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BOUNDARY LAYER TRANSITION

10 by F.N.M. Brown

11

15 May 1963
Contract NOrd 17702

16 17 18 + 19 NA
20 21 NA

Department of Aeronautical Engineering

UNIVERSITY OF NOTRE DAME
NOTRE DAME
INDIANA
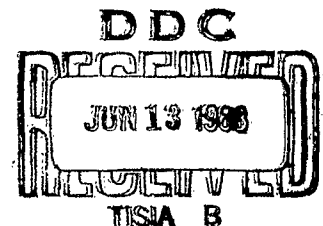
SUMMARY

* ~~is~~ *made*

A determination of the mechanism of transition in a single pressure gradient*by means of high-speed motion picture photography.

is made

A comparison of hot wire and stroboscope techniques used for the determination of the frequencies of the organized motion that preceeds transition.

TABLE OF CONTENTS

INTRODUCTION

In 1953 a flow visualization technique, utilizing smoke in
low turbulence wind tunnel (Reference 1, 2) revealed that
the separated laminar boundary layer invariably rolled up
into series of vortices of speed linked frequency whose
axes were perpendicular to the stream and parallel to the
surface of the body, if two dimensional (Figure 1). If
the body were one of revolution, such as a sphere, the
axis of the vortices were circles lying in a plane per-
pendicular to the stream.

In 1958, during a study of the periptery of spinning and
non-spinning ogive nosed cylinders in various attitudes
of pitch and yaw (Reference 3) it was observed with a
mechanical stroboscope that this body form, non-spinning
and at zero pitch and zero yaw, in a mildly favorable
pressure gradient possessed a periodic or organized
boundary layer over a considerable length of body. This
region of organization ended in the fully developed tur-
bulent boundary layer after first exhibiting three dim-
ensional (annular) motion (Figure 1a) at a distance from
the surface approximating the total thickness of the layer.

Inasmuch as a natural phenomenon of this nature had never
before been photographed (Reference 4 & 5) financial
support was sought for study of the matter. Preliminary
findings were reported in February 1960 (Reference 6)
and a paper with some additional material was presented at

a Picatinny Arsenal Symposium the same year (Reference 7).

This paper will contain all the experimental data shown in References 6 and 7 along with additional data.

APPARATUS

The Wind Tunnel

The wind tunnel used has been fully described in Reference 6. It suffices to say here that the tunnel is non-return with heavy anti-turbulence screening and a reduction ratio of 24 to 1. Mechanical vibration is absent because of isolation of fan from the diffuser and the diffuser from the working section. Isolation is achieved by separate suspension and by a sponge rubber section downstream of the working section.

The sound level and the turbulence level is low. In Figure 2 the noise intensity spectrum and the turbulence spectrum are shown at the same scale. A study of the two curves indicates that the turbulence present is, in all probability, due to particle velocities present in the sound waves. There is however a long period (one second and more) velocity fluctuation that may be as high as 3% at low tunnel speeds. This fluctuation is due to changes in pressure impressed by the natural wind.

The axial pressure gradient with the models in place is shown in Figure 3. It is to be noted that the

gradient in the area of interest is slightly adverse but close to zero. This is achieved by using a tapered working section whose cross-section is everywhere square. This method is thought to be superior to methods wherein only one or two walls are manipulated.

The Models

The models used were tangent ogive nosed circular cylinders. One was 2.42 inches in diameter and 48 inches long and one 4 inches in diameter and 28 inches long. Each had 2.0 caliber noses. The aluminum alloy models were finished to 10 micro-inches and anodized black. They were waxed and polished before use.

Hot Wire and Associated Equipment

The hot wire equipment consisted of Flow Corporation's Model HWB2 anemometer, Model HWP-B hot wire probe and model F-7 low pass filter, Bruel & Kjaer's Type 2111 Audio Frequency Spectrometer and a Tektronix Type 502 Dual-Beam Oscilloscope.

The Model HWB2 anemometer is of the constant current type and consists of a precision galvanometer and bridge circuits for d.c. measurements, a low-noise, broad-band amplifier to resolve high frequency fluctuations, a calibrating signal for determining the amplitude of velocity fluctuations directly, and

low-noise power supplies and controls. The gal-
vanometer has sufficient sensitivity to balance the
bridge within 0.1% with a 5 ohm wire at 1 ma. heat-
ing current. The bridge circuit is provided with
a bridge null potentiometer, "Hot-Cold" switch, and
a selector switch for setting any of ten pre-determined
hot to cold d.c. wire resistance ratios. The amplifier
has a correctly compensated frequency range of from
2 cps to 100,000 cps with any hot-wire probe and an
equivalent noise level at the transformer input of
1/4 microvolt r.m.s. Continuously variable R-C com-
pensation is provided to match any hot wire with a
time constant between .23 milliseconds and 30 milli-
seconds. A square-wave circuit is used to find the
correct value of the compensation frequency. The
wire current supply allows continuous regulation to
300 ma. With a 5 ohm hot wire operated at 100 ma,
a 1% change in wire resistance produces a 1/100%
change in wire current.

The Model F-7 Low Pass Filter has a cutoff frequency
of 7 KC. The attenuation is zero at low frequency,
1 db at the cutoff frequency, and 12 db per octave
above the cutoff frequency. The Model F-7 filter
when used in conjunction with the Model HWB2 Hot
Wire Anemometer increases the systems resolution of
low frequency signals fourteen times.

The Type 2111 Spectrometer was used to measure the
true r.m.s. value of the voltage signals from the
anemometer in the determination of the turbulence
intensity. The 1/3 octave band-pass filters pro-
vided a means for determining the turbulence spectrum.

Wave Analyzer

Input signals were measured with a Hewlett Packard
Model 302A wave analyzer with an effective range of
20 cps to 50 kc. The input signals were broken into
their fundamentals and harmonics so that each was
separately measured and evaluated. The instrument
is equipped with a voltmeter which is calibrated to
read signal strength in either volts or decibels
directly. For purposes used here, the stated select-
ivity ranged over bandwidths of ± 3 cycles/sec at
low frequencies to $\pm \frac{1}{2}$ cycle/sec at high frequencies.
The frequencies of aerodynamic activity were indicated
on a linear scale dial with a stated accuracy of $\pm 1\%$
± 5 cps

The Stroboscope

A conventional pierced, rotating disc stroboscope
capable of 2500 light interruptions per second was
used. The rate of rotation of the disc was determined
by an electric tachometer.

The Smoke

During the early part of this investigation smoke

was produced by coking grain straw. That is to say,
burning the material with insufficient oxygen and
under a slight pressure. Coking is, of course, a
process of distructive distillation usually leaving
behind the desired product, coke. In this use how-
ever the desired product was a portion of the dis-
tillate, the smoke. The entire distillate, composed
of CO, CO_2, water droplets, a variety of tars and
alcohols and some ash, was cooled and filtered be-
fore introduction to the stream (upstream of the
anti-turbulence screening). The actual state of
the smoke, as used, is not certain but it was prob-
ably of the nature of a fog; droplets of liquid. It
is known that the particle size was very small. The
smoke was barely visible in red light and highly
visible in blue light.

Toward the end of the investigation it became nec-
essary (for another purpose) to design an oil fog
apparatus. This apparatus was modified and tried in
the smoke tunnel. It proved to be remarkably success-
ful. Remarkable because none of the previously tried
designs (notably the British design) had been success-
ful at speeds above 30 ft/sec.

The device is simple. Kerosene is permitted to drip
from a sight feed oiler onto a strip heater inclined
along its length and contained in a tube. The upper
end of the tube connects to the smoke distribution

system and air is admitted to the lower end. The
resulting smoke (kerosene fog) is cooled to air
temperature in the distribution system.

This smoke is now used in all boundary layer work.
Fouling of the model is practically non-existant
whereas the straw smoke fouled the model in the tur-
bulent boundary layer at high speeds.

The Photography

The periodic activity present in all wakes and
transitioning boundary layers in air invariably
take place at a frequency well above the minimum
interval of retina retention so that simple viewing
or photography at common time intervals is all but
worthless. Such viewing or photography differentiates
only between undisturbed and disturbed flow and that
poorly.

It is necessary therefore that the time interval be
as short as possible. Short interval flash lamps
(20 to 40 micro-seconds) have been used successfully
at all air speeds up to 220 ft/sec. Spark photo-
graphy (one micro-second) has been used successfully
in supersonic smoke photography at Mach 1.38. High
speed cine-photography (2000 to 5000 frames/second)
was used.

EXPERIMENTAL PROCEDURE

Introduction

Experimental procedure did not change materially during the progress of the investigations, but it has been thought desirable to repeat briefly the techniques reported in Reference 6 and 7 as well as to explain added techniques.

Model Mounting

Models were sting-mounted from the base to a strut attached variously to the top and the bottom of the working section. Axial location and zero pitch and yaw was achieved by means of location templates frequently used. Error in pitch or yaw did not exceed 0.034°. No vibration at the model nose was observable with a 12 power transit at an object distance of 12 feet.

The Gradients

The axial pressure gradients were determined by static pressure measurements along the length of the working section (Figure 3).

The Speeds

The speeds mentioned are true speeds (corrected for pressure and temperature) measured in the stagnation streamline one foot upstream of the model nose. No blockage corrections have been made since such would have changed the speed less than 1%.

The Photographs

The still photographs of the smoke indicator in the boundary layer were made with a 4 x 5 view camera using film with a A.S.A. tungsten rating of 160. Short interval lighting (20 micro-seconds) was supplied by commercially available high intensity flash lamps. Four such lamps were used. A minimum of five exposures was made for each speed. Speeds ranged from 35 to 120 ft/second. More than 20 runs through the speed range over a period of 3 years were made. Each run confirmed the others.

It must be mentioned that all photographs were not of equal quality especially during the early runs when the straw coking process for producing smoke was being used. This process was subject to pressure variations in the burner due to unsteady combustion which in turn resulted in uneven smoke delivery to the manifold system. The smoke layer on the model then varied in thickness and sometimes was so thick as to hide the periodic motion deep within the layer. (Figures 8, 9 and 10 of Ref. 6).

Motion pictures at the rate of 5000 frames/second were taken. In this case the model was lighted from a slit in the back of the tunnel. The pictures resulting were a vertical cross-section of the boundary layer on the model.

The Frequencies

The frequencies were determined visually by stroboscope and electronically by means of a hot wire signal fed into an oscilloscope.

The visual determinations were made with the simple light interruption stroboscope previously mentioned. With this instrument the entire length of the established organized or periodic motion within the boundary layer was visible at any instant.

The first hot wire observations (Reference 6) were taken at a fixed radial distance from the model and only the axial or station traverse was made. An oscillograph was used to record the hot wire signal. The frequencies were determined by simple counting between time lines.

At the instance of the sponsor effort was concentrated on correlation of the hot wire technique with the visual technique. Accordingly, more sophisticated equipment was procured. This equipment included a Flow Corporation instrument capable of handling two hot wire circuits simultaneously, capable of sum and difference measurements and with a R.M.S. meter for turbulence measurements. Two oscilloscopes of good quality (Tecktronix 502) were also purchased.

The hot wire investigations with the new equipment were far more extensive than before. Radial as well as axial positions were examined and polyrepetative measurements were made to confirm data previously taken.

Perturbation Introduction

A series of three auxiliary models were used to produce perturbations near but not in the boundary layer of the ogive nosed cylinder. These models were circular cylinders of 0.43, 0.50 and 0.62 inches in diameter and were introduced singly at station 18 at a distance of 2 3/4 inches (surface of model to centerline of auxiliary models). (Figure 3).

The perturbations so introduced were the strong periodic vortices common to the wake of a circular cylinder perpendicular to the stream. The diameters were selected to give trail frequencies near but not equal to the frequency of the activity in the boundary layer of the ogive nosed cylinder.

With each of the auxiliary models in place the optic determination of frequency of the organized motion on the basic model was made over the entire speed range. The determinations were identical to those made without the auxiliary models.

DATA ANALYSIS

The Photographs

Analysis of the photographs included the determina-
tion of the station at which the organized motion
was first visible and determination of the station
at which the fully developed turbulent layer began.
This was accomplished with the aid of a scale cal-
ibrated in inches and included in each photograph
and determined the extent of the organized activity.

The spacing of the organized elements or bands of
thickened smoke revealed the translational speed of
these elements. (Reference 6).

The Hot Wire Data

As was stated the hot wire signal was first recorded
on an oscillograph. The later and larger mass of
data was recorded by photographing a single passage
of the cathode beam across the screen of a good,
calibrated oscilloscope. In each instance all or
part of the trace was plainly of a periodic nature
with the frequencies readily countable on the photo-
graph. In all instances the amplitude of the wave
varied along the trace. This variation was of irreg-
ular nature and became more pronounced toward the
after portion of the organized motion. However even
when the irregular change in amplitude was the most
pronounced, inflections in the curve appeared at the

regular period points. These inflections were interpreted, reasonably I believe, as evidence that the fixed, speed linked, frequency was still present but was being hidden, in part, by an irregular (both in frequency and in amplitude) wave.

The nature of the tunnel, with a 50 by 108 by 12 foot room serving as the pressure chamber and with the diffuser discharging outside of this room to the atmosphere permits working section speed variations due to pressures imposed at entry and exit by the natural wind.

This variation was measured over a fixed period of time (50 seconds) with the liquid manometer used regularly to indicate static draw down (and so speed). The maximum variations are shown in Figure 4.

The irregular wave which partially obscures the fundamental and natural frequency is believed to be caused by these small irregular changes of speed within the working section.

The hot wire signal for a range of speeds was taped on an inexpensive (Revere 1100) recorder and forwarded to the sponsor for wave analysis. The results of this analysis were completely indefinative. No fundamental frequency such as that counted on the oscilloscope trace or observed with the stroboscope could be found.

