1-1-1986

Response of an anemometer with an oscillating hot-wire.

Vernon Marian Fernandez
University of Windsor

Recommended Citation
Fernandez, Vernon Marian, "Response of an anemometer with an oscillating hot-wire." (1986). *Electronic Theses and Dissertations*. 6796.
https://scholar.uwindsor.ca/etd/6796

RESPONSE OF AN ANEMOMETER WITH AN OSCILLATING HOT-WIRE

A Thesis
submitted to the
Faculty of Graduate Studies
through the Department of
Mechanical Engineering in Partial Fulfilment
of the requirements for the Degree
of Master of Applied Science at
the University of Windsor

by
VERNON MARIAN FERNANDEZ

Windsor, Ontario, Canada
1986

ABSTRACT

The effects of various factors on the response of a hot-wire, subjected to a sinusoidal oscillation in a steady flow, have been studied.

A magnetic shaker was used to oscillate the hot-wire. The output of an accelerometer was used to determine the hot-wire velocity. The output from the accelerometer and the hot-wire were recorded on a floppy diskette by using a computer and an A/D converter.

A comparison between the static and dynamic response indicates that within the range of frequency of oscillation (0 to 55 Hz), amplitude of oscillation (0 to 2.52 mm) and mean velocity tested (0.0 to 5.19 m/s), the response of the hot-wire is independent of the frequency and the amplitude of oscillation.

ACKNOWLEDGEMENTS

The author expresses his deep and sincere gratitude to Drs. K. Sridhar and G. W. Rankin for their excellent guidance and generous aid during this study.

Thanks are due to Dr. Z. F. Reif, Head of the Mechanical Engineering Department for his kindheartedness, interest and support.

Thanks are also due to the University of Windsor and the Natural Sciences and Engineering Research Council, Canada for their financial support through Grant Numbers A-2190 and A-1403.

Technical assistance rendered by Mr. Werner Beck and Mr. Robert Tattersall during this study is gratefully acknowledged.

TABLE OF CONTENTS

VI CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A, B, n	constants in King's Law
D	diameter of jet nozzle (m)
d	diameter of the hot-wire (m)
E, E_1, E_2	output voltage of the hot-wire (volts)
f	frequency of oscillation (Hz)
Gr	Grashof number
h	total heat transferred out of the hot-wire (J)
I	electric current (amps)
k	instrument sensitivity factor
k_f	heat conductivity of the gas (J/m/K)
l	length of the wire (m)
m	mass of water collected in drum (kg)
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
R_w, R_o R_g	total electric resistance of the wire (ohms)
S_o, S_i	temperature coefficients of resistance (ohms/K)
T	period of oscillation (s)
T_g	temperature of the gas (K)
T_o	reference temperature (K)
T_w	temperature of the hot-wire (K)
t	time for collecting water (s)
U	velocity of the fluid (m/s)
U_j	jet velocity (m/s)

u	instantaneous probe velocity (m/s)
u_p	probe velocity amplitude (m/s)
v_a	output voltage from charge amplifier (volts)
X	displacement amplitude of oscillation (m)
x	probe position (m)
α	heat transfer coefficient (J/m^2/K)
π	3.14159
ρ_f	density of the gas at the film temperature (kg/m^3)
μ_f	viscosity of the gas at the film temperature (kg/m*s)
ω	radian frequency of oscillation (rad/s)

CHAPTER I

INTRODUCTION

1.1 Subject of Study

One of the main variables in experimental fluid mechanics is the velocity of the fluid. Several methods and instruments have been developed to measure velocities in a flow. The hot-wire anemometer is an instrument used for measurement of mean and fluctuating velocities in turbulent flows. The principle of operation of this instrument relies on the phenomenon of heat flow from a heated element due to forced convection. The sensing element is a fine platinum or tungsten wire, which is heated by electrical power. When introduced into a flow, heat is transferred out of the wire mainly by forced convection. A measure of the heat loss, which is proportional to the power supplied is taken as a measure of the flow velocity.

The hot-wire responds mainly to the component of the velocity normal to the wire axis. The heat loss from the wire is insensitive to the sense of the flow direction and hence the output voltage of the hot-wire, may be expressed in general as:

$$E = g(U) = g(-U). \tag{1.1}$$

This is referred to as directional ambiguity and is represented by a graph in Figure 1.1. The function g relates the output voltage, E, to the flow velocity, U, and is most commonly given by King's Law [H1]. In practice, E is obtained by measurement and the graph (calibration curve), is used to determine U. However, due to the problem of directional ambiguity there are two values of U (positive or negative), for one value of E . Therefore, the hot-wire can only be used to measure the magnitude of the flow. This places a severe limitation on the use of hot-wires, especially in situations where flow reversals occur.

Several researchers have developed techniques to solve this problem and improve the capability of the hot-wire. These techniques, however, suffer from drawbacks of their own. Application of a bias velocity of sufficient magnitude so as to prevent a local flow reversal over the hot-wire has been shown to be an effective solution to this problem. The equipment that has been used to provide the bias velocity, however, is cumbersome to operate and requires a large space [W1]. This problem may be overcome by applying a sinusoidal probe velocity of amplitude u_p as shown in Figure 1.2. The hot-wire output would be recorded between points E-F and G-H, where the velocity is assumed to be constant. Using the above mentioned form of the bias velocity there are two methods of obtaining the magnitude and sense of the flow.

Method 1

The probe is given a sinusoidal velocity of such a magnitude u_p, that the relative velocity $(U-u_p)$ never changes sign. This is shown in Figure 1.3. This way of imposing a probe velocity allows the path of travel to be limited in order to apply this method in small regions. The acceleration, however, would have to be kept low to prevent the hot-wire from breaking. This restricts its application to very low velocities.

Method 2

An improvement over the first solution is to take two readings, one between E-F and the other between G-H in Figure 1.2. The two equations obtained are:

$$E_1 = g(U + u_p) \quad \text{and} \tag{1.2}$$

$$E_2 = g(U - u_p), \tag{1.3}$$

where E_1 and E_2 are the hot-wire voltages. The larger value of these two voltages corresponds to a reading where the flow velocity is opposite to the probe velocity, thus the sense of the flow is determined. Using a calibration curve, the magnitude of U can be obtained. The advantage of this method over the first is that the flow velocity U is not restricted in magnitude to that of u_p.

1.2 Objectives

The objective of the present study is to evaluate the response of an oscillating hot-wire by comparing the dynamic and static calibrations.

The parameters that influence the response of an oscillating hot-wire are:

1) frequency of oscillation,
2) amplitude of oscillation and
3) the mean flow velocity.

The effect that each of these has on the output of the hot-wire anemometer is to be determined.

1.3 Significance

In every fluid flow situation, whether experimental or in industrial applications, knowledge of the flow velocity involves simultaneous determination of three unknowns. These are:

1) the magnitude of the flow,
2) the direction of the flow and
3) the sense of the flow.

In some cases the direction of the flow is known from past experience, however, the magnitude and sense have to be determined. The flow sense is important in situations that experience flow reversals. Flow reversals may be time dependent as in oscillatory flows or space dependent as in recirculating flows. In such cases the hot-wire is subjected to errors due to its ambiguous response to variations in the sense of the flow direction. The oscillating hot-wire can be used in such a case to determine the sense and magnitude of the flow velocity. Oscillatory flows occur in the inlet and outlet pipes of internal combustion engines and piston compressors.

Another area of application of the oscillating hot-wire technique is in situations that experience recirculating flows. In recirculating flows the sense of velocity changes sign as the flow region is traversed. The oscillating hot-wire can be used to measure the sense and magnitude of the flow in such cases. These flows occur around buildings, in wakes, cavities and in certain fluidic devices.

CHAPTER II

LITERATURE SURVEY

The literature covered in this survey can be grouped into three major areas. These are:

1) existing hot-wire techniques used to measure the sense and magnitude of the velocity,
2) hot-wires in oscillation and
3) heat transfer from oscillating heated wires.

2.1 Existing Hot-wire Techniques to Measure the Sense and Magnitude of the Velocity

In order to solve the problem of directional ambiguity several methods have been developed. Although they are conceptually different from the method used in the present work, a brief description is presented in the following.

Neuerburg [NI] designed an instrument to measure flow reversal. The directional sensitivity of this instrument is accomplished by means of a simple hood in the form of an obliquely cut pipe end which partially encloses the probe wire. Due to the "wind shadow" effect there is only one maximum and one minimum output as the probe is turned through 360° in the flow, as shown in Figure 2.1. The disadvantages of this method are that a large obstruction is introduced in the flow and mercury slip rings are required.

Bradbury and Castro [B3] developed a technique which relies on the time of flight required for a heated tracer, emitted by a pulsed wire, to reach a sensor wire placed at a known distance from the pulsed wire. By placing two sensor wires one on each side of the pulsed wire, the sense can be determined (Figure 2.2). The disadvantages are that very specialized electronic equipment and three wires are required.

Cook and Redfearn [CI] constructed a probe, shown in Figure 2.3, similar to the probe constructed by Gunekal et al. [GI]. The directional ambiguity of the flow is resolved by shielding the probe with a disk having a hole in its centre. Two wires are placed close and parallel to each other inside the hole, normal to the hole axis. Due to the effect of the thermal wake of the upstream wire on the downstream wire, the output from the downstream wire is lower than that from the upstream wire. A comparison is made by an electronic logic circuit, which determines the flow direction. The disadvantages are that it introduces a large obstruction in the flow and two wires are required.

The reverse flow sensing hot-wire probe designed by Downing [DI], and shown in Figure 2.4, consists of a single hot-wire with temperature sensors on either side to detect the thermal wake of the hot-wire and hence the sense of the flow. The major disadvantage is that, while it is able to resolve flow reversals, it is unable to cope with large lateral components of velocity. Another drawback is that it is a three wire system, which requires more complex electronics.

The directional sensitivity of the hot-wire anemometer designed by Mahler [M1], is caused by placing one wire in the flow, to be measured and another in the wake of a cylinder, as shown in Figure 2.5. Each wire is placed in a different arm of the bridge. When a current of air passes over the wires there is an imbalance in the bridge and the voltage is measured. The disadvantages are that it uses two hot-wires and hence specialized equipment is required. Also the probe acts as an obstruction.

2.2 Hot -wires in Oscillation

One of the earliest studies on an oscillating hot-wire was published in 1923 by Richards [R1]. In his study and in some of the subsequent work by other researchers, the constant current anemometer was used (at present, constant temperature anemometers are used). These studies are not discussed but are included in the references ([M3], [M4]). Studies concerning the oscillation of a hot-wire which are pertinent to the present work are discussed below.

Perry and Morrison [P1] developed an alternate hot-wire calibration procedure for the use of the hot-wire in determining turbulent fluctuations based on oscillating the hot-wire. The conventional approach is to first obtain a static calibration curve by plotting the output E vs the velocity U. This curve is then differentiated at a set of velocity values to obtain the sensitivity factor, $(\partial E/\partial u)$, at those values. A calibration curve is obtained by plotting $\partial E/\partial u$ vs U.

In the new method of calibration, the hot-wire is oscillated in a mean flow. The rms voltage and velocity are recorded. The sensitivity factor at a particular mean velocity is obtained by dividing the rms voltage by the rms velocity. The calibration curve is obtained by plotting this ratio vs U. The calibration is performed for a peak velocity perturbation in the range of 0.3 to 5 m/s at frequencies of 1 - 15 Hz respectively. The dynamic calibration method gives more accurate results than the conventional calibration method.

Hon and Teong [H2] oscillated a hot-wire in the vertical plane, in a stagnant fluid (air). The output of the hot-wire was observed on an oscilloscope. The output of the hot-wire which was expected to represent a rectified sine wave, actually showed distortions, as shown in Figure 2.6 . They assumed that the oscillating hot-wire heated the surrounding air, along its path and due to natural convection, created a positive temperature gradient along the vertical direction. Thus the output voltage at the lowest point of its travel was higher than that at the top most point.

2.3 Heat Transfer from Oscillating Heated wires

In the references quoted above the main emphasis is on dynamic calibration of a hot-wire. A study was also made of the available basic heat transfer literature on oscillating cylinders and wires.

Armaly and Madsen [A1] experimentally investigated the effect of oscillation on the heat transfer from a heated wire in free convection. They oscillated the wire along a horizontal straight line keeping the wire axis horizontal. The wire was electrically heated. The range of amplitude variation was 0-67.5 mm. and the frequency varied from 0 to 20 Hz. They obtained the correlation,

$$Nu = 0.891*(Re)^{0.33}, \tag{2.1}$$

for $1 < Re < 4$ and

$$Nu = 0.821 * (Re)^{0.385}, \tag{2.2}$$

for $4 < Re < 40$.

Thrasher and Schaetzle [T1] experimentally studied the instantaneous heat transfer from an oscillating wire in free convection. They subjected the wire to an alternating current. Due to the internal resistance of the wire, the alternating current produced thermal expansions and contractions in the wire thus producing the vibrating motion. The frequency of variation of the current matched the natural frequency of the wire which was from 20 Hz to 40 Hz. The amplitude of oscillation was from 0 - 31.75 mm. The wire diameters used were 0.20 mm and 0.08 mm. They obtained the correlation,

$$\mathrm{Nu} = 0.76, \tag{2.3}$$

for $\mathrm{Re} \leq 1.3$ and

$$\mathrm{Nu} = 0.76\,(\mathrm{Re})^{0.291}, \tag{2.4}$$

for $\mathrm{Re} > 1.3$

using a wire diameter of 0.20 mm and

$$\mathrm{Nu} = 0.74, \tag{2.5}$$

for $\mathrm{Re} \leq 1.4$ and

$$\mathrm{Nu} = 0.66\,(\mathrm{Re})^{0.312}, \tag{2.6}$$

for $\mathrm{Re} \geq 1.4$, with a wire diameter of 0.08 mm.

Sreenivasan and Ramachandran [S1] studied the effect of vibration on heat transfer from a horizontal copper cylinder. The cylinder was placed normal to an air stream and was sinusoidally vibrated in a direction perpendicular to the air stream. The flow velocity varied from 5.79 m/s to 28 m/s. The frequency of vibration was 3 Hz to 47 Hz, with an amplitude of 3.75 mm to 16 mm. They obtained the correlation,

$$\mathrm{Nu} = 0.226\,(\mathrm{Re})^{0.6}, \tag{2.7}$$

for $2500 < \mathrm{Re} < 15000$.

CHAPTER III

PRINCIPLE AND THEORY OF HOT-WIRE ANEMOMETER

3.1 General Theory of Hot-wire Anemometry

The detecting element of a hot-wire anemometer consists of a very fine, short metal wire, which is usually made of tungsten or platinum and has a diameter of the order of 5 microns (10^{-6}m); having a length of 1-2 mm and welded to the tips of two prongs. The wire is heated to about 300°C by applying electrical power so that its resistance becomes almost double its ambient value of approximately 3.5 ohms [B1,B2]. The total amount of heat transferred out of the wire depends on:

1) the flow velocity,
2) the difference in temperature between the wire and the fluid,
3) the physical properties of the fluid and
4) the dimensions and physical properties of the wire.

The last three parameters mentioned above are known and kept constant in order to measure the first parameter. The modes by which heat is transferred out of the wire are:

1) conduction,
2) free-convection,
3) forced-convection and
4) radiation.

In general, radiation heat transfer to the ambient air is negligible for wire temperatures less than 300°C. Experimentally it has been determined that the free convection effect is a function of the non-dimensional group, Gr*Pr. Van der Hegge Zijnen [V1] demonstrated that this effect may be neglected if $Re > 0.5$ and if $Gr{*}Pr < 10^{-4}$. For air and a wire of 5 micron diameter, Gr*Pr is of the order 10^{-6}. The effect of conduction to the prongs is minimized by using large posts and hence keeping the heat loss due to conduction a constant.Therefore, when introduced into a flow, the major contribution to the heat transfer is due to forced convection. The convective heat transfer coefficient, which is expressed by the Nusselt number, Nu, is a function of the Reynolds number, Re, Prandtl number, Pr, and Grashof number, Gr [HI].

Kramer's empirical formula, which gives very satisfactory results for many gases [HI], is expressed as

$$Nu = 0.42\, Pr^{0.2} + 0.57\, Pr^{0.33} * Re^{0.5}, \tag{3.1}$$

for $0.01 < Re < 10{,}000$, where

$$Nu = \alpha\, d / k_f, \tag{3.2}$$

and α is the heat transfer coefficient; k_f, the heat conductivity of the gas at the film temperature and d is the diameter of the wire. The heat loss per unit time, h, out of the wire with length l and uniform temperature distribution is given by

$$h = \alpha\, \pi\, d\, l\, (T_w - T_g) \tag{3.3}$$

where T_g and T_w are the gas and wire temperature respectively. When the value of α is substituted in Equation 3.3, according to Equation 3.1 and Equation 3.2,

$$h = k_f \pi l (T_w - T_g) [0.42 Pr^{0.2} + 0.57 Pr^{0.33} * Re^{0.5}]. \tag{3.4}$$

For thermal equilibrium conditions, this heat loss per unit time from the wire must be equal to the amount of heat generated per unit time by the electric current passing through the wire; i.e.; it must be equal to I^2R_w. Where I is the electric current through the wire and R_w the total electric resistance of the wire. Thus for the thermal equilibrium of the wire

$$I^2R_w = \pi k_f l (T_w - T_g) [0.42 Pr^{0.2} +0.57 Pr^{0.33} * Re^{0.5}]. \tag{3.5}$$

Also, the resistance of the wire R_w, may be expressed in terms of the resistance R_o and a series expansion as

$$R_w = R_0 [1 + S_0 (T_w - T_0) + S_1 (T_w - T_0)^2 + \text{-----}] \tag{3.6}$$

where S_0, S_1, ... are the temperature coefficients of electric resistivity of the wire and R_0 is the resistance of the wire at a reference temperature T_0. Neglecting higher order terms, Equation 3.6 may be expressed as

$$R_w = R_0 [1+ S_0(T_w-T_o)]. \tag{3.7}$$

From Equation 3.7

$$(R_w - R_o)/(R_oS_o) = T_w - T_o \tag{3.7a}$$

and

$$(R_g - R_o)/(R_oS_o) = T_g - T_o. \tag{3.7b}$$

Where R_g is the resistance of the wire at the gas temperature. Using Equation 3.7a and Equation 3.7b, the temperature difference may be expressed as

$$T_w - T_g = (R_w - R_g)/(S_0 R_0). \tag{3.8}$$

Substituting Equation 3.9 into Equation 3.6 the relationship can be written as

$$I^2 R_w = k_f \pi l(Rw - Rg)[0.42\ Pr^{0.2} + 0.57\ Pr^{0.33} * Re^{0.5}]/(R_0S_0). \tag{3.9}$$

For application to hot-wire anemometry, it is convenient and usual to write this relationship in the form

$$(I^2 R_w) / (R_w - R_g) = A + B\ \sqrt{U}, \tag{3.10}$$

where

$$A = 0.42\, \pi\, K_f l(Pr^{0.20})/(S_0R_0) \tag{3.11}$$

U is the velocity of the fluid and

$$B = 0.57\, k_f\, (Pr^{0.33})(\rho_f d/\mu_f)^{0.50}/(S_0 R_0). \qquad (3.12)$$

Equation 3.10 is a widely accepted relationship and is known as King's law. It is generally used for calibrating the hot-wire.

