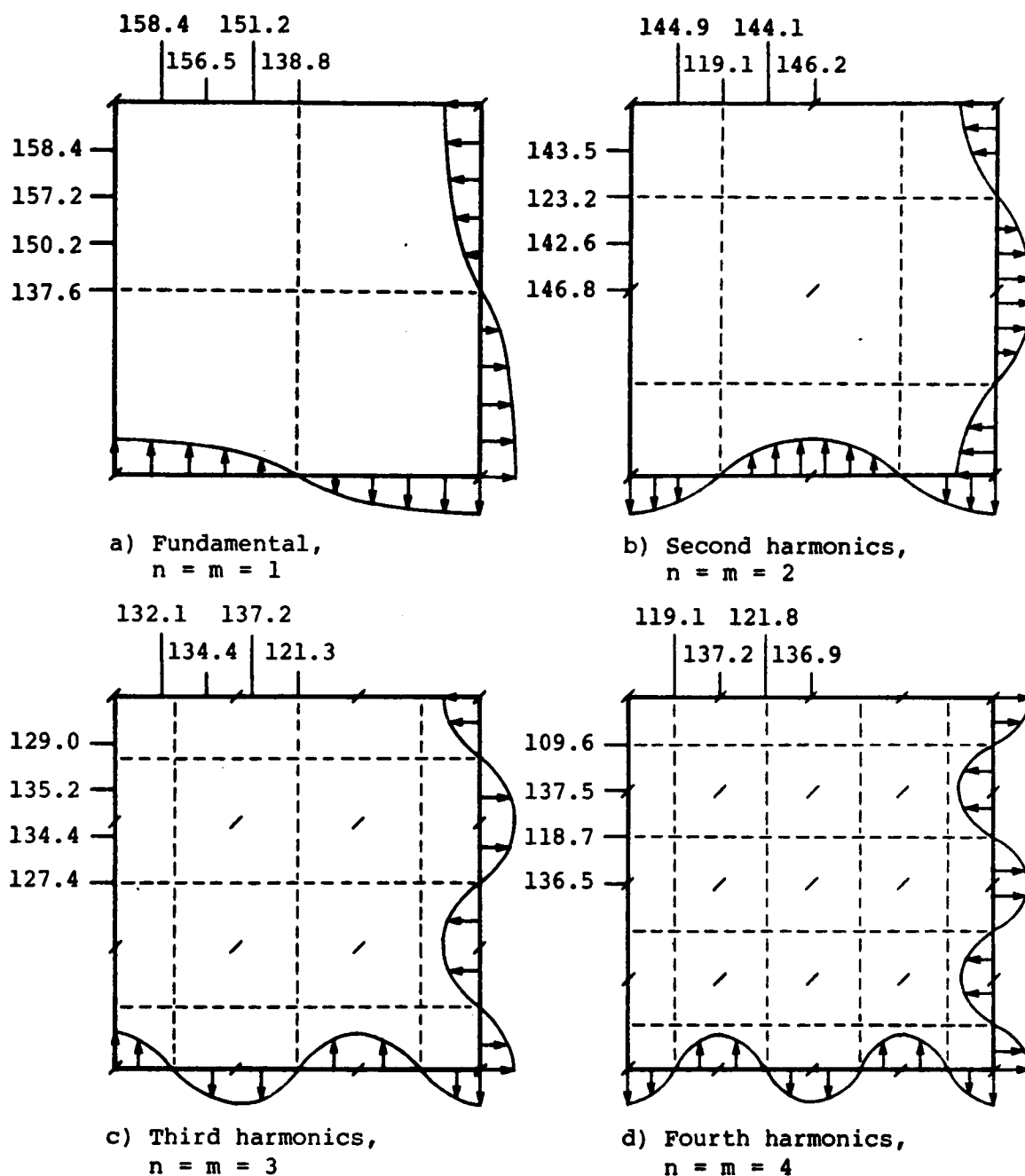
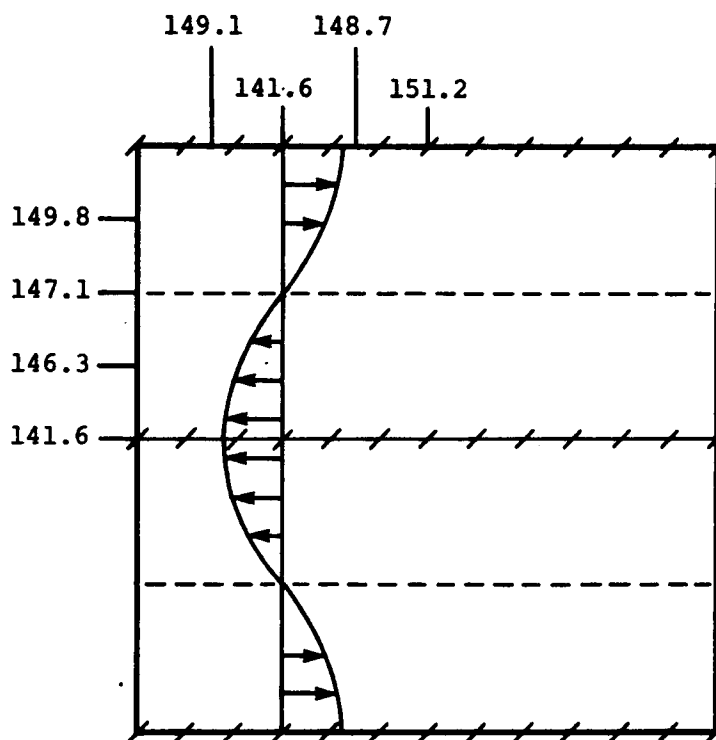


Figure 5. Comparison of Expected Acoustic Modes for p' and Decibels Measured on the Wall at the Second Lock-in, $M_\infty = 0.305$. Numbers in figures denote measured decibels corresponding to a) f_{a2} , b) $2f_{a2}$, c) $3f_{a2}$, and d) $4f_{a2}$.



—— Predicted Loop of p'

----- Predicted Node of p'

Figure 6. Comparison of the Expected Acoustic Mode for p' ($n = 0, m = 2$) and Decibels Measured on the Wall at the Third Lock-in, $M_\infty = 0.426$. Numbers in the figure denote measured decibels corresponding to f_{a3} .

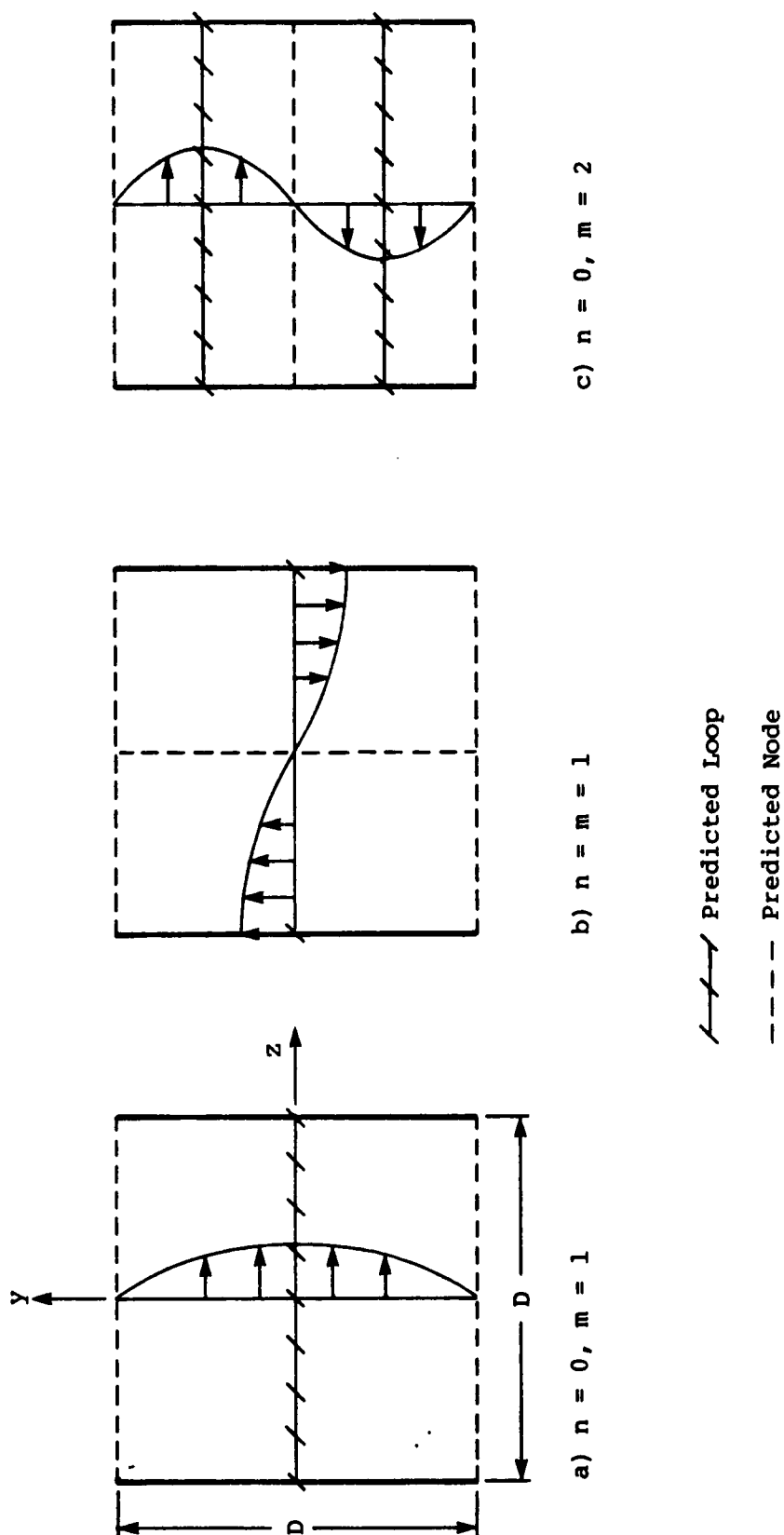


Figure 7. Predicted Acoustic Modes for v' .

fundamental frequency of the first lock-in, $n = m = 1$ to the fundamental of the second lock-in, and so forth.

Such an ability of acoustic resonance to reproduce with fidelity even higher normal modes as well as the fundamental one can, in the present case, be turned into several advantages, the points best described by referring to Figure 7. Within the square cross section of the wind tunnel surrounded by the top, bottom, and side walls, the flow being perpendicular to the paper, Figure 7 shows schematically the expected positions of loops and nodes for the vertical, y -component of acoustic velocity v' , for the first three normal modes (since for the fundamental and third harmonics, it is difficult to visualize the appropriate waveform corresponding to the vertical motion, arrows depicting the movement are drawn horizontally but they in fact represent the y -component of acoustic velocity). Waveforms are shown in the absence of the test cylinder, which would be nominally placed along the z -axis; as the order of modes becomes higher, corresponding acoustic frequencies increase.

If the cylinder is put in place along the z -axis and when the vortex shedding frequency, which increases proportionally to the flow velocity, approaches any of the acoustic frequencies, it is expected that the shedding frequency becomes locked to the acoustic frequency and

remains, over a certain range of Mach number, at that value. Thus, as the Mach number is progressively increased, the vortex shedding process undergoes a sequence of locked-in regimes: the first lock-in corresponding to the fundamental acoustic mode, the second lock-in, and so forth. Although at these lock-ins the strength of Kármán vortex becomes, in general, intensified, its degree of intensification and details of local flow response to it may differ depending on the very location of acoustic modes and loops.

For instance, as indicated in Figure 7, at the first lock-in the loop of the vertical acoustic velocity coincides with the cylinder position, the z-axis; hence, the acoustic loop is located in the vicinity of vertically fluctuating fluid induced by the vortex street. Thus, strong resonance is expected here and, as the result, intensification of a Kármán vortex street. Furthermore, due to the alignment of the loop and cylinder axis, such intensification is expected to manifest itself more or less uniformly along the span of the cylinder; if the Kármán vortex street indeed causes the cooling effect, one may be able to demonstrate that the temperature behind the cylinder drops in a spanwise uniform fashion.

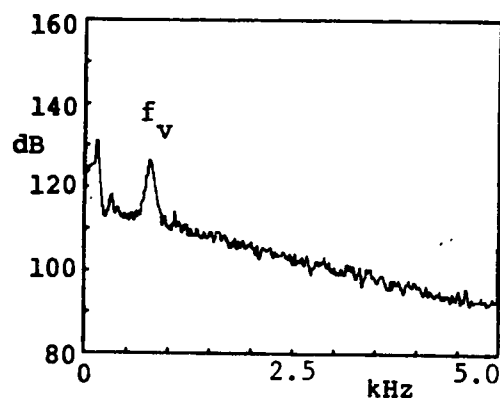
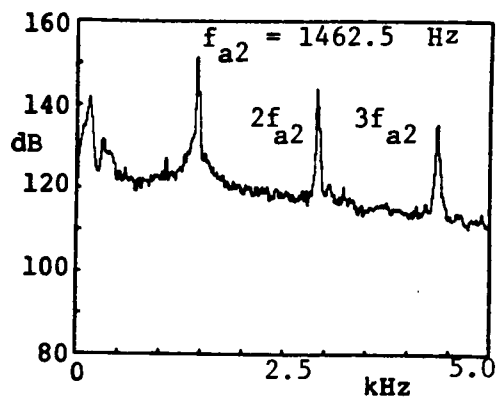
At the second lock-in, where a node is located at the midspan and loops on side walls, the vortex street

might become intensified in a spanwise nonuniform manner. That is, if and when the strength of the Kármán vortex street differs, from one point to another, along the span in direct response to locally varying stimuli (and it is not groundless to expect that the "strip theory" might hold for the process of the vortex shedding from evidence gleaned from different contexts to be elaborated later), then little change is anticipated in the vortex at the midspan in contrast to stronger Kármán vortex at off-midspan points. Again, if the cooling effect in the wake is controlled by the Karman vortex street, the temperature drop behind the cylinder may vary along the span accordingly.

CHAPTER V

MAIN RESULTS AND DISCUSSION

Figures 8 (a) through (f) display the frequency spectra as the Mach number is progressively increased, the successive change of the frequency spectra is obtained by the microphone placed at the aforementioned nominal position. At the low Mach number of 0.61, (a), there exists only a single peak, f_v , which increases as the Mach number is increased. The peak corresponds to the Strouhal number of approximately 0.19, a typical value for the vortex shedding in the subcritical Reynolds number of 4.7×10^4 . As the Mach number approaches 0.206 a ringing sound emerges; for $0.206 < M_\infty < 0.231$, the shedding frequency becomes, as shown in (b), locked to $f_{a1} = 1075.0$ Hz, which will soon be confirmed to be the fundamental frequency for the acoustic mode with $n = 0$, $m = 1$. During this first lock-in, not only the sound power increases, but also higher harmonics sprout up. Once past the first lock-in, the sound level falls off sharply and the frequency disengages from the acoustic frequency and resumes its increase with free-stream velocity. The spectrum, (c), reverts to the one with a single peak until the second lock-in, another audible regime, is reached, (d); there the shedding frequency becomes now locked to

a) $M_\infty = 0.1610$ d) $M_\infty = 0.3016$ second

lock-in

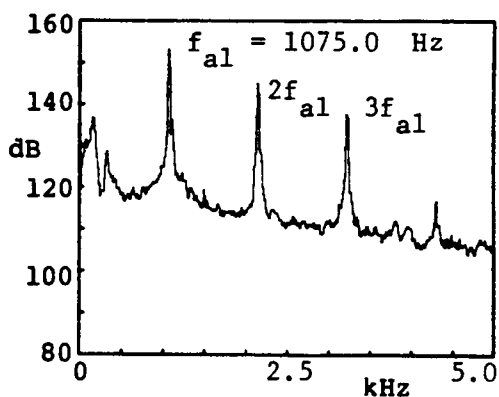
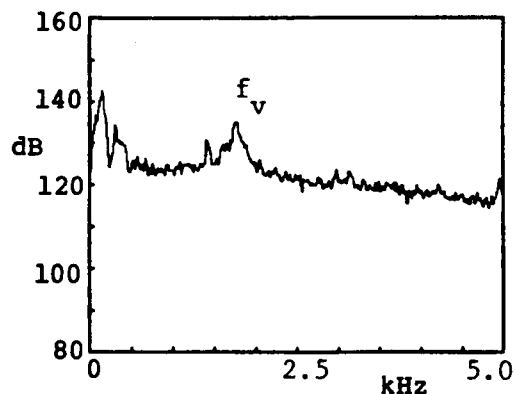
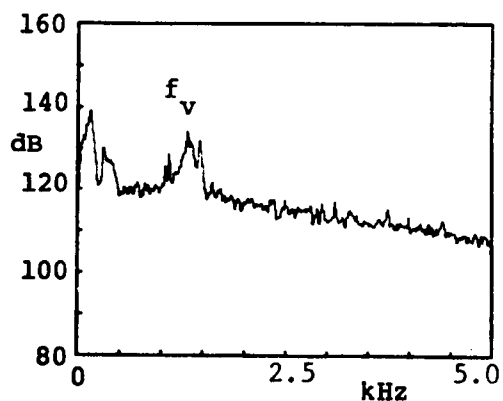
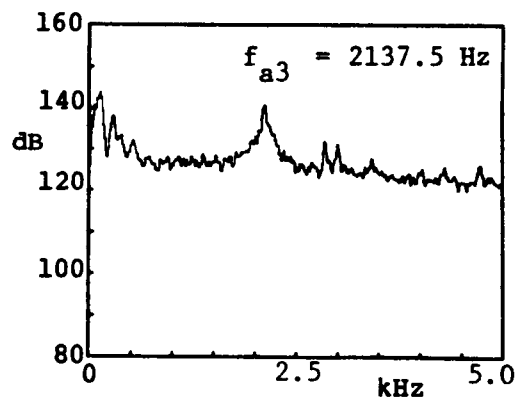
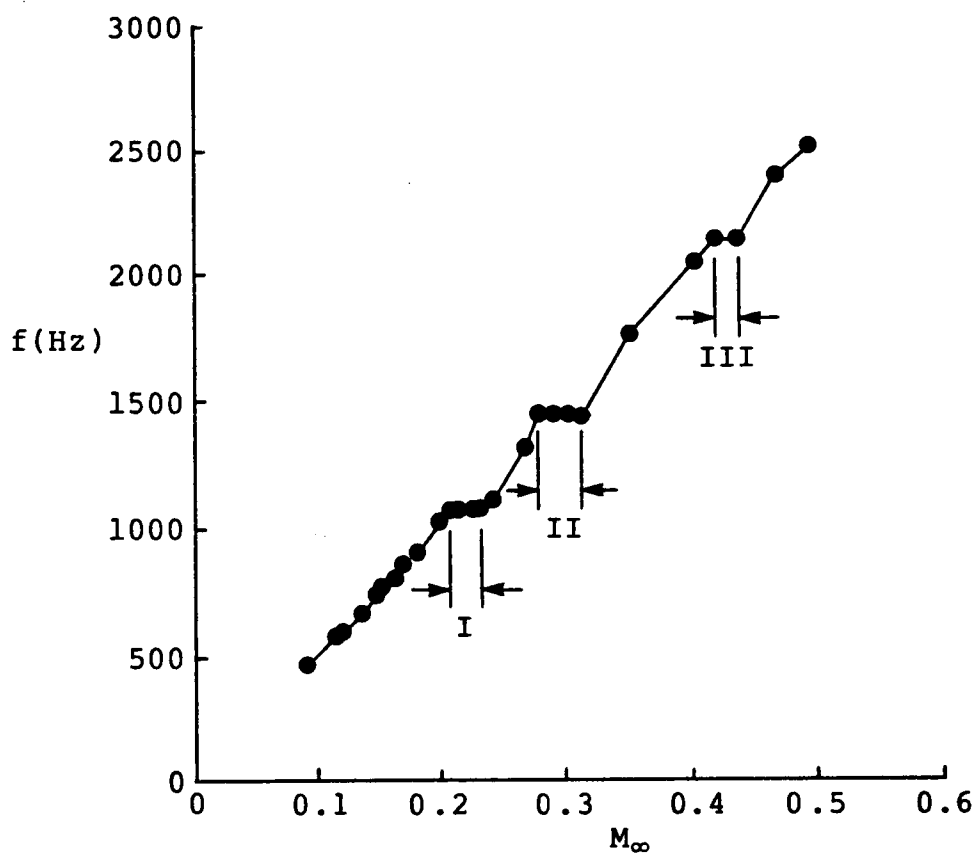
b) $M_\infty = 0.2267$, first
lock-ine) $M_\infty = 0.3535$ c) $M_\infty = 0.2674$ f) $M_\infty = 0.4240$

Figure 8. Change of Frequency Spectra, Test No. W204.