Our own attempts with the wave analyzer (described above) on the same tapes and on the direct signal from the hot wire were equally indefinative.

In December 1962 a recording wave analyzer (Mosely Autograph Model 135) was purchased. The results from this machine were definative and a curve of frequency against velocity was obtained. (Figure 29).

STATEMENT OF RESULTS

Introduction

It has only been implied in this report that the periodic motion observed and reported occurs only within the boundary layer. It should be emphasized, perhaps, that when the probe is drawn away from the surface of the model in the regions where periodic activity is observed the amplitude of this periodic activity diminishes with height until the periodicity finally disappears and the oscilloscope trace becomes a simple straight line as it is in the early laminar layer and in the free stream. (Figure 28).

Too, it must be restated that the activity within the boundary layer reported herein is completely spontaneous. No vibrating ribbon or wire trip or external excitation of any kind was used.

All results herein are presented graphically in order that the report be not overburdened with a mass of

tabular data.

The work reported herein has extended over a period
of more than four years and includes the experimental
work of seven individuals using two techniques; the
hot wire and the optical.

Current (1962-63) work, undertaken without sponsor-
ship by the Bureau of Naval Weapons, is included.

The Frequency of the Activity

The hot wire survey for axial stations 25" to 32"
and for radial stations from 0.010" to 0.080" from
the surface of the model with speeds ranging from
35 to 65 feet per second is presented in Figures 7
through 13. The graphical representation shows fre-
quency distribution along the model for various
speeds and heights and is believed to be self ex-
planatory and shows no trend of frequency change
with distance from the model.

Figures 14 through 23 presents the same hot wire
data plotted as frequency vs speed for various
stations and heights.

The frequency as a function of speed, taken by
means of the optic technique, is shown in Figures
5 and 6. These data confirm the $f = K U^{3/2}$ rel-
ationship but indicate a smaller value of K.

Frequency data read from the Mosely autograph using the hot wire signal direct is shown in Figure 29.

Extent of Periodic Activity

The extent of the visible periodic activity along the length of the body as a function of speed is shown in Figure 24.

Perturbation Introduction

In Figure 25 are shown the results (or lack of results) of the effect of strong periodic activity introduced within the working section on the periodic activity within the boundary layer.

High Speed Motion Pictures

Several hundred feet of 5000 frames/second 16mm motion pictures were made of the transitioning boundary layer. These pictures should be considered a part of this report and may be obtained on loan from the author.

CONCLUSIONS

Neither the hot wire nor the optic technique revealed the true character of transition. The high speed motion pictures (Reference 8) show the mechanism to be a trine of flow states each occuring in its turn. The trine of flow states is, (1) a region of periodic motion or waves in which there is an adverse gradient (2) a region of fully turbulent motion growing out of the periodic region and in a state of linear

acceleration in the downstream direction and a (3) region
of laminar motion, within which there is a favorable gradient,
which is being drawn after the accelerating turbulent region.

The greater portion of the investigation was done under the
false assumption that each of the trine of flow states was
in simultaneous existance at different stations along the
surface. That is to say, as observation progressed downstream
along the model there would be first laminar flow, then periodic
motion and finally fully developed turbulent motion. And when
the flow is observed by stroboscope this appears to be true.
The periodic motion state is definative and is retained by
the eye in preference to the laminar or the turbulent states
because each of these is indefinative and vague. Short in-
terval light motion pictures taken at 16 frames/second were
equally misleading and for the same reason. (Any motion
picture has some characteristics of a stroboscope).

From all of the data taken by means of (1) high speed motion
pictures, (2) stroboscope, (3) hot wire and (4) still pictures
the following conclusions can be drawn:

1. Full transition arises out of a region or length of
    boundary layer that is in periodic, sinusoidal motion.
    (High Speed Motion Picture).

2. Transition occurs first at the downstream end of the
    length of sinuous motion and proceeds until all of
    the previously sinuous motion is involved. (High
    speed motion pictures). Prior to the onset of
    transition a three dimensional (perepheral in the

case of the longitudinal cylinder) motion takes
place. (Figure la). This motion in cross-section
is not unlike a breaking wave. (Figure 27). In
plan, however, the "crest" appears as an isosceles
triangle and seems to be fed from the sides of its
base (the three dimensional motion). These crests
never follow each other but are staggered giving an
appearance of thatching (Figures la and 26).

3. The transition encompases the length of organized
motion downstream end to upstream end at about the
rate of translation of the organized motion section
As each part goes into full transition that part
accelerates downstream. This increase in speed is
thought to produce a favorable gradient in the region
following and prevent its immediate transition.
This laminar section proceeds downstream followed in
turn by another length of sinuous boundary layer
which transitions in the usual way, accelerates and
overruns the laminar section ahead.

4. At stations successively downstream one from the other
a probe would indicate the following:

    a. Continuously laminar.

    b. Alternating laminar and periodic.

    c. Successively periodic, turbulent and
       laminar.

    d. Alternating turbulent and laminar.

    e. Continuously turbulent.

5. The frequency of appearance of the group of the
   three states of flow is estimated at one fifth of
   the frequency within the periodic state.

6. The frequency of the spontaneous periodic motion
   from which full transition stems is approximated by
   the equation

$$f = 0.55 \; U^{3/2}$$

7. The frequency of the periodic motion within the
   boundary layer is uninfluenced by strong vortex
   street formations (wakes of circular cylinders)
   of slightly different frequencies. (Figures 25).

8. Fair, even good agreement obtained between the
   optic and the hot wire techniques (counting the
   oscilloscope trace) in the upstream portions of
   the periodic boundary layer where there is alter-
   nating periodic and laminar motion. Further down-
   stream where the layer is periodic only one third
   of the time or less the agreement is poor. It is
   probable that the lag compensation characteristics
   of the wire are inadequate for this use. The strob-
   oscope (optic) technique is the more reliable.

9. The failure of the wave analyzers to resolve the
   frequencies is understandable when the characteris-
   tics of the boundary layer are known. Succeeding
   signals from periodic, laminar and turbulent sections
   of the layer were being put into the analyzer. The

signal from the turbulent section was of very high
level and contained a wide range of frequencies;
the signal from the periodic motion section was weak.
The dwell time of the analyzer on each frequency per-
mitted several hundred alternations of flow states to
enter the analyzer and masked the periodic intervals.
The limited success with the Mosely Autograph
(Figure 29) is due to the data being taken at an early
station where only periodic and laminar states were
succeeding each other.

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A Motion Picture, 5000 frames per second.
Available from the author.

Figure 1 Transitioning Boundary Layer (Adverse Gradient)
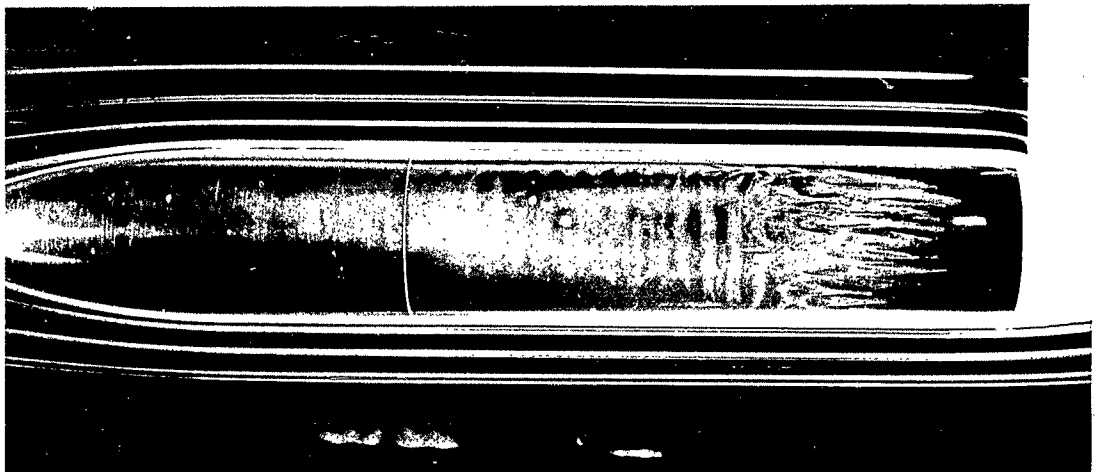
Figure 1a Transitioning Boundary Layer (Favorable Gradient)

TURBULENCE INTENSITY SPECTRUM
COMPARED TO
TUNNEL NOSE SPECTRUM
4 SQ. FT. SECTION, U = 30 FT/SEC.

O — TURBULENCE INTENSITY
HOT WIRE

□ — NOSE LEVEL CONVERTED
TO EQUIVALENT TURBULENCE
INTENSITY BY USE OF
$\frac{\sqrt{U'^2}}{U}$ = $\frac{R.M.S. PARTICLE VEL.}{FREESTREAM VEL.}$

FIGURE 2

FREQUENCY (CPS)
(1/3 OCTIVE BANDS)

10^2 10^3 10^4

TURBULENCE INTENSITY (%)

0.03   0.02   0.01   0   -0.01

PERTURBATION GENERATOR

$18"$

$2\frac{3}{4}$

P_9

AREA TAPER RATIO = 0.0617 FT^2/FT

O 45.2 F.P.S.
□ 61.8 F.P.S.
◇ 75.4 F.P.S.

NOTE: P_9 TAKEN AT
STATION 9
P_s TAKEN AT OTHER
STATIONS

P_s/P_9

2.0

1.0

0   10   20   30   40   50   60

STATION (INCHES)

Figure 3

FIGURE 4

$2\frac{1}{2}$" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM

FREQUENCY VS. VELOCITY

FIGURE - 5

NAT. LOG VELOCITY (FPS)

NAT. LOG FREQUENCY (CPS)

VISUAL TECHNIQUE
VISUAL TECHNIQUE
HOT WIRE TECHNIQUE
HOT WIRE TECHNIQUE

STATION 25.8"
STATION 29.0"
JAN-FEB 1960
OCT 1961
DEC 1959 — FEB 1960
SEPT — NOV 1960

LOG FREQUENCY vs. LOG VELOCITY
VISUAL TEHNIQUE
2 1/2" OGIVE NOSE CYLINDER

○ 29 JUNE 1961
◻ 17-20 OCT 1961
◇ 23 FEB 1962

NAT. LOG VELOCITY (FPS)