The wire forms one arm of a Wheatstone Bridge, as shown in Figure 3.1. The heat transferred is indirectly measured as a change in the voltage. There are two types of anemometers.

1) Constant current anemometer (CCA): In this case, the heating current which passes through the wire is kept constant and the variation in the voltage across the wire is taken as a measure of the flow velocity. Due to the thermal inertia of the wire it cannot follow fluctuations which have a frequency higher than approximately a thousand Hertz [B2, H1]. To improve the performance at high frequencies, a compensation circuit must be used.
2) Constant Temperature Anemometer (CTA): This type uses a negative feedback loop in an attempt to keep the resistance of the wire constant. A feedback amplifier is used across the diagonal of the Wheatstone Bridge which senses a bridge imbalance. If an imbalance is detected the current through the hot-wire is changed so as to keep the temperature and hence the resistance of the wire constant. The voltage across the feedback resistor is taken as a measure of the flow velocity.

CHAPTER IV

EXPERIMENTAL DETAILS

4.1 Introduction

This chapter describes the facility constructed for the experiment. It also includes a description of the experimental procedure. A schematic diagram of the setup is shown in Figure 4.1 and consists of three main units. These are:

1) the Flow Unit,
2) the Shaker and Hot-wire Unit and
3) the Data Acquisition Unit.

4.1.1 The Flow Unit

This unit was constructed to provide a constant mean flow of air and consisted of a constant head tank, airtight drum, weighing scale and settling chamber. The constant head tank (approximately 479 mm by 479 mm by 277 mm) was suspended at an approximate height of 3.9 meters above the floor. Water was supplied to the constant head tank by a 25 mm diameter nozzle, which was connected to the main water supply and the water level in the constant head tank was maintained by overflow outlets (nozzle and outlets are not shown in the diagram).

The main outlet was at the base of the tank and had a nozzle diameter of approximately 32 mm. It was connected to a copper tube through a plastic hose, which was provided for flexibility. The copper tube had an internal diameter of 25 mm, and ended in an airtight drum. A valve mounted on the copper tube, controlled the flow of water into the drum. In order to prevent air from escaping through the tube, the lower end was connected below the water level in the drum. The diameter of the drum was approximately 550 mm. The drum was placed on a scale, to measure the weight of the water collected in the drum. A drain with a stop cock (not shown in the diagram) was provided at the base of the drum to drain it when necessary. An inverted L-shaped copper tube of diameter 15.88 mm was connected to the upper lid of the drum. This was the main air outlet from the drum and was connected to the jet chamber by means of plastic tube. The jet chamber consisted of a settling chamber and a nozzle. The settling chamber was made of a cylindrical shell, fabricated out of sheet metal and closed at one end by a sheet metal disc, through which the air supply was connected. Two wire mesh screens were provided inside the settling chamber. The length of the chamber was approximately 693 mm and the outer diameter was 302mm . The other end of the jet chamber consisted of a plexiglass disc on which the jet nozzle was mounted. The inner diameter of the nozzle was 19.05 mm.

4.1.2 The Shaker and Hot-wire Unit

The unit consisted of a magnetic shaker, power amplifier, shaker controller, accelerometer, charge amplifier, Constant Temperature Anemometer and hot-wire probe. The hot-wire probe (DISA Type P11), was mounted in a brass sleeve, which was threaded onto a steel rod. The hot-wire was modified by connecting lead wires directly to the posts. Details of the brass sleeve and steel rod assembly are shown in Figure 4.2.

The natural frequency of the steel rod and brass sleeve assembly was greater than the operating frequency range.

The steel rod assembly was mounted on a flat plate whose acceleration was monitored by an accelerometer (B&K Type 4339) also mounted on it. The plate was mounted on a magnetic shaker head (B&K Type 4811). The displacement range of the shaker was ± 6.35 mm and had a velocity range of 0 to1.25 m/s. The mass of the head was 0.18 kg and the maximum acceleration was 210 g (2060 m/s^2). The magnetic shaker was mounted on a steel frame, which conformed to the exciter body (B&K Type 4801S) which was mounted on a work bench. The oscillation produced was in the horizontal plane. The magnetic shaker was connected to a shaker controller (B&K Type 1047), through a power amplifier (B&K Type 2707). In order to ensure an accurate sine wave , a closed loop feedback system was employed. An accelerometer (B&K Type 4339) was used in conjunction with the charge amplifier (B&K Type 2626), to measure the probe velocity and served as a feedback sensor.

4.1.3 The Data Acquisition Unit

An Apple II microcomputer was the heart of the data acquisition unit. An A/D converter card manufactured by Interactive Structures, Inc. (Type AI13), was used. The card was inserted into slot number 5 of the Apple II microcomputer. The AI13 A/D converter had the capability of reading a voltage between -5v to +5v and returned a number proportional to the result for analysis. It had 16 input channels each of which could be scaled to any of the 8 full-scale ranges. One reading could be taken in about 128 * 10^{-6}s. In order to activate the A/D converter to record the readings and feed it into the computer memory, program B.1 was developed in Basic. The program makes use of an assembly language subroutine, program B.2. Program B.1 and program B.2 are listed in appendix B. The accuracy of the A/D converter was 0.024% of full scale . Since some of the voltages were higher than 5 volts, a signal conditioner which subtracted a fixed voltage was used. The CTA and charge amplifier were connected to channels 1 and 2 of the A/D converter respectively.

4.2 Procedure

The probe and steel rod assembly were mounted on the shaker head. The CTA (DISA Type D01) was then set up according to the instructions given in the manual for a 1:20 bridge ratio. The probe was connected to the CTA unit through a 5-metre cable. Before using the CTA for any measurements, optimum adjustments of the 'GAIN', HF FILTER' 'L' and 'Q' settings had to be made, while applying a square wave signal to the wire. This was done until an output, shown in Figure 4.3 (as per the manual), was obtained.

After the optimum settings were made, the probe support axis (see Figure 4.2) was aligned with the axis of the jet. The hot-wire was then placed in the potential core region of the jet and subjected to oscillations at a known frequency and amplitude. The frequency was controlled by means of the shaker controller.

Water was supplied to the constant head tank and a steady overflow maintained. The flow into the drum was then started by controlling the valve. After permitting sufficient time for the flow to settle, the computer was activated and the data recorded. The computer recorded the hot-wire and accelerometer voltage alternately, every 128 microseconds. The data were stored in the computer memory and later saved on a diskette. This was done by running program B.1 of Appendix B.

The same procedure was repeated for different jet velocity settings, (0 - 5.2m/s), while maintaining the same amplitude and frequency of oscillation. This constituted one data set. Different data sets were obtained by changing the amplitude settings, (0 - 2.5 mm), for frequencies of 25, 35, 45 and 55 Hz. After every fifth data set, a static calibration was performed, to check for drifts in the instrument.

CHAPTER V

RESULTS AND DISCUSSION

In section 1.1, the problem of directional ambiguity was discussed. Thus, when a hot-wire is subjected to a sinusoidal velocity in a stagnant fluid (air), the output voltage is expected to be a rectified sine wave. The hot-wire output would therefore have twice as many peaks as the probe velocity (or acceleration). This effect is shown in Figure 5.1. The output from the hot-wire as well as the output from the accelerometer are plotted on the y-axis and time on the x-axis, for a frequency of 35 Hz, an amplitude of 2.35 mm and a jet velocity of 0 m/s. However, when the hot-wire is oscillated in a jet with a mean velocity greater than or equal to the amplitude of the probe velocity, there is no rectification and the output is a sine wave superimposed on a dc. voltage. This is shown in Figure 5.2 for the same conditions as in Figure 5.1 except the jet velocity is 4.93 m/s.

5.1 Data Reduction

The maximum hot-wire voltage corresponding to the maximum probe velocity and the time mean voltage were determined from the previously recorded data using program B.3. Program B.3 is listed in Appendix B and is briefly explained below. In order to compute the maximum hot-wire voltage, the program first scans the accelerometer output for data points that lie on either side of the zero line, shown in Figure 5.3 (between 85^0 and 95^0). The data consist of a sequence of alternate hot-wire and accelerometer output voltage readings, hence, the value of the data point that lies between the above mentioned acceleration data points is a maximum and therefore stored. This value, when multiplied by a gain constant represents the hot-wire voltage, which corresponds to the maximum relative velocity (i.e., probe velocity at its maximum value in the direction opposite to the jet velocity). At least seven hot-wire voltages were stored in an array. The elements in this array were averaged. This average voltage is shown in the first column of Table 1 for $f = 25$ Hz, $X = 2.16$ mm.

The probe velocity amplitude was determined by scanning the accelerometer data for maximum and minimum values. These values were first averaged and then multiplied by $k/2\pi f$, where k is an instrument sensitivity factor and f is the frequency. The jet velocity was obtained by using the formula

$$U_j = 4m/\rho \pi D^2 t, \tag{5.1}$$

where m is the mass of the water collected in the drum, is the density of water, D is the diameter of the jet nozzle and t is the time required for collecting the water. The relative velocity which is entered in the second column of the above mentioned table, is obtained by subtracting the probe velocity amplitude from the jet velocity. The program then computes a time average of a certain number of complete cycles of the hot-wire voltage and it is tabulated in the third column. The fourth column contains the jet velocity. Each row in Table 1 corresponds to a different value of jet velocity. Tables 2 to 19 are similar to Table 1 but obtained for different combinations of f and X.

A static calibration of the hot-wire was also performed by placing the hot-wire in the potential core of the jet. The hot-wire voltage readings for different jet velocities were recorded. The static calibration data are presented in Table 20. A graph of the voltage vs the velocity gives the static calibration curve. Dynamic calibration curves were obtained by plotting the maximum and mean hot-wire voltage on the y-axis and the relative velocity on the x-axis. A comparison and discussion of the calibration curves corresponding to the maximum, mean and static hot-wire values are presented in the following sections.

5.2 Comparison of Maximum and Mean Calibrations

A comparison of the above mentioned calibrations is presented in Figures 5.4 through 5.22. At high relative velocity there is no significant difference between the two methods of processing the data. This indicates that the probe velocity has negligible effect on the response of the hot-wire at a fixed frequency and amplitude. Time averaging of the instantaneous voltage to obtain the mean voltage, in effect amounts to nulling the effects of the probe velocity. However, it is noticed that the calibration curve which corresponds to the maximum values is lower than the mean curve. As can be seen from the figures, the two curves converge as the mean flow increases. This effect can be explained by the results presented by Perry and Morrison [P1]. As the flow velocity increases, while holding the probe velocity amplitude constant, the relative velocity increases and the system sensitivity, $\partial E/\partial U$, decreases. The lower the value of $\partial E/\partial U$, the closer the two curves get. e.g., if $\partial E/\partial U$ is zero the two curves will coincide exactly.

At low relative velocity there is a significant difference between the two methods. This observation may be explained in the following way.

Consider the time variation of the position of a hot-wire probe which is oscillating in a jet of velocity U_j. This is shown in Figure 5.23. The path of oscillation is in the x-direction along ABC. The probe velocity is maximum at point B (i.e., X = 0) and the maximum used in this study occurs at B' (i.e., $t = t_{probe}$). When the hot-wire is at point A it heats a particle of the fluid. The time for this heated particle to be transported by the jet to point B is given by

$$t_{particle} = X/U_j, \tag{5.2}$$

where X is the distance between point A and B (displacement amplitude). The time required by the probe to travel along ABCB is given by

$$t_{probe} = 3*T/4, \tag{5.3}$$

where T is the period of oscillation. Equation 5.3 can be expressed as

$$t_{probe} = 3/4f, \tag{5.4}$$

where f is the frequency of oscillation. For a sinusoidal oscillation of frequency f the probe velocity amplitude u_p is given by

$$u_p = 2\,\pi*X*f. \tag{5.5}$$

Using Equations 5.4 and 5.5

$$t_{probe} = 3\,\pi*X/2u_p. \tag{5.6}$$

In order that the heated particle not affect the probe output, the time for the particle to reach point B should be less than the time required by the probe. Thus combining Equations 5.2 and 5.6

$$U_j/u_p > 2/3\,\pi = 0.21. \tag{5.7}$$

When the ratio U_j/u_p is less than or equal to 0.21 the output will be affected by the heated particle. The hot-wire output in this case is expected to be lower than the output at a velocity of magnitude u_p. This is due to the fact that when the hot-wire is placed in a heated region, the temperature difference between the hot-wire and its surroundings decreases. As a result the heat transferred out of the hot-wire reduces, causing its output voltage to drop. In the above discussion the heat diffusion effects have been neglected.

A value of $U_j/u_p = 0.21$ corresponds to a relative velocity of $1.21*u_p$. This condition is shown by a vertical dotted line in Figures 5.4 to 5.22 inclusive. It is seen that the difference between the two methods is applicable in the region to the left of the dotted line. This agrees with the explanation given above.

5.3 Comparison of Maximum Response for Different Amplitudes

The effect of variation of the amplitude of oscillation at a fixed value of frequency on the maximum output of the hot-wire is shown in Figure 5.24 to Figure 5.27. These figures indicate that, for the range of variables considered, the amplitude of oscillation has negligible effect on the response of the hot-wire. A small difference between the curves is observed at low relative velocities. This is possibly due to the fact that the probe velocity is directly dependent on the amplitude at a constant frequency and hence the value $1.21*u_p$ shifts to the right with increasing amplitude.

5.4 Comparison of Maximum Response for Different Frequencies

Figure 5.28 shows the calibration corresponding to the maximum values of the hot-wire output for frequencies of 25, 35, 45 and 55 Hz at an amplitude of 2.00 mm. This figure indicates that, within the experimental range, the frequency has negligible effect on the response of the hot-wire. A slight scatter is observed at lower jet velocities. At higher jet velocities, however, the points seem to be distributed about a mean value. There is one exception. At a frequency of 35 Hz, it is noticed that the calibration curve is higher than the rest, considering an uncertainty of 0.01volts (see appendix A). An explanation of this observation is not currently available.

5.5 Comparison of Static and Dynamic Calibration

The calibration corresponding to the maximum and mean values at a frequency of 25 Hz and an amplitude of 2.16 mm are compared with the static calibration in Figure 5.29. It is observed that the dynamic calibration compares well with the static calibration. As the frequency tends to zero, it is expected that the static calibration would coincide with the dynamic calibration. Hence it appears that King's Law can be used, with negligible error at frequencies lower than 25 Hz.

In the region where the relative velocity is less than 1.21 times the probe velocity amplitude, the calibration curve corresponding to the maximum and the mean values disagree as seen previously. However, the static and mean calibration curves agree. At a relative velocity of 0.0 m/s, the mean voltage is higher than the static value. This may be explained as follows. Whenever the probe velocity amplitude is more than the jet velocity, the hot-wire voltage is, approximately, a rectified sine wave and hence its time average is higher than the unrectified signal.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The response of an oscillating hot-wire in a mean flow has been studied experimentally. This information leads to the following conclusions.

1) The static and maximum calibration curves indicate that, for a relative velocity greater than $1.21 * u_p$, the maximum calibration curve is close to the static. However, at lower relative velocties there is a significant difference.

2) The effect of the amplitude on the response of an oscillating hot-wire is negligible within the range of the experiments.

3) The effect of the frequency on the response of the hot-wire is negligible within the range of the experiments.

6.2 Recommendations

1) The experiment should be performed with a different style and size of probe (eg. DISA sub-miniature probe).

2) The effect of orientation of the hot-wire axis, on the voltage output waveform should be investigated.

3) The response of the hot-wire should be studied more closely at lower jet velocities where the ratio of jet velocity to probe velocity is less than unity.

REFERENCES

A1 Armaly, B.F. and Madsen, D.H., "Heat Transfer From An Oscillating Horizontal Wire". Journal of Heat Transfer, May 1971, vol 93, pp 239-40.

B1 Bradshaw, B.A., Experimental Fluid Mechanics. Pergamon Press: London, 1970. pp 88-95.

B2 Bradshaw, B.A., An Introduction To Turbulance and It's Measurement. Pergamon Press: London, 1941. pp 106-133.

B3 Bradbury, L.J.S. and Castro, I.P., "A Pulsed-wire Technique for Velocity Measurement in Highly Turbulent Flows". Journal of Fluid Mechanics, 1971, vol 47, Part 4, pp 657-691.

C1 Cook, N.J. and Redfearn, D., "Calibration and Use of A Hot-wire Probe for Highly Turbulent and Reversing Flows". Journal of Industrial Aerodynamics, 1976, vol 1, pp 221-231.

D1 Downing, P.M., "Reverse Flow Sensing Hot-wire Anemometer". J. Phy. E.: Scientific Instruments, 1972, vol 5, pp 849-851.

F1 Fernandez, V.M., Rankin, G.W., Sridhar, K. and Swaminathan, M.K., "Response of An Oscillating Hot-wire", International Symposium on Fluid Control and Measurement, Tokyo, Japan, September 1985.

G1 Gunekal, D.A., Patel, R.P. and Weber M.E., "A shielded Hot-wire Probe for Highly Turbulent Flows and Rapidly Reversing Flows". Ind. Eng. Chem. Fundam, 1971, vol 10, pp 627-631.

H1 Hinze, J.O., Turbulence. McGraw-Hill: New York, 1959. pp 73-122.

H2 Hon, C.C. and Teong, K.H., "Hot-Wire Anemometer Calibration at Low Speeds". Final Year Project Report, Department of Mechanical Engineering, University of Windsor, Ontario, Canada, 1984.

K1 Kirchoff, R.H. and Burbank, R.A., "Response of a Hot Wire Oscillating in a Shear Flow". AIAA Journal, 1974, Vol 12, No 1, pp 96-98.

M1 Mahler, O.S., "Bidirectional Hot-wire Anemometer". Rev. Sci. Instruments, 1982, vol 53, No 9, pp 1465-1466.

M2 Mulhearn, P.J. and Finnigan, J.J., The Journal of Physics,1978, E. 11, pp. 679-81.

M3 Maxwell, R.S., "The Escape of Heat from a Harmonically Oscillating Hot-wire". Philosophical Magazine and Journal of Science, 1928, vol. 6, No 39, pp. 945-965.

M4 Martinelli, R.C. and Randall, R.D., "The Behavior of a Hot-wire Anemometer Subjected to a Periodic Velocity". Transactions of ASME, January,1946, vol. 68, pp. 75-79.