$f_{a2} = 1462.5$ Hz, which turns out to correspond to $n = 1$ mode and higher harmonics reappear. Beyond this, f_v disengages from f_{a2} once again, (e), until at the third lock-in it becomes locked to $f_{a3} = 2137.5$ Hz, almost twice that of f_{a1} ; the sound level at the third lock-in, however, is not as high as the first and second lock-in and only the peak of the fundamental (f_{a3}) stands out. In the present range of the Reynolds number, 10^5 at $M_\infty = 0.4$, a peak cannot be identified as that which is commonly referred to as the Bloor frequency [13], a transitional wave observed for the Reynolds number of 10^4 .

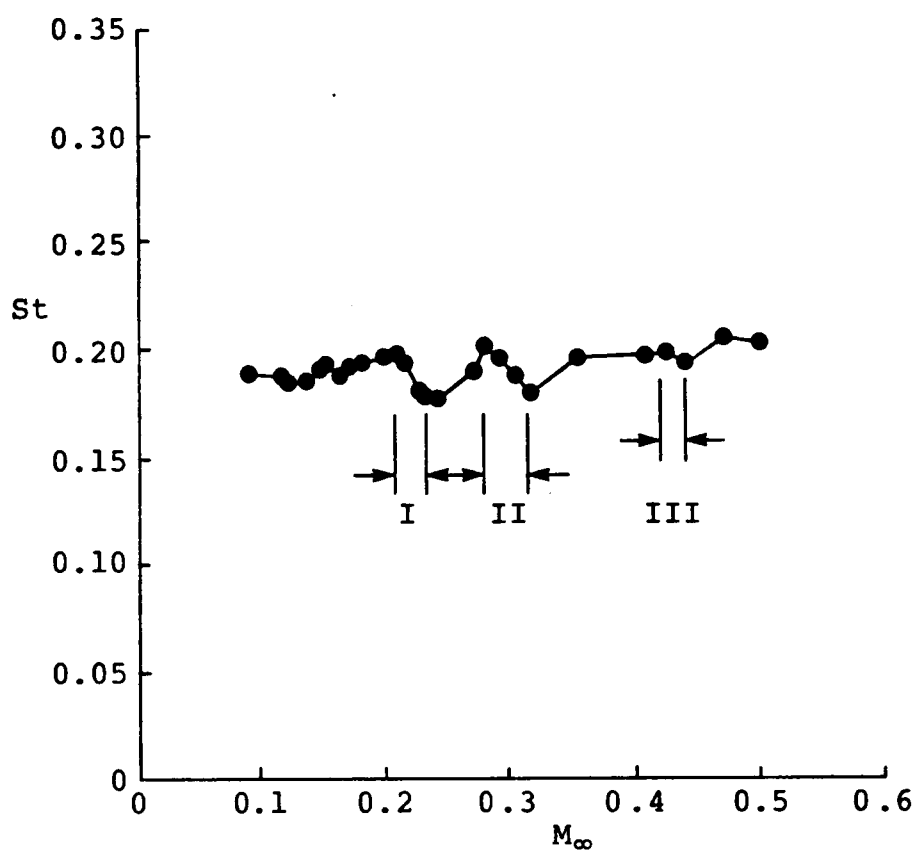
The above successive changes in unsteady signals are summarized in Figures 9 (a), (b), and (c), where the frequency, corresponding Strouhal number, and decibels of the fundamental frequency are plotted against the free-stream Mach number. The labels I, II, and III denote the aforementioned three lock-in regimes.

The key results are presented in Figures 9 (d), the base pressure coefficient C_{pb} and (e), the recovery factor, $R(180^\circ)$, both at $\theta = 180$ deg, T_t is the upstream total temperature, here taken as the value measured at $\theta = 0$, on the opposite side of the point $\theta = 180$ deg (the choice of this as T_t rather than the one in the settling tank is found to reduce the scatter in data). The measurements are taken at aforementioned three spanwise stations:



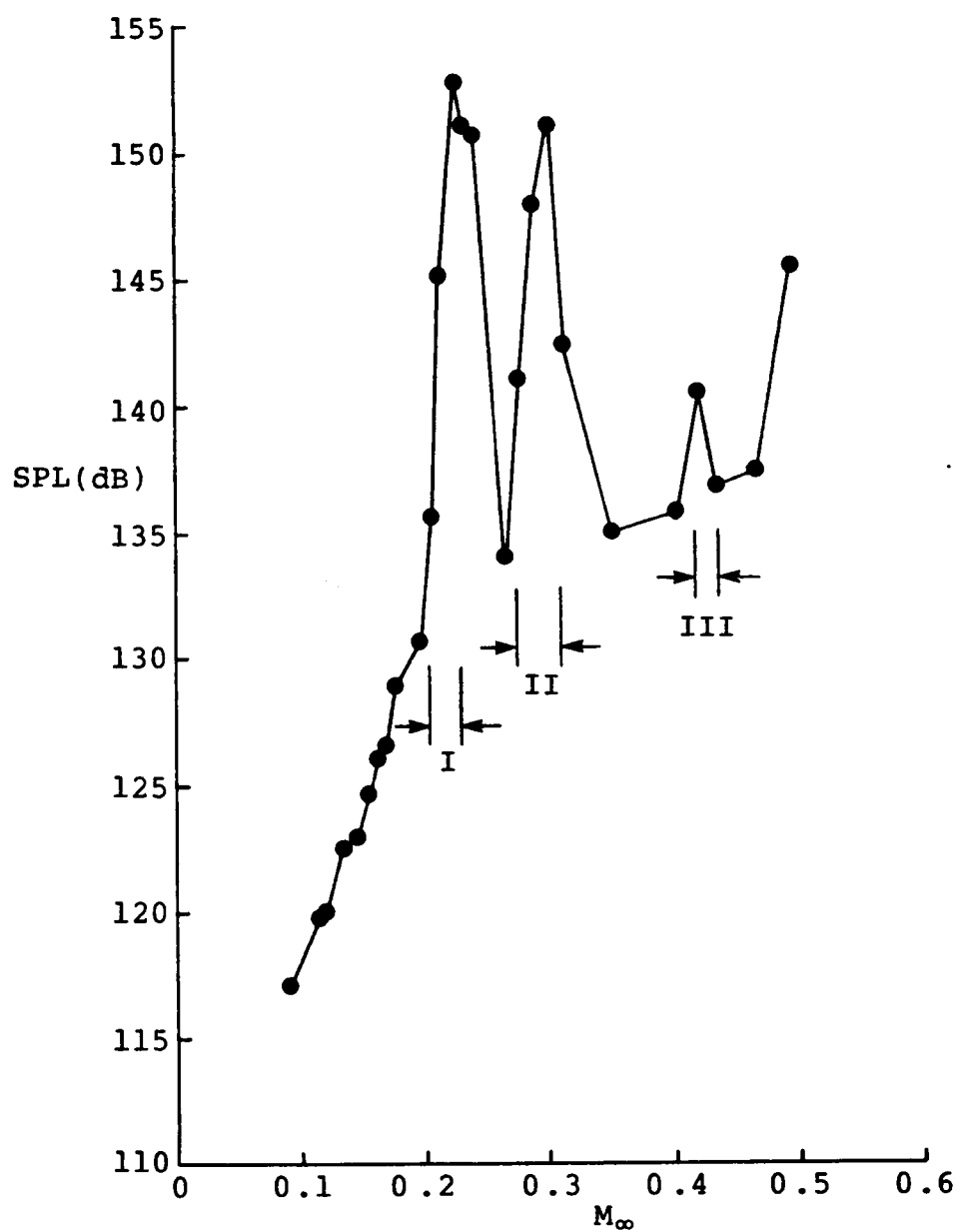
a) Fundamental frequency versus free-stream Mach number

Figure 9. Main Test Results, Test No. W204.



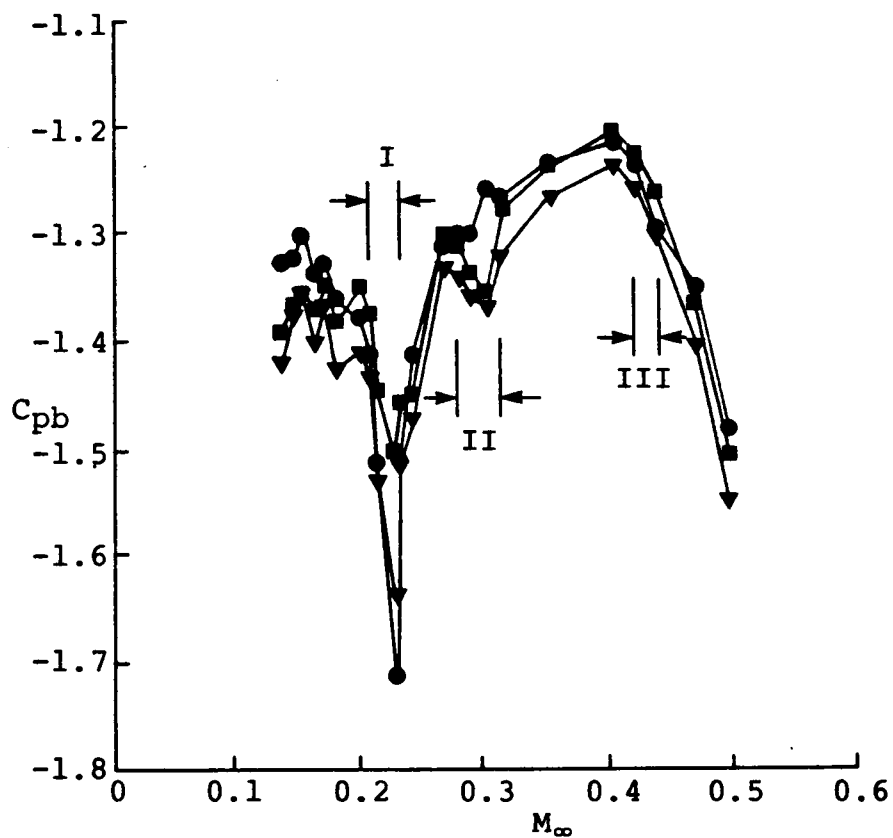
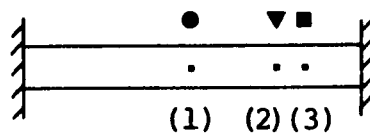
b) Strouhal number versus free-stream Mach number

Figure 9. (Continued)



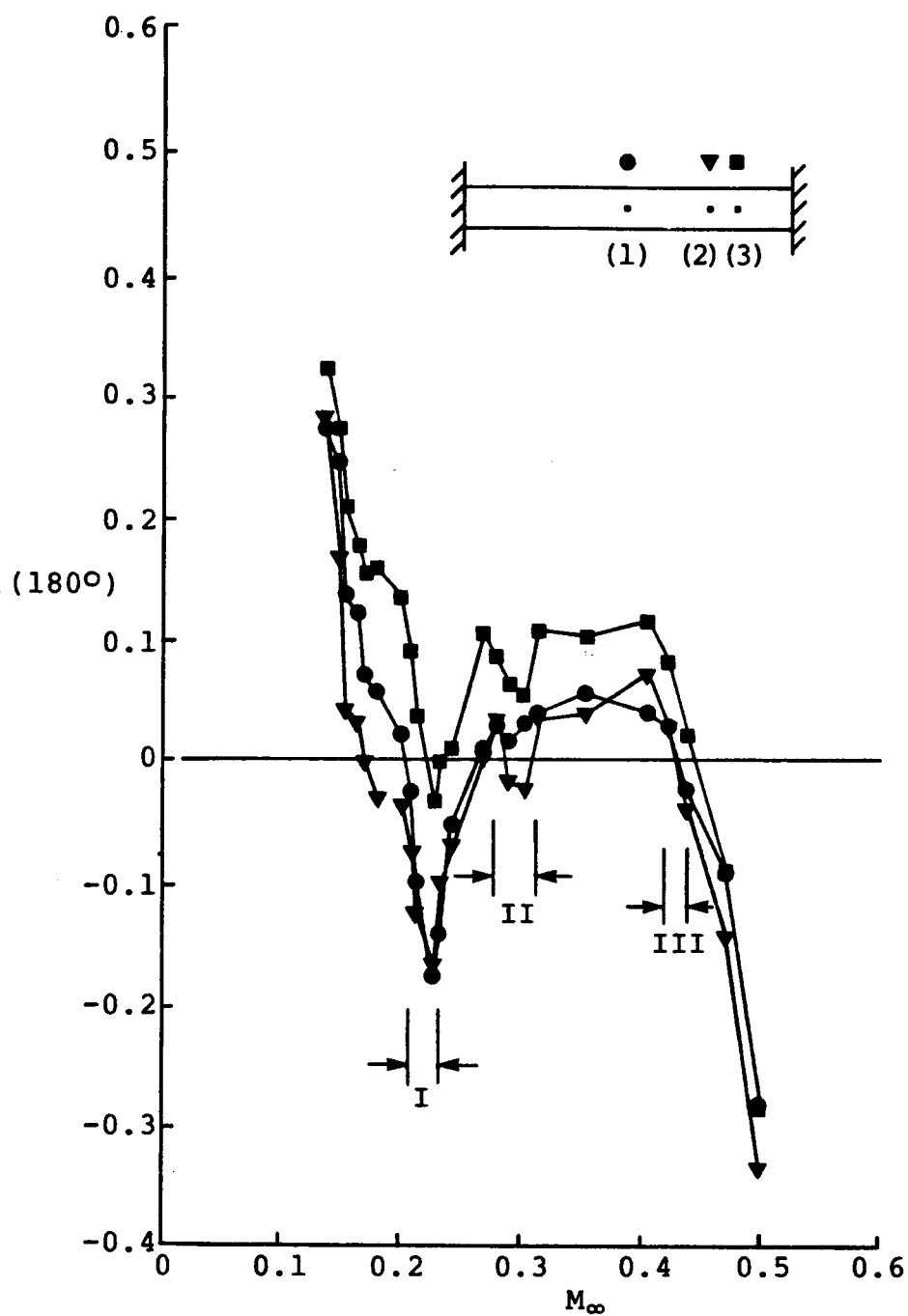
c) Sound intensity of fundamental frequency
versus free-stream Mach number

Figure 9. (Continued)



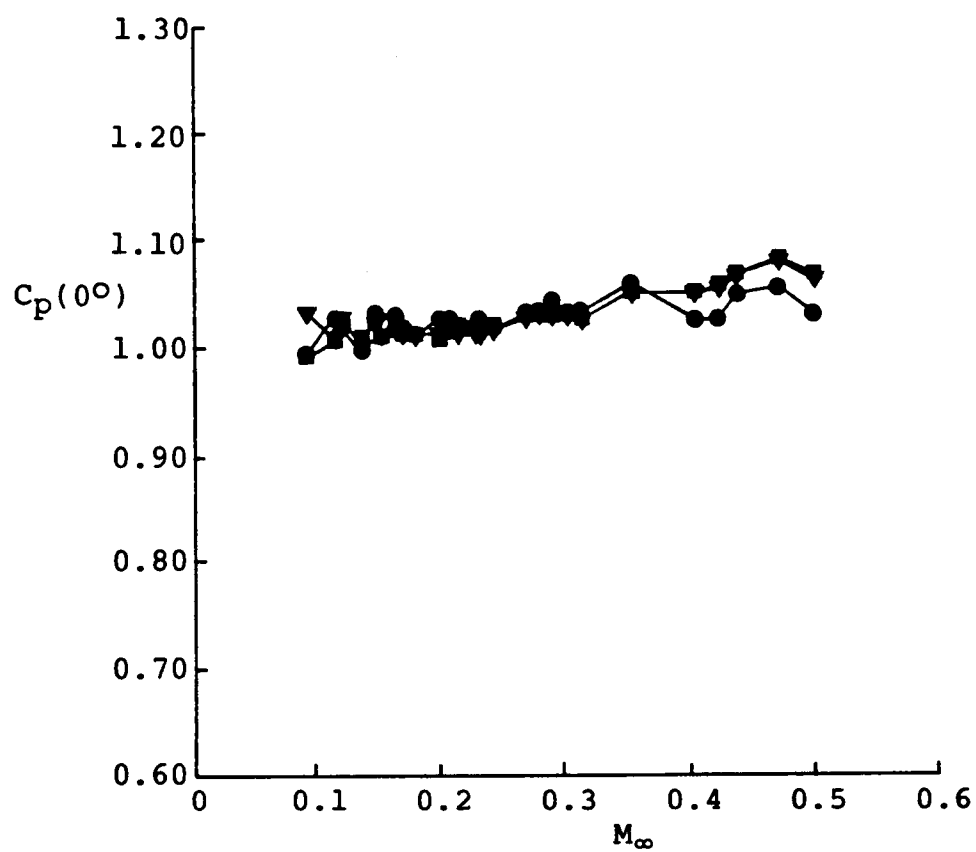
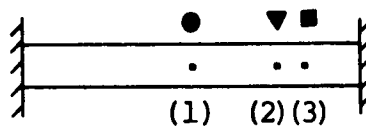
d) Base pressure coefficient versus free-stream Mach number

Figure 9. (Continued)



e) Base recovery factor versus free-stream Mach number

Figure 9. (Continued)



f) Pressure coefficient at forward stagnation point versus free-stream Mach number

Figure 9. (Continued)

(1) midspan point, (2) a quarter-span point, and (3) near-wall point. For the present purpose, no corrections to C_{pb} by the wind tunnel blockage are judged to be necessary and the data presented are uncorrected.

In Figures 9 (d) and (e), it is immediately observed that at the first lock-in, I, both C_{pb} and $R(180^\circ)$ take a significant plunge simultaneously and this occurs regardless of the spanwise station, fulfilling the expectation stated in Chapter I. This dip of C_{pb} , or increased suction behind the cylinder, indicates an increase in drag, which in turn implies intensification of the Kármán vortex street. This does indeed cause the drop of the recovery factor at $\theta = 180$ deg, and a special note is directed to the fact that $R(180^\circ)$ becomes negative even at this low subsonic Mach number of 0.21. The reason for the intensified strength of Kármán vortex at acoustic resonance may be attributable to the increase of circulation around the cylinder caused by the shift in the forward stagnation point due to the presence of fluctuating acoustic velocity. The process of intensification is similar to that of a transversely vibrating cylinder, where the increase of circulation at the lock-in was found to be as high as 65% by a direct measurement (Griffin and Ramberg [14]) or indirectly through the 20% increase in $|C_{pb}|$ (Toebes [15] and Taneda and Honji [16]).

In contrast to C_{pb} , the pressure coefficient at the forward stagnation point, $C_p(0^\circ)$, is almost constant, regardless of spanwise position, as to be expected (Figure 9 (f)).