NAT. LOG FREQUENCY (CPS)
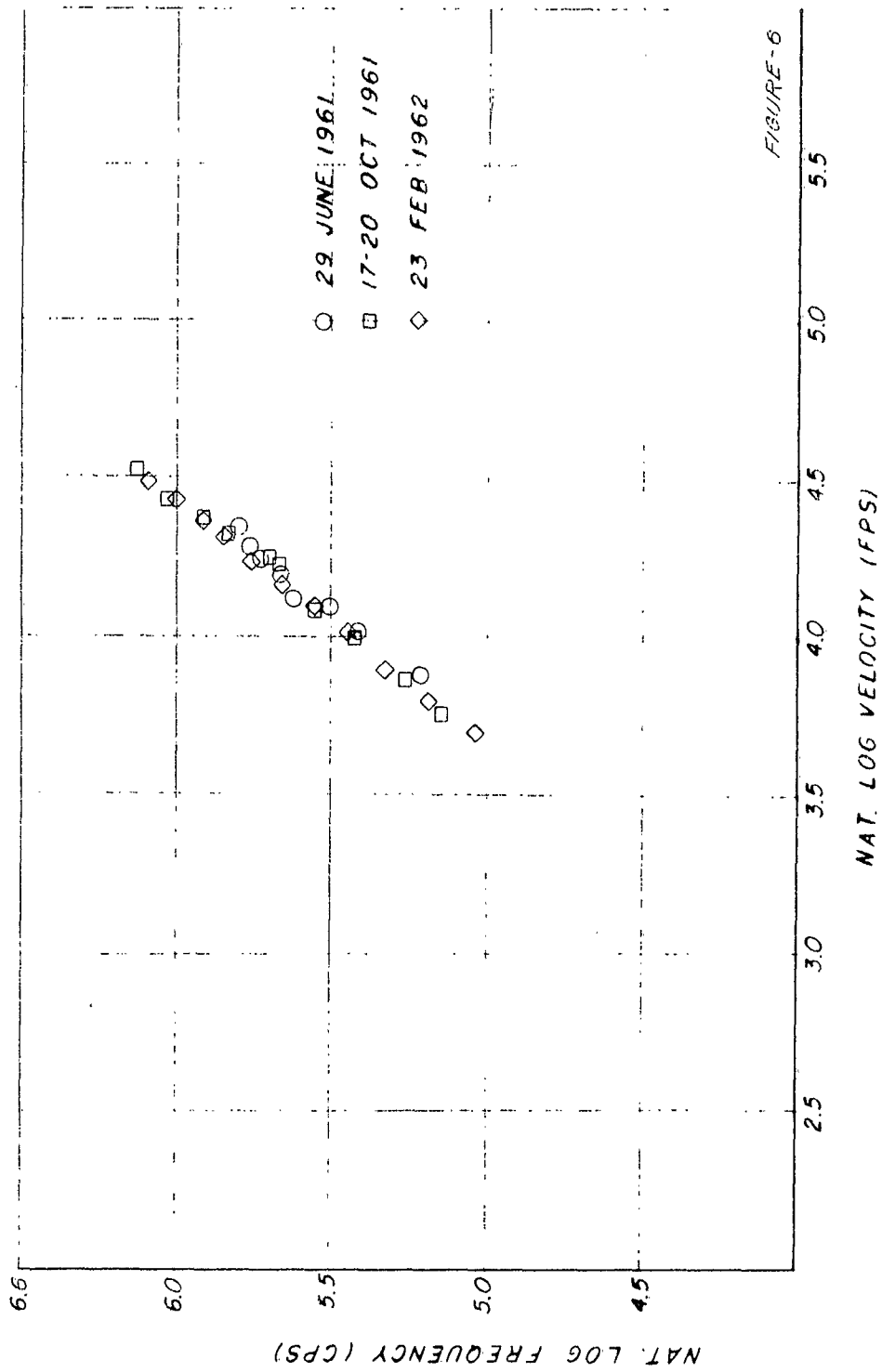
FIGURE-6

FREQUENCY VS STATION
2½" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
VELOCITY = 35 FT/SEC*
SEPT.-NOV. 1960

*VELOCITY FLUCTUATION:
31.8 - 34.9 FT/SEC.
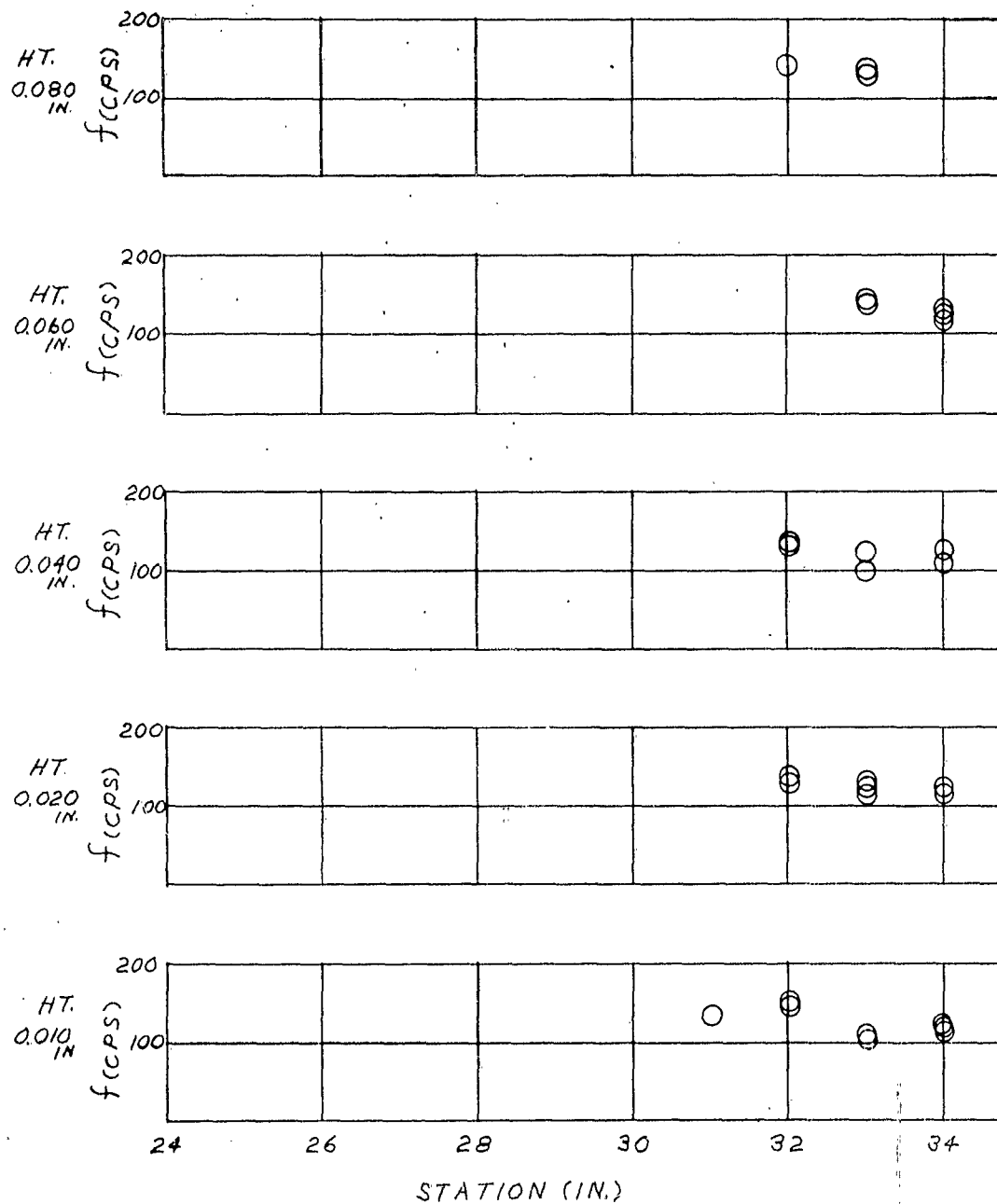
FIGURE 7

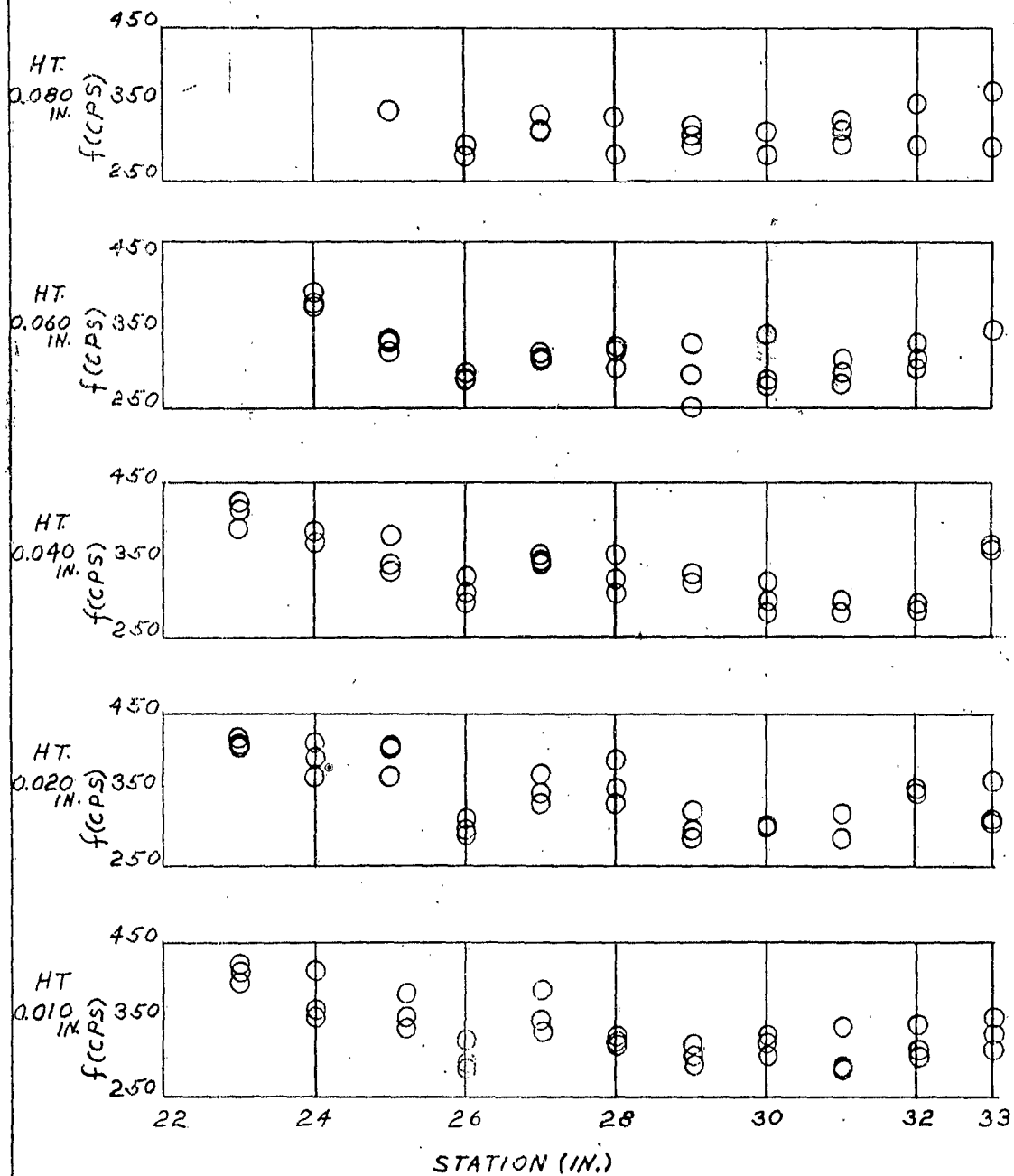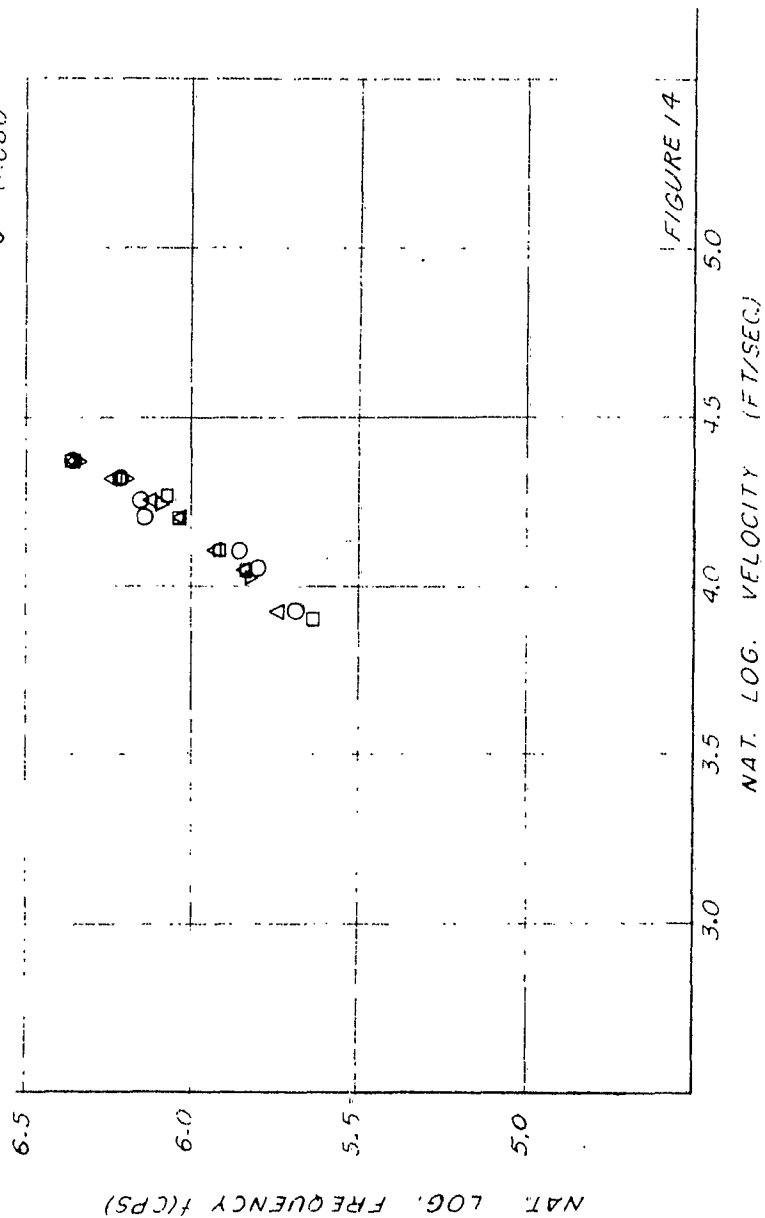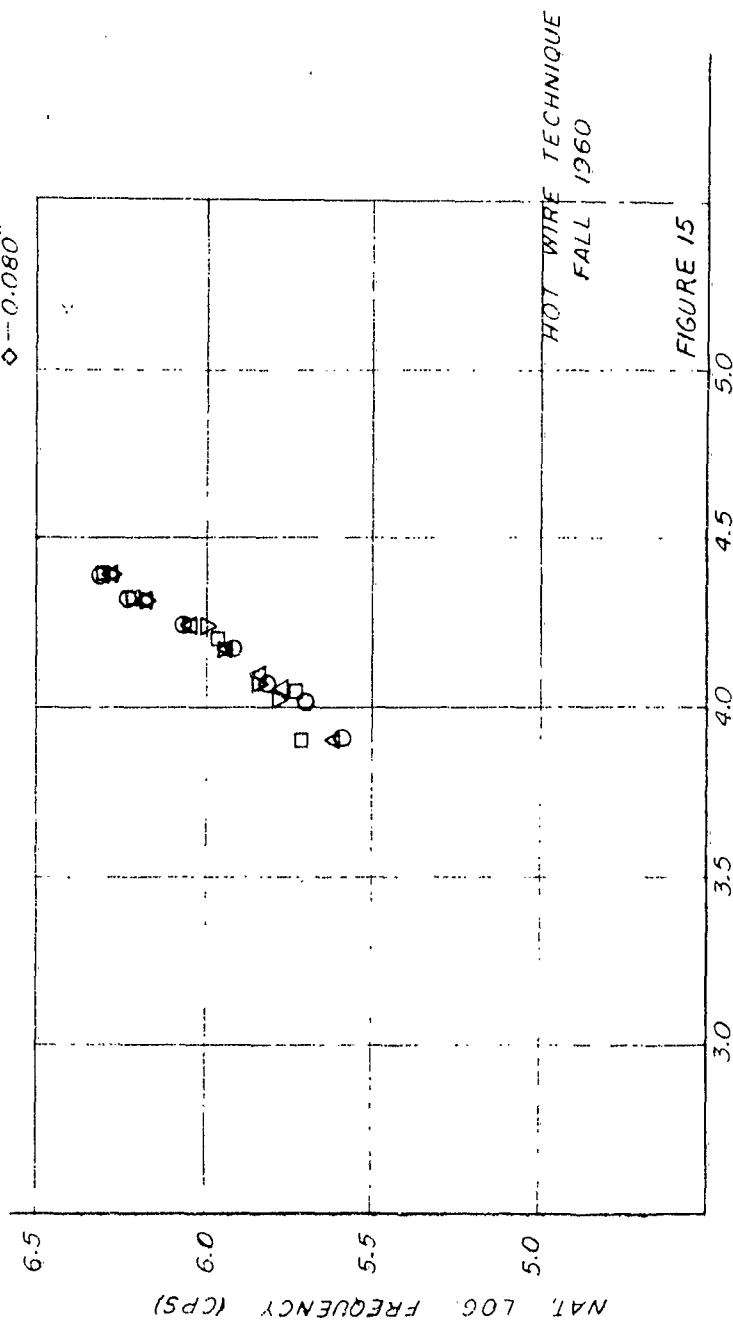FREQUENCY VS. STATION
2½" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
VELOCITY = 40 FT/SEC*
SEPT-NOV 1960