N1 Neuerburg, W., "Directional Hot-wire Probe". DISA Information No 7, January 1969. pp 30-31.

P1 Perry, A.E. and Morrison, G.L., "Static and Dynamic Calibration of Constant Temperature Hot-wire Systems". Journal of Fluid Mechanics, 1971, vol 47, Part 4, pp 765-777.

R1 Richards, R.C., "The Resistance of a Hot-wire in an Alternating Air Current". Philosophical Magazine and Journal of Science,1923, No 45, pp. 926-934.

S1 Sreenivasan, K. and Ramachandran, A., "Effect of Vibration on Heat Transfer from a Horizontal Cylinder to a Normal Air Stream". Int. J. Heat Mass Transfer, 1961,vol. 3, pp. 60-67.

T1 Thrasher, B.H. and Schaetzle, W.J., "Instantaneous Measurement of Heat Transfer from An Oscillating Wire in Free Convection". Transactions of ASME, Journal of Heat Transfer,August 1970, pp 439-446..

V1 Van Der Hegge Zijnen, B.G., "Modified Correlation Formulae for the Heat Transfers by Natural and by Forced Convection from Horizontal Cylinders". Applied Science Research, section A, vol. 6, pp. 129-140.

W1 Watmuff, J.H. and Perry, A.E., "A Flying Hot-wire System". Experiments in Fluids, 1983, vol. 1, pp. 63-71.

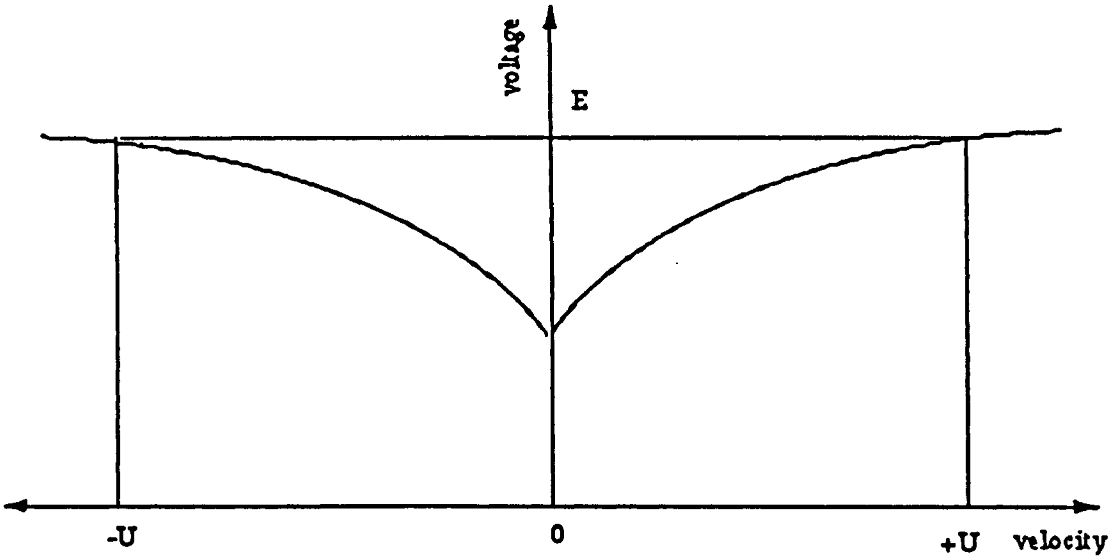


Figure 1.1 Calibration Curve of a Hot-wire

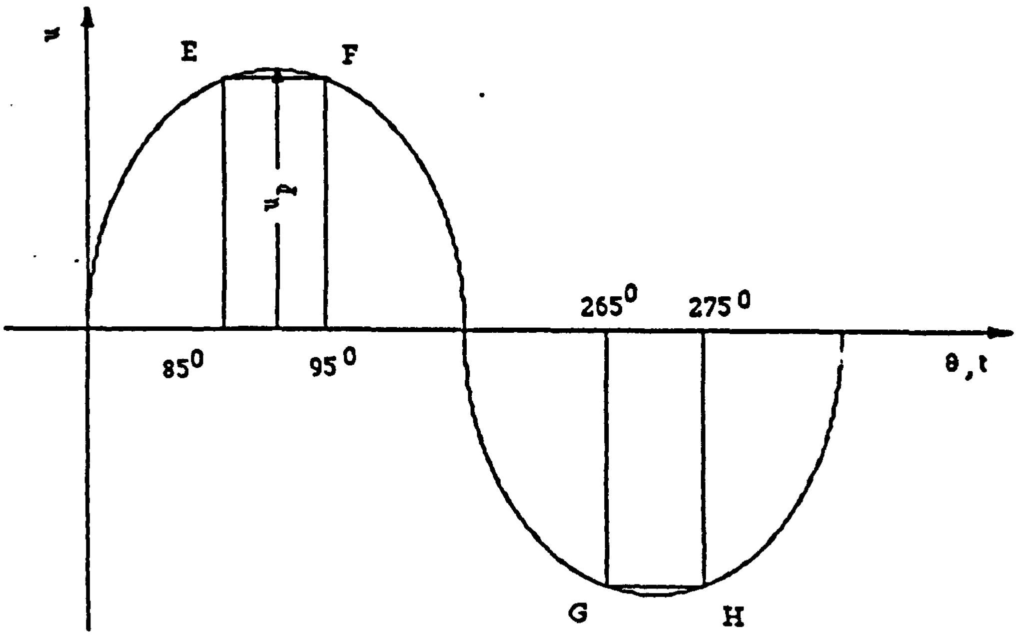


Figure 1.2 Sinusoidal Probe Velocity

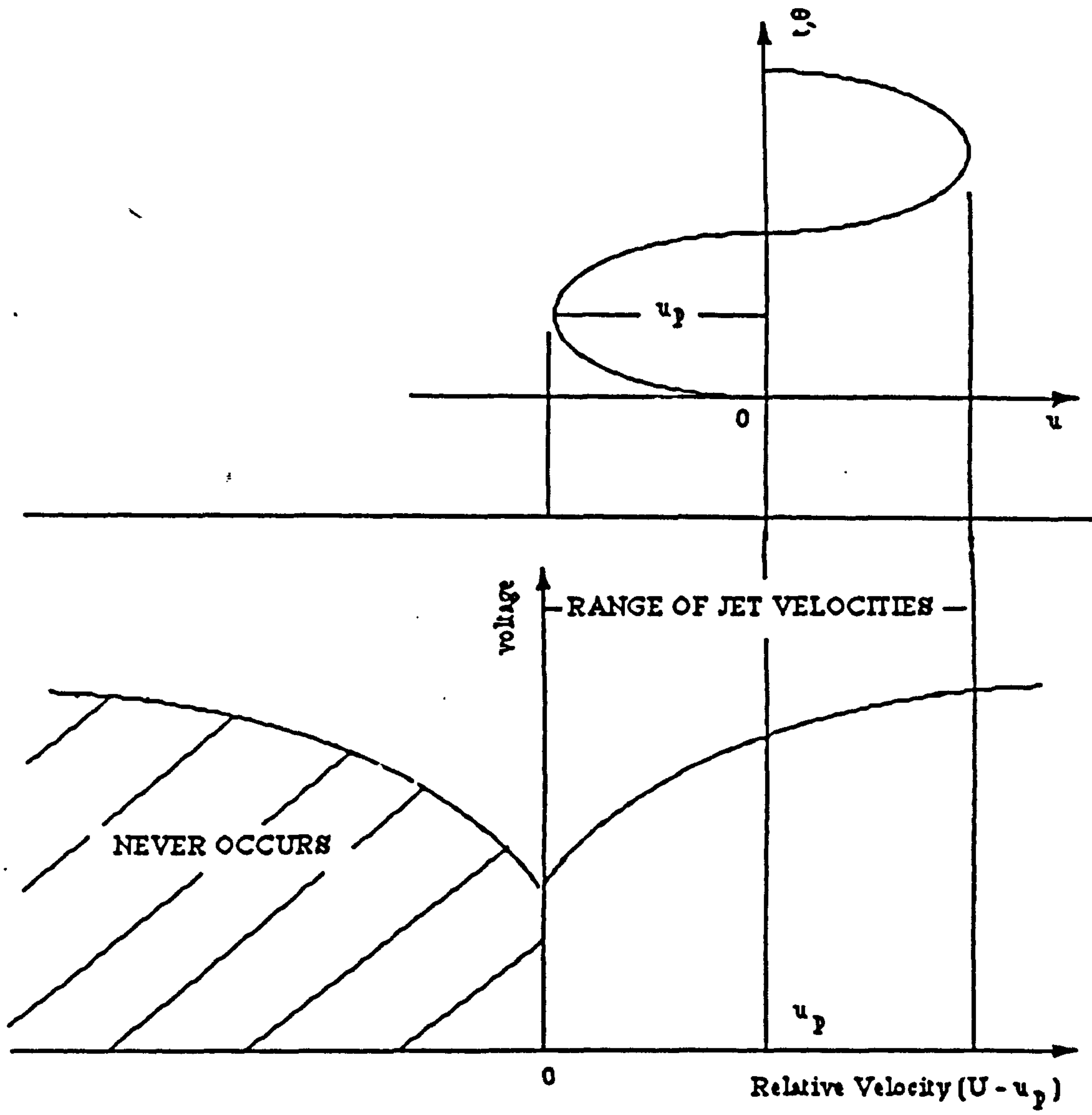


Figure 1.3 Sketch of Hot-wire Voltage vs Relative Velocity

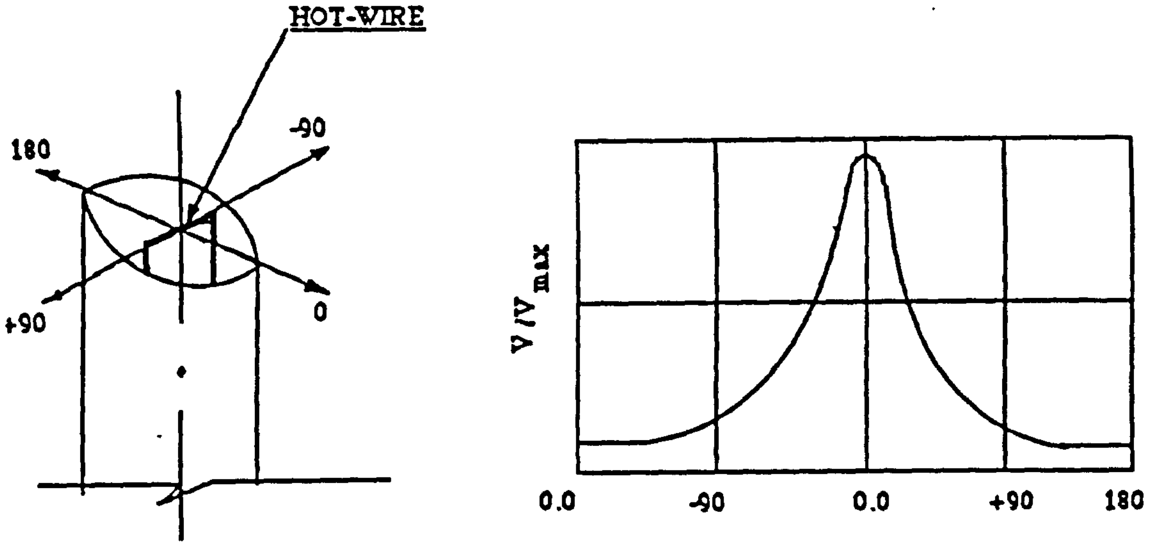


Figure 2.1 Probe with Hood and the Velocity Output Characteristic [N1]

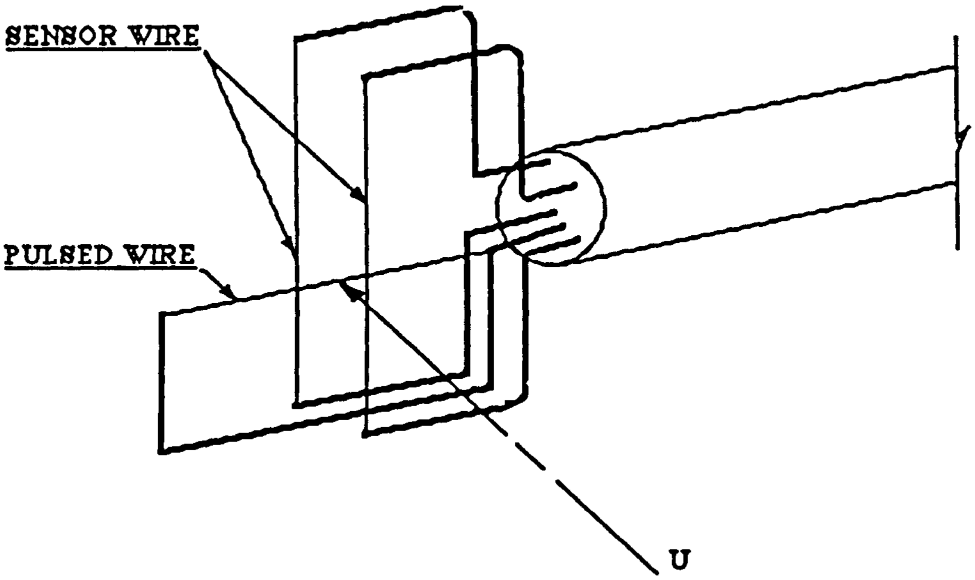


Figure 2.2 Pulsed-wire Probe [B3]

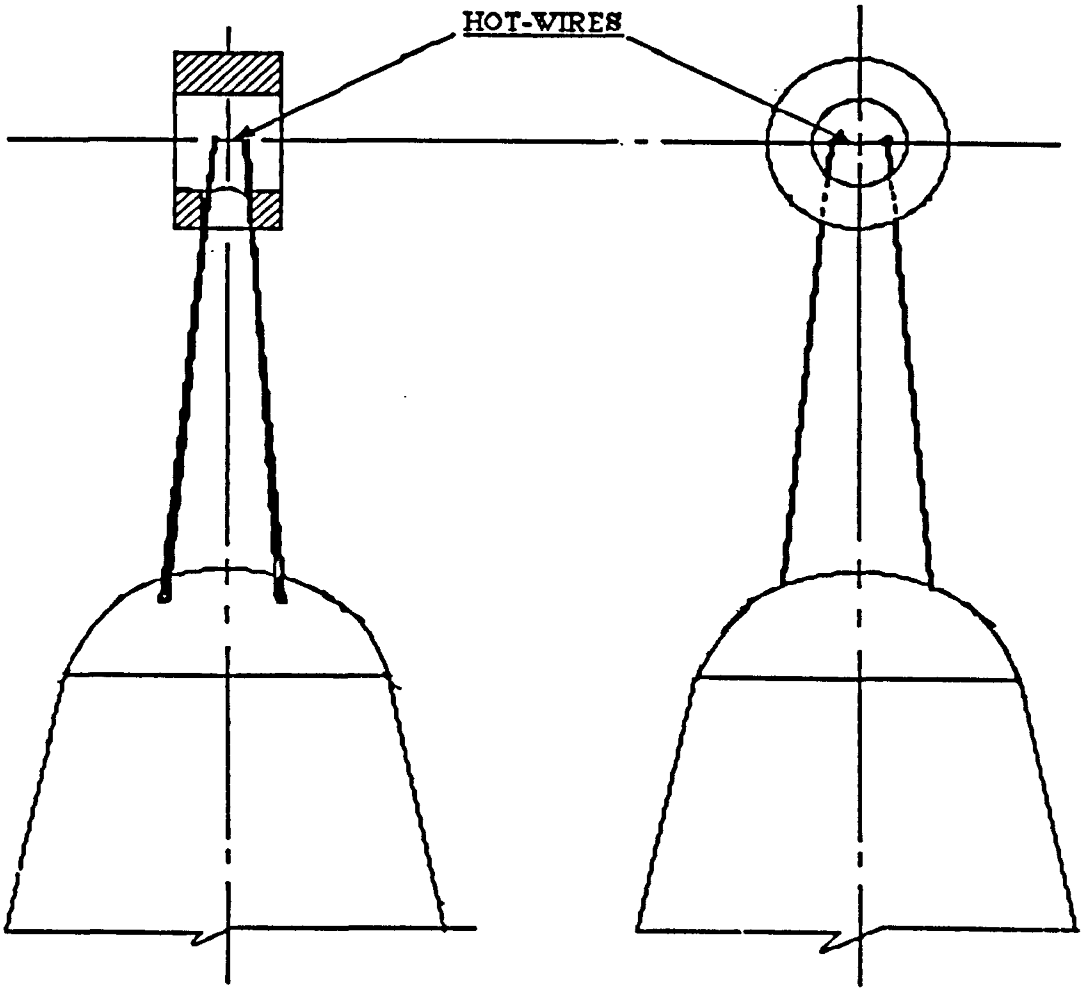


Figure 2.3 Shielded Dual-Sensor Hot-Wire Probe [C1]

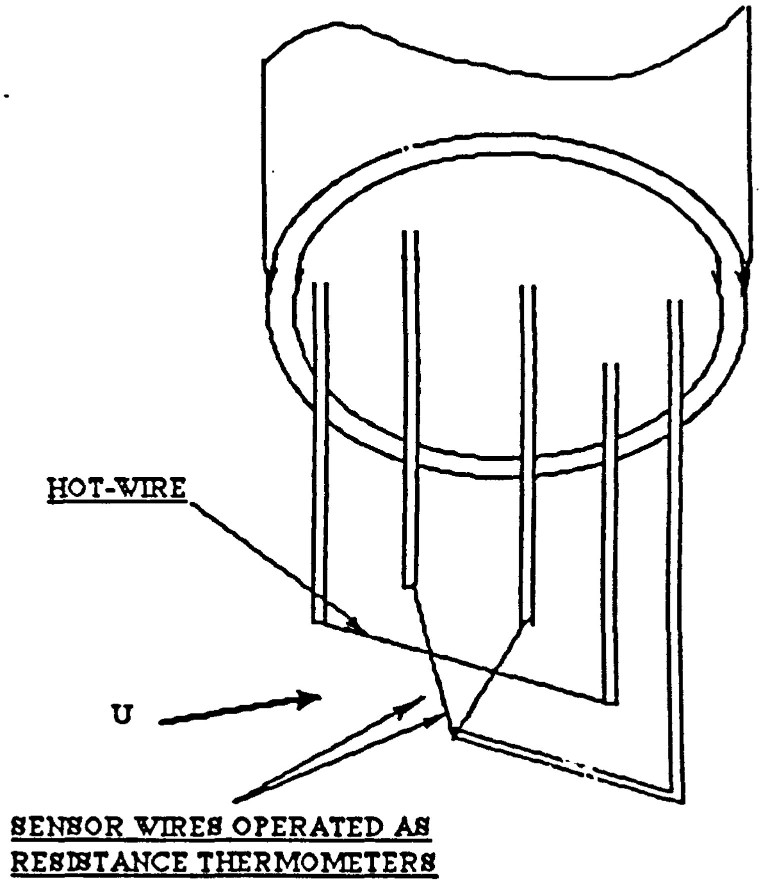


Figure 2.4 Reverse Flow Sensing Hot-wire Probe [D1]