For a vibrating cylinder, the fact that the vortex street becomes spanwise uniform at the lock-in is, of course, well known (e.g., Berger and Willie [17]). For acoustic resonance with a flat plate, the drop in $|C_{pb}|$ and the improvement in spanwise correlation was also reported by Wood [18] and Graham and Maull [19], respectively. However, as far as the thermal effect, the focal point of interest, is concerned, no results such as the present one establishing the direct link with the strength of vortices appear to have been obtained either for a vibrating cylinder or in any of the previous investigations on acoustic resonance.

Contrary to the first lock-in, at the second lock-in, II, Figures 9 (d) and (e) show that dips in C_{pb} and R occur only at stations (2) and (3), points located off the center, while at the mid-span point, (1), no such drop is observed. This substantiates the expectation stated in Chapter I: spanwise different strength of Kármán vortex in response to acoustic nodes and loops. This sectionally different reaction of Kármán vortex was previously found in somewhat different circumstances: for a stationary

straight cylinder immersed in a shear flow (Chen and Mangione [20] and Maull and Young [10]), or for a stationary tapered cone in a uniform flow (Taneda [21]), the vortex shedding frequency varies along the span in such a way that if one takes either a local velocity or a local diameter, the Strouhal number always remains the same as that of a two-dimensional case, a straight cylinder in a uniform flow. Here, in the present case, the strength of the Kármán vortex varies along the span in such a way that it responds two-dimensionally to spanwise varying stimuli; in all of these the "strip theory" apparently holds.

From the waveform of Figure 7 (b), page 25, which shows a 180-deg phase lag between the two loops of v' on the side walls, at the second lock-in the vortex shedding near both ends of the cylinder may well be out of phase; though this point has not been pursued, among the data obtained for a flat-plate cascade acoustic resonance (Kaji, Hiramoto, and Okajaki [8]), there is a supporting evidence showing that the response of vortex shedding for such two loops is indeed out of place.

In contrast to the first and second lock-ins, at the third lock-in corresponding to $n = 0$, $m = 2$ acoustic node, no dips are detected in either C_{pb} or $R(180^\circ)$. The reason for this can also be drawn from the acoustic waveform shown in Figure 7 (c), page 25: there, the node for

v' is located on the cylinder axis, a wrong place to elevate Kármán vortex to higher intensity.

As the Mach number is increased further, the strength of Kármán vortex, which scales with free-stream velocity, becomes vigorous on its own, even in the absence of resonance, resulting in the gradual, general decrease of C_{pb} and $R(180^\circ)$. Since the objective of this study is focused on realizing the lowered wake temperature or negative recovery factor at resonance in the low subsonic flow, the present range of the Mach number is less than 0.5. The trend beyond this Mach number may be discerned from the measurements of Thomann [4], taken in the absence of acoustic resonance: $R(180^\circ)$ attains minimum around $M_\infty = 0.65$ and then it starts to increase until it reaches 0.8 around $M_\infty = 1$. This increase at the transonic flow and beyond is almost certainly caused by the narrow "necked" wake and the resulting weakened vortex strength.

For a vibrating cylinder, subharmonic or superharmonic resonance is found to occur (Bishop and Hassen [22] and Toebe [15]): lock-in takes place not only when the frequency of the vibrating cylinder (f_C) coincides with that of the vortex shedding frequency (f_V), but also when $nf_C = mf_V$ (n, m : integers). Although Berman and Graham [14] cite the report of Welsh, Parker, and Stoneman where such a phenomenon was observed for a flat-plate

cascade at acoustic resonance, it was not detected in any of the present tests of a cylinder. In all tests, C_p at $\theta = 0$ deg remained close to unity, as expected. Throughout these tests, no movement of the cylinder was detected. Test data are shown in the Appendix.

CHAPTER VI

DETAILS OF STANDING ACOUSTIC WAVES

Identification of various acoustic modes corresponding to multitudinous peaks in the frequency spectra at lock-ins can most easily be accomplished by looking at Figures 4 and 5, pages 22 and 23, respectively: at the first and second lock-in, measured sound levels corresponding to a given peak are shown together with the expected waveform of fluctuating acoustic pressure p' , its loops and nodes corresponding to a combination of n and m . In measuring the sound intensity, the position of the microphone was moved along the periphery of the test section at a cross section corresponding to $x = 2.0$ inches (5.08 cm), four diameters downstream of the 0.5-inch (12.7 mm) diameter cylinder. The loop of p' is defined as the location where the amplitude of p' takes its maximum value, p_0 , of Eq. (2), and the node at $p' = 0$. To avoid any possible misunderstanding, mark with attention that while Figures 4, 5, and 6, pages 22, 23, and 24, respectively, display the waveform of p' , Figures 7 (a) through (c), page 25, show those of v' . In addition to the agreement between the measured level for the fundamental and its expected waveform, in Figures 4 and 5 observe that even those for higher harmonics stand similarly favorable comparison.

The measured acoustic mode at the third lock-in does not compare favorably with the expected mode as shown in Figure 6, page 24. The hydrodynamic pressure variations due to the vortex shedding increase in magnitude due to the higher Mach number at the third lock-in and do not allow the acoustic pressure variation to be measured separately.

Besides these, further confirmation of acoustic nodes, n and m , can be established from the comparison of the measured frequency, $f = \omega/2\pi$ with the values calculated from Eq. (4). Table 1 shows a good agreement between the calculated and measured frequencies. Though for the reason already stated, at the third lock-in, the measured sound level and acoustic loop and node for $n = 0$, $m = 2$ do not agree (Figure 6), the frequency calculated for such values of n and m still compares favorably with the data.

In calculating frequency from Eq. (4), the propagation of acoustic wave in the streamwise x -direction is neglected. The wavelength in the x -direction is in fact measured to be larger compared to the one in the y - and z -direction (λ_y and λ_z): from Lissajous figures obtained from two microphones placed at different stations in the x -direction, λ_z for the fundamental at the first lock-in is found to be about 59.8 inches (152 cm), in comparison

Table 1. Comparison of the Calculated and Measured Fundamental Frequencies

	Acoustic Speed Calculated from Measured Temperature (m/sec)	Calculated Fundamental Frequency (Hz)	Measured Fundamental Frequency (Hz)
(I) First lock-in	338	1109($n = 0, m = 1$)	1075.0
(II) Second lock-in	333	1544($n = m = 1$)	1462.5
(III) Third lock-in	325	2132($n = 0, m = 2$)	2137.5

to $\lambda_y = \lambda_z = 12.0$ inches (30.4 cm). Thus, the influence λ_z on ω amounts to only 6%.

For a flat-plate cascade at resonance, Parker [7] found the existence of what he calls α or β mode characterized by the presence of either node (α mode) or loop (β mode) at the midchord of the plate; even for a single plate at resonance, the presence of β mode was identified by Whitehead and Cumpsty [8]. In the present case of a single cylinder at acoustic resonance, no such nodes appear to exist, as seen from Figure 10, which displays the sound intensity distribution in the streamwise x-direction at lock-ins. The absence of standing waves in the streamwise direction may be attributable to the lack of clear-cut wave reflection in the present situation; for a flat plate, its leading edge would reflect back waves created at the trailing edge.

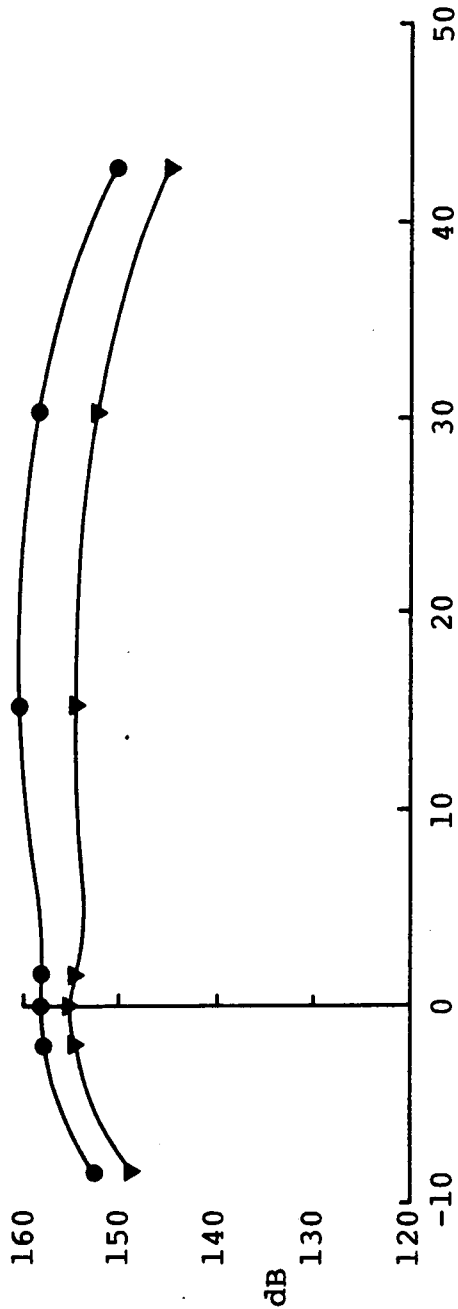


Figure 10. Sound Intensity Distribution in the x-direction at the First and Second Lock-ins. The dB level at $x/d = 42.25$ corresponds to Test No. W172; $x/d = 30$ to Test No. W166; $x/d = 15$ to Test No. W170; $x/d = 1.625$ to Test No. W163; $x/d = 0$ to Test No. W165; $x/d = -1.625$ to Test No. W164; $x/d = -8.8$ to Test Nos. W160 and W186 ($d = 0.5$ inch (12.7 mm)).

- Fundamental frequency at first lock-in, $M_\infty = 0.225$
- ▼ Fundamental frequency at second lock-in, $M_\infty = 0.305$

CHAPTER VII

CONCLUSIONS

The conclusions reached are:

1. By the noninvasive use of acoustic resonance, the Kármán vortex street is confirmed to be the cause of the lowered temperature in the wake behind a bluff body.
2. The Kármán vortex street is found to be intensified in a spanwise different manner in direct response to locally varying stimuli and results in spanwise varying wake temperature distribution.
3. Acoustic synchronization between the transverse acoustic wave and vortex shedding from the cylinder is found to reproduce with fidelity precise modes of standing acoustic waves.

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BIBLIOGRAPHY

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APPENDIX

LIST OF APPENDIX SYMBOLS

Ac Vel	Acoustic velocity
Cp 0	Pressure coefficient based on free-stream conditions calculated using P 0
Cp 180	Pressure coefficient based on free-stream conditions calculated using P 180
M nom	Approximate Mach number calculated from settling tank pressure and atmospheric pressure
M	Free-stream Mach number calculated from the total and static pressure probe
Ps yct	Free-stream static pressure in the test section
Pt yct	Free-stream total pressure in the test section
P 0	Pressure measured on the surface of the cylinder at the forward stagnation point
P 180	Pressure measured on the surface of the cylinder at $\theta = 180$ deg
R 0	Recovery factor based on free-stream conditions calculated using T 0
R 180	Recovery factor based on free-stream conditions calculated using T 180

Tt (1) through (3)	Total temperature defined as T 0 (1) through (3), respectively; used in the calculation of R 0 (1), (2), and (3)
Tt (4) through (6)	Total temperature defined as T 0 (1) through (3), respectively; used in the calculation of R 180 (1), (2), and (3)
Tt yct (1) through (6)	Total temperature measured by the combination total and static pressure probe in the test section
Ts (1) through (6)	Static temperature calculated from Tt (1) through (6), respectively; used in the calculation of R 0 (1), (2), (3), and R 180 (1), (2), and (3), respectively
T sc (1) through (6)	Total temperature measured by a thermocouple in the settling tank
T 0	Temperature measured on the surface of the cylinder at the forward stagnation point
T 180	Temperature measured on the surface of the cylinder at $\theta = 180$ deg
Velocity	Free-stream velocity
(1),(2),(3)	Denotes spanwise position

APPENDIX

TEST DATA

Figures A-1 (a) through (z) illustrate the frequency spectrum for Test W204 at various Mach numbers. Tables A-1 through A-9 are computer printouts of parameters, pressures, coefficients, temperatures, and recovery factors for Test W204.

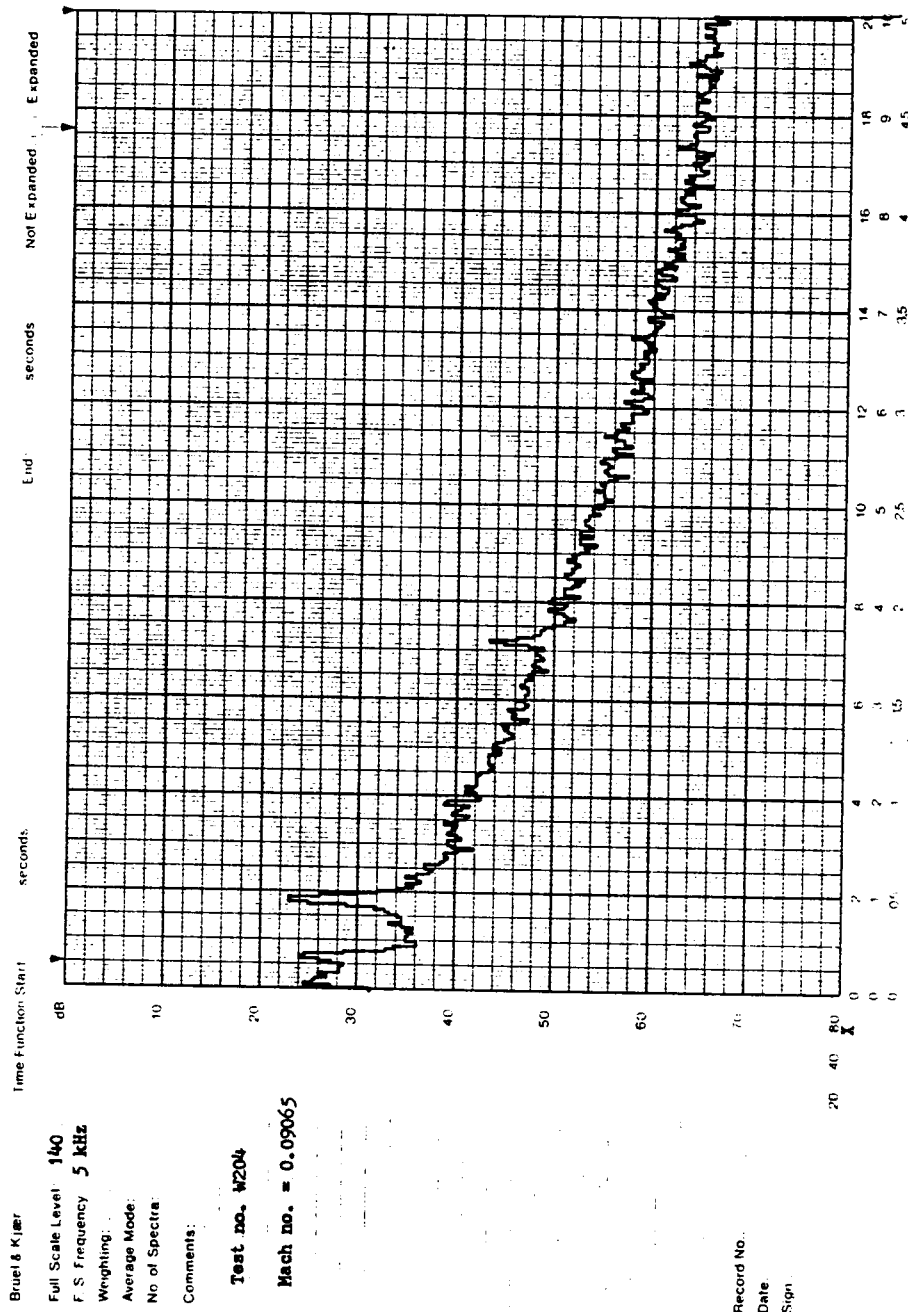
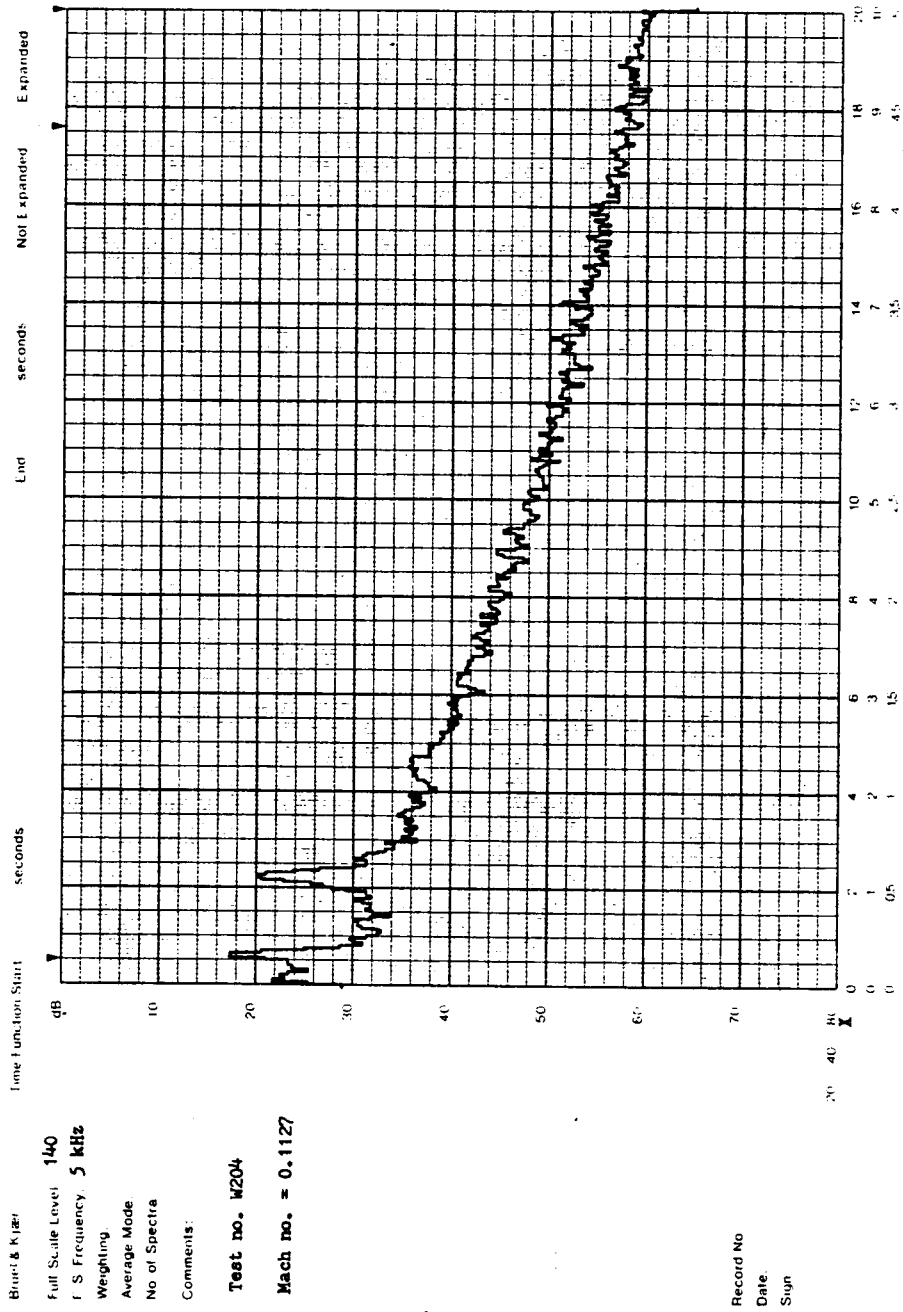


Figure A-1. Frequency Spectrum, Test W204.



b). Mach number 0.1127

Figure A-1. (Continued)