*VELOCITY FLUCTUATION:
39.7 - 41.4 FT/SEC.
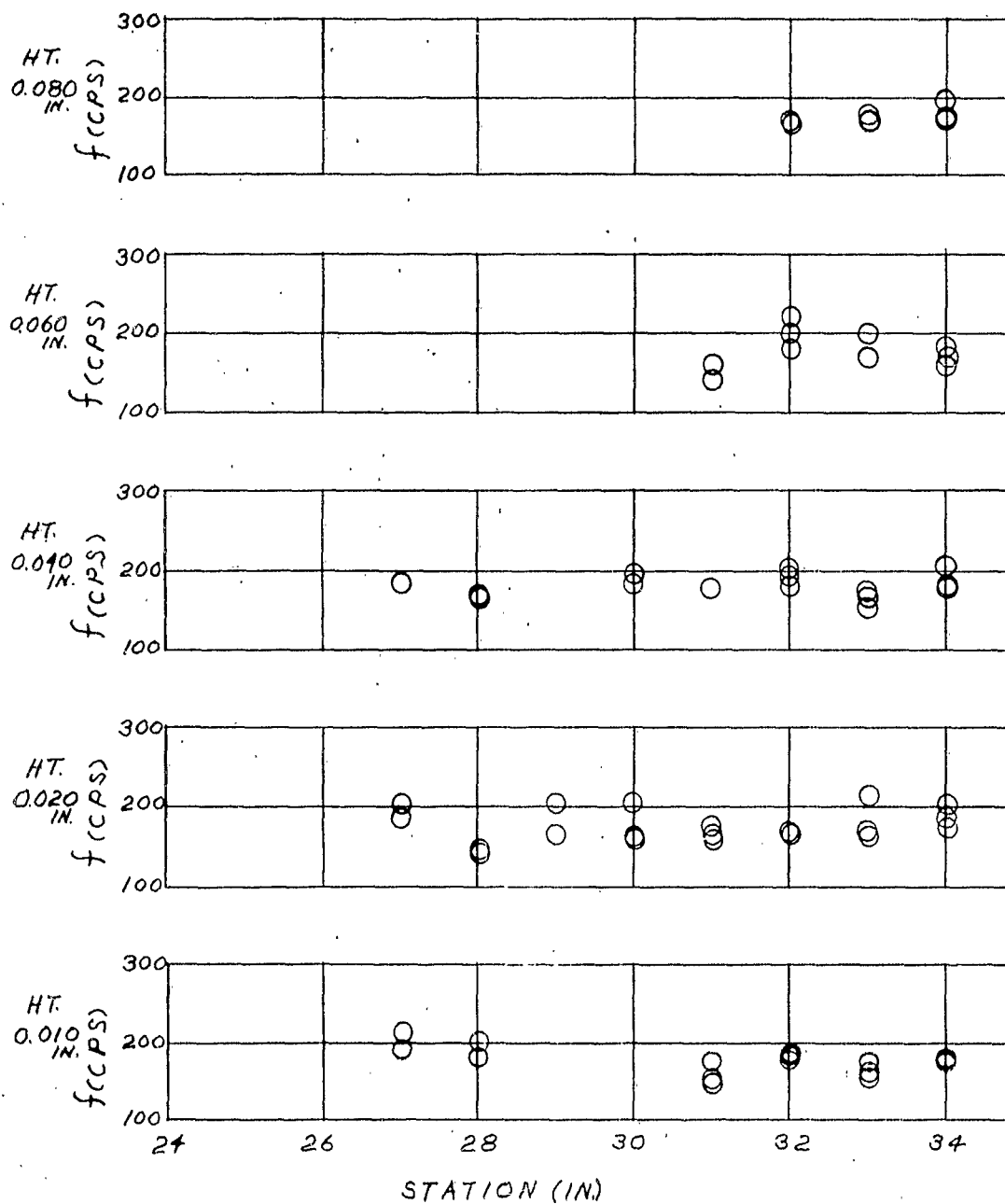
FIGURE 8

FREQUENCY VS. STATION
2½" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
VELOCITY = 45 FT/SEC *
SEPT - NOV. 1960

* VELOCITY FLUCTUATION:
44.0 - 46.4 FT/SEC.
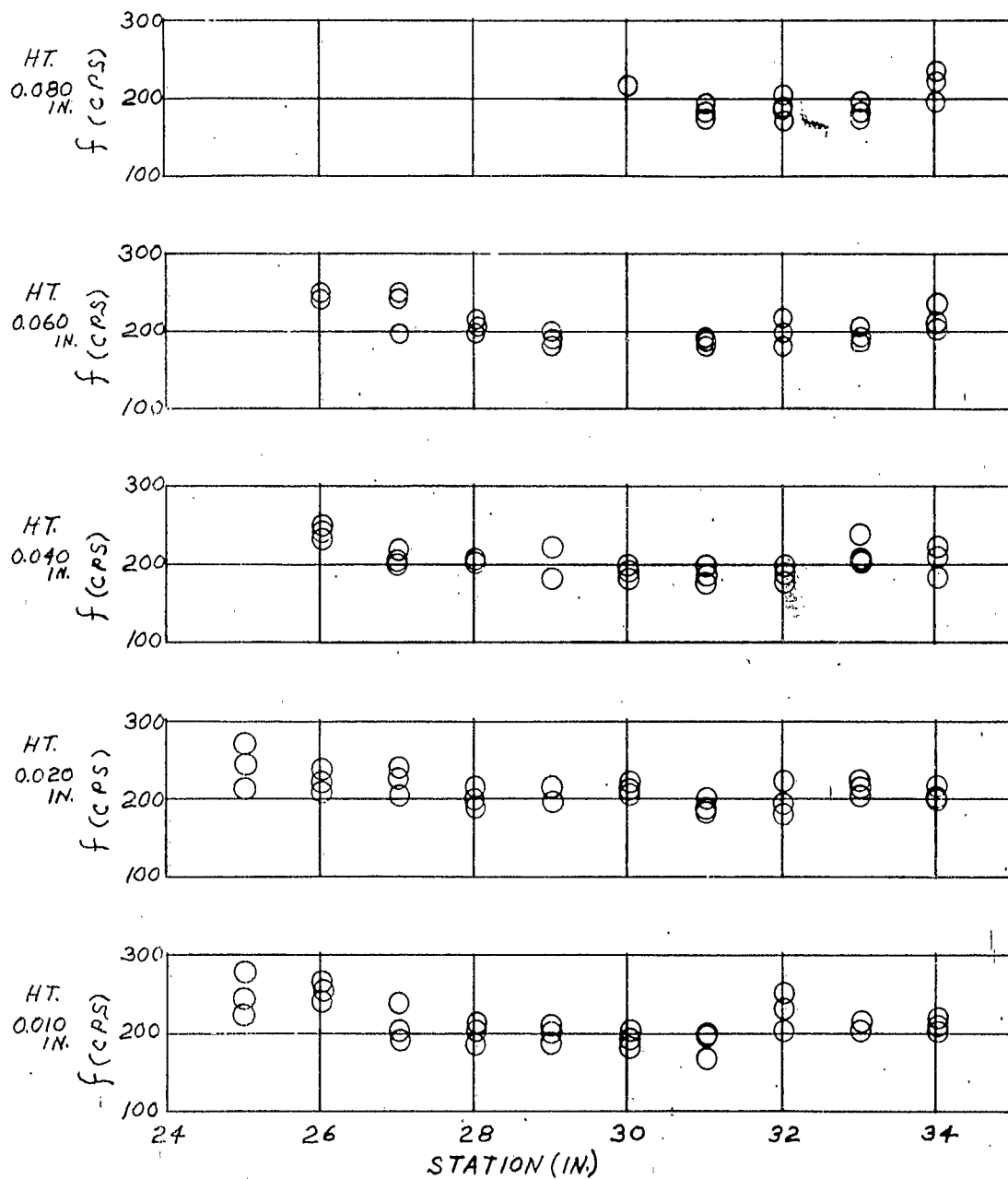
FIGURE 9

FREQUENCY VS. STATION
2½" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
VELOCITY = 50 FT./SEC.*
SEPT.—NOV. 1960

*VELOCITY FLUCTUATION
48.5-51.8 FT./SEC.
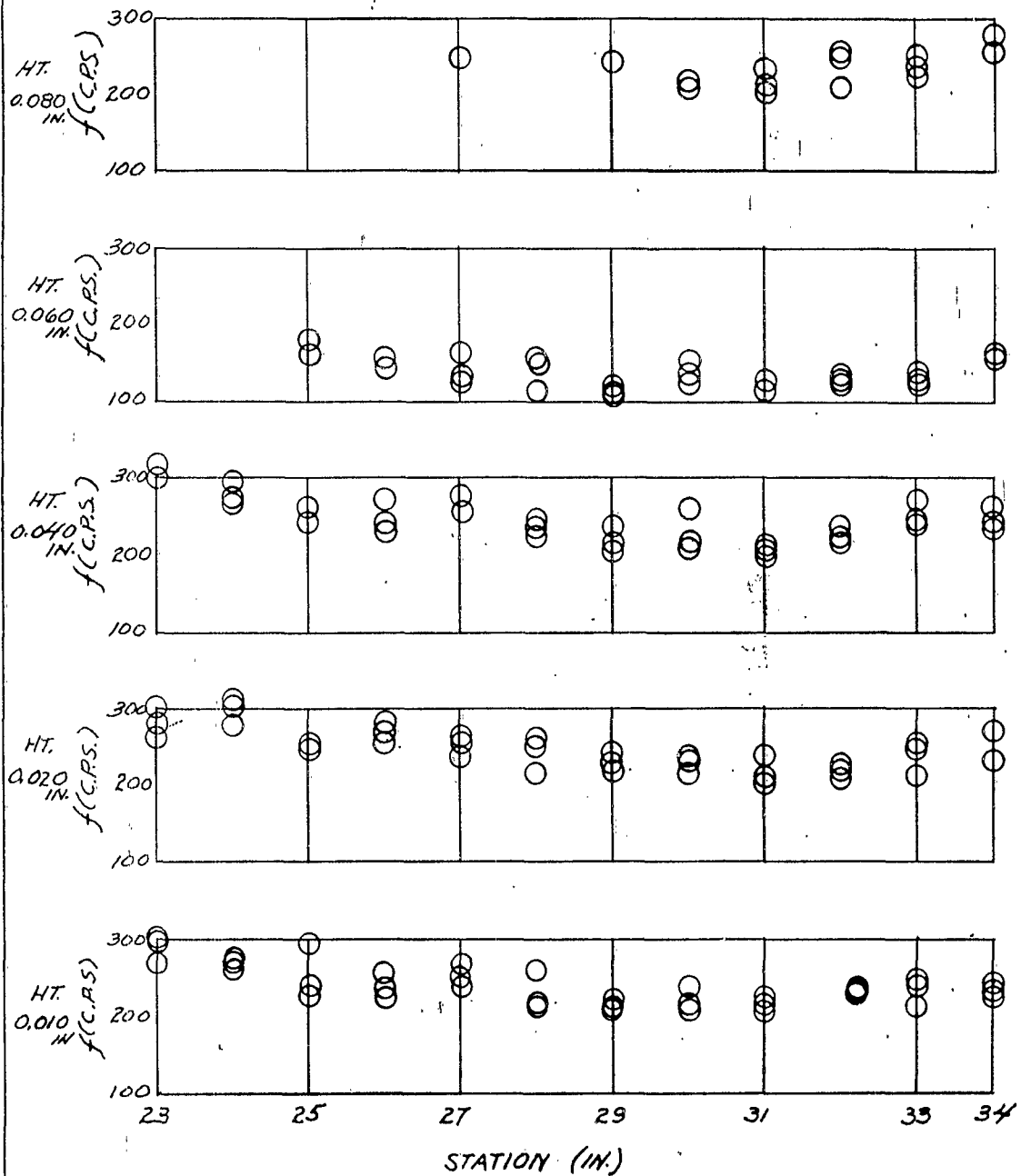
FIGURE 10

FREQUENCY VS. STATION
$2\frac{1}{2}''$ OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
VELOCITY = 55 FT./SEC.*
SEPT. - NOV. 1960