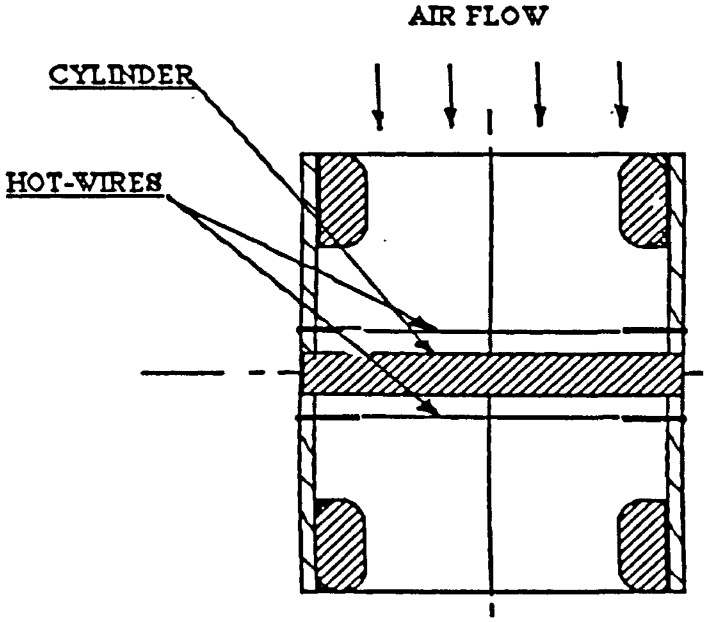


Figure 2.5 Bidirectional Hot-wire Probe [M1]

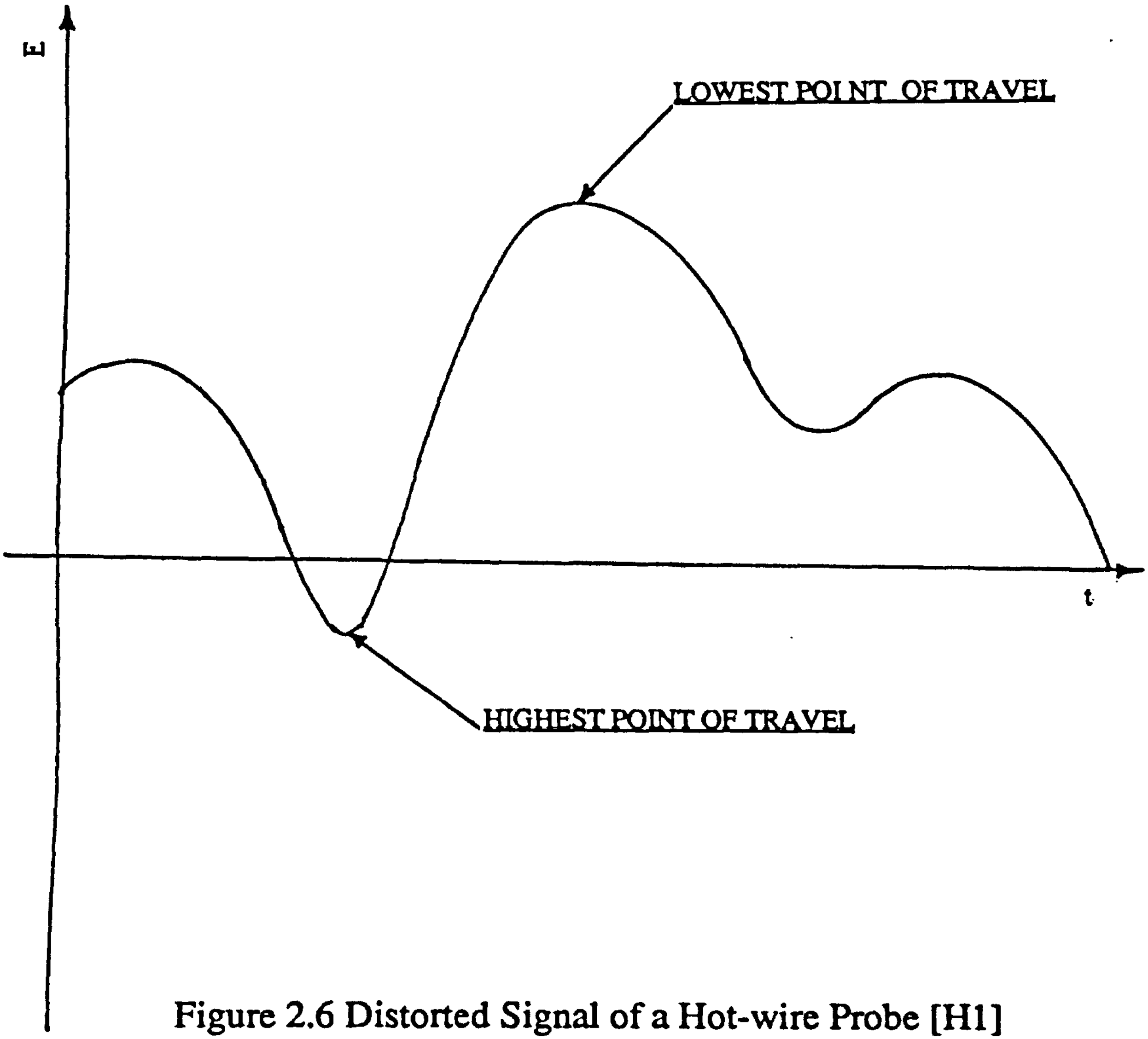


Figure 2.6 Distorted Signal of a Hot-wire Probe [H1]

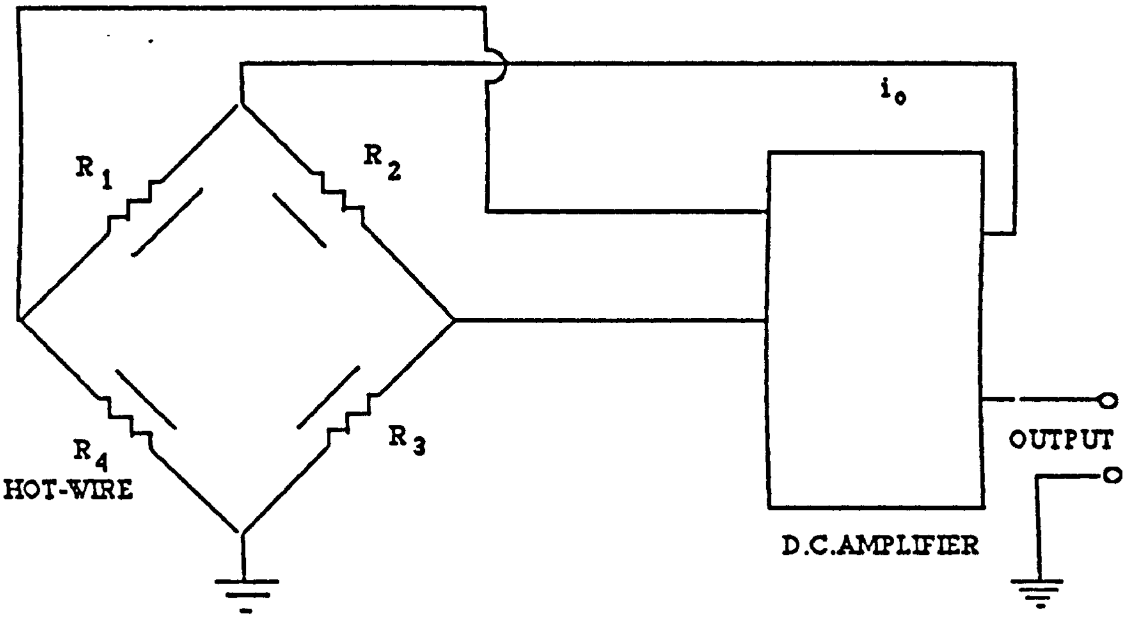


Figure 3.1 Schematic of a Constant Temperature Hot-wire Anemometer

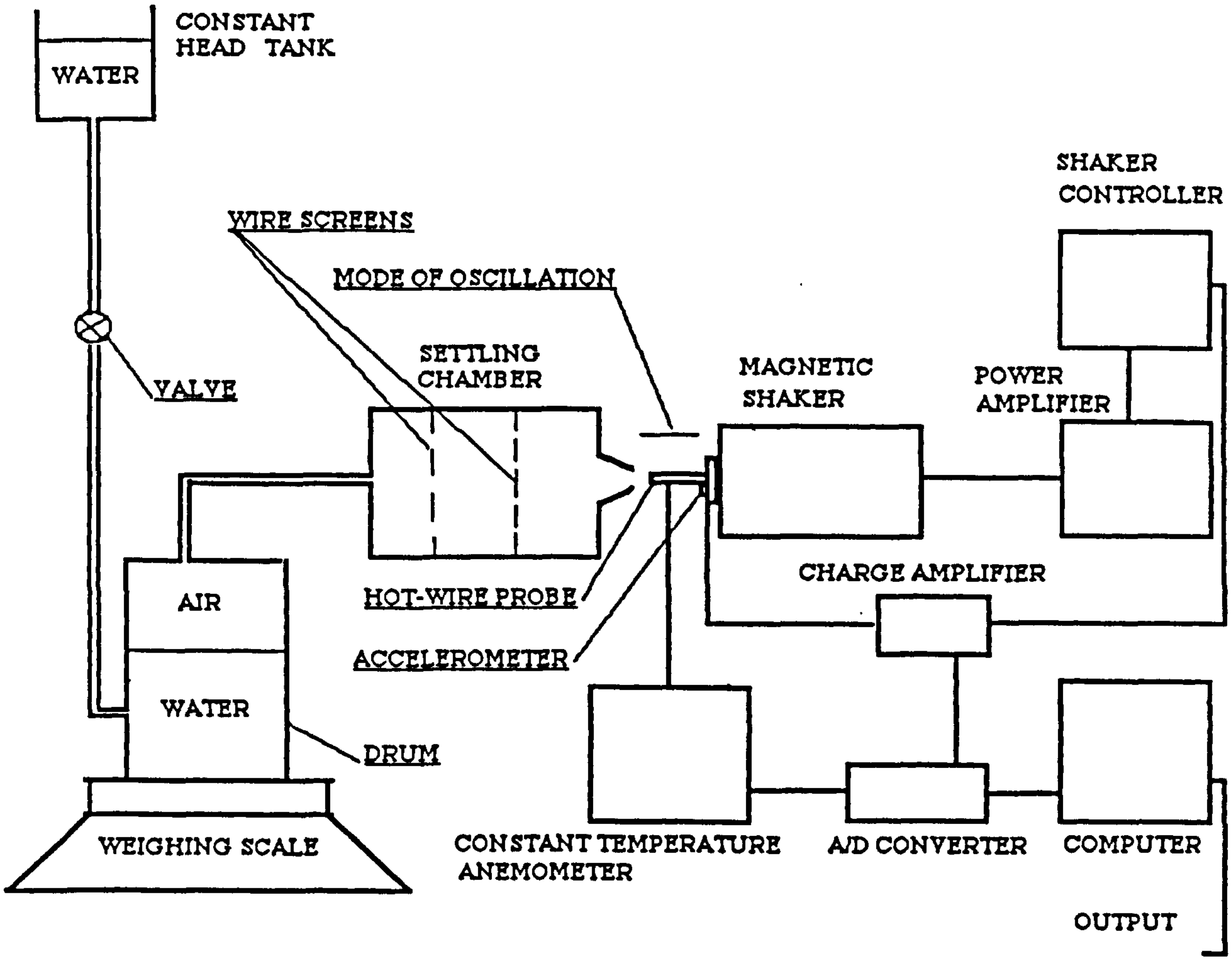
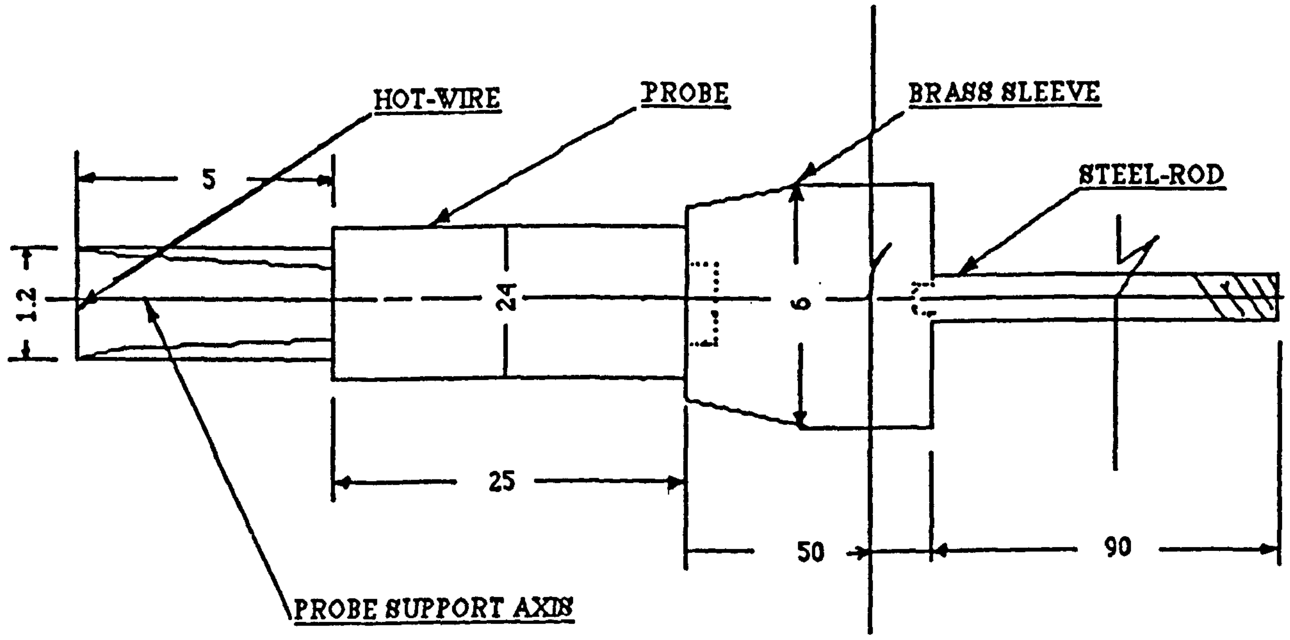


Figure 4.1 Schematic of the Experimental Set-up



ALL DIMESIONS IN mm (NOT TO SCALE)

Figure 4.2 Probe with Brass Sleeve and Steel-rod Assembly

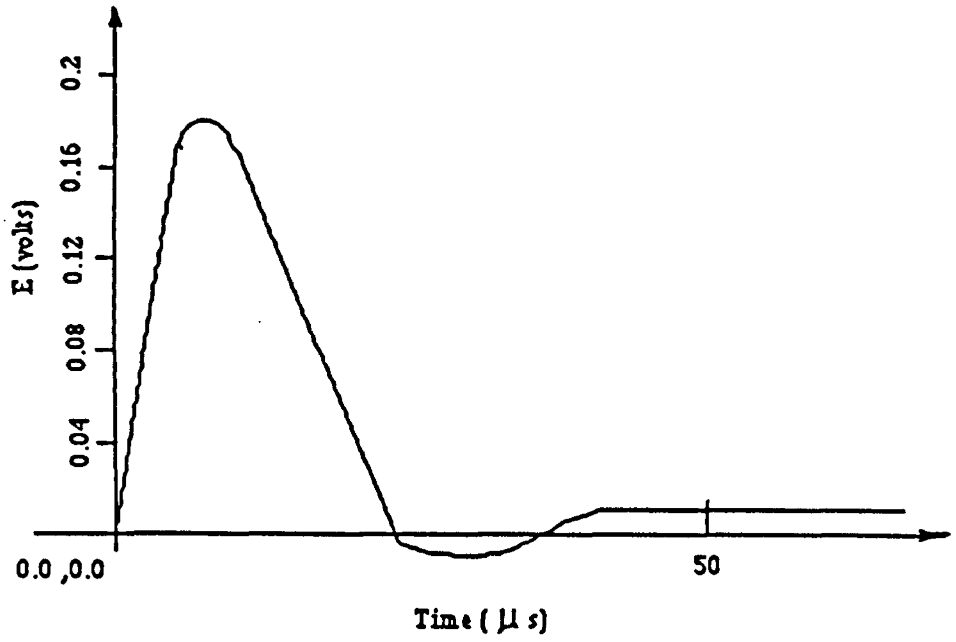


Figure 4.3 Square Wave Response of the CTA

Frequency = 35 Hz. Amplitude = 2.35 mm. Jet Velocity = 0.0 m/s.