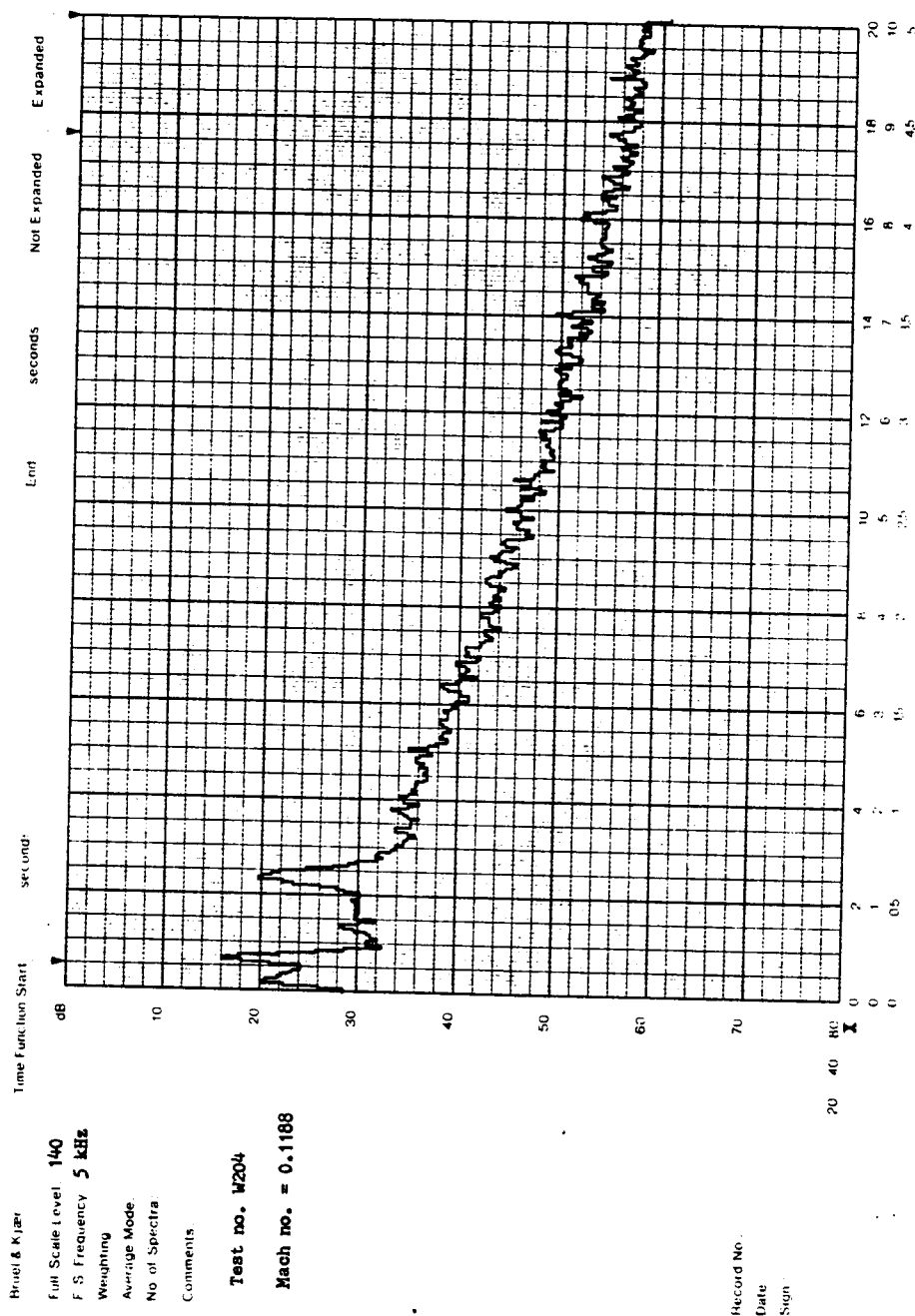
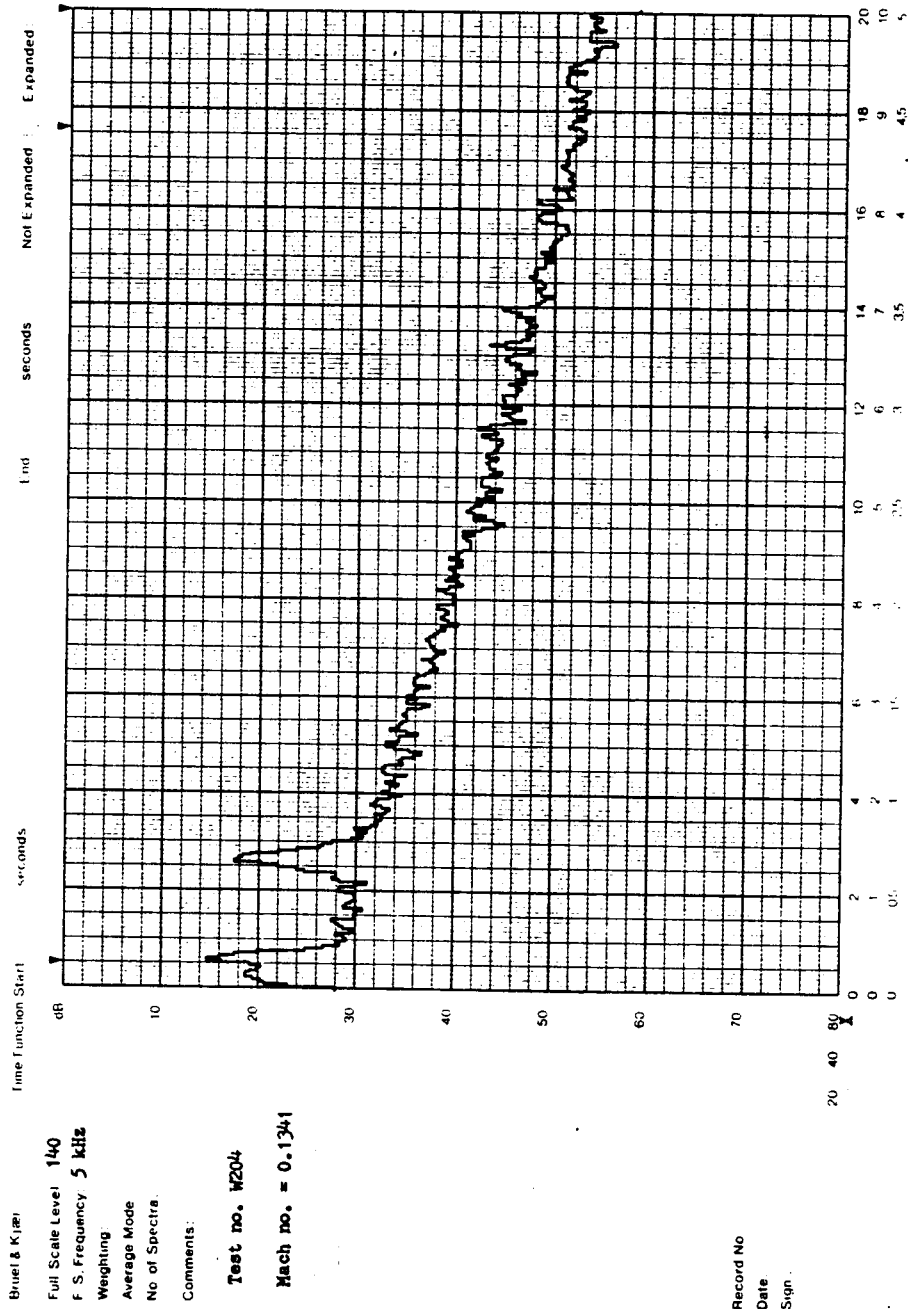
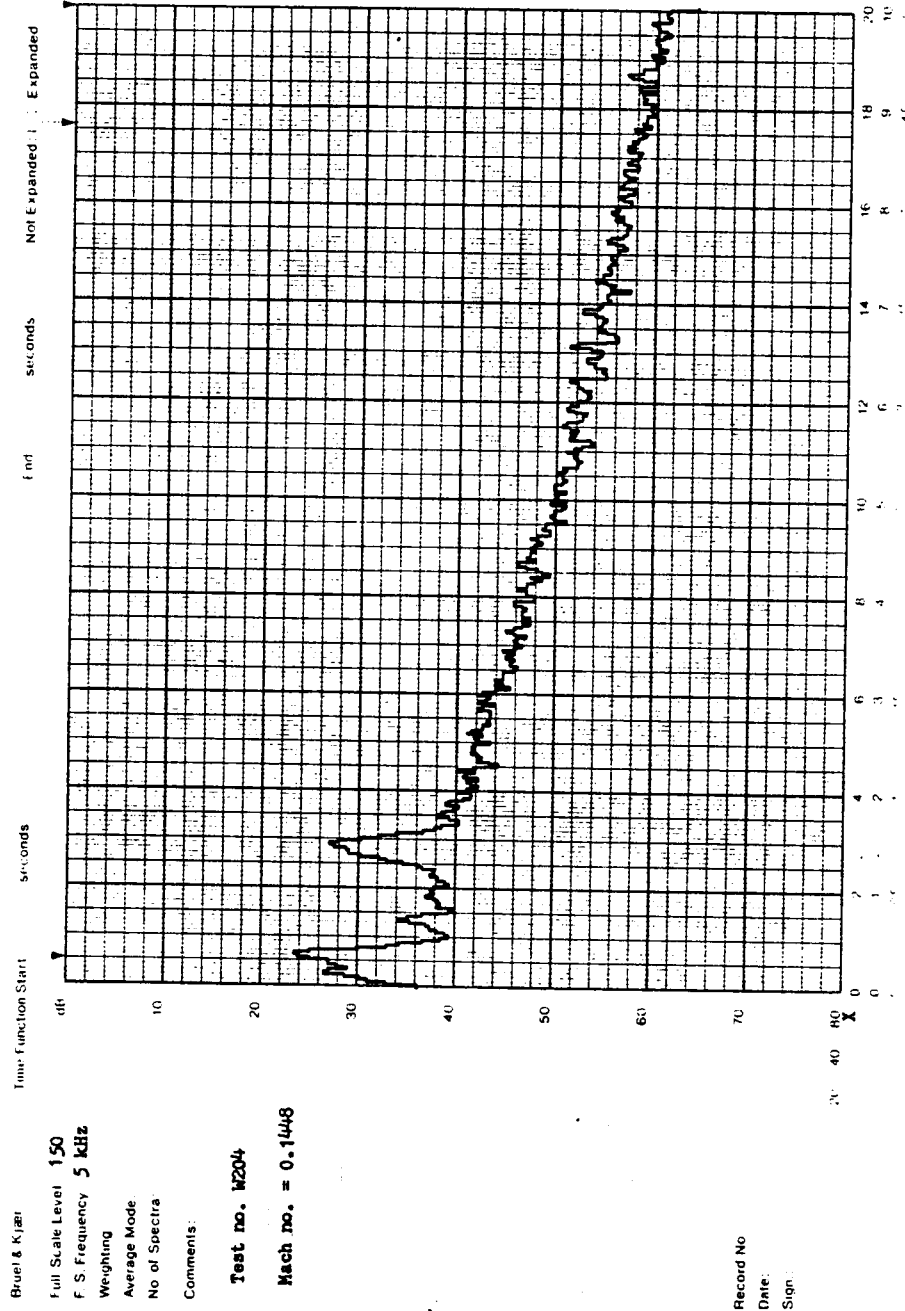


Figure A-1. (Continued)



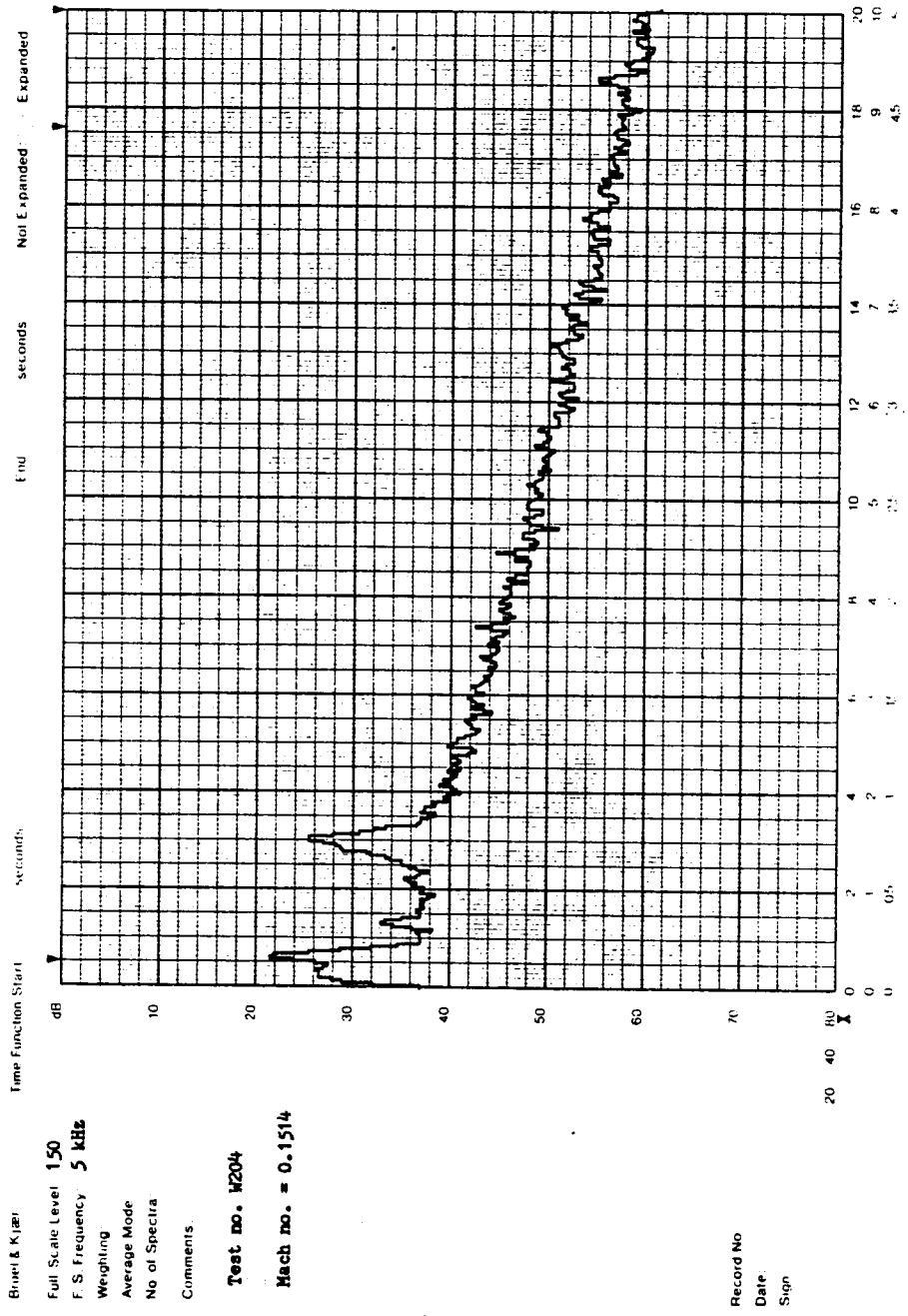
d) Mach number 0.1341

Figure A-1. (Continued)



e) Mach number 0.1448

Figure A-1. (Continued)



f) Mach number 0.1514

Figure A-1. (Continued)

Full Scale Level 150
F. S. Frequency 5 kHz

Weighting.

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No of Spectra:

• **Planned:** 300

Comments:

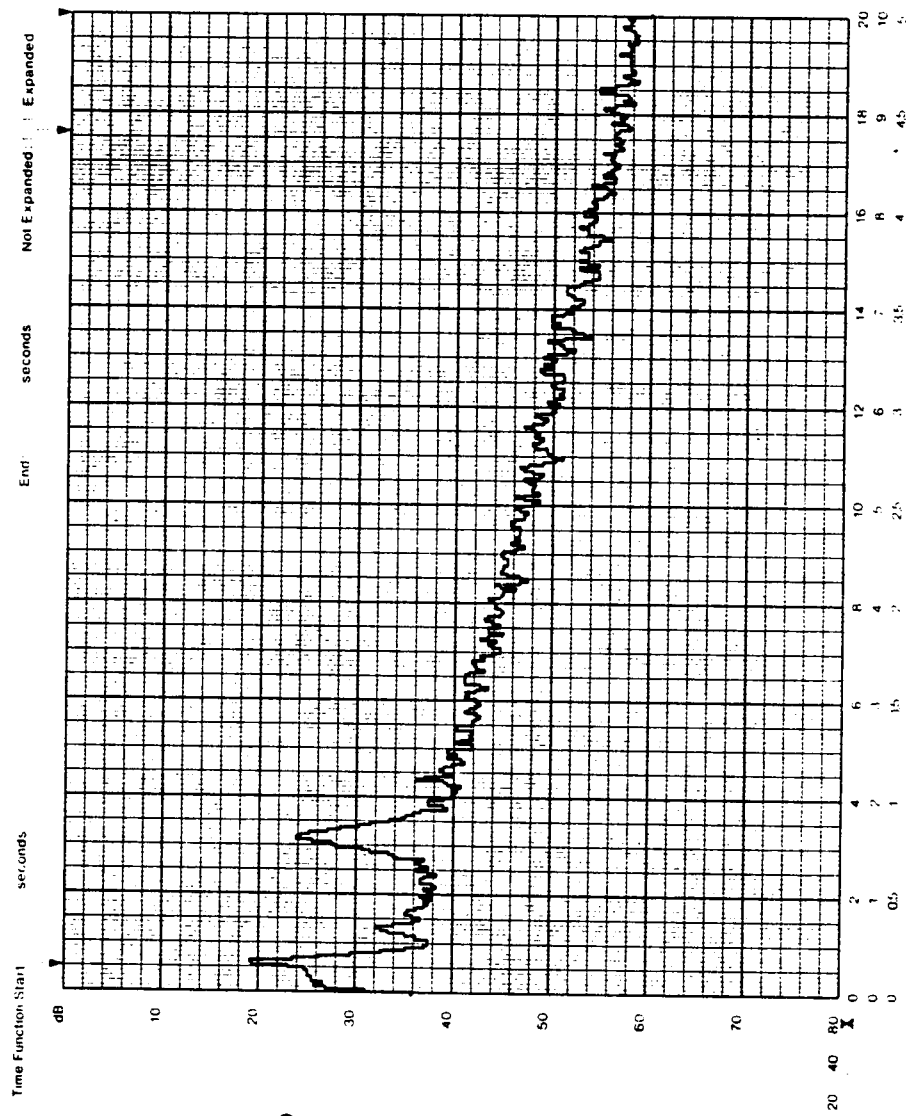
Test no. W204

Mach no. = 0.1610

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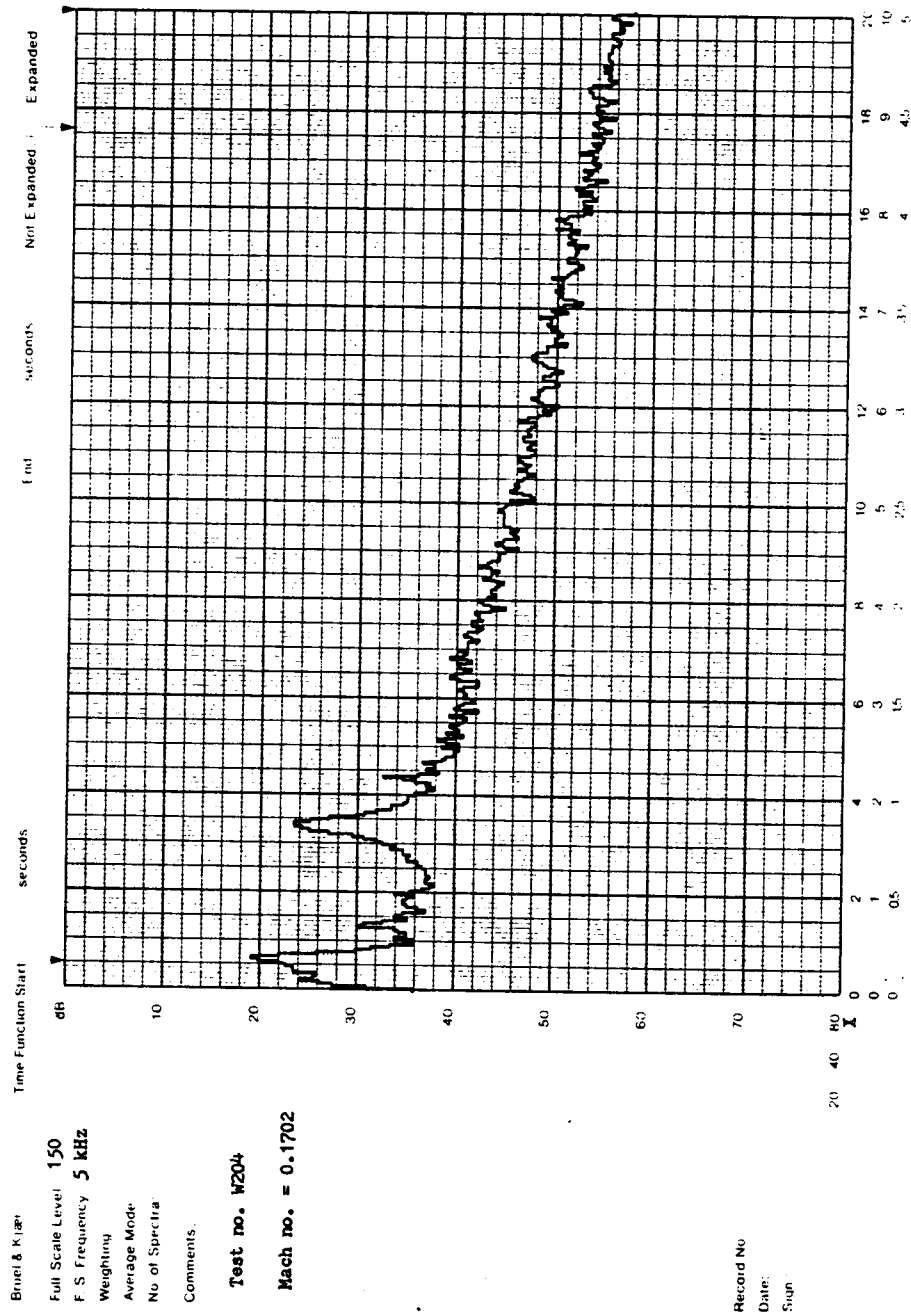
Date:

Sign...