*VELOCITY FLUCTUATION:
52.9 - 58 FT./SEC.
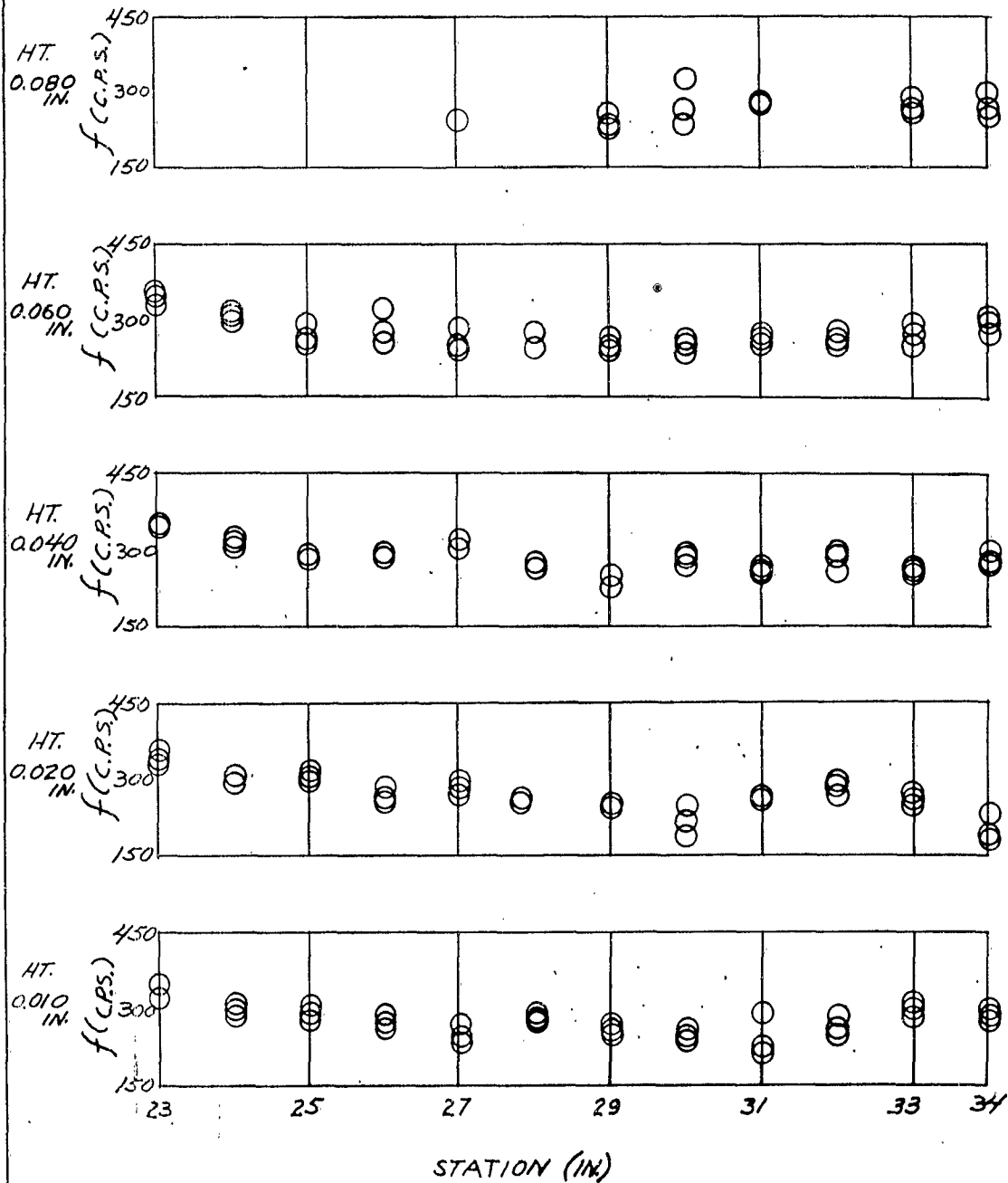
FIGURE 11

FREQUENCY VS. STATION
2½" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
VELOCITY = 60 FT./SEC.*
SEPT-NOV. 1960

*VELOCITY FLUCTUATION:
59.5 - 61.3 FT./SEC.
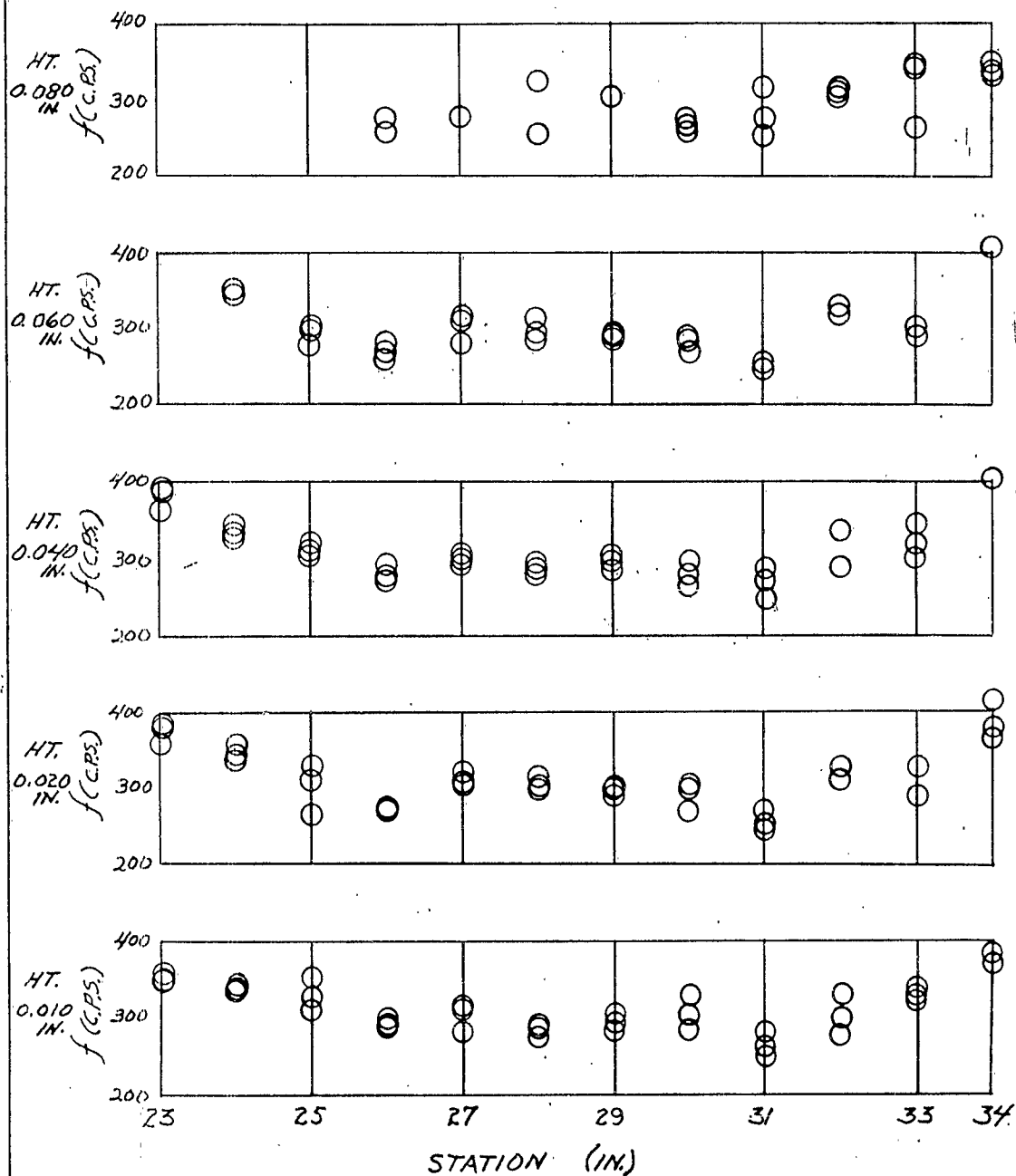
FIGURE 12

FREQUENCY VS STATION
2 ½" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
VELOCITY = 65 FT./SEC*
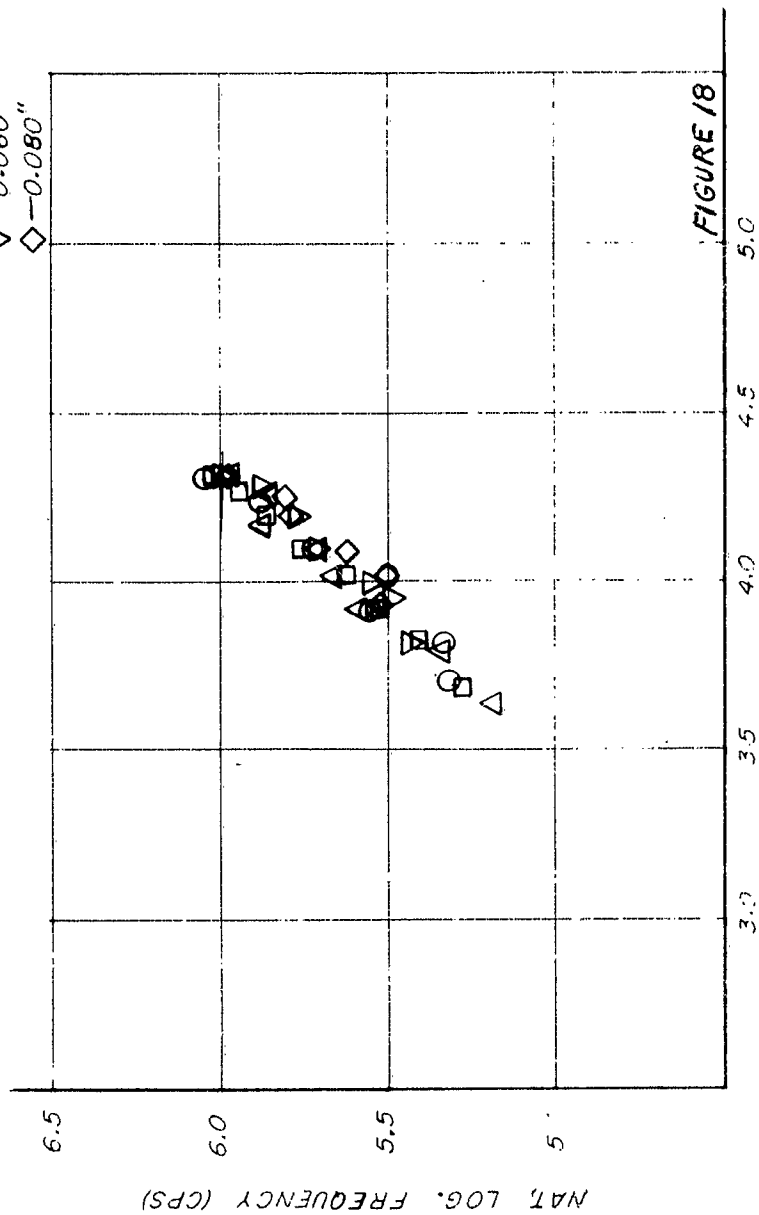SEPT.-NOV. 1960

* VELOCITY FLUCTUATION:
63.7 - 66.3 FT./SEC.
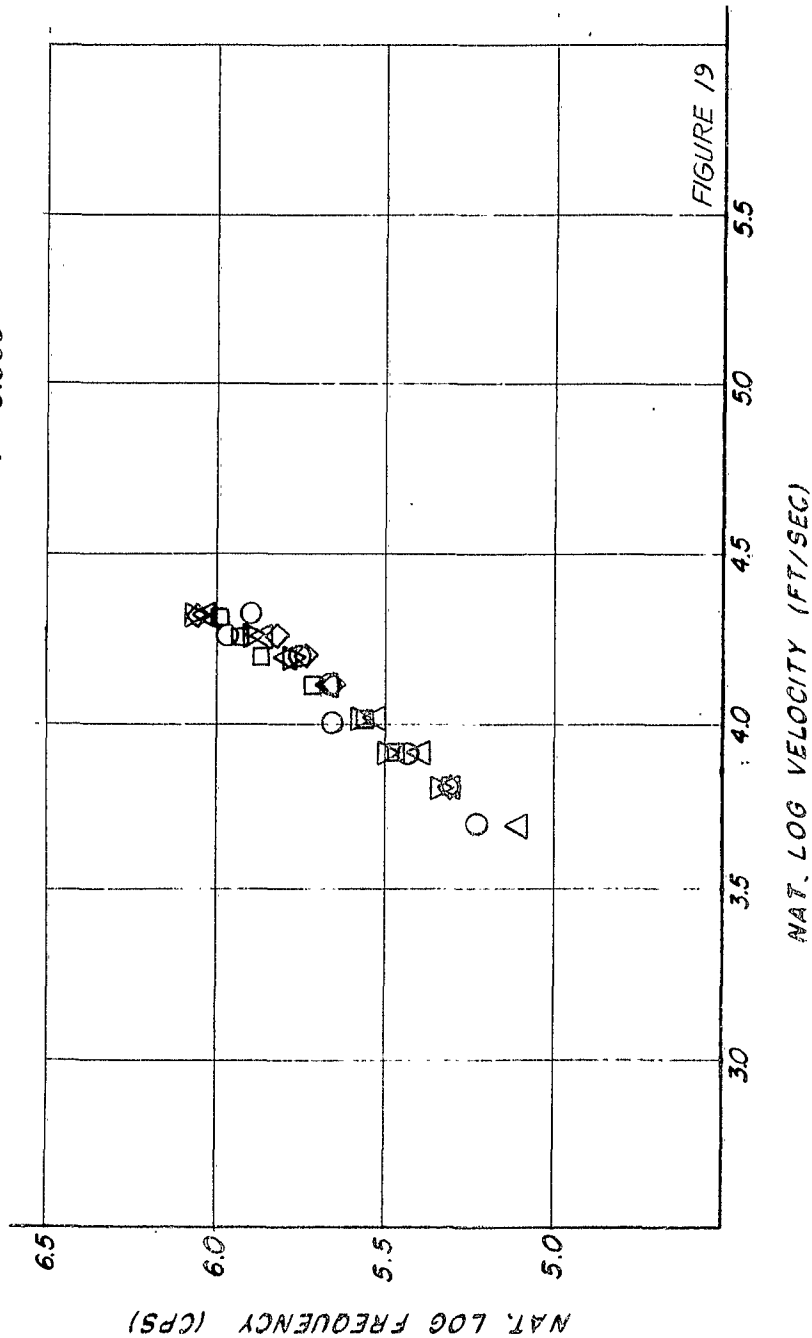
FIGURE 13

FREQUENCY VERSUS VELOCITY

2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 23

O — 0.010"
□ — 0.020"
△ — 0.040"
▽ — 0.060"
◇ — 0.080"

NAT. LOG. VELOCITY (FT/SEC.)