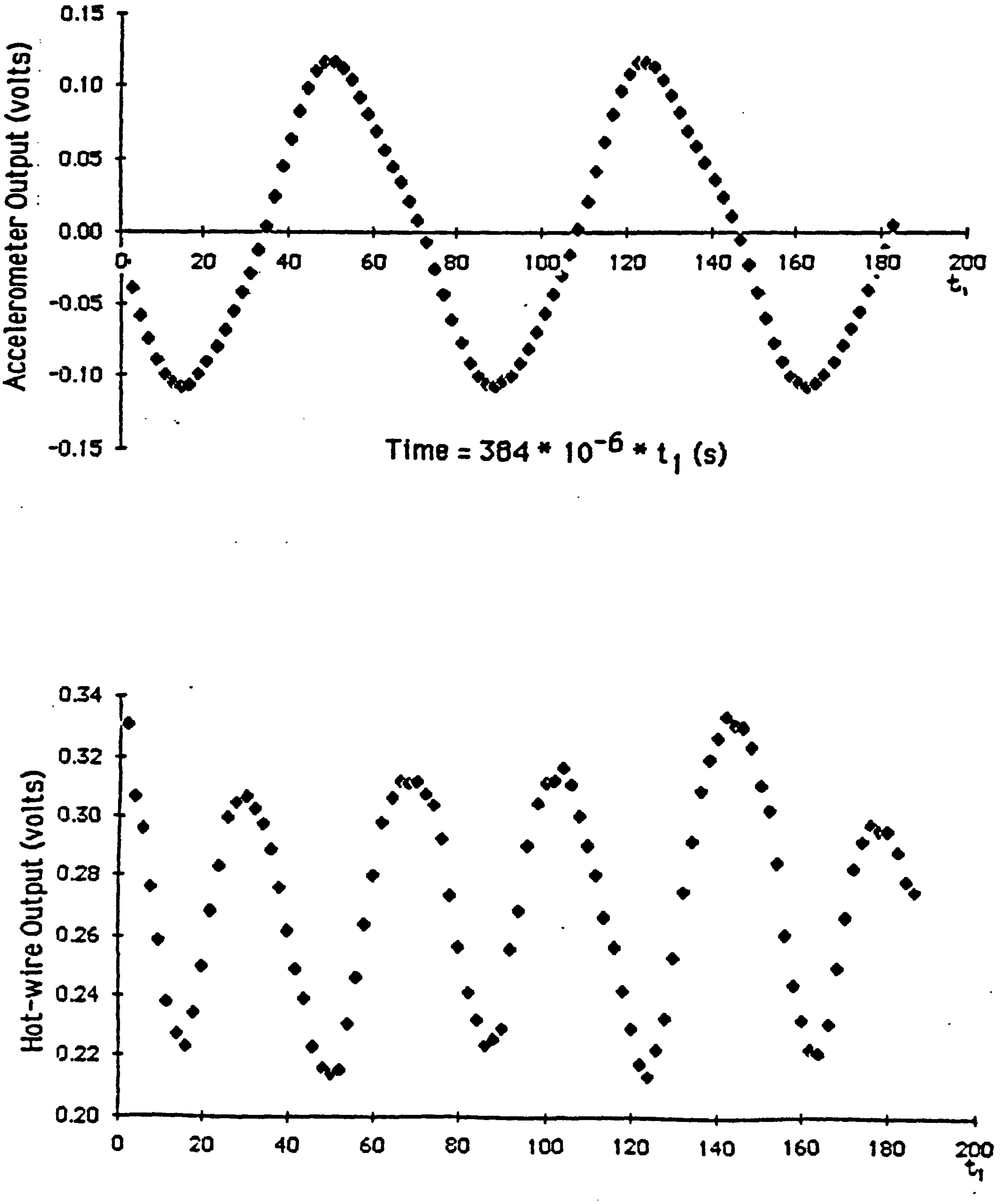


Figure 5.1 Accelerometer and Hot-wire Outputs(U_j < u_p)

Frequency = 35 Hz. Amplitude = 2.35 mm. Jet Velocity = 4.93 m/s.

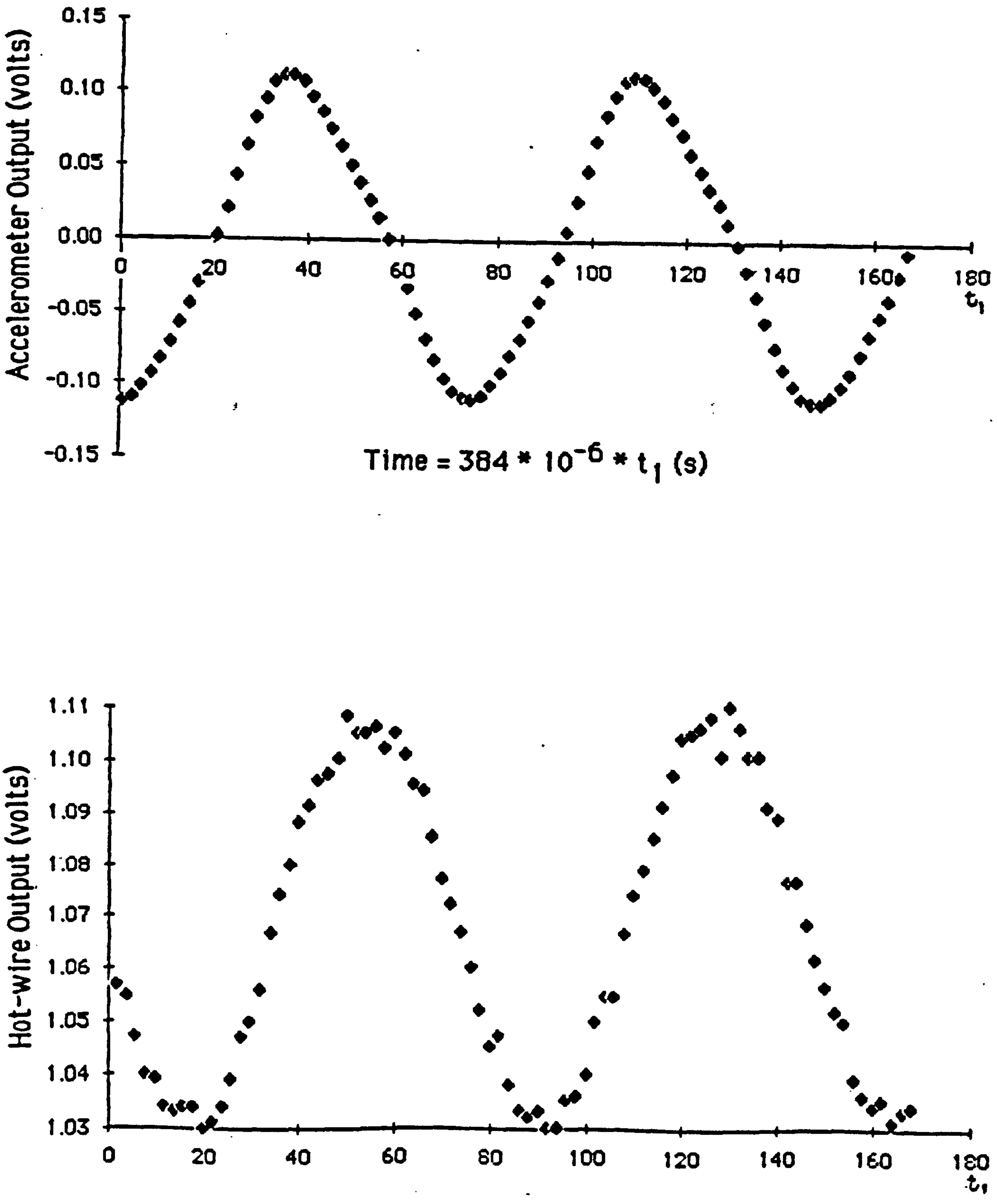


Figure 5.2 Accelerometer and Hot-wire Outputs($U_j > u_p$)

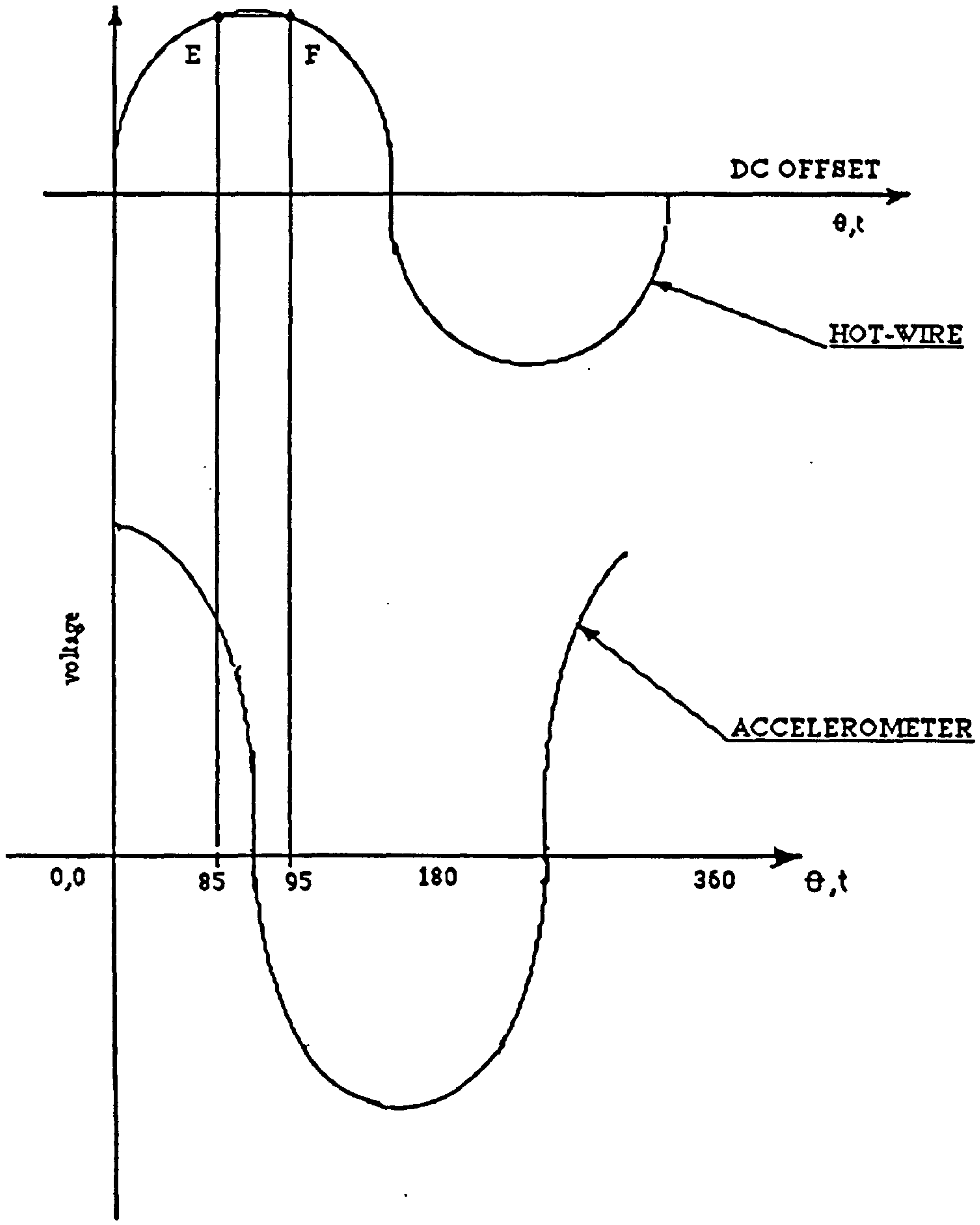


Figure 5.3 Accelerometer and Hot-wire Output Voltage

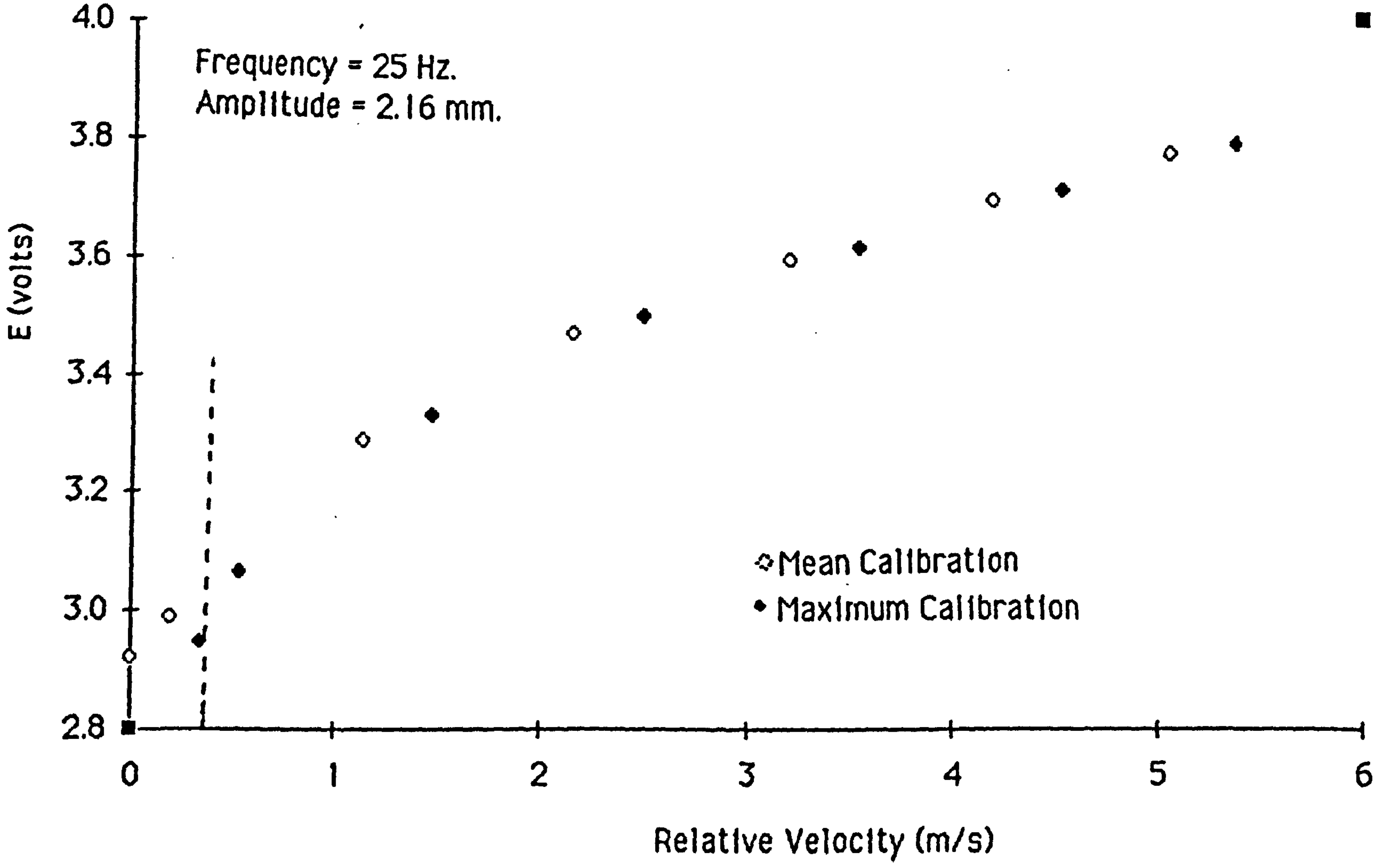


Figure 5.4 Dynamic Calibration.

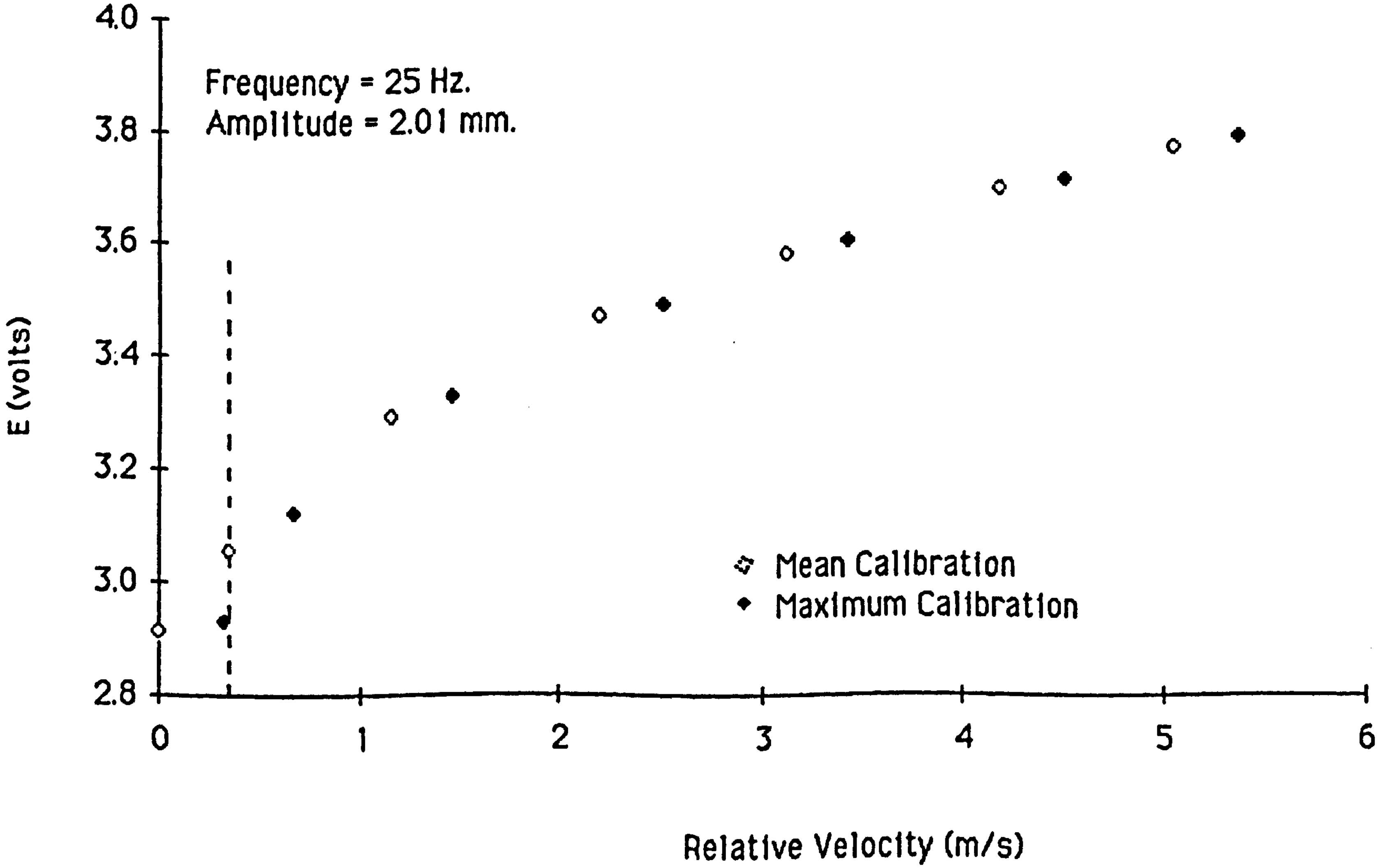


Figure 5.5 Dynamic Calibration.