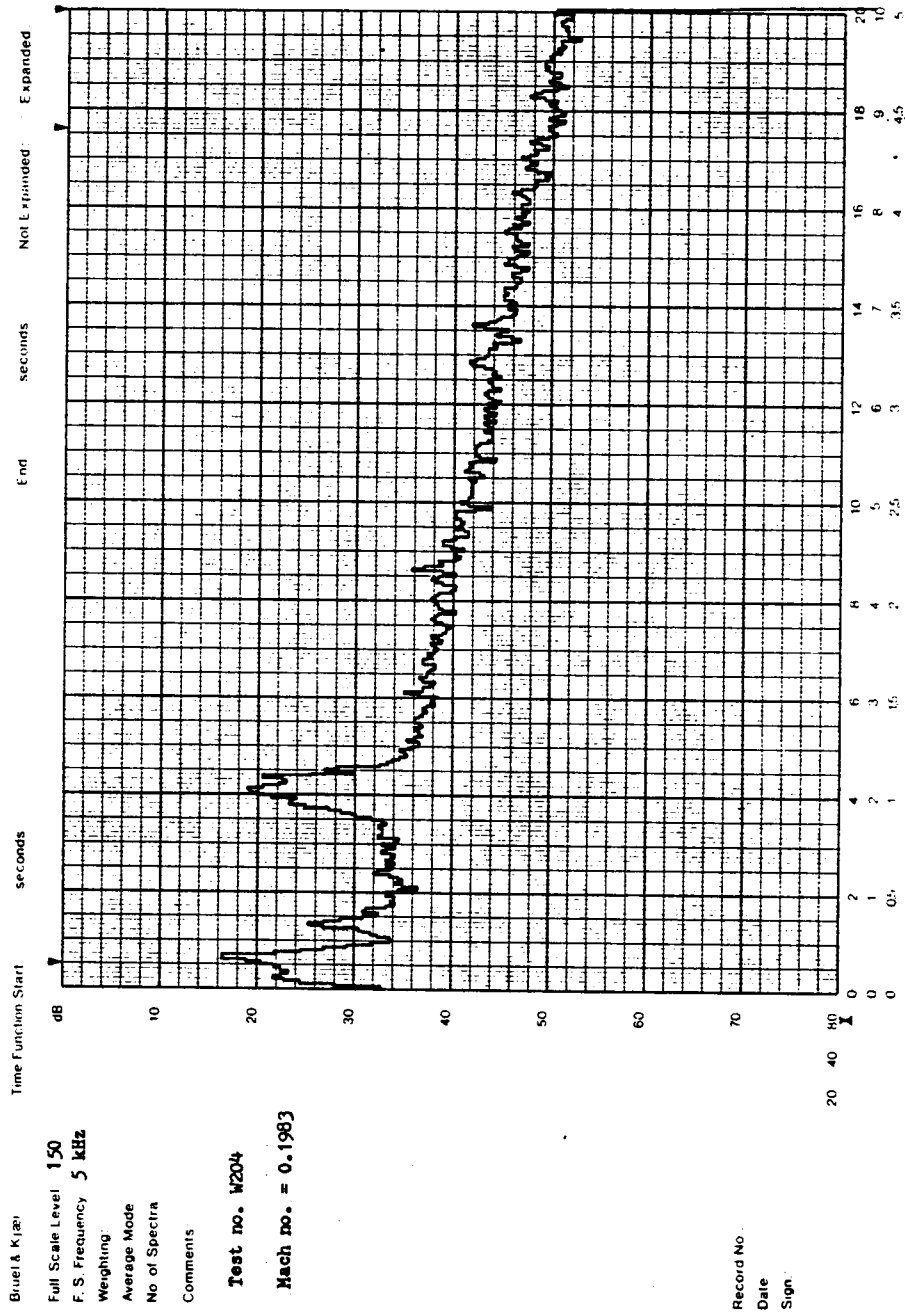
g) Mach number 0.1610

Figure A-1. (Continued)



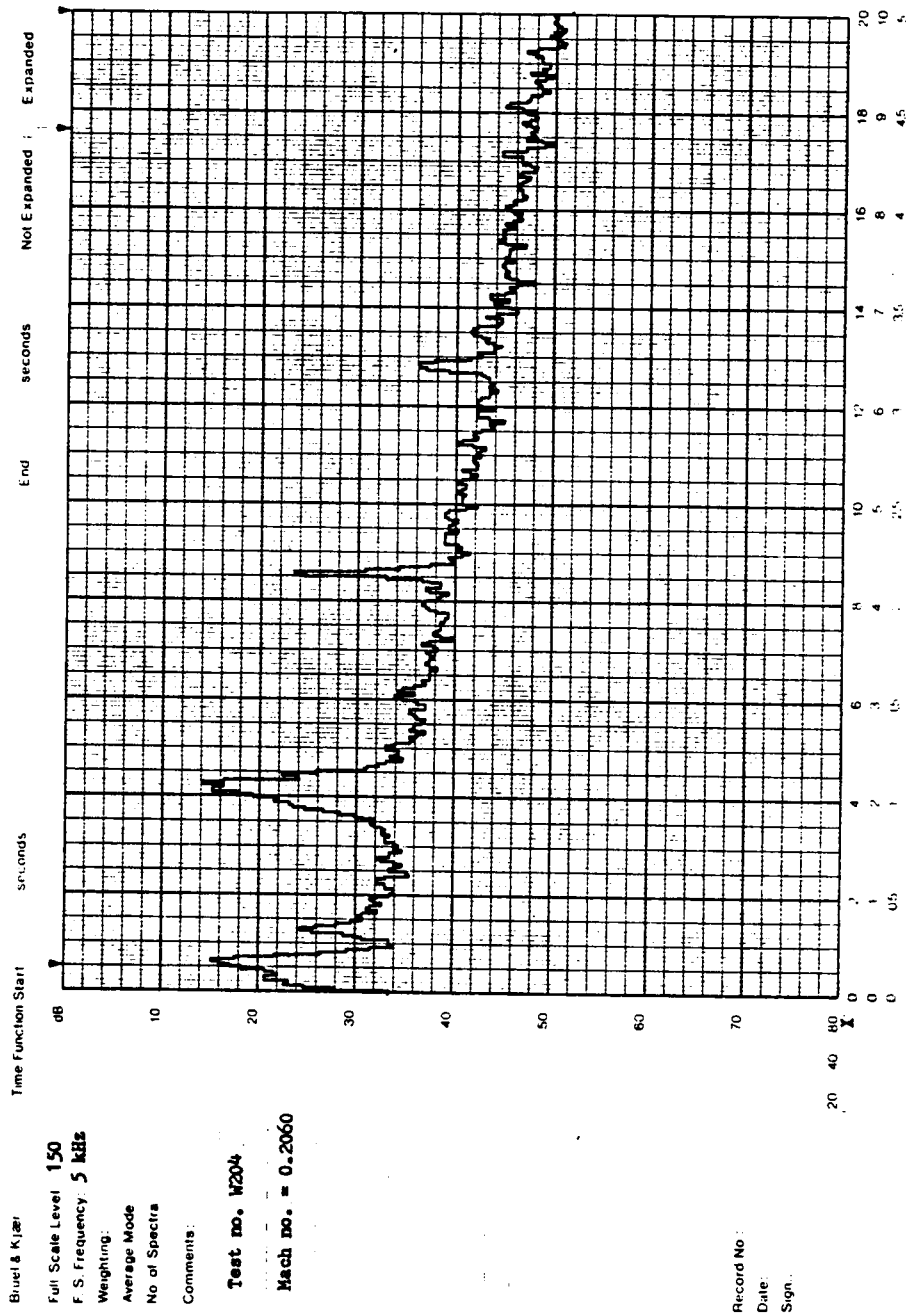
h) Mach number 0.1702

Figure A-1. (Continued)



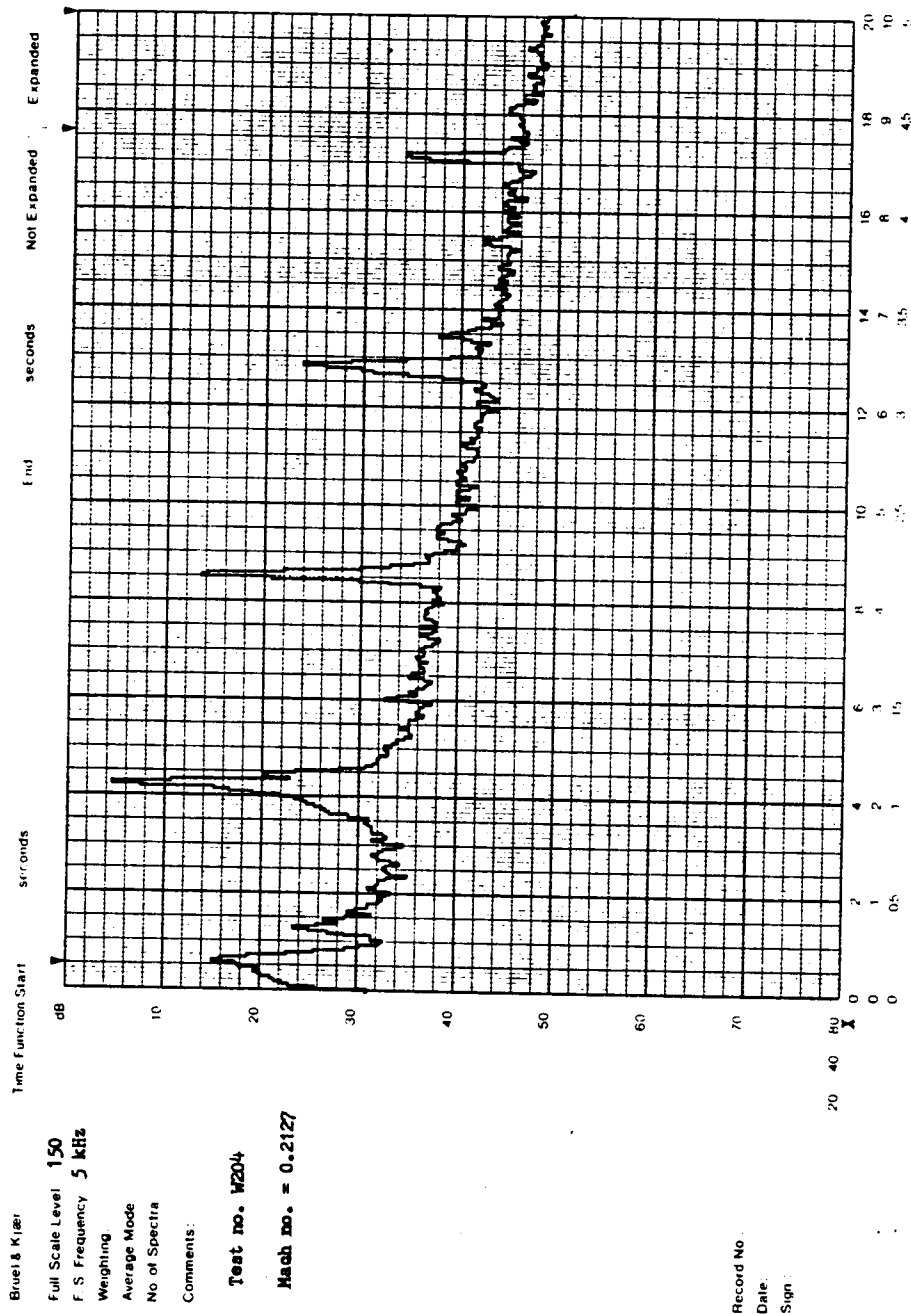
j) Mach number 0.1983

Figure A-1. (Continued)



k) Mach number 0.2060

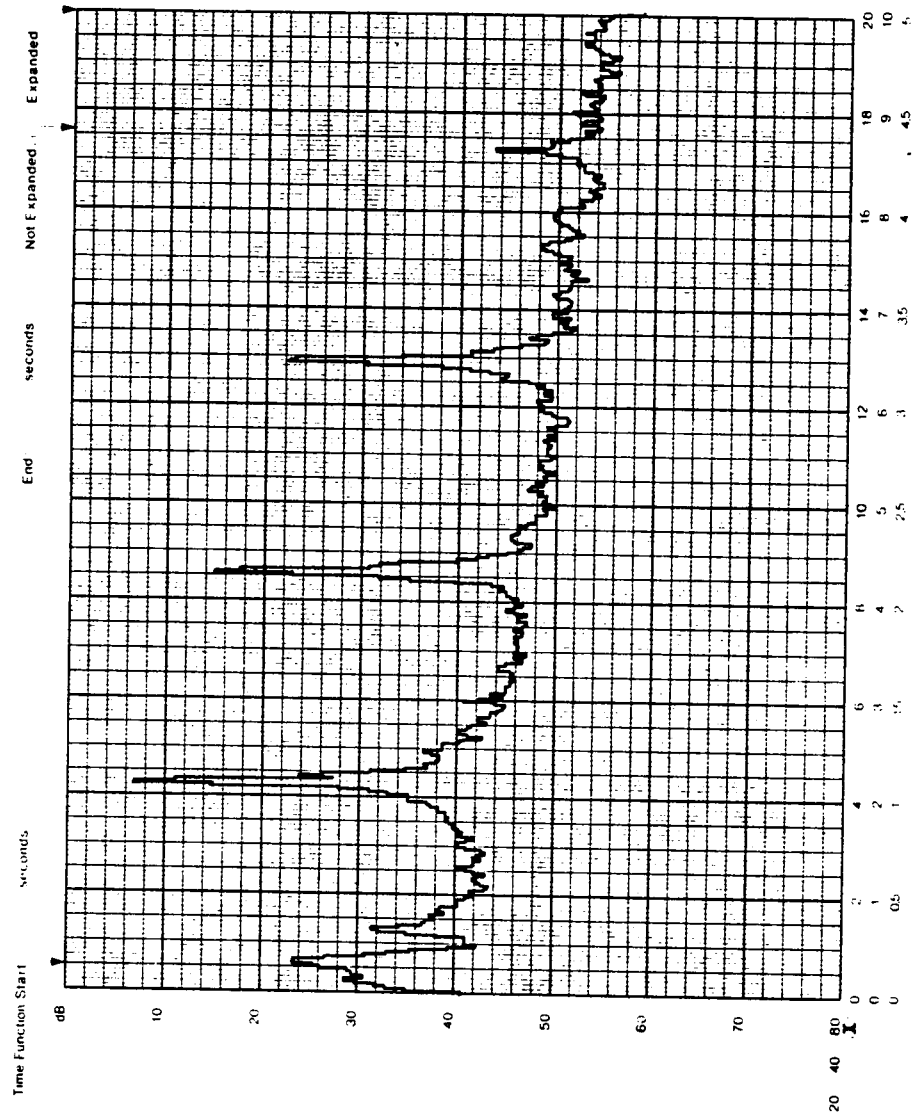
Figure A-1. (Continued)



1) Mach number 0.2127

Figure A-1. (Continued)

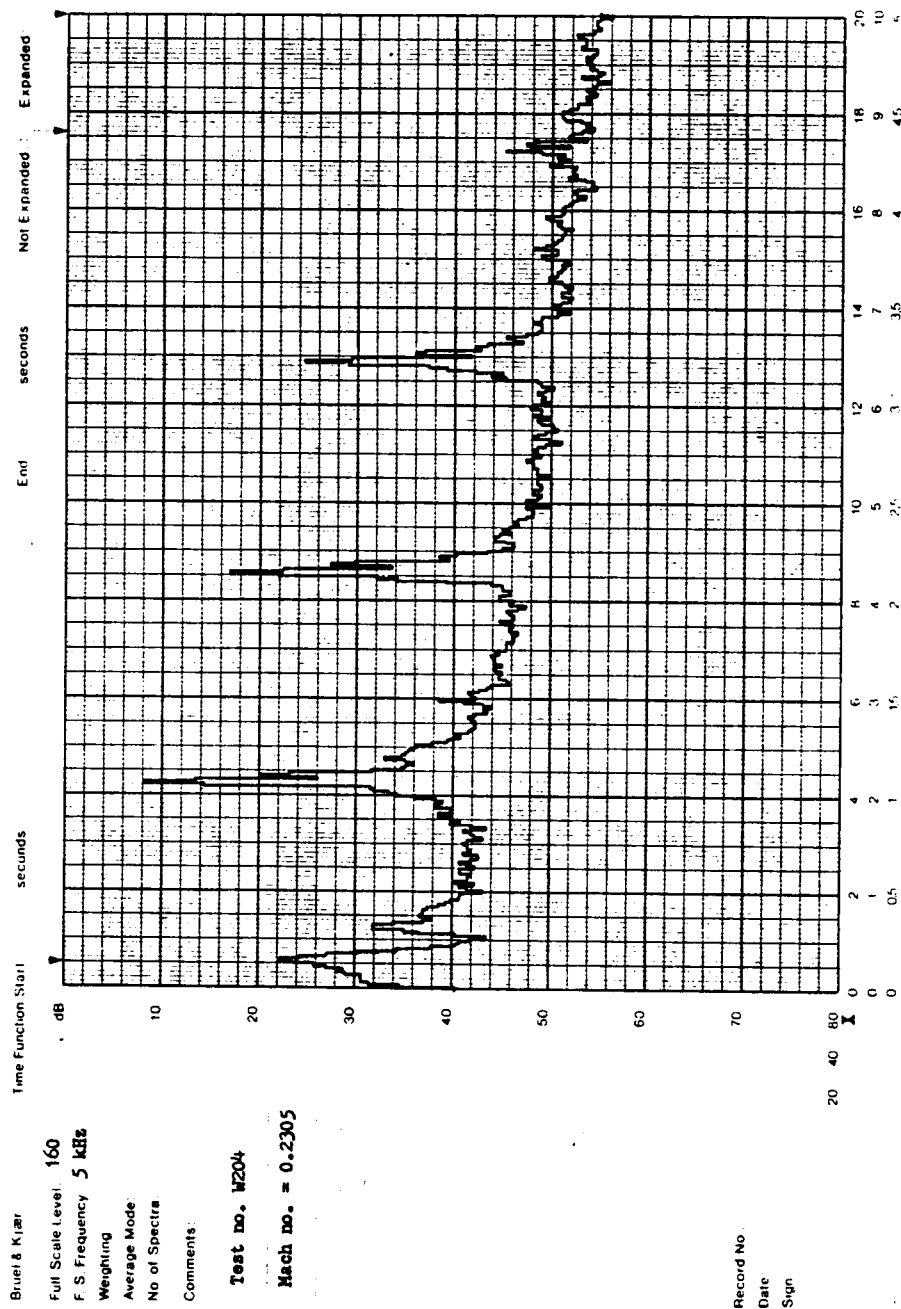
Bruel & Kjaer
 Full Scale Level. 160
 F. S. Frequency 5 kHz
 Weighting
 Average Mode
 No of Spectra
 Comments.
 Test no. W204
 Mach no. = 0.2267