NAT. LOG. FREQUENCY f(CPS)

FIGURE 14

FREQUENCY VERSUS VELOCITY
2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 24

O — 0.010"
□ — 0.020"
△ — 0.040"
▽ — 0.060"
◇ — 0.080"

HOT WIRE TECHNIQUE
FALL 1960

FIGURE 15

NAT. LOG. VELOCITY (FT/SEC)

NAT. LOG. FREQUENCY (CPS)

FREQUENCY VERSUS VELOCITY
2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 25

O — 0.010"
□ — 0.020"
△ — 0.040"
▽ — 0.060"
◇ — 0.080"

NAT. LOG. FREQUENCY (CPS)

NAT. LOG. VELOCITY (FT/SEC)
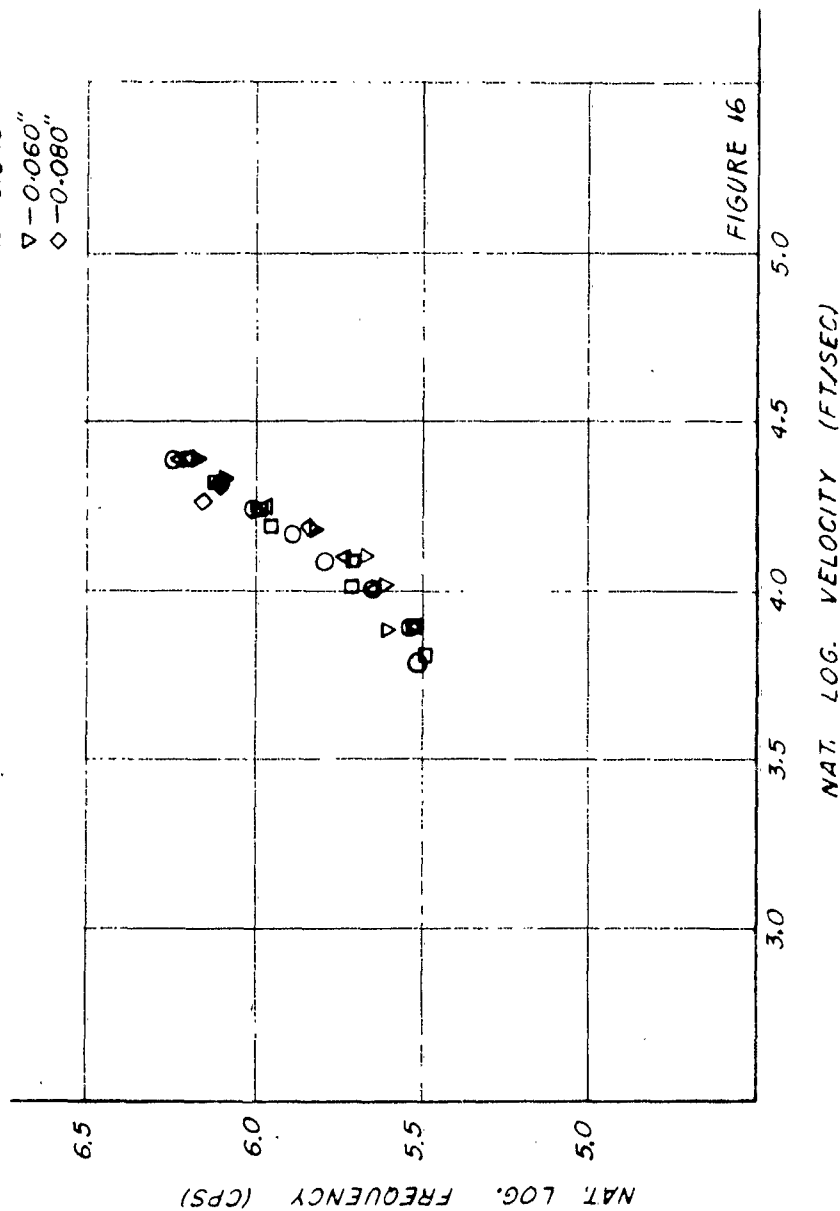
FIGURE 16

FREQUENCY vs VELOCITY

2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM

STATION 26

○ — 0.010"
□ — 0.020"
△ — 0.040"
▽ — 0.060"
◇ — 0.080"

HOT WIRE TECHNIQUE
FALL 1960

FIGURE 17.

NAT LOG VELOCITY (FT/SEC)

NAT LOG FREQUENCY (CPS)
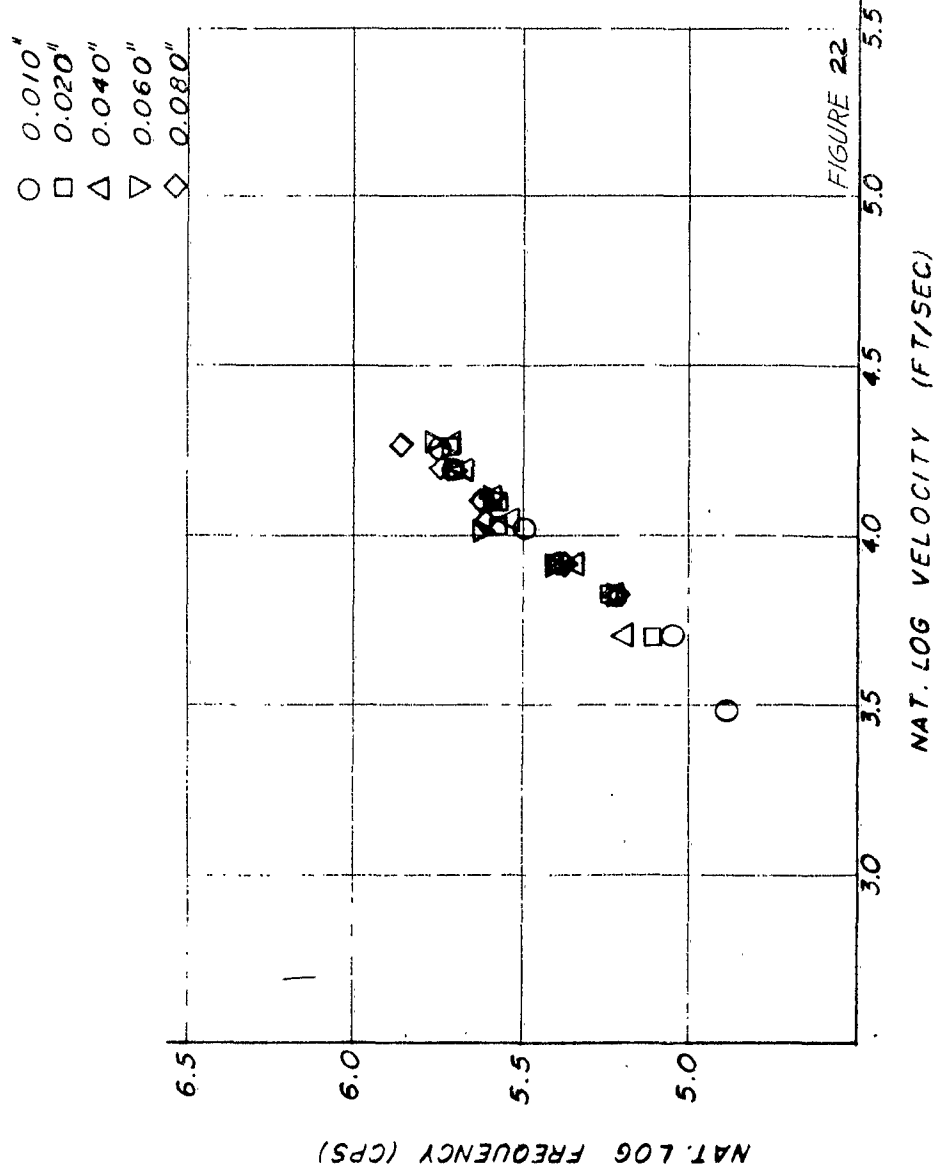
3.0   3.5   4.0   4.5   5.0

5.0   5.5   6.0   6.5
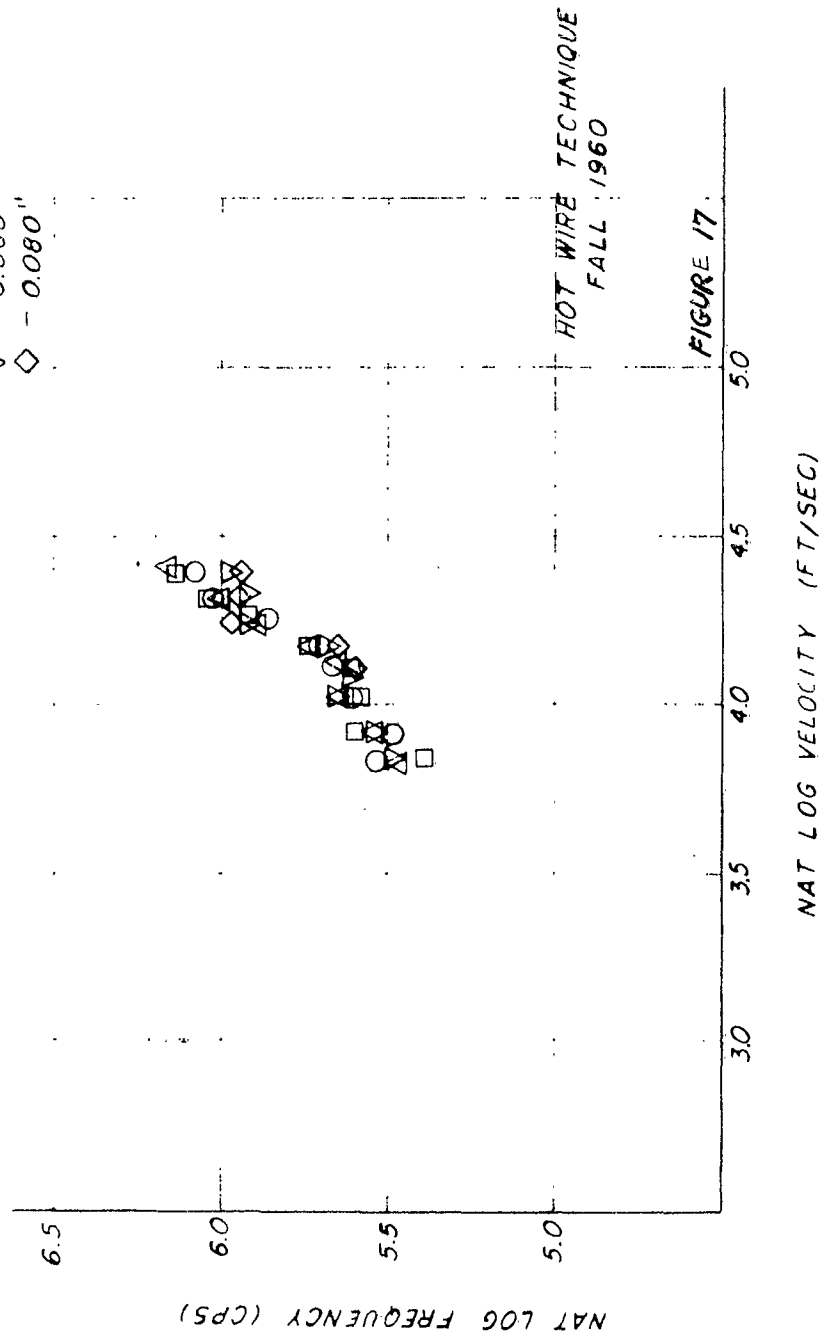
FREQUENCY VERSUS VELOCITY

2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 27

○ - 0.010"
□ - 0.020"
△ - 0.040"
▽ - 0.060"
◇ - 0.080"

NAT. LOG. VELOCITY (FT/SEC)

NAT. LOG. FREQUENCY (CPS)

FIGURE 18

FREQUENCY VERSUS VELOCITY
2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 28
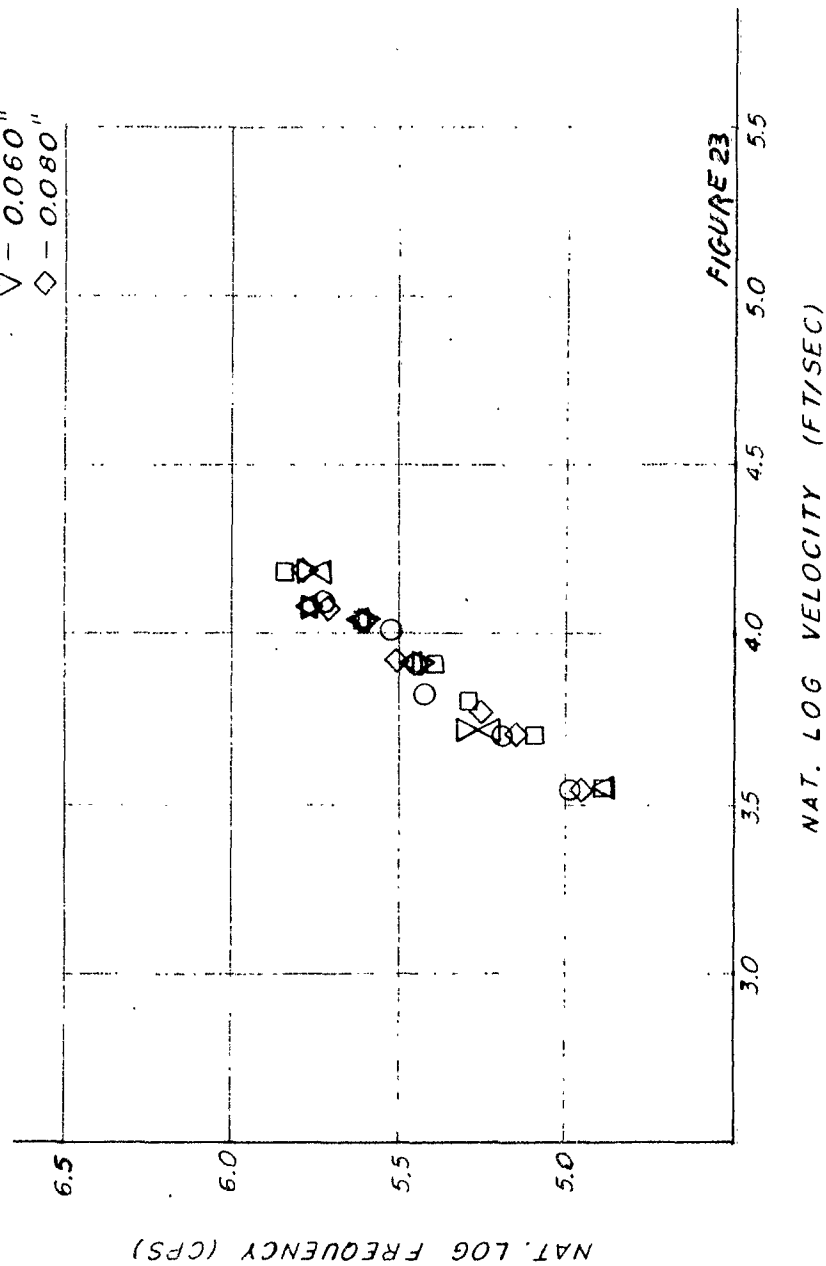
○ − 0.010"
□ − 0.020"
△ − 0.040"
▽ − 0.060"
◇ − 0.080"