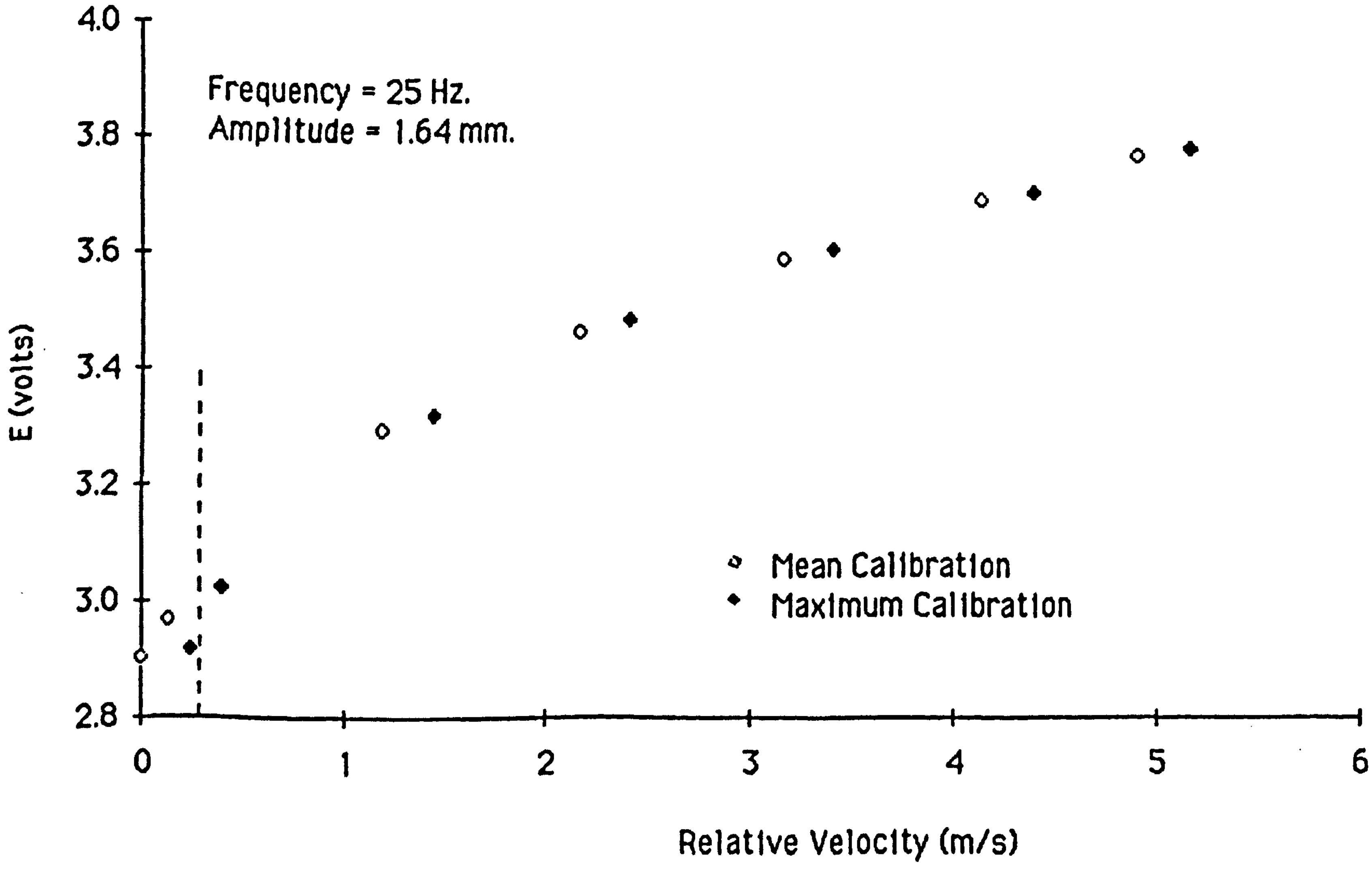


Figure 5.6 Dynamic Calibration.

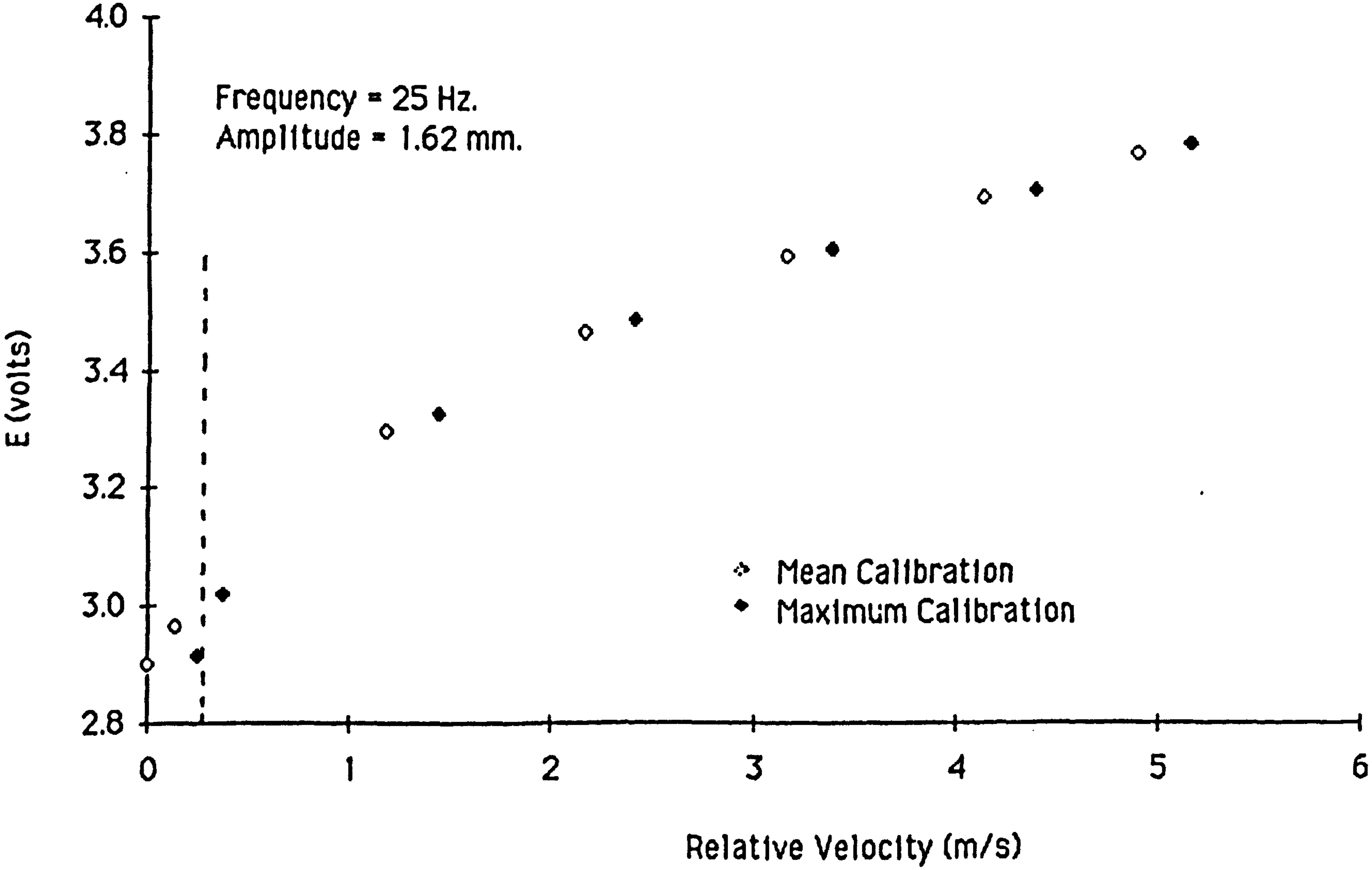


Figure 5.7 Dynamic Calibration.

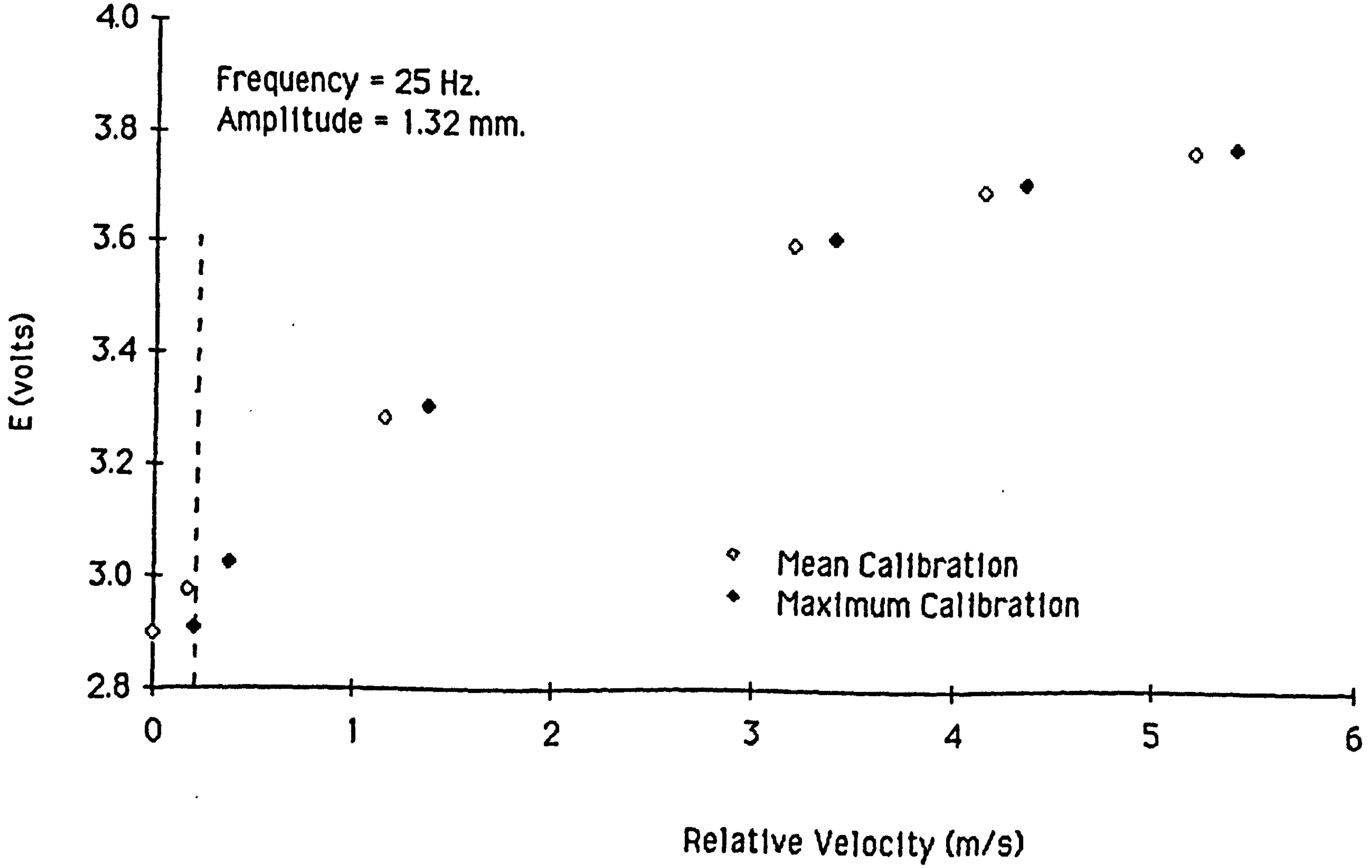


Figure 5.8 Dynamic Calibration.

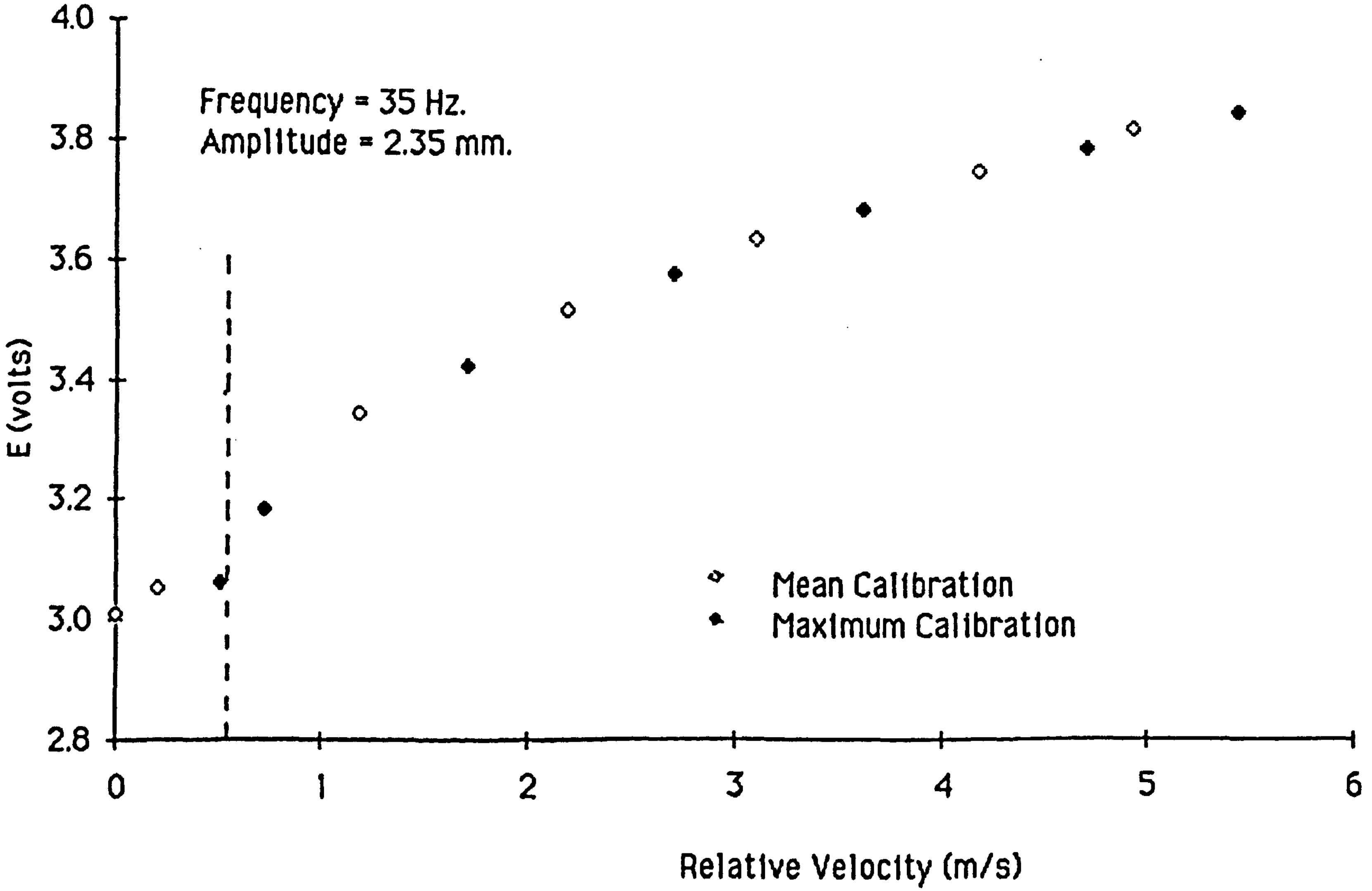


Figure 5.9 Dynamic Calibration.

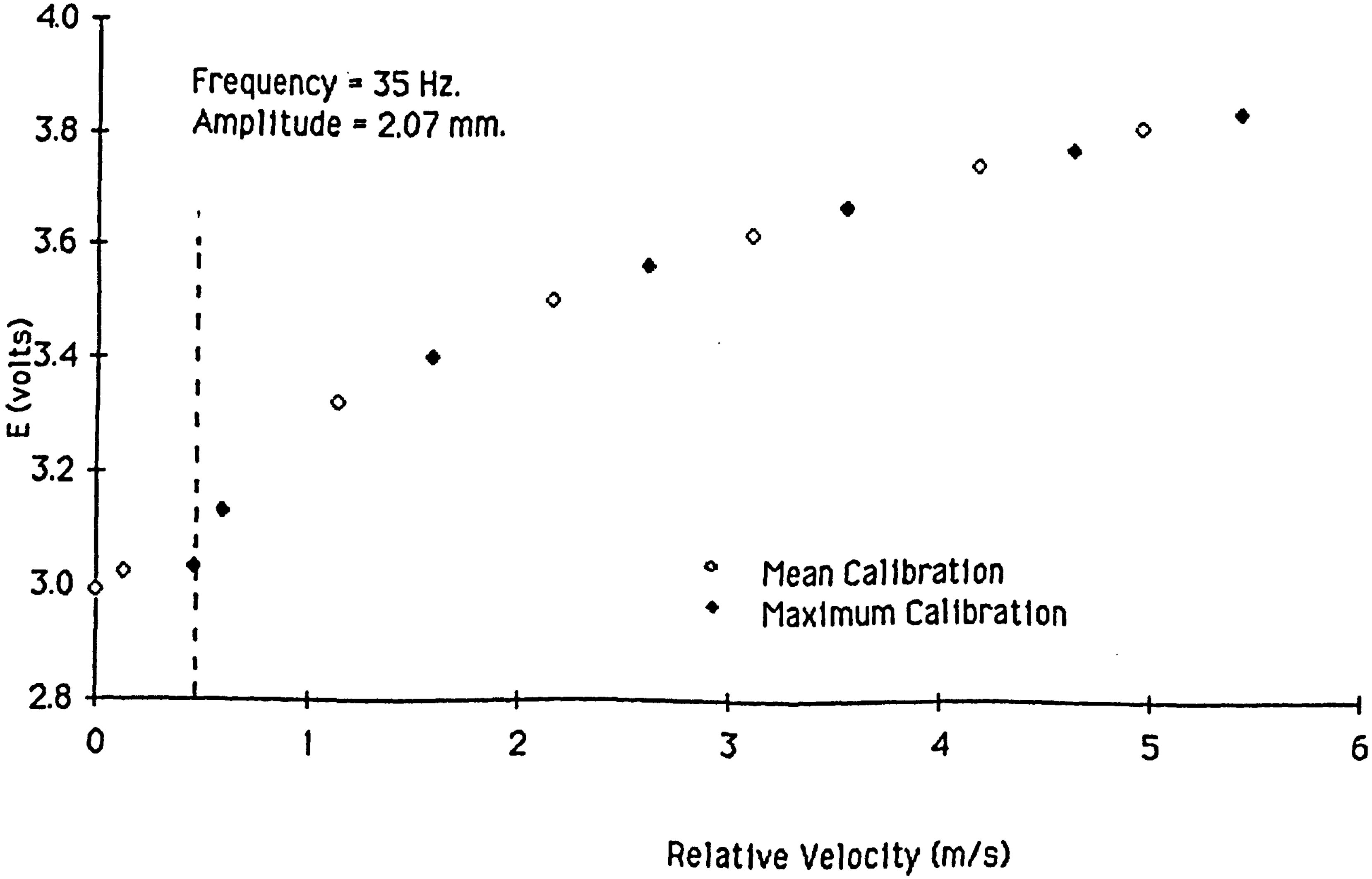


Figure 5.10 Dynamic Calibration.