Record No.
 Date
 Sign

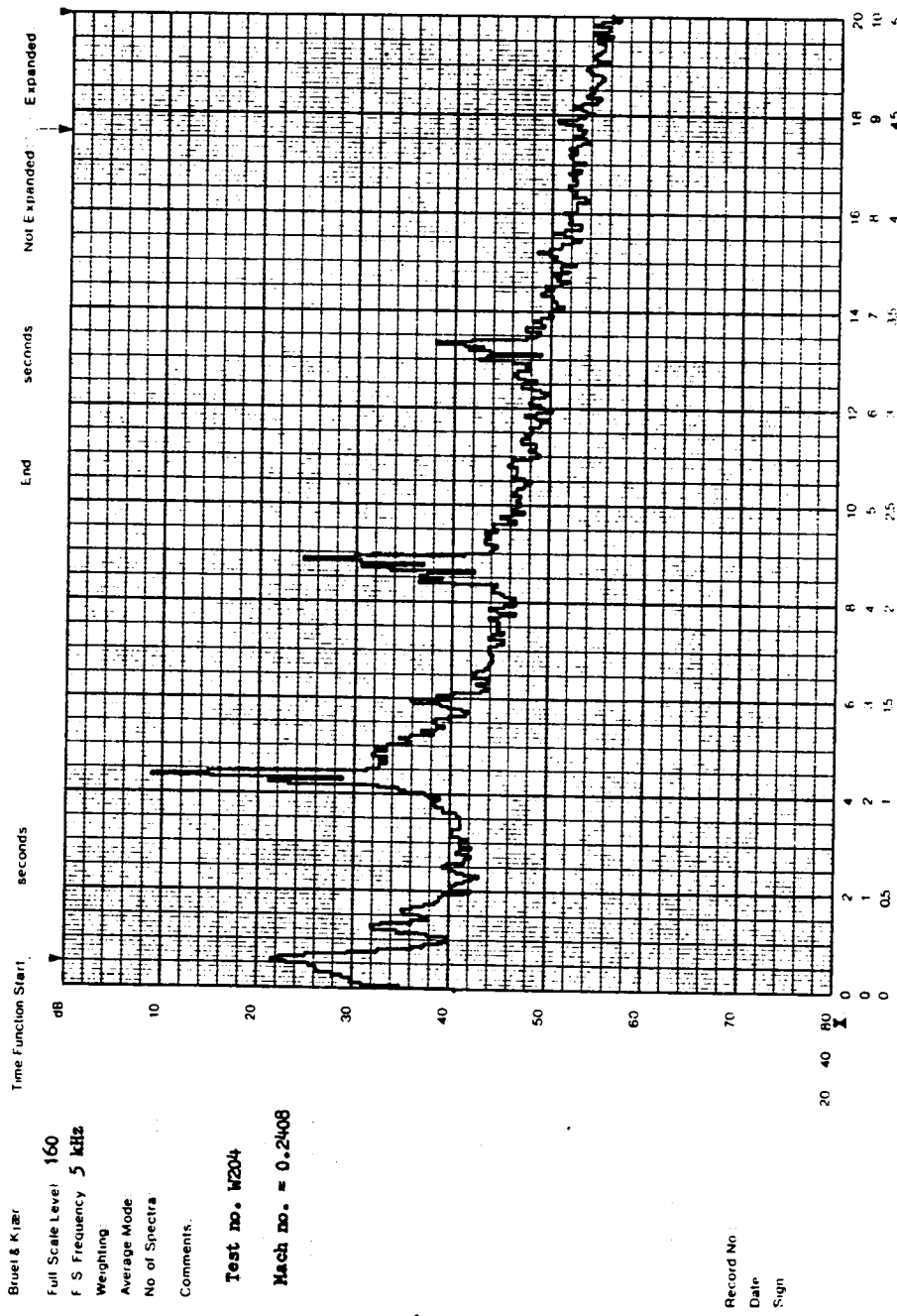
m) Mach number 0.2267

Figure A-1. (Continued)



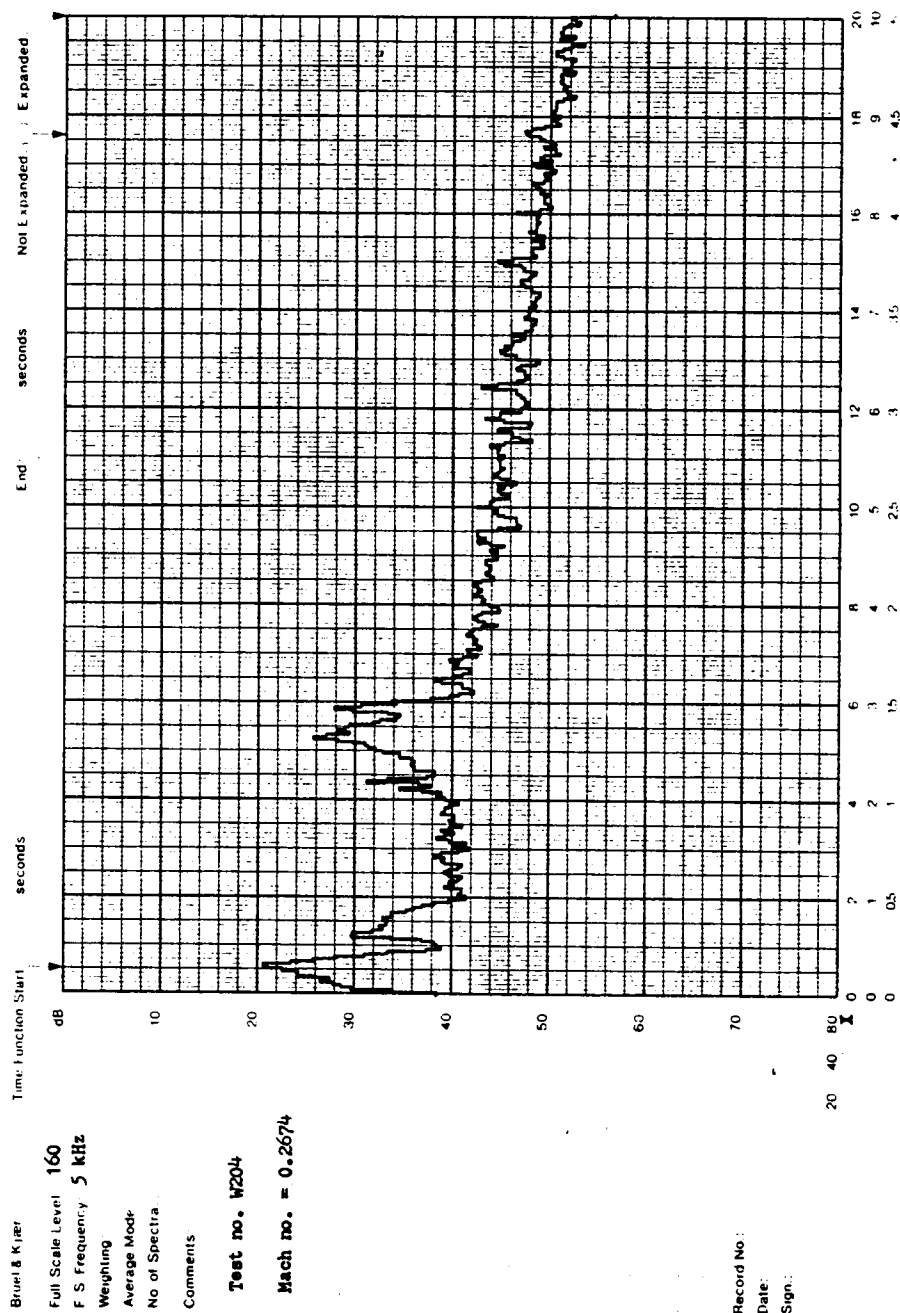
n) Mach number 0.2305

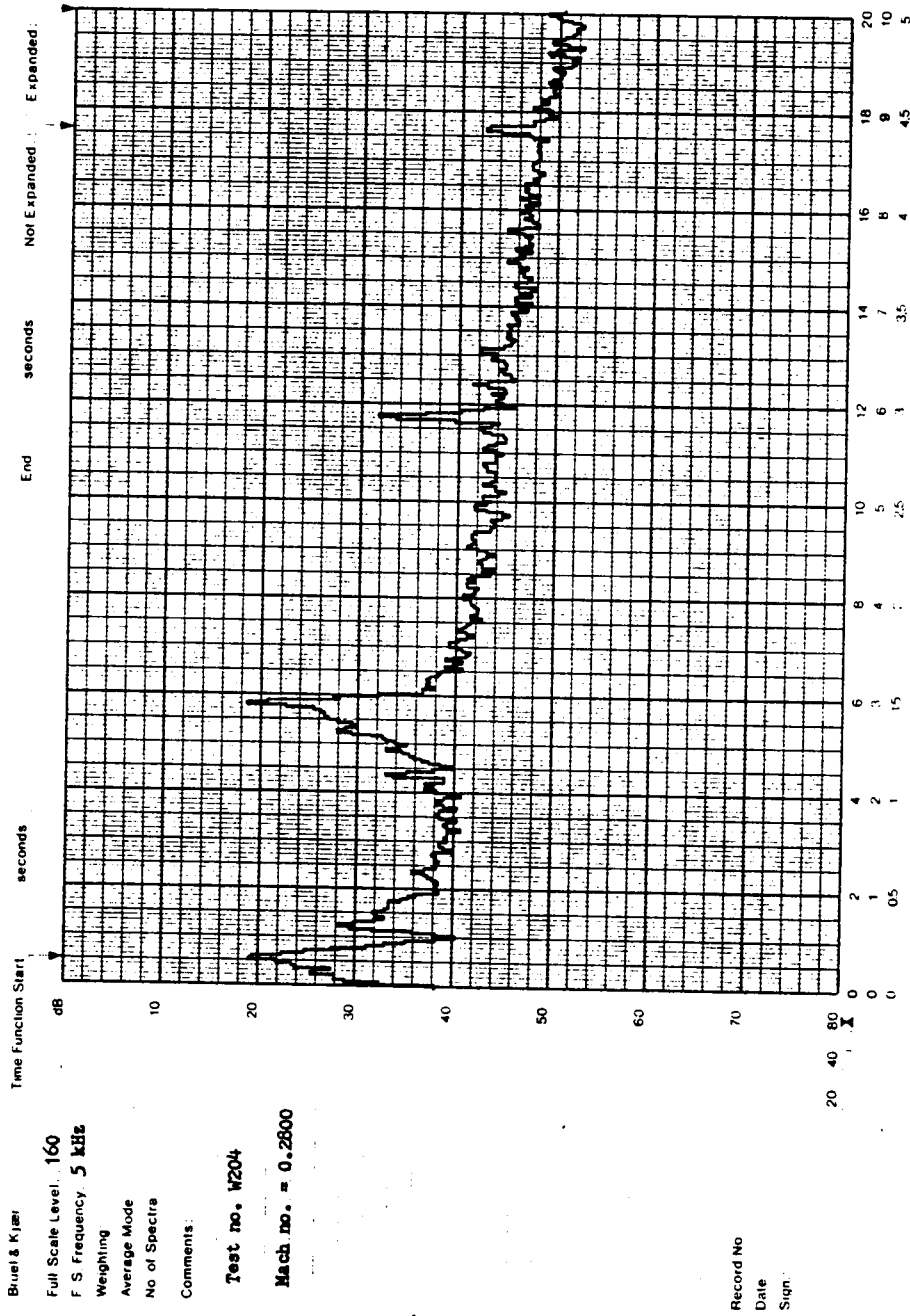
Figure A-1. (Continued)



o) Mach number 0.2408

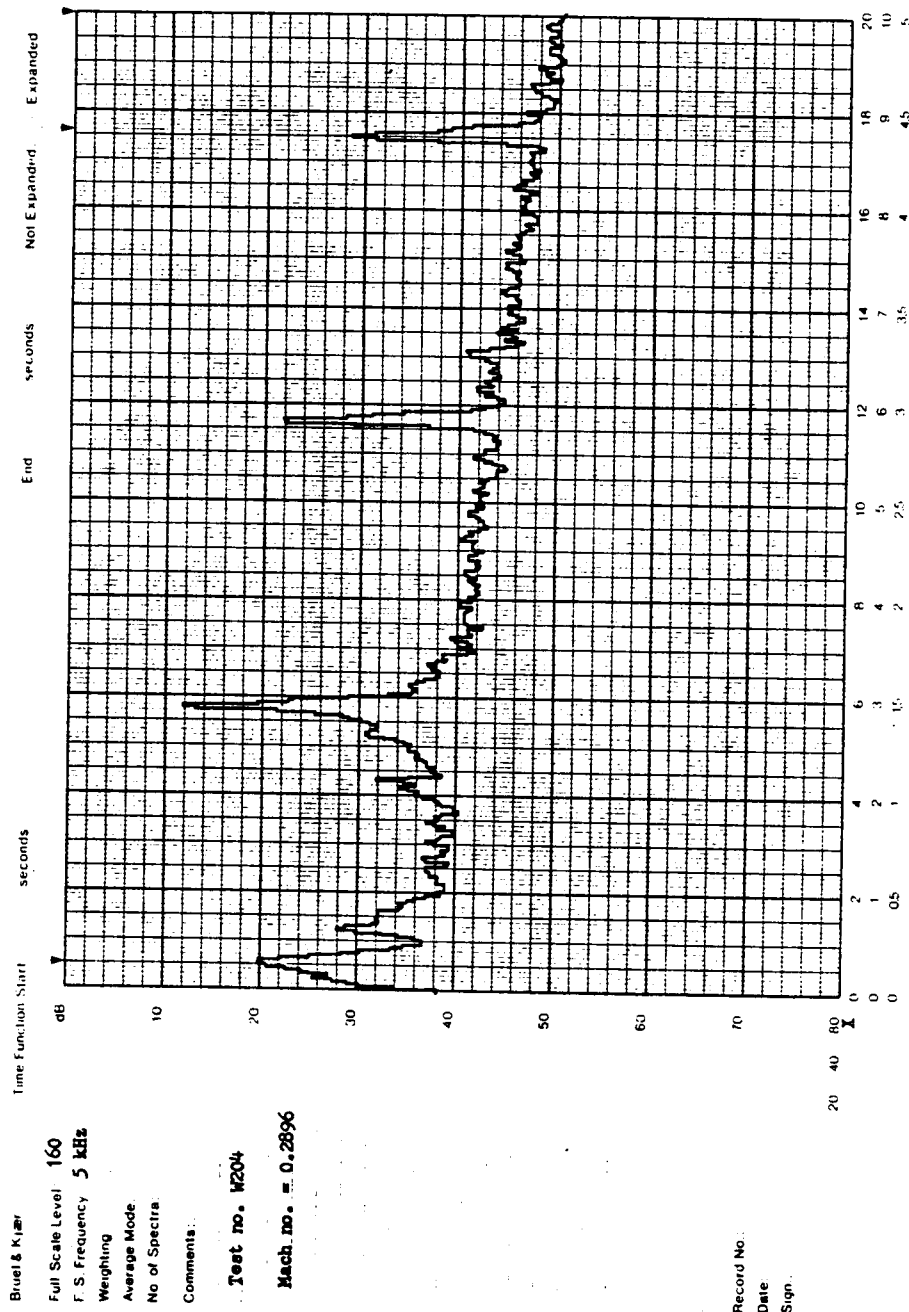
Figure A-1. (Continued)





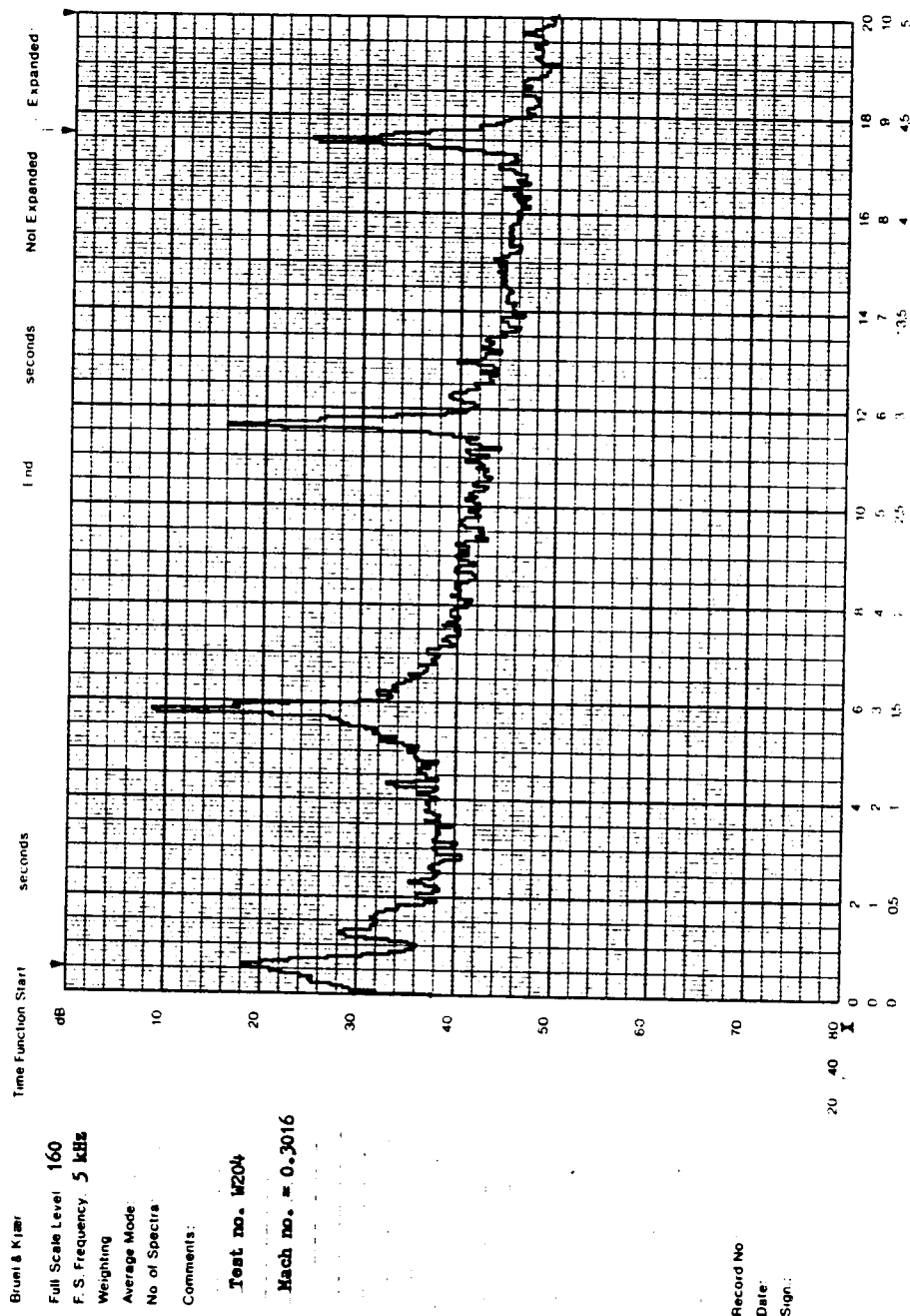
q) Mach number 0.2800

Figure A-1. (Continued)