NAT. LOG FREQUENCY (CPS)

NAT. LOG VELOCITY (FT/SEC)

FIGURE 19

FREQUENCY VERSUS VELOCITY
2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
CONSTANT TEMPERATURE HOT WIRE
STATION 29

O — 0.010"
□ — 0.020"
△ — 0.040"
▽ — 0.060"
◇ — 0.080"

HOT WIRE TECHNIQUE
FALL 1960
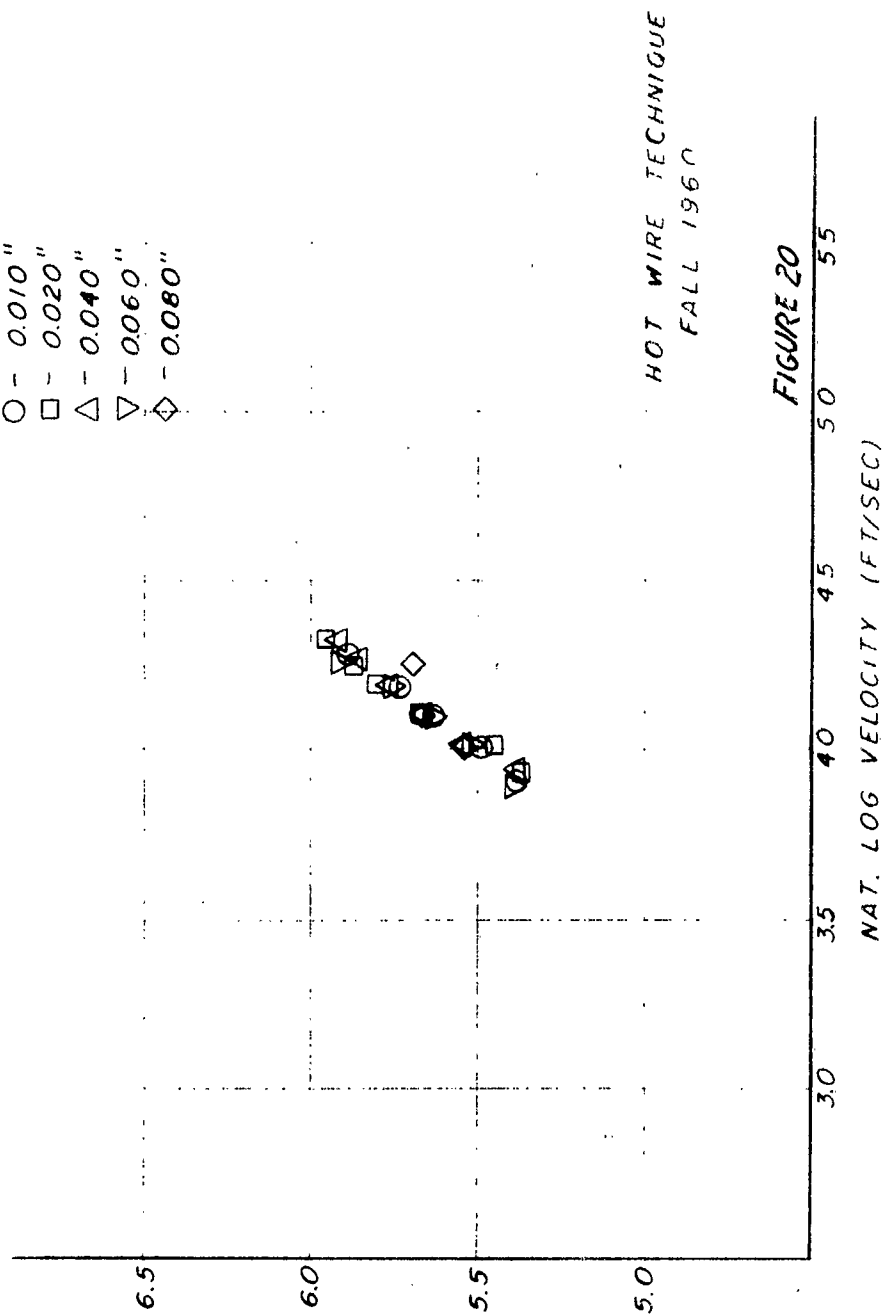
FIGURE 20

NAT. LOG VELOCITY (FT/SEC)

NAT. LOG FREQUENCY (CPS)

3.0   3.5   40   45   50   55

5.0   5.5   6.0   6.5

FREQUENCY VS. VELOCITY

$2\frac{1}{2}$" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 30

Legend:
○ — .010"
□ — .020"
△ — .040"
▽ — .060"
◇ — .080"

NAT. LOG VELOCITY (FT/SEC.)

NAT. LOG FREQUENCY (CPS)

FIGURE 21

FREQUENCY VERSUS VELOCITY
2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 31

○ 0.010"
□ 0.020"
△ 0.040"
▽ 0.060"
◇ 0.080"

NAT. LOG VELOCITY (FT/SEC)

NAT. LOG FREQUENCY (CPS)
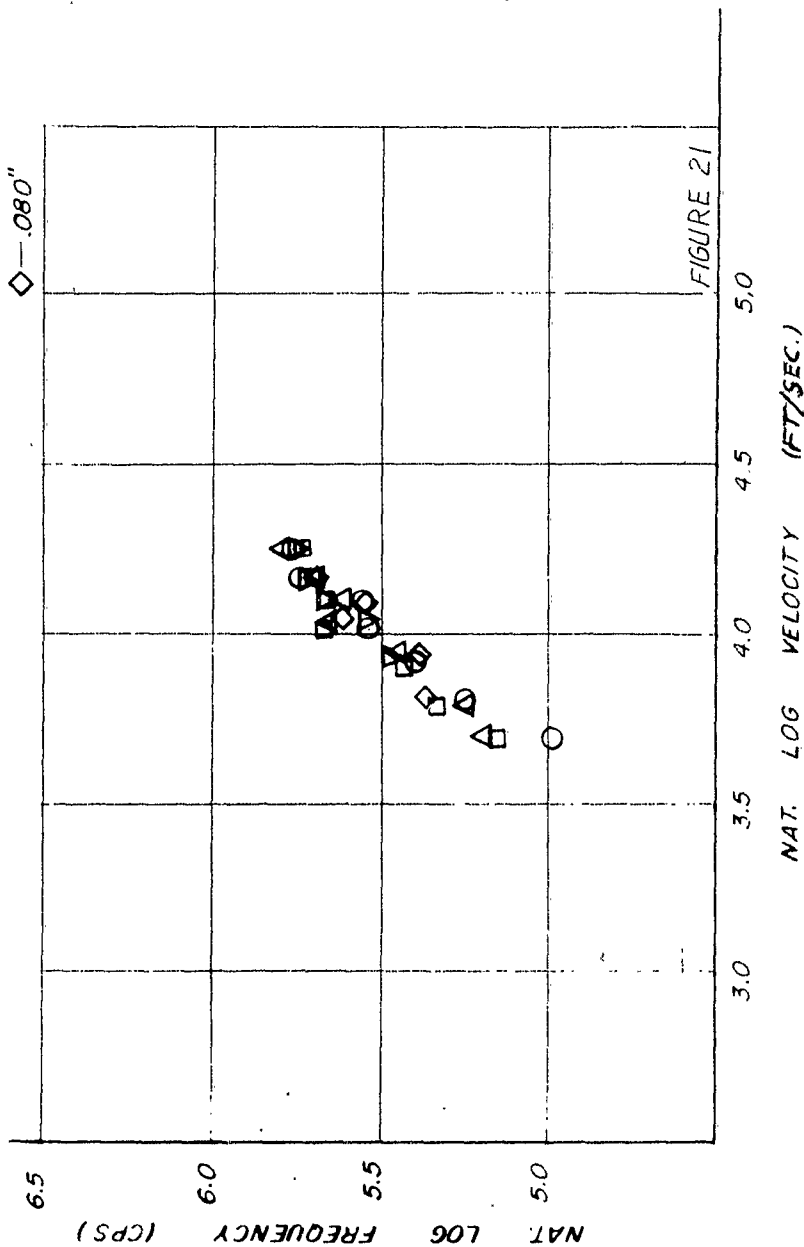
FIGURE 22

FREQUENCY VERSUS VELOCITY

2 1/2" OGIVE NOSE CYLINDER PARALLEL TO AIRSTREAM
STATION 32

○ — 0.010"
□ — 0.020"
△ — 0.040"
▽ — 0.060"
◇ — 0.080"

NAT. LOG VELOCITY (FT/SEC)

NAT. LOG FREQUENCY (CPS)

FIGURE 23

VELOCITY VERSUS STATION
2 1/2" OGIVE NOSE CYLINDER
VISUAL TECHNIQUE

O — BEGINNING OF ORGANIZED MOTION
□ — BEGINNING OF FULLY TURBULENT FLOW

STATION (INCHES)