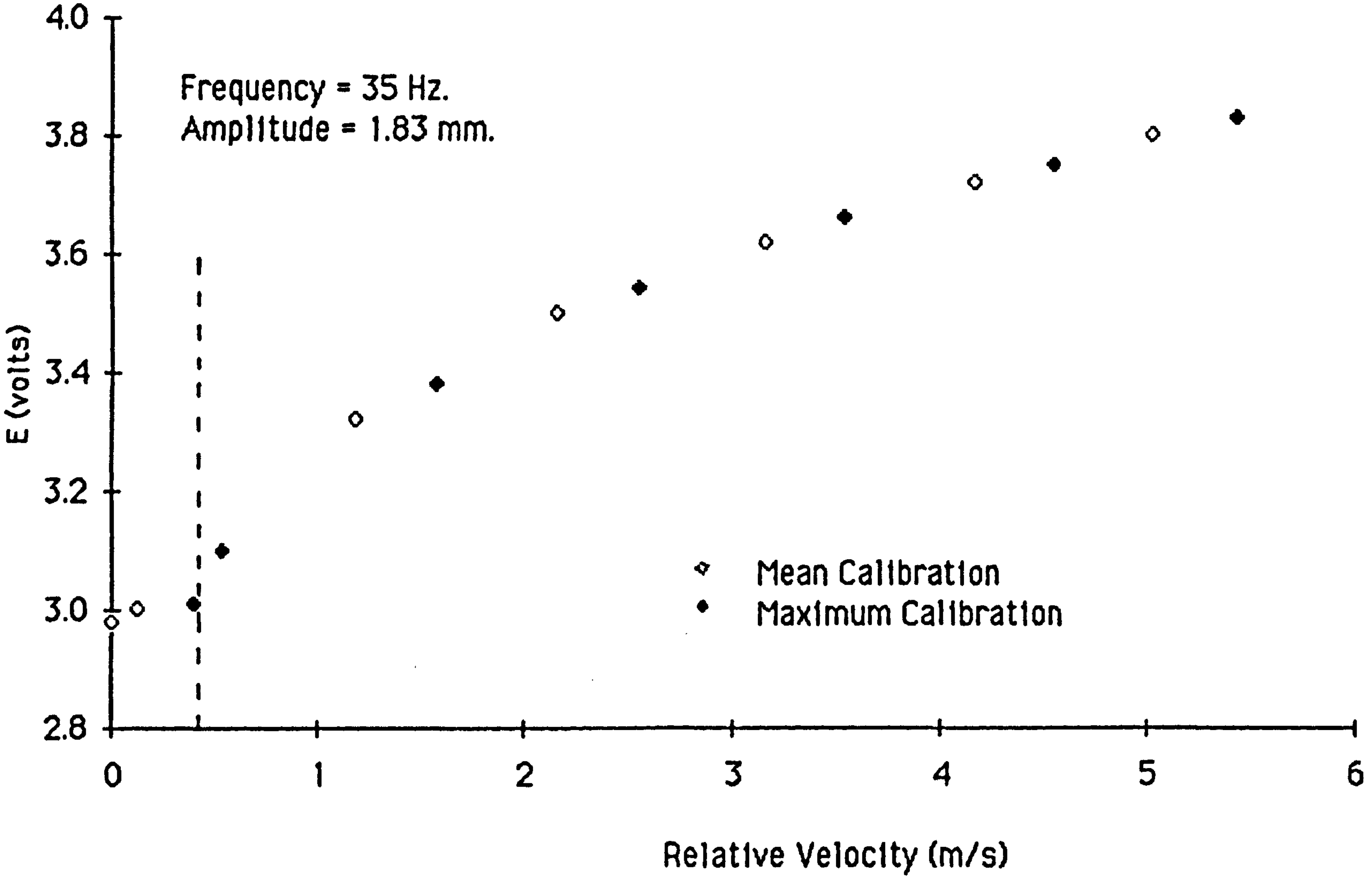


Figure 5.11 Dynamic Calibration.

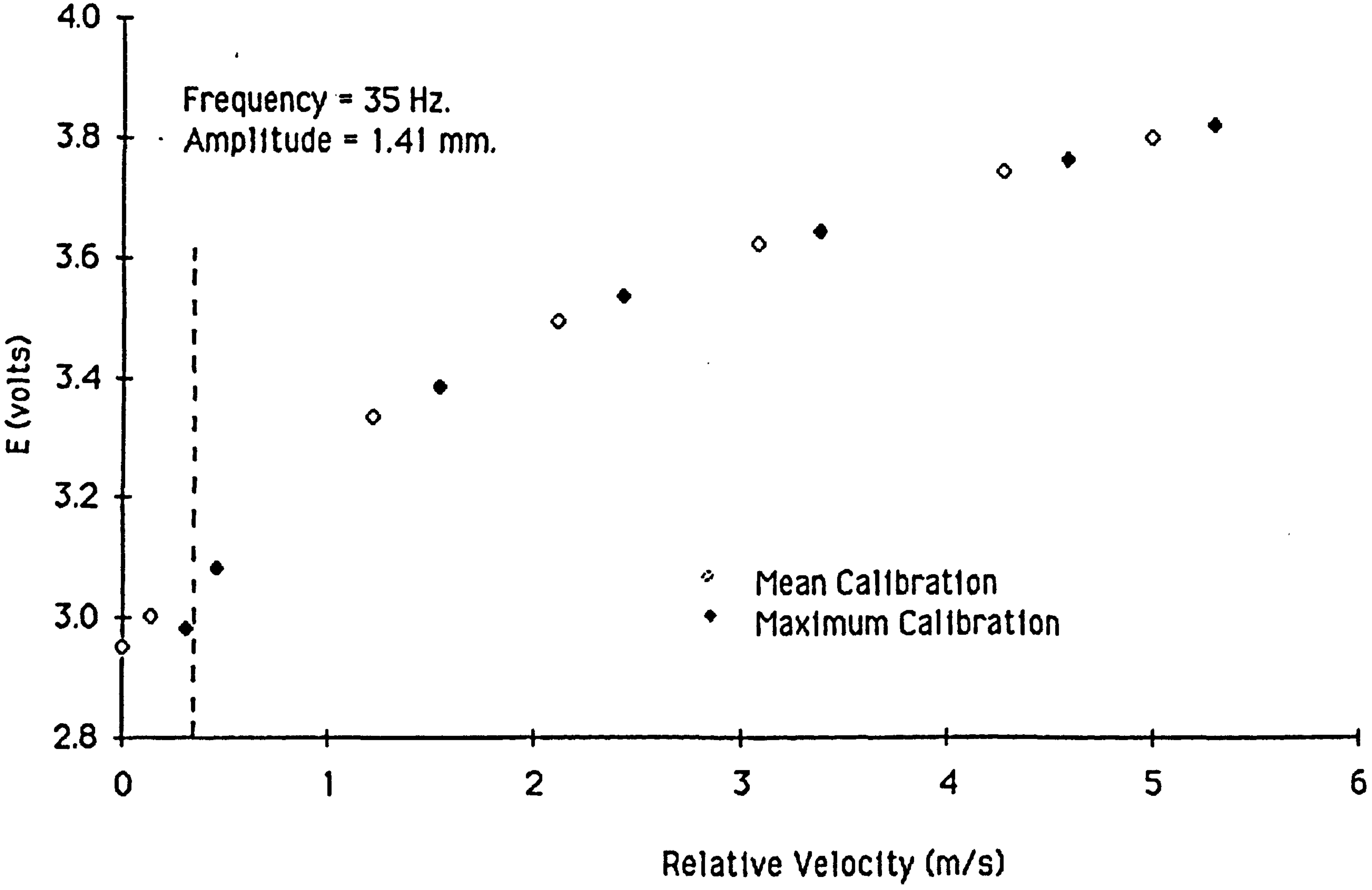


Figure 5.12 Dynamic Calibration.

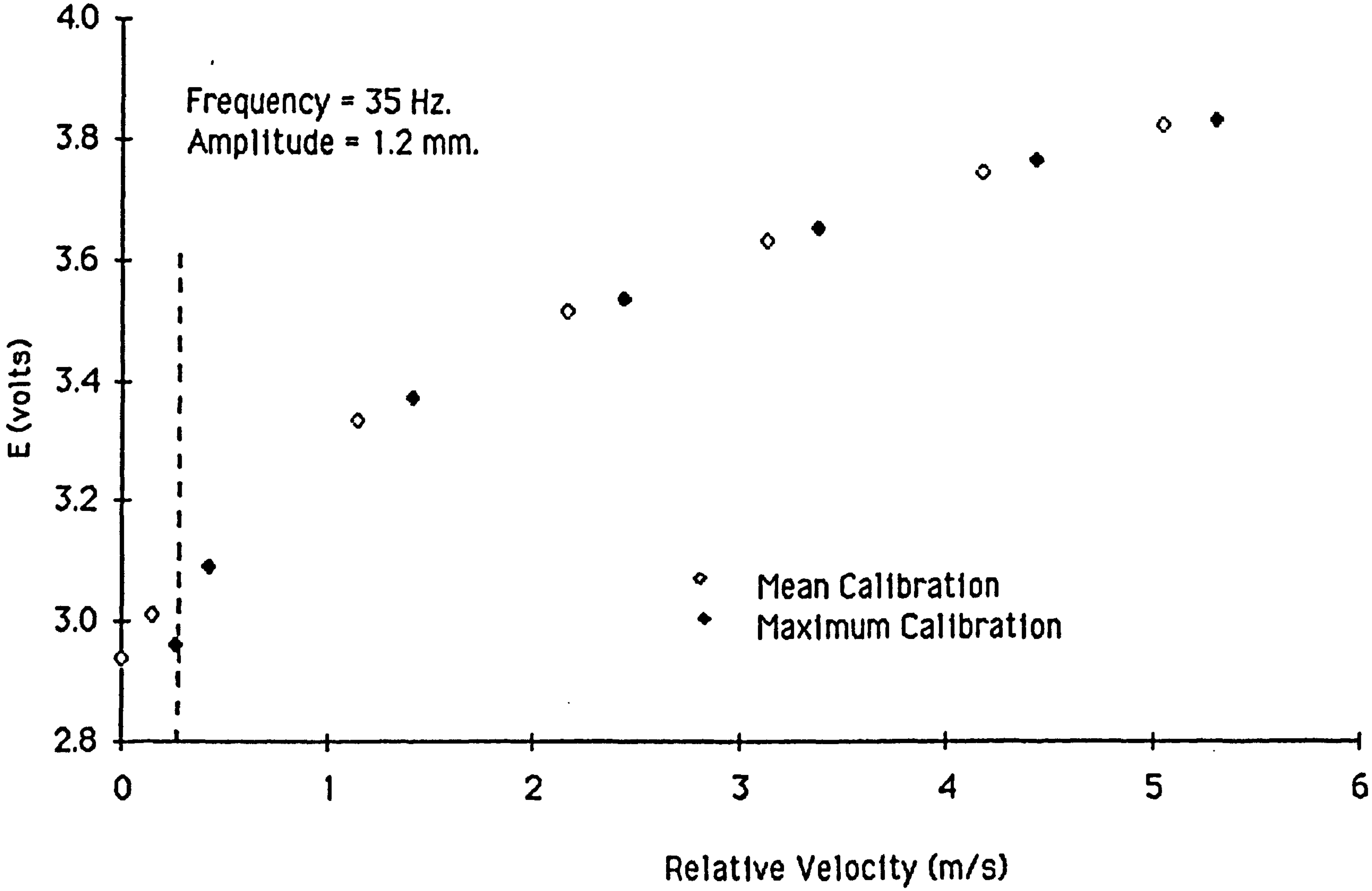


Figure 5.13 Dynamic Calibration.

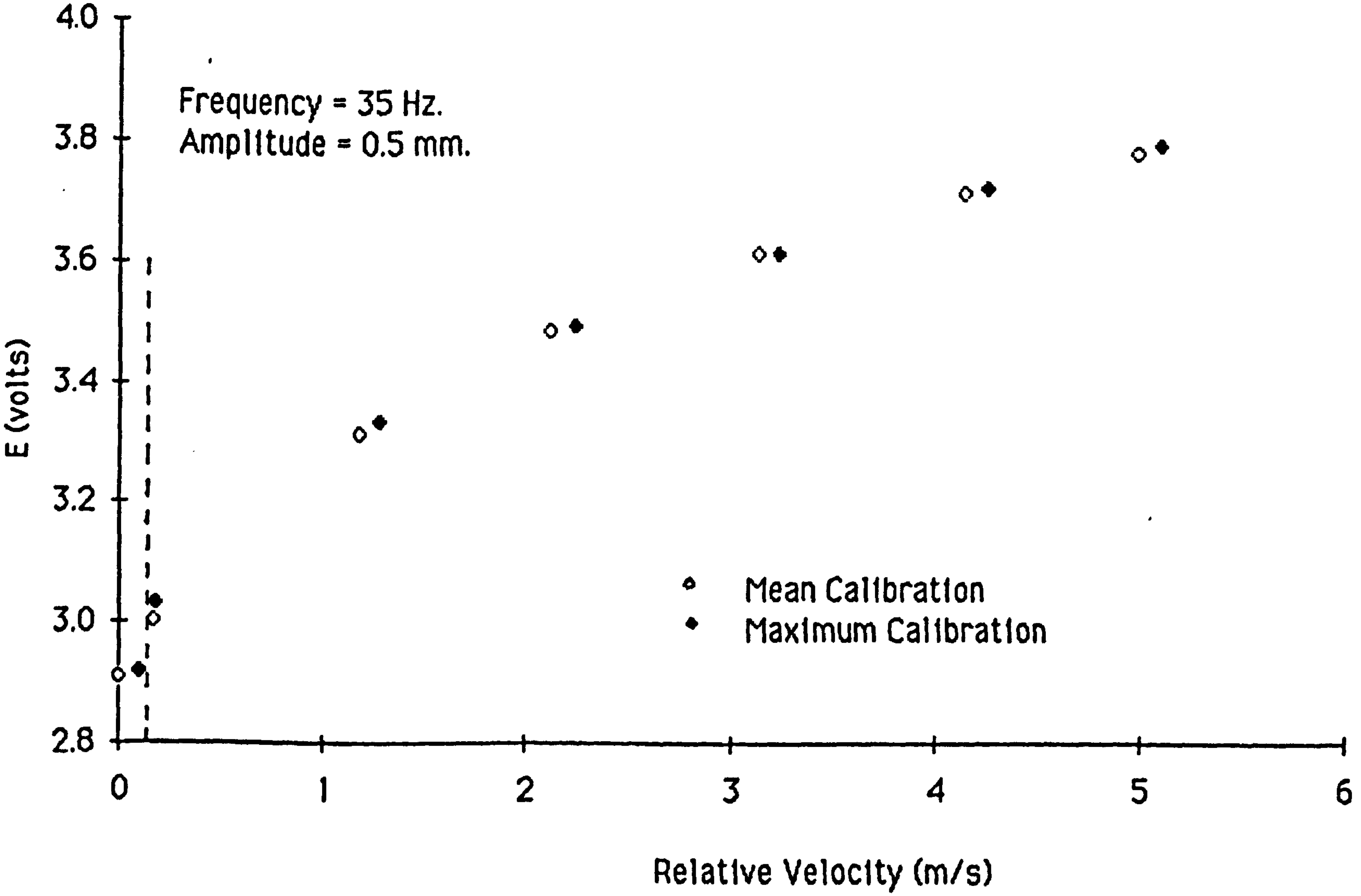


Figure 5.14 Dynamic Calibration.

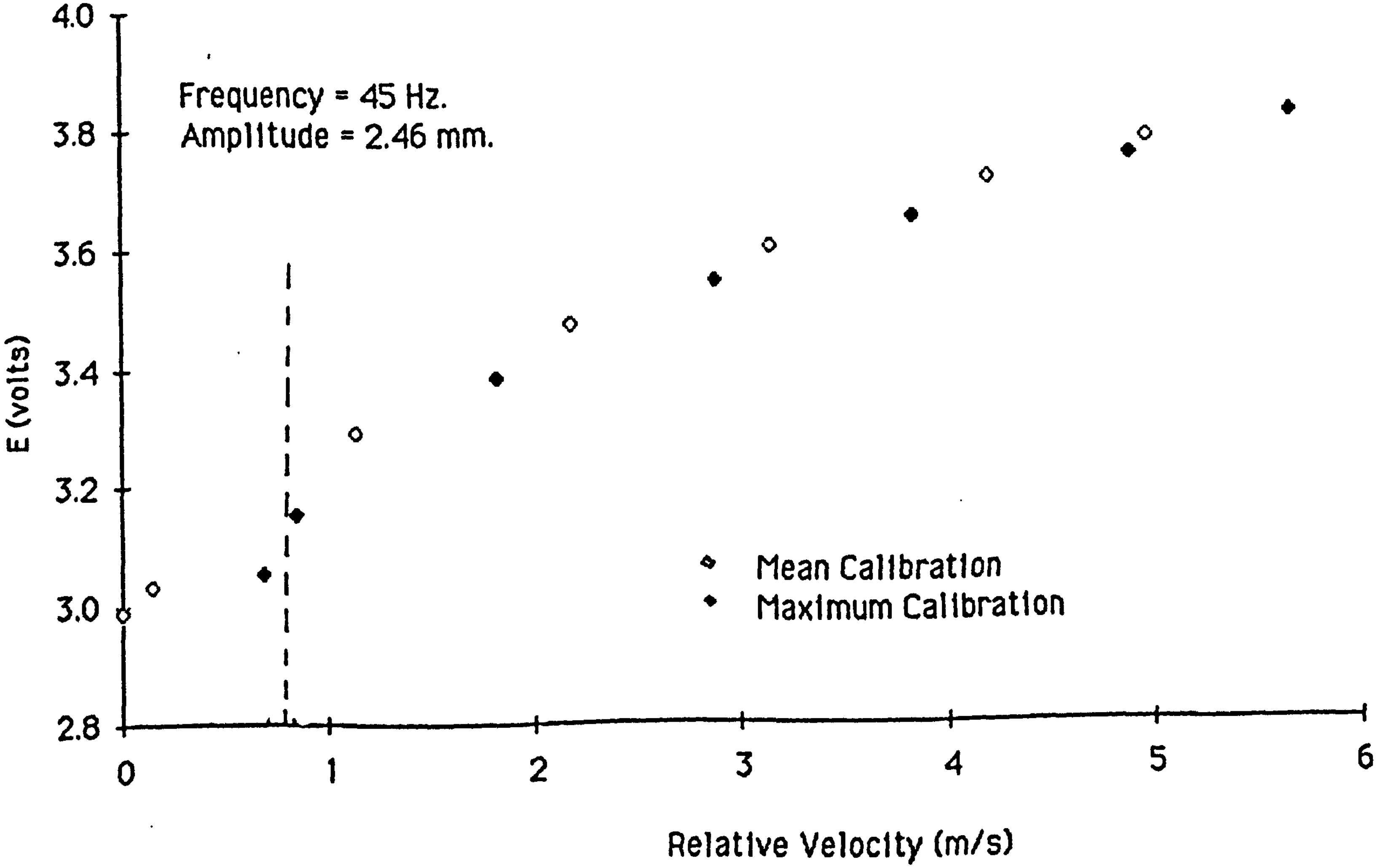


Figure 5.15 Dynamic Calibration.