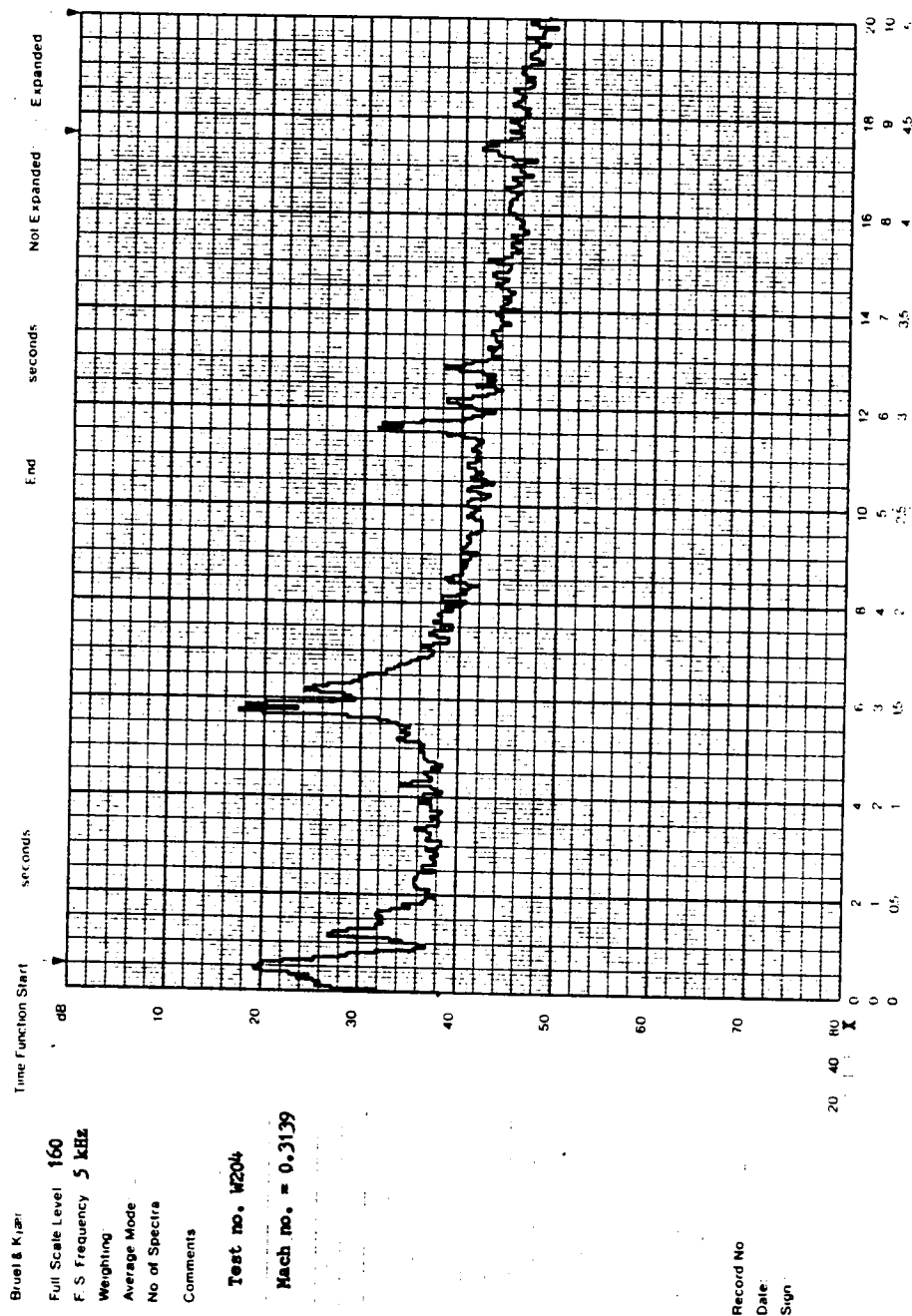
r) Mach number 0.2896

Figure A-1. (Continued)



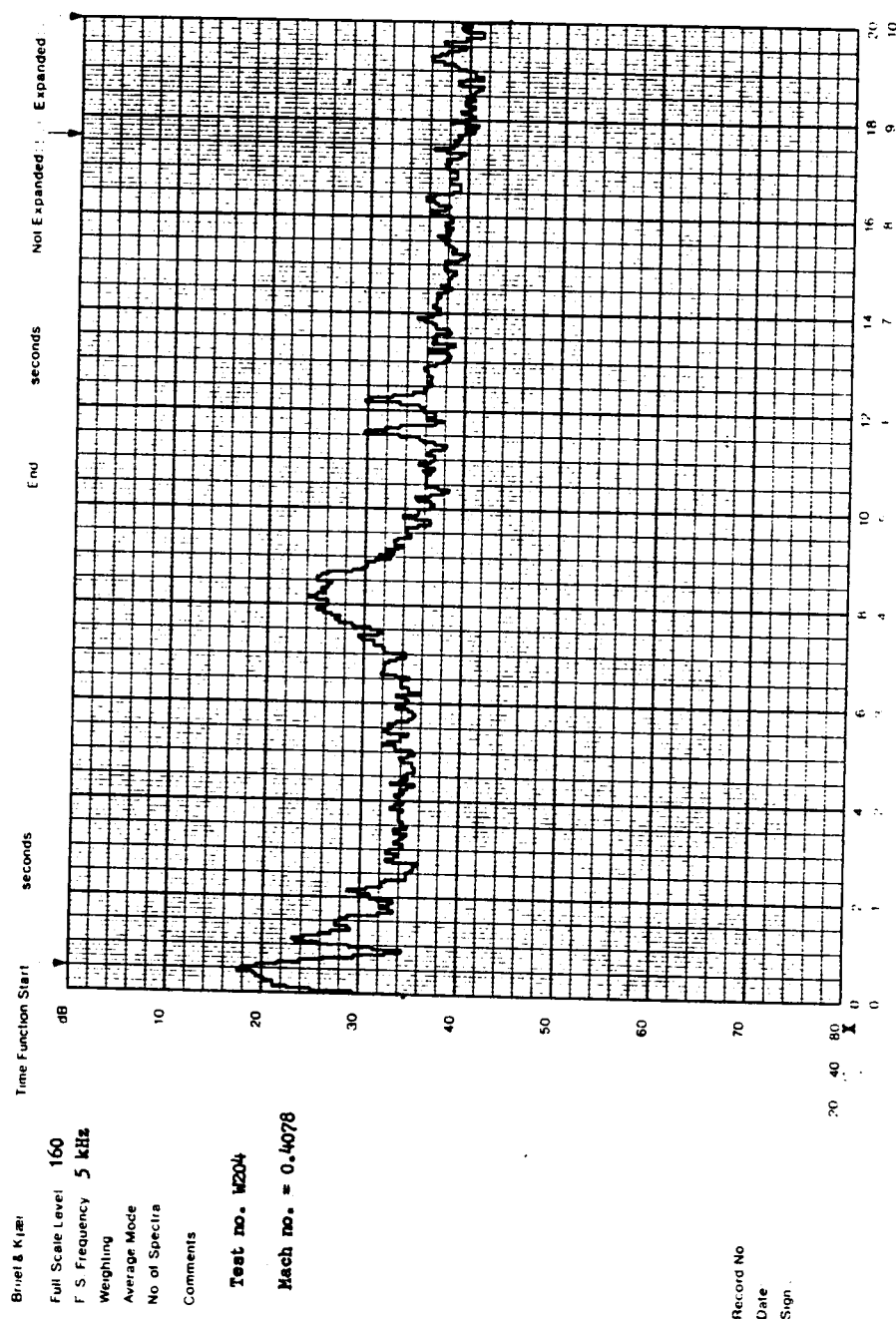
s) Mach number 0.3016

Figure A-1. (Continued)



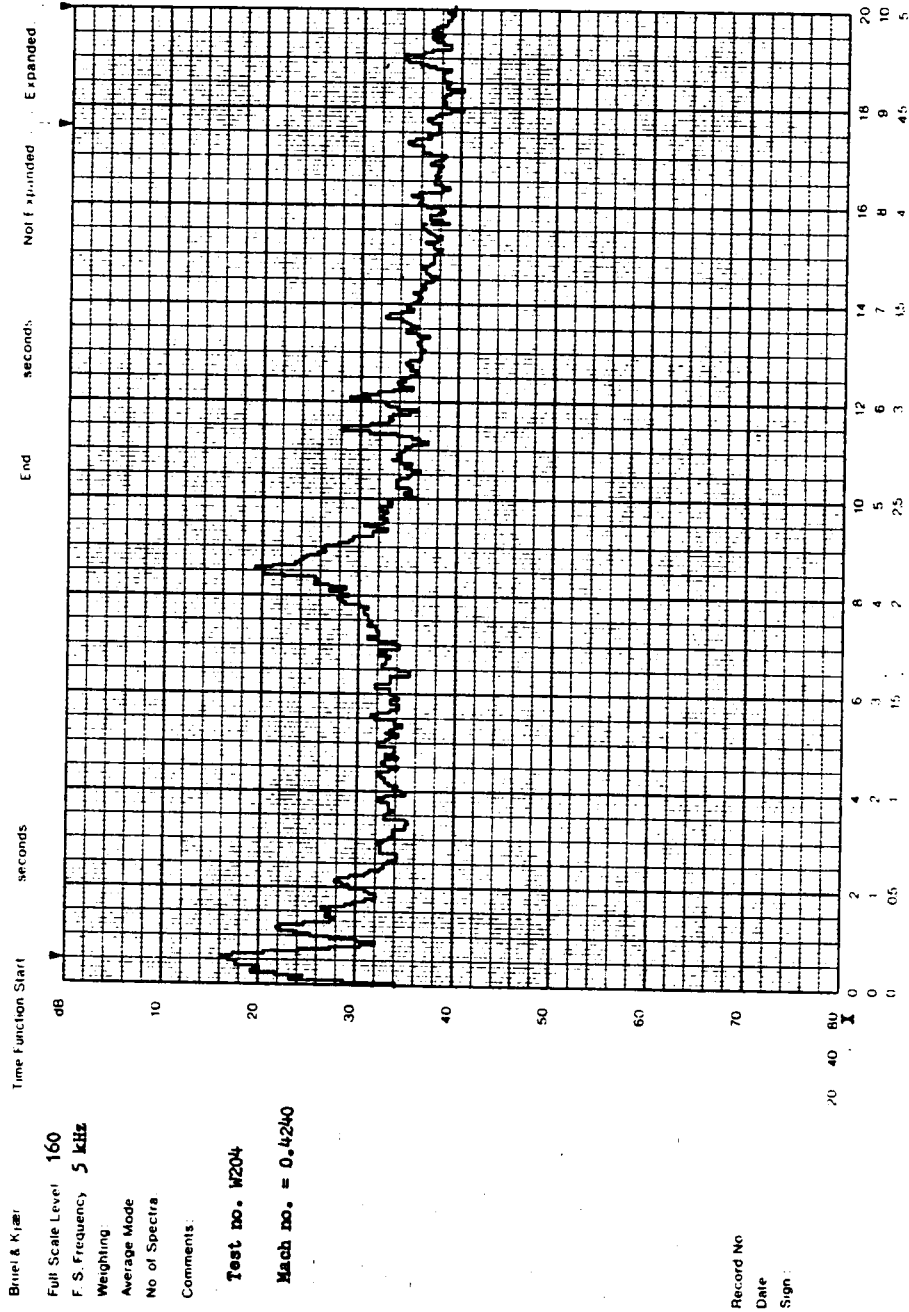
t) Mach number 0.3139

Figure A-1. (Continued)



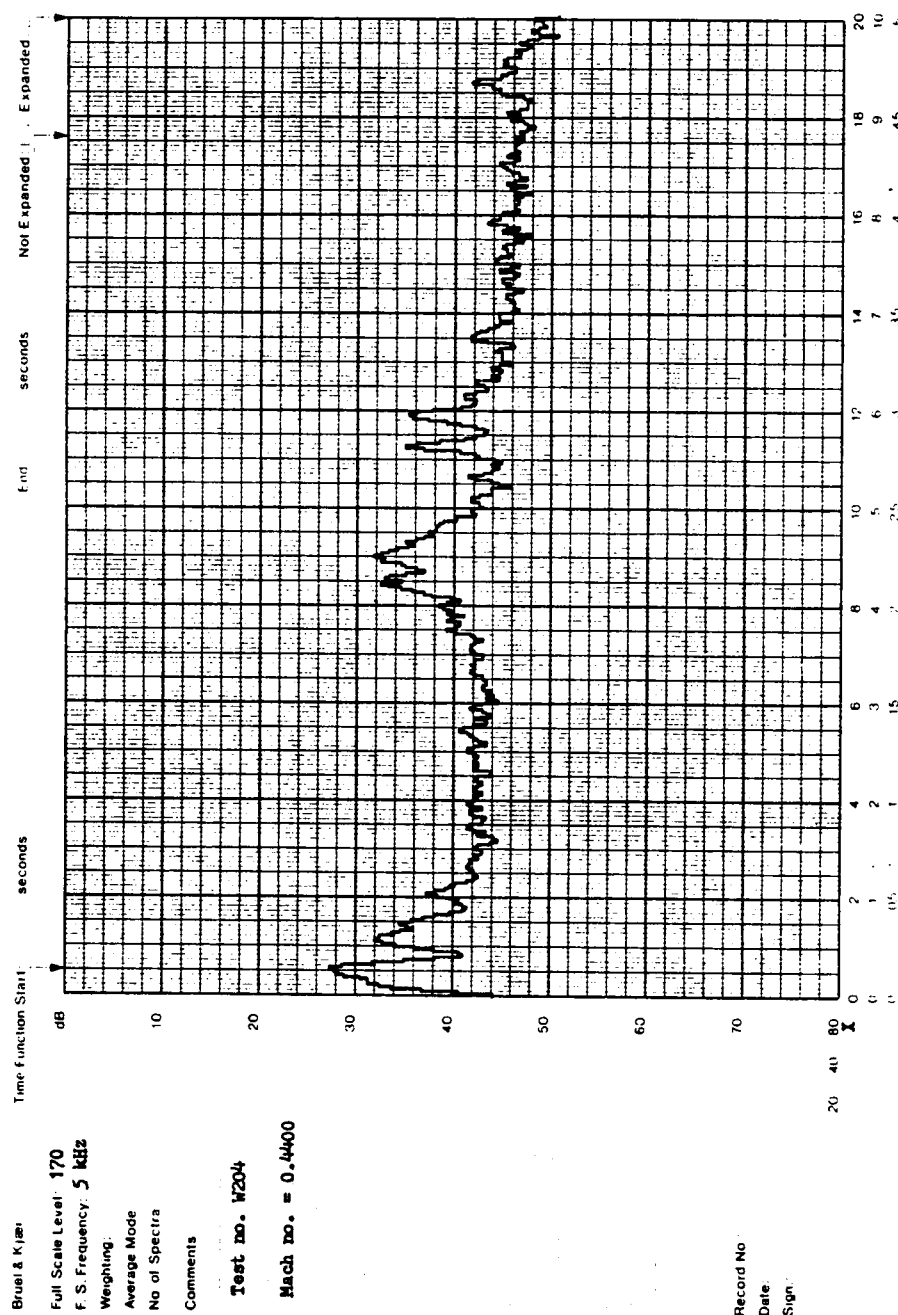
v) Mach number 0.4078

Figure A-1. (Continued)



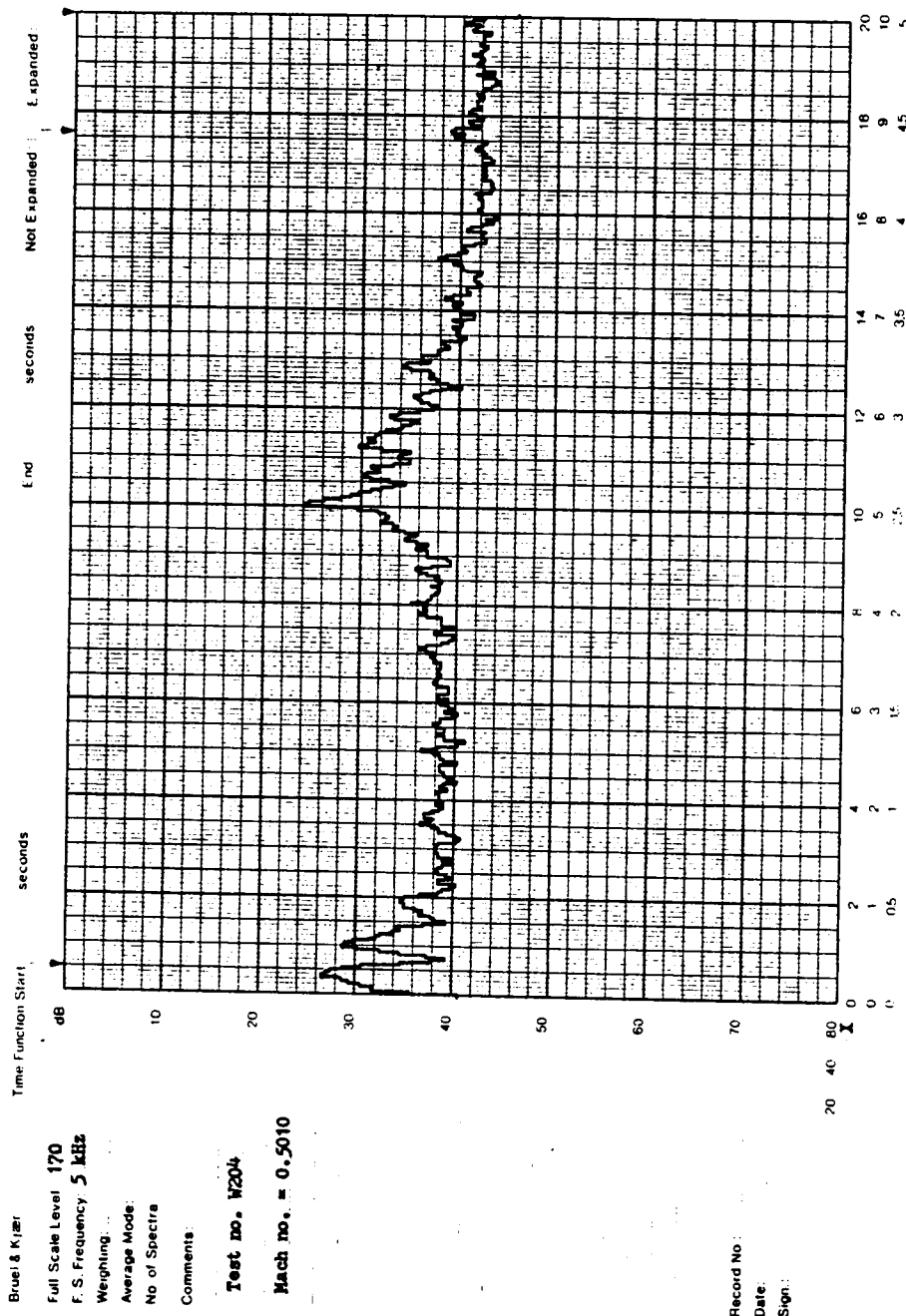
w) Mach number 0.4240

Figure A-1. (Continued)



x) Mach number 0.4400

Figure A-1. (Continued)



z) Mach number 0.5010

Figure A-1. (Continued)