VELOCITY (FT/SEC)
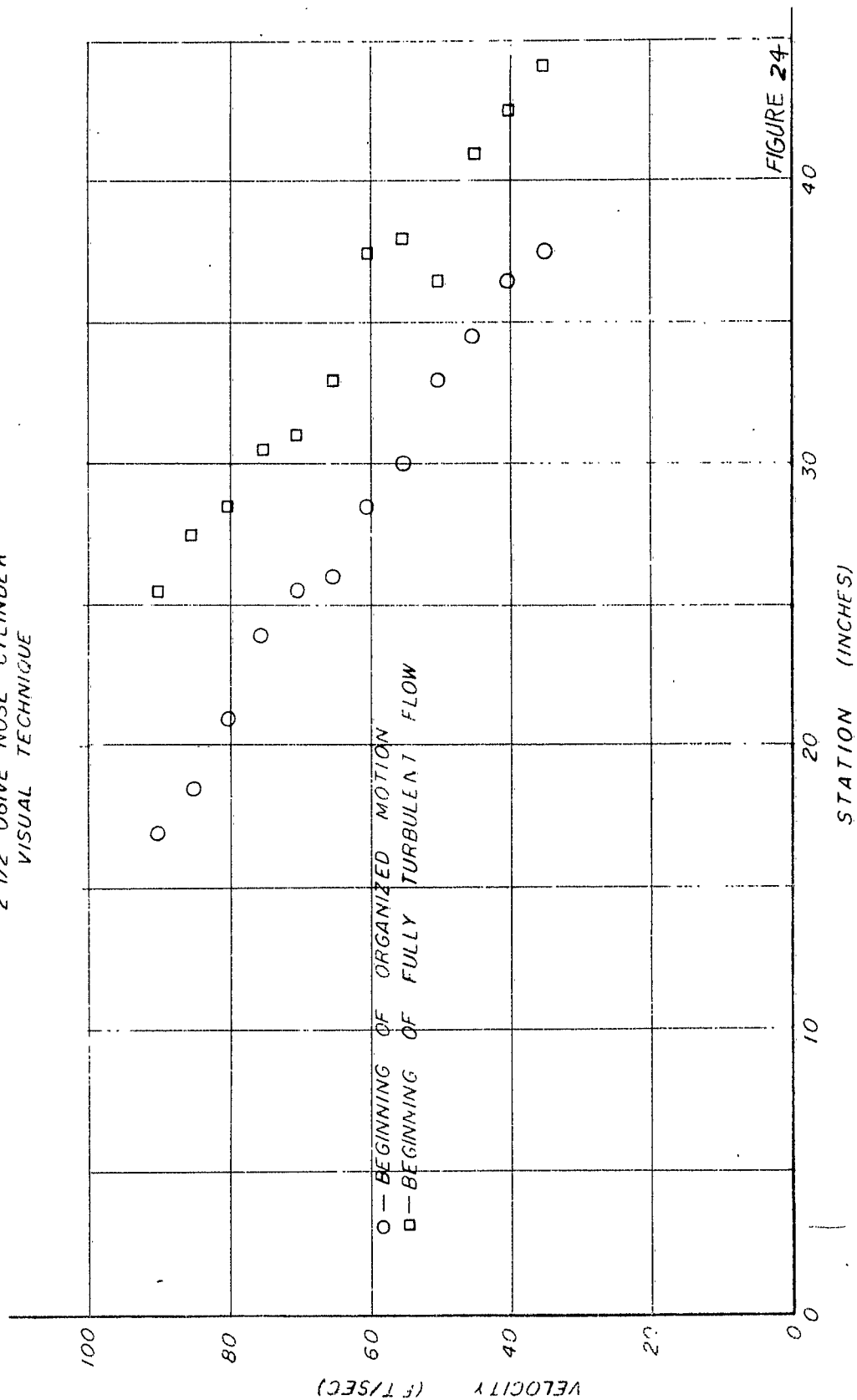
FIGURE 24

FREQUENCY VS VELOCITY
2 1/2" OGIVE NOSE CYLINDER
WITH AUXILIARY MODELS
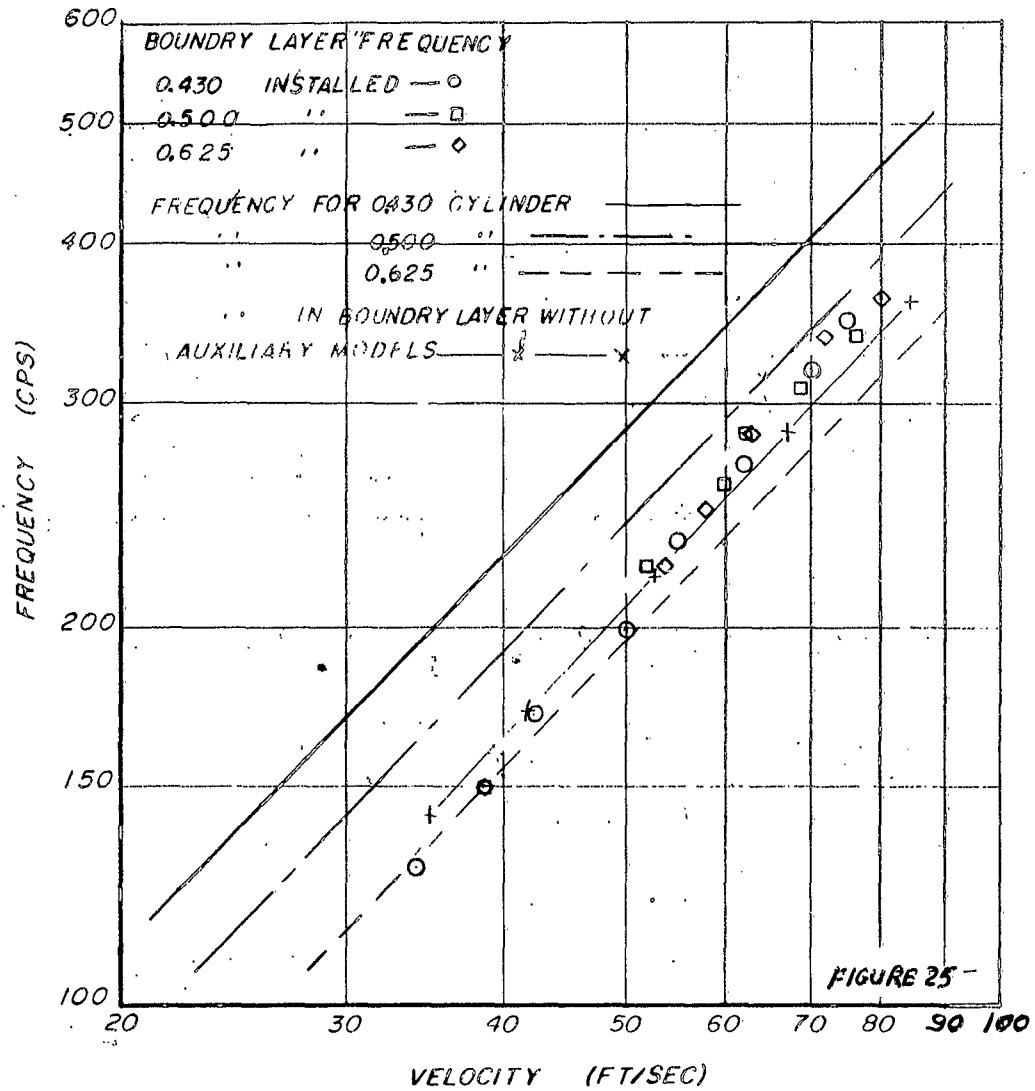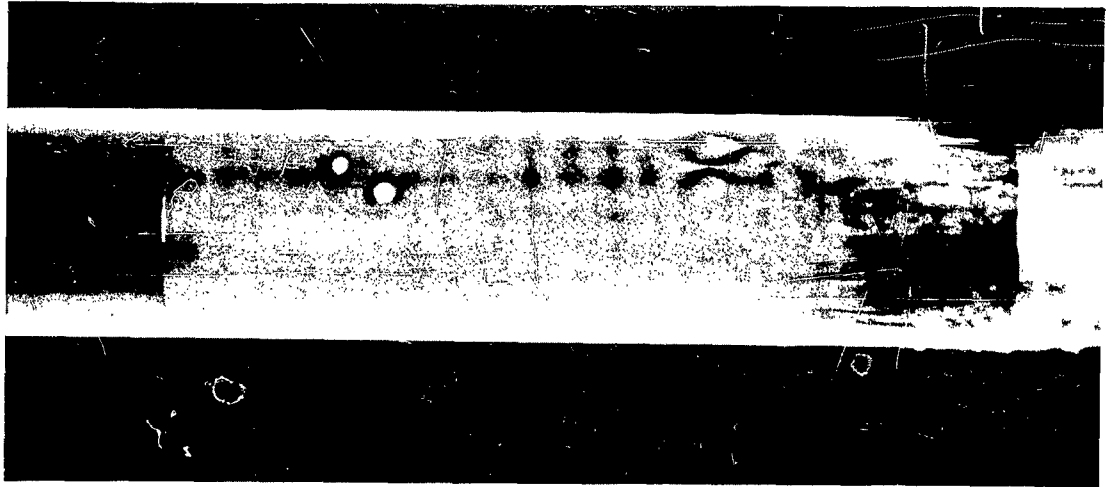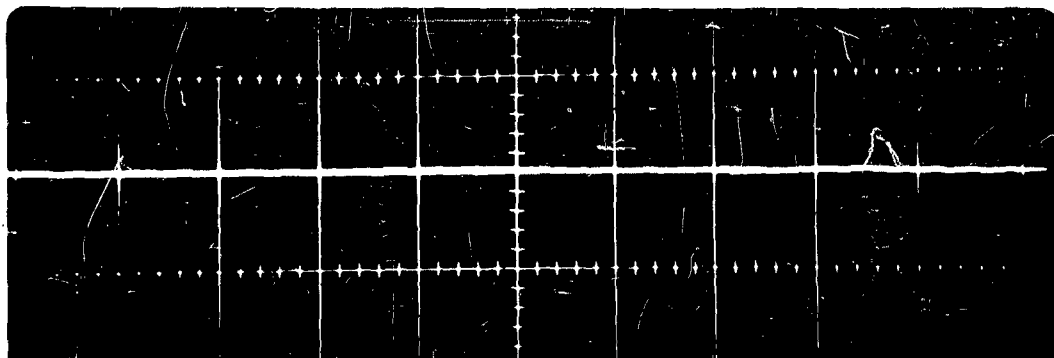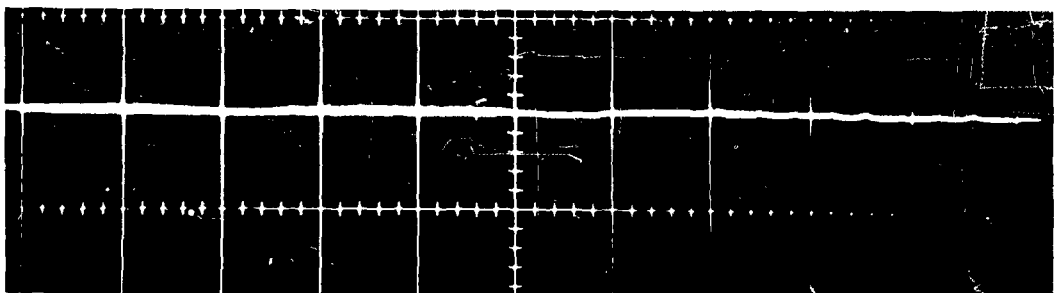
FIGURE 25

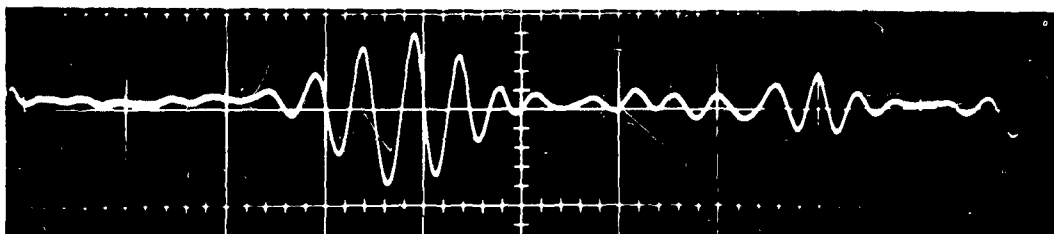Figure 26 Example of "Thatching"
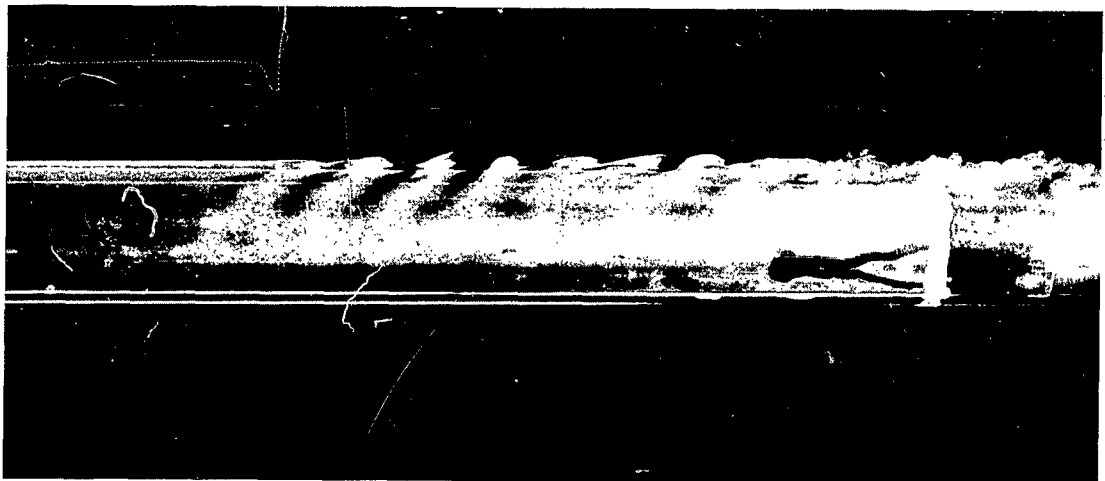
Figure 27 Transition

LAMINAR REGION, STATION 5.25",
HEIGHT 0.010", VELOCITY 42 FPS.

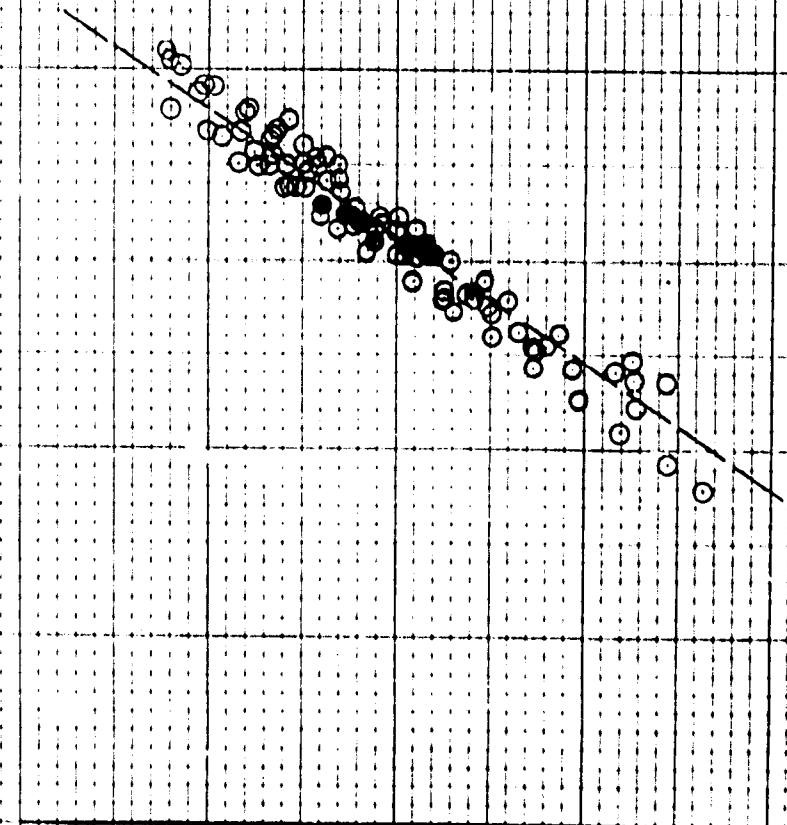
FREESTREAM, STATION 5.25",
HEIGHT 0.260", VELOCITY 42 FPS.

FREESTREAM, STATION 32",
HEIGHT 0.080", VELOCITY 35 FPS.

TRANSITION REGION, STATION 32",
HEIGHT 0.010", VELOCITY 55 FPS.,
FREQUENCY 255 CPS.

Figure 28

FIGURE 29

Legend within figure:
◯ DATA FROM FIGURES 5 & 6
● DATA TAKEN ON {1 DEC. 1962 / 12 DEC. 1962} MOSELEY AUTOGRAPH {14 of 2: 1962}

$$f = 0.549\ U^{3/4}$$

Axis labels:
NATURAL LOG VELOCITY (FPS)
NATURAL LOG FREQUENCY (CPS)

FIGURE 29