Table A-1. Wind Tunnel Operating Parameters

TEST NO. 1 V284					
Atmospheric pressure (in. Hg.) = 29.38					
Cylinder diameter (in.) = .888					
M nom.	M	Ac. Vel. fps	Velocity fps	Ps yct psfg	Pt yct psfg
.000	.000	1123.	.000	.000	.000
.100	.0065E-01	1126.	182.1	2.233	14.21
.120	.1127	1128.	156.2	3.238	21.77
.130	.1188	1128.	132.7	3.273	23.89
.150	.1341	1116.	149.2	4.655	38.95
.160	.1446	1112.	168.5	5.144	35.84
.170	.1514	1108.	167.3	5.711	39.29
.180	.1618	1105.	177.4	6.848	44.86
.190	.1702	1102.	187.2	7.363	49.91
.200	.1798	1097.	196.3	8.725	55.83
.220	.1983	1094.	216.8	18.37	68.36
.230	.2068	1092.	224.9	11.38	73.96
.240	.2127	1089.	231.7	12.54	79.42
.255	.2267	1087.	246.5	16.72	98.52
.268	.2385	1085.	258.2	18.41	94.24
.278	.2488	1083.	268.8	18.15	102.3
.300	.2674	1080.	288.7	19.86	125.8
.315	.2800	1078.	301.8	21.18	138.6
.325	.2896	1076.	311.4	22.74	148.5
.330	.3016	1073.	323.6	24.37	161.2
.350	.3139	1070.	335.9	26.64	175.2
.400	.3535	1056.	376.4	34.23	224.6
.450	.4078	1056.	438.8	47.79	365.4
.480	.4248	1056.	445.4	52.74	322.9
.500	.4408	1047.	468.6	59.88	353.5
.540	.4728	1037.	489.3	76.85	438.5
.580	.5018	1032.	516.3	96.37	592.6

Table A-2. Cylinder Pressures

M nom.	M	P (1) psfg	P (2) psfg	P (3) psfg	P (1) psfg	P (2) psfg	P (3) psfg
.000	.000	.000	.000	.000	.000	.000	.000
.100	.905E-01	14.13	14.61	14.11	-14.19	-15.44	-15.28
.120	.1127	22.27	21.88	21.86	-21.65	-23.01	-22.89
.130	.1188	24.24	24.42	24.29	-24.09	-25.51	-24.95
.140	.1241	30.80	30.83	31.12	-30.84	-32.56	-31.76
.150	.1341	36.76	36.39	36.41	-35.23	-36.82	-36.45
.160	.1448	39.51	39.47	39.49	-37.74	-39.52	-39.51
.170	.1514	45.08	45.49	45.41	-43.65	-46.11	-44.86
.180	.1618	50.44	50.18	50.11	-48.59	-50.35	-49.38
.190	.1702	56.13	56.05	56.13	-54.88	-57.93	-55.78
.200	.1798	69.35	68.88	68.23	-60.74	-70.67	-67.56
.210	.1860	74.82	74.58	74.54	-76.16	-77.56	-73.89
.220	.1927	80.15	79.56	80.19	-87.45	-88.62	-83.43
.230	.2000	91.45	91.22	91.56	-114.8	-108.5	-98.63
.240	.2067	95.38	94.43	94.77	-102.8	-102.5	-97.62
.250	.2127	102.7	102.6	102.9	-103.7	-109.8	-107.8
.260	.2188	107.6	127.8	127.2	-118.4	-128.2	-117.4
.270	.2274	127.5	139.8	140.8	-128.5	-132.9	-123.6
.280	.2396	140.5	149.6	149.7	-137.4	-144.6	-129.1
.290	.2516	151.6	162.1	162.3	-144.8	-156.7	-156.5
.300	.2616	162.6	175.4	175.7	-156.7	-164.4	-158.1
.310	.2708	176.8	228.2	228.5	-193.2	-199.8	-193.4
.320	.2896	229.9	307.6	308.2	-252.2	-257.1	-249.5
.330	.3139	308.8	387.6	386.8	-278.6	-283.6	-275.8
.340	.3355	327.6	358.9	359.3	-314.9	-316.9	-305.1
.350	.3535	364.1	438.3	439.8	-376.7	-394.8	-382.4
.360	.3720	431.8	501.2	504.4	-469.3	-494.8	-478.6
.370	.3918	490.2	582.5				

Table A-4. Test Section Total Temperatures

M nom.	M	Tt yct (1) deg. F	Tt yct (2) deg. F	Tt yct (3) deg. F	Tt yct (4) deg. F	Tt yct (5) deg. F	T sec (6) deg. F
.1000	.0000	63.22	63.33	63.34	63.38	63.38	63.18
.1200	.0000	67.77	67.66	67.54	67.42	67.32	67.06
.1300	.0055E-01	62.68	62.57	62.38	62.36	62.19	62.14
.1500	.1127	59.91	59.82	59.62	59.42	59.31	59.19
.1600	.1341	56.76	56.51	56.56	56.57	56.49	56.27
.1700	.1448	53.47	53.43	53.33	53.27	53.26	53.19
.1800	.1514	51.82	51.17	51.82	51.82	51.81	51.83
.1900	.1618	48.77	48.77	48.66	48.57	48.39	48.21
.2000	.1702	46.76	46.98	46.99	46.93	46.61	46.49
.2200	.1798	44.82	44.82	44.58	44.61	44.61	44.58
.2300	.1983	42.23	42.41	42.21	42.23	42.13	42.24
.2400	.2068	40.54	41.83	41.84	40.88	40.92	40.83
.2550	.2127	38.99	39.88	38.96	39.83	38.88	38.98
.2600	.2267	37.61	37.41	37.36	37.32	37.28	37.42
.2700	.2385	36.17	36.28	36.28	35.98	35.99	35.35
.2800	.2488	34.68	34.63	34.75	34.55	34.37	34.65
.3000	.2674	32.82	32.59	32.61	32.63	32.61	32.55
.3150	.2896	31.36	31.42	31.21	31.46	31.15	31.23
.3250	.2896	30.87	30.83	29.85	29.92	29.88	29.78
.3380	.3016	28.54	28.28	28.38	28.38	28.48	28.28
.3500	.3139	26.65	26.47	26.51	26.54	26.26	26.37
.4000	.3535	24.88	24.11	23.83	24.13	23.92	23.91
.4600	.4878	19.95	19.84	20.87	20.85	20.37	19.98
.4800	.4248	15.81	15.62	15.56	15.53	15.91	16.12
.5000	.4400	14.35	14.14	13.99	13.85	13.39	13.42
.5400	.4728	7.517	7.539	7.537	7.469	7.457	7.431
.5800	.5010	5.867	5.285	5.223	5.191	5.883	4.954

Table A-5. Settling Tank Total Temperatures

M nom.	M	T _{sc} (1) deg. F	T _{sc} (2) deg. F	T _{sc} (3) deg. F	T _{sc} (4) deg. F	T _{sc} (5) deg. F	T _{sc} (6) deg. F
.0000	.0000	68.24	68.40	68.57	68.60	68.38	68.52
.1000	.0065E-01	70.24	69.83	69.50	69.50	69.37	69.71
.1200	.1127	64.84	65.20	64.90	64.39	64.20	64.16
.1300	.1188	61.98	61.66	61.59	61.53	61.37	61.23
.1500	.1341	58.35	58.40	58.26	57.95	57.63	57.44
.1600	.1448	54.73	54.37	53.99	53.85	53.76	53.69
.1700	.1514	51.85	51.85	51.34	51.23	51.62	51.23
.1800	.1610	49.29	49.23	49.13	49.00	48.64	48.58
.1900	.1702	47.05	47.05	46.78	46.46	46.57	46.78
.2000	.1798	44.58	44.68	44.92	44.52	44.33	44.78
.2200	.1983	42.10	42.25	42.25	42.22	42.09	41.98
.2300	.2060	40.64	41.03	40.56	40.42	40.66	40.88
.2400	.2127	38.49	38.66	38.40	38.56	38.33	38.39
.2550	.2267	37.35	36.92	37.15	37.12	36.74	37.15
.2600	.2305	35.70	35.74	35.91	35.45	35.63	35.88
.2700	.2400	34.41	34.04	34.11	34.07	33.97	34.25
.3000	.2674	32.79	32.30	32.68	32.22	32.57	32.08
.3150	.2800	31.03	31.44	30.96	31.24	31.09	30.95
.3250	.2895	29.67	30.06	29.53	29.77	29.77	29.37
.3300	.3016	28.53	27.95	28.41	27.86	28.26	27.95
.3500	.3139	26.56	26.43	26.63	26.51	26.10	26.62
.4000	.3535	24.20	24.34	23.86	24.22	23.69	24.13
.4000	.4078	20.55	20.32	20.28	19.98	20.24	20.37
.4000	.4240	16.07	16.27	15.32	16.28	16.30	16.27
.5000	.4400	14.03	14.47	13.87	13.89	14.04	14.05
.5400	.4720	7.45	7.717	7.320	7.694	7.25	7.679
.5000	.5010	5.751	5.470	5.696	5.429	5.569	5.362

Table A-6. Cylinder Total Temperatures

M nom.	M	Tt (1) deg. F	Tt (2) deg. F	Tt (3) deg. F	Tt (4) deg. F	Tt (5) deg. F	Tt (6) deg. F
.0000	.0000	65.09	65.30	65.31	65.09	65.30	65.31
.1000	.0005E-01	68.08	68.44	68.43	68.08	68.44	68.43
.2000	.1127	63.47	63.25	63.22	63.47	63.25	63.22
.3000	.1188	60.31	60.16	60.08	60.31	60.16	60.08
.4000	.1341	56.95	56.94	56.72	56.95	56.94	56.72
.5000	.1448	53.26	53.40	53.26	53.26	53.40	53.26
.6000	.1514	50.80	51.04	50.82	50.80	51.04	50.82
.7000	.1610	48.16	48.51	48.24	48.16	48.51	48.24
.8000	.1702	46.16	46.61	46.38	46.16	46.61	46.38
.9000	.1790	44.02	44.55	44.16	44.02	44.55	44.16
1.0000	.1883	41.35	42.02	41.57	41.35	42.02	41.57
1.2000	.2068	40.16	40.83	40.38	40.16	40.83	40.38
1.4000	.2127	38.00	38.61	38.34	38.00	38.61	38.34
1.6000	.2267	36.51	37.19	36.96	36.51	37.19	36.96
1.8000	.2305	35.30	35.94	35.53	35.30	35.94	35.53
2.0000	.2408	33.75	34.44	34.12	33.75	34.44	34.12
2.2000	.2674	31.94	32.58	32.18	31.94	32.58	32.18
2.4000	.2808	30.56	31.25	30.88	30.56	31.25	30.88
2.6000	.2896	29.20	29.88	29.43	29.20	29.88	29.43
2.8000	.3016	27.63	28.31	27.85	27.63	28.31	27.85
3.0000	.3139	25.75	26.55	26.13	25.76	26.55	26.13
3.2000	.3250	23.45	24.14	23.68	23.45	24.14	23.68
3.4000	.3355	19.67	20.34	19.91	19.67	20.34	19.91
3.6000	.4078	15.46	16.16	15.72	15.46	16.16	15.72
3.8000	.4240	13.59	14.08	13.59	13.59	14.08	13.59
4.0000	.4400	6.884	7.607	7.222	6.884	7.607	7.222
4.2000	.4720	4.978	5.552	4.976	4.978	5.552	4.976
4.4000	.5010						

Table A-7. Cylinder Static Temperatures

M nom.	M	Ts (1) deg. F	Ts (2) deg. F	Ts (3) deg. F	Ts (4) deg. F	Ts (5) deg. F	Ts (6) deg. F
0.000	0.000	65.09	65.30	65.31	65.09	65.30	65.31
.1000	.0065E-01	68.02	67.58	67.57	68.02	67.58	67.57
.1200	.1127	62.15	61.93	61.89	62.15	61.93	61.89
.1300	.1160	58.85	58.70	58.61	58.85	58.70	58.61
.1500	.1341	55.09	55.09	54.87	55.09	55.09	54.87
.1600	.1448	51.12	51.34	51.11	51.12	51.34	51.11
.1700	.1514	48.47	48.71	48.49	48.47	48.71	48.49
.1800	.1610	45.54	45.89	45.62	45.54	45.89	45.62
.1900	.1702	43.25	43.69	43.47	43.25	43.69	43.47
.2000	.1798	40.81	41.34	40.95	40.81	41.34	40.95
.2200	.1983	37.43	38.11	37.66	37.43	38.11	37.66
.2300	.2060	35.95	36.62	36.17	35.95	36.62	36.17
.2400	.2127	34.14	34.14	33.87	34.14	33.87	33.87
.2500	.2217	31.46	32.13	31.90	31.46	32.13	31.90
.2600	.2305	30.09	30.73	30.32	30.09	30.73	30.32
.2700	.2386	28.09	28.77	28.46	28.09	28.77	28.46
.3000	.2674	25.00	25.63	25.25	25.00	25.63	25.25
.3150	.2800	22.99	23.66	23.30	22.99	23.66	23.30
.3250	.2896	21.13	21.80	21.36	21.13	21.80	21.36
.3300	.3016	18.91	19.58	19.14	18.91	19.58	19.14
.3500	.3139	16.30	17.15	16.74	16.30	17.15	16.74
.4000	.3535	11.66	12.34	11.89	11.66	12.34	11.89
.4200	.4078	4.237	4.803	4.465	4.237	4.803	4.465
.4300	.4200	-1.840	-3.684	-3.884	-1.840	-3.684	-3.884
.4800	.4800	-4.868	-7.972	-7.972	-4.868	-7.972	-7.972
.5000	.4900	-13.03	-12.34	-12.71	-13.03	-12.34	-12.71
.5100	.4720	-17.25	-16.70	-17.25	-17.25	-16.70	-17.25
.5800	.5010						

Table A-8. Cylinder Temperatures

M nom.	M	T _B (1) deg. F	T _B (2) deg. F	T _B (3) deg. F	T _{10B} (1) deg. F	T _{10B} (2) deg. F	T _{10B} (3) deg. F
.0000	.0000	65.09	65.30	65.31	65.08	65.25	65.09
.1000	.0000	68.08	68.44	68.43	68.40	68.08	67.78
.1200	.0000	63.47	63.25	63.22	62.76	62.59	62.37
.1300	.0000	60.31	60.16	60.08	59.48	59.20	58.90
.1500	.0000	56.95	56.94	56.72	55.60	55.61	55.47
.1600	.0000	53.26	53.48	53.26	51.64	51.69	51.70
.1700	.0000	50.80	51.04	50.82	48.79	48.80	48.96
.1800	.0000	48.16	48.51	48.24	45.85	45.97	46.08
.1900	.0000	46.16	46.51	46.38	43.45	43.69	43.91
.2000	.0000	44.22	44.55	44.16	40.99	41.24	41.46
.2200	.0000	41.35	42.02	41.57	37.51	37.95	38.18
.2300	.0000	38.16	38.83	38.38	33.83	34.30	34.54
.2400	.0000	36.51	37.19	36.96	30.57	31.29	31.74
.2500	.0000	35.30	35.94	35.53	29.34	30.19	30.31
.2600	.0000	33.75	34.44	34.12	27.78	28.37	28.51
.2700	.0000	31.94	32.68	32.18	25.86	26.65	26.90
.2800	.0000	30.56	31.25	30.88	23.20	23.91	23.94
.3250	.2896	29.20	29.88	29.43	21.25	21.64	21.85
.3300	.3016	27.63	28.31	27.85	19.18	19.36	19.59
.3500	.3139	25.76	26.55	26.13	16.74	17.46	17.76
.3800	.3535	23.45	24.14	23.60	12.31	12.76	13.07
.4000	.4078	19.27	20.34	19.91	4.826	5.901	6.212
.4200	.4248	15.46	16.16	15.72	-1.5740	.5893E-01	.5331
.4400	.4400	13.65	14.00	13.59	-4.510	-4.332	-3.701
.4700	.4720	6.884	7.607	7.222	-14.87	-15.24	-14.52
.5000	.5010	4.978	5.552	4.976	-23.53	-24.15	-23.61

Table A-9. Cylinder Recovery Factors

M nom.	M	R S (1)	R S (2)	R S (3)	R 180 (1)	R 180 (2)	R 180 (3)
.000	.000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
.100	.9065E-01	1.0000	1.0000	1.0000	.4300	.4931	.2486
.120	.1127	1.0000	1.0000	1.0000	.4638	.4988	.3566
.130	.1188	1.0000	1.0000	1.0000	.3749	.3457	.2509
.140	.1341	1.0000	1.0000	1.0000	.2713	.2884	.3241
.150	.1440	1.0000	1.0000	1.0000	.2428	.1641	.2717
.160	.1514	1.0000	1.0000	1.0000	.1342	.4803E-01	.2053
.170	.1610	1.0000	1.0000	1.0000	.1190	.3872E-01	.1744
.180	.1702	1.0000	1.0000	1.0000	.6927E-01	.1130E-02	.1523
.190	.1798	1.0000	1.0000	1.0000	.6537E-01	.3114E-01	.1572
.200	.1903	1.0000	1.0000	1.0000	.1866E-01	.3077E-01	.1340
.210	.2060	1.0000	1.0000	1.0000	.2886E-01	.7389E-01	.8655E-01
.220	.2127	1.0000	1.0000	1.0000	.1915	.1253	.3622E-01
.230	.2267	1.0000	1.0000	1.0000	.1767	.1673	.3255E-01
.240	.2385	1.0000	1.0000	1.0000	.1434	.1823	.2237E-02
.250	.2488	1.0000	1.0000	1.0000	.5363E-01	.7131E-01	.9193E-02
.260	.2674	1.0000	1.0000	1.0000	.6602E-02	.1789E-02	.1864
.270	.2800	1.0000	1.0000	1.0000	.2915E-01	.3243E-01	.8416E-01
.280	.2896	1.0000	1.0000	1.0000	.1419E-01	.2839E-01	.6112E-01
.290	.3016	1.0000	1.0000	1.0000	.3886E-01	.2568E-01	.6173E-01
.300	.3139	1.0000	1.0000	1.0000	.3864E-01	.3400E-01	.1983
.350	.3535	1.0000	1.0000	1.0000	.5478E-01	.3595E-01	.9987E-01
.400	.4078	1.0000	1.0000	1.0000	.3816E-01	.2184E-01	.1132
.450	.4240	1.0000	1.0000	1.0000	.2822E-01	.6666E-01	.8666E-01
.500	.4400	1.0000	1.0000	1.0000	.5552E-01	.4287E-01	.2014E-01
.550	.4720	1.0000	1.0000	1.0000	.2333E-01	.1452	.9876E-01
.580	.5010	1.0000	1.0000	1.0000	.2626	.3344	.2059

VITA

William C. Riner was born in Nashville, Tennessee, on January 17, 1961. He attended elementary schools in that city and was graduated from John Overton High School in June 1979. He attended Tennessee Technological University, Cookeville, Tennessee, and in August 1983 received a Bachelor of Science degree in Engineering Science and Mechanics. In the fall of 1983 he accepted a research assistantship at The University of Tennessee Space Institute, Tullahoma, Tennessee, and began study toward a Master's degree in Mechanical Engineering. This degree was awarded in August 1985.

Mr. Riner is a member of the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, and Lambda Chi Alpha. He is married to the former Anna Beth Wynn of Chattanooga, Tennessee, and now resides in Huntsville, Alabama.