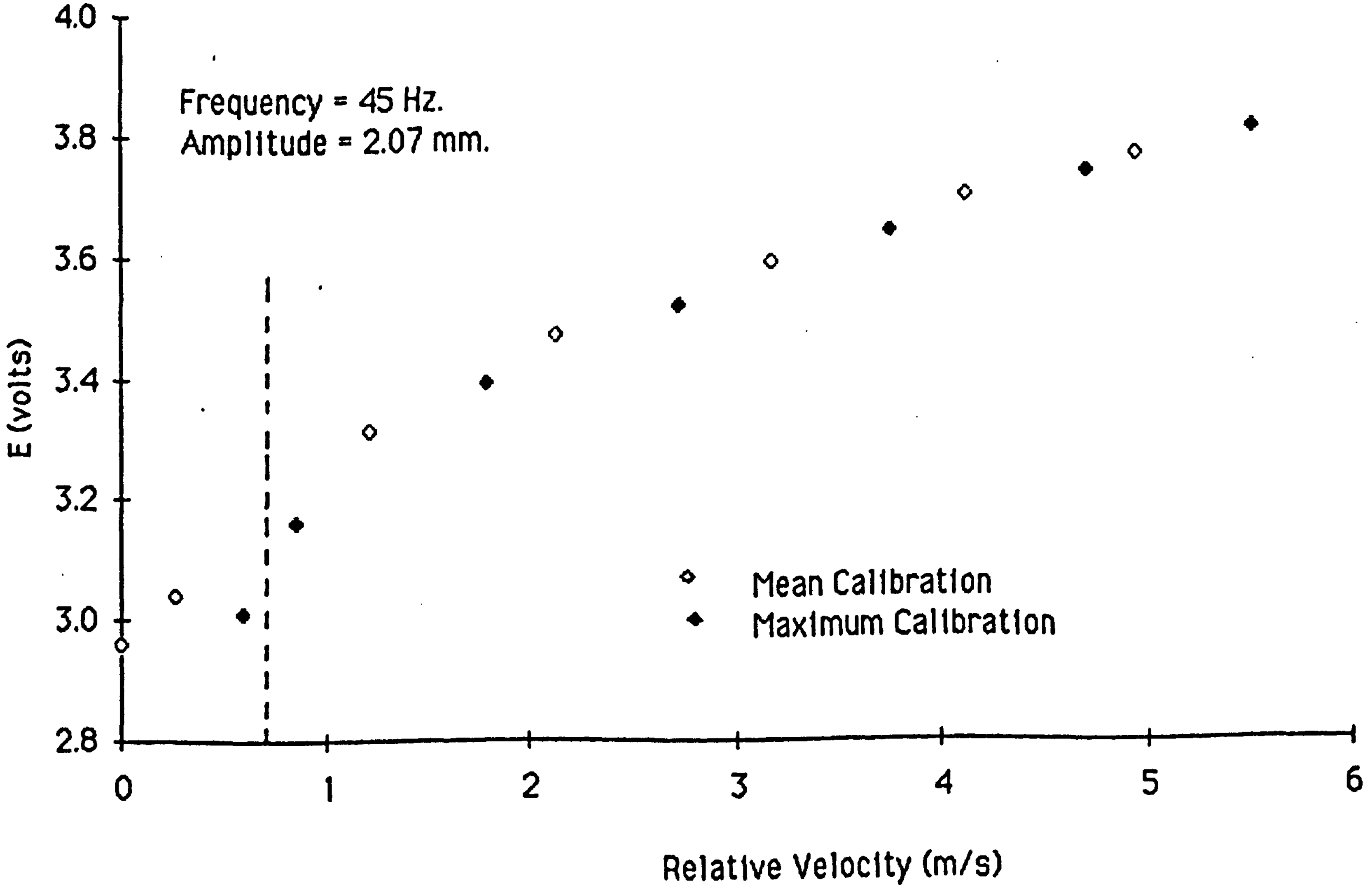


Figure 5.16 Dynamic Calibration.

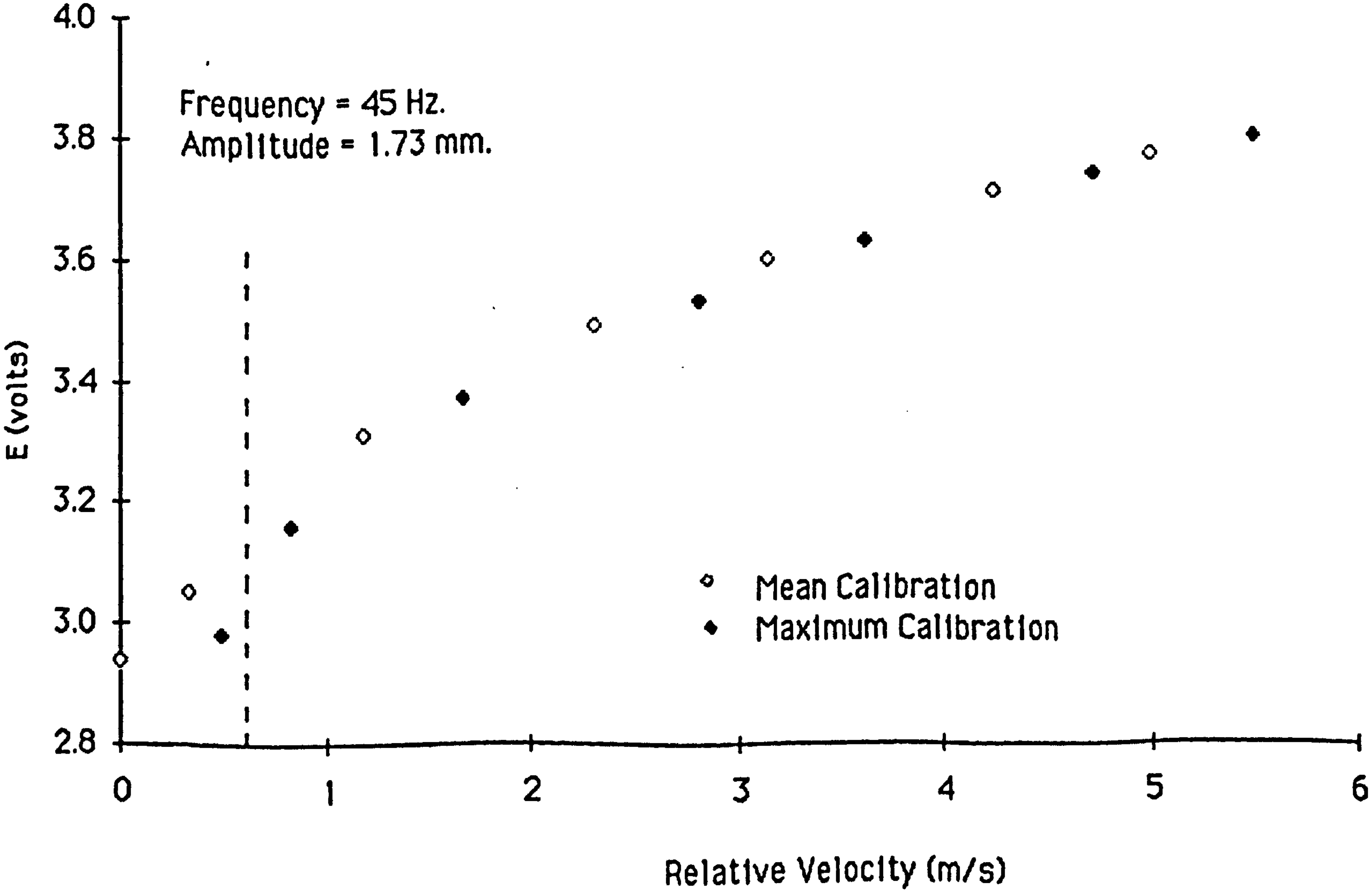


Figure 5.17 Dynamic Calibration.

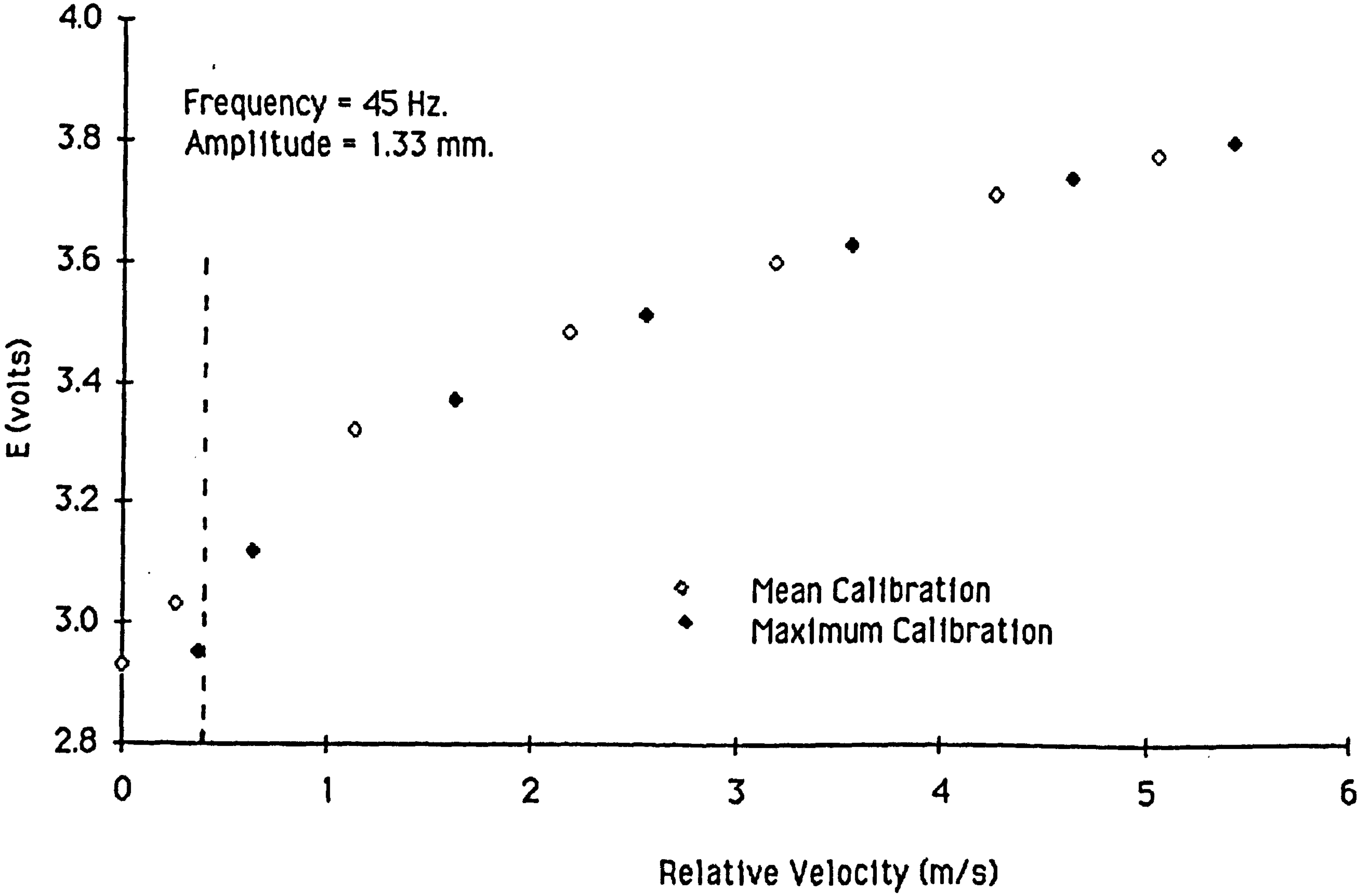


Figure 5.18 Dynamic Calibration.

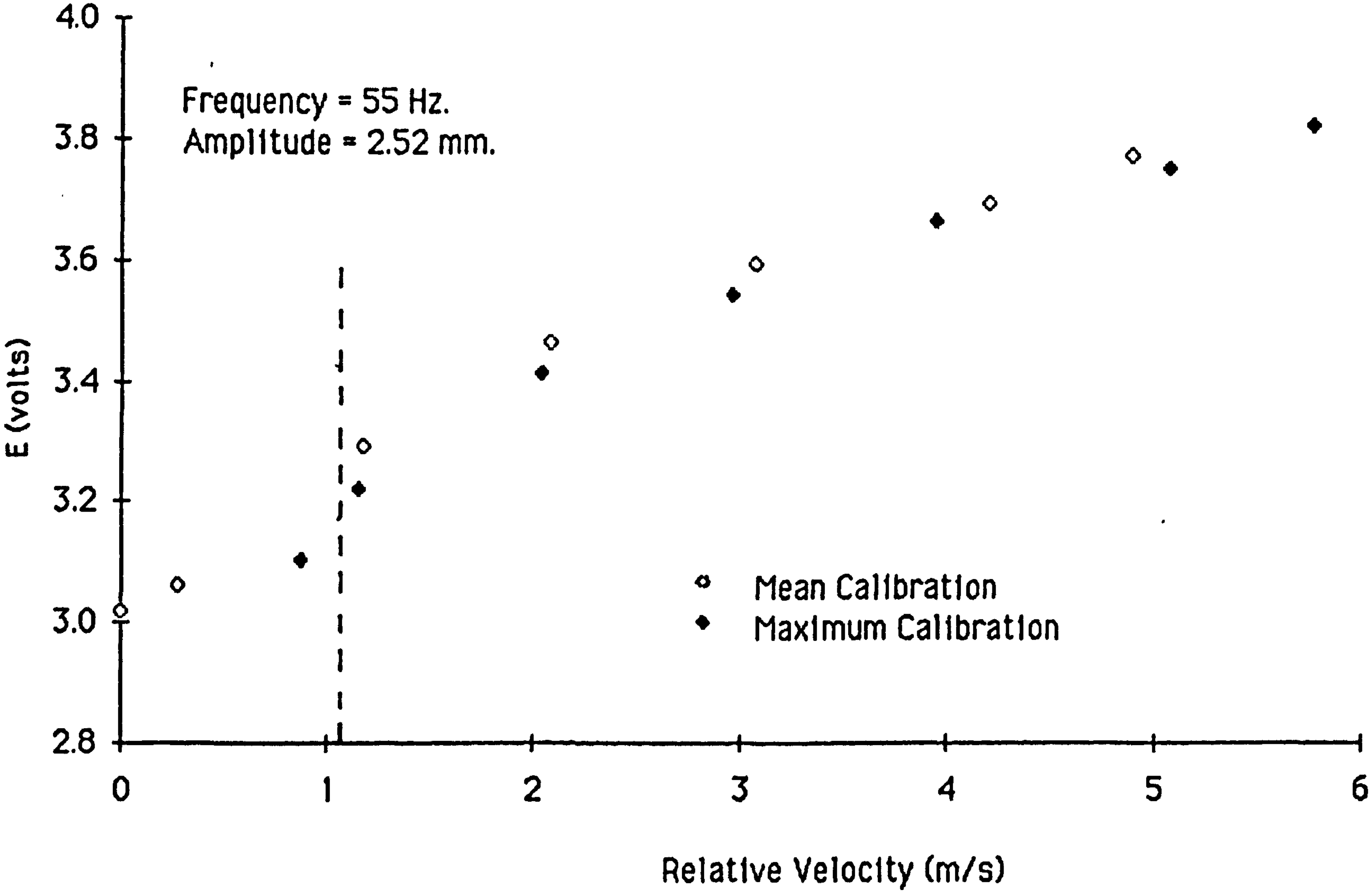


Figure 5.19 Dynamic Calibration.

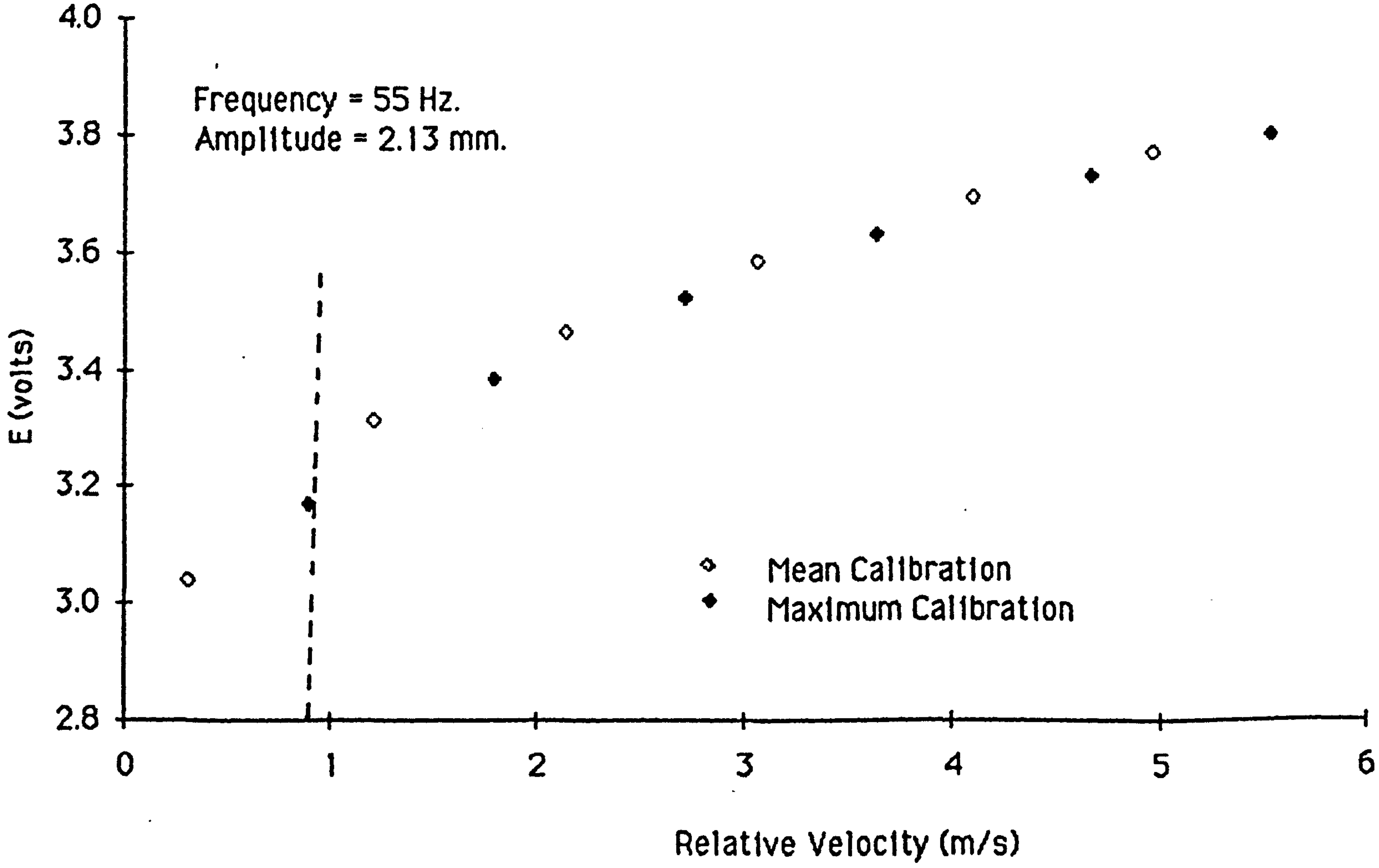


Figure 5.20 Dynamic Calibration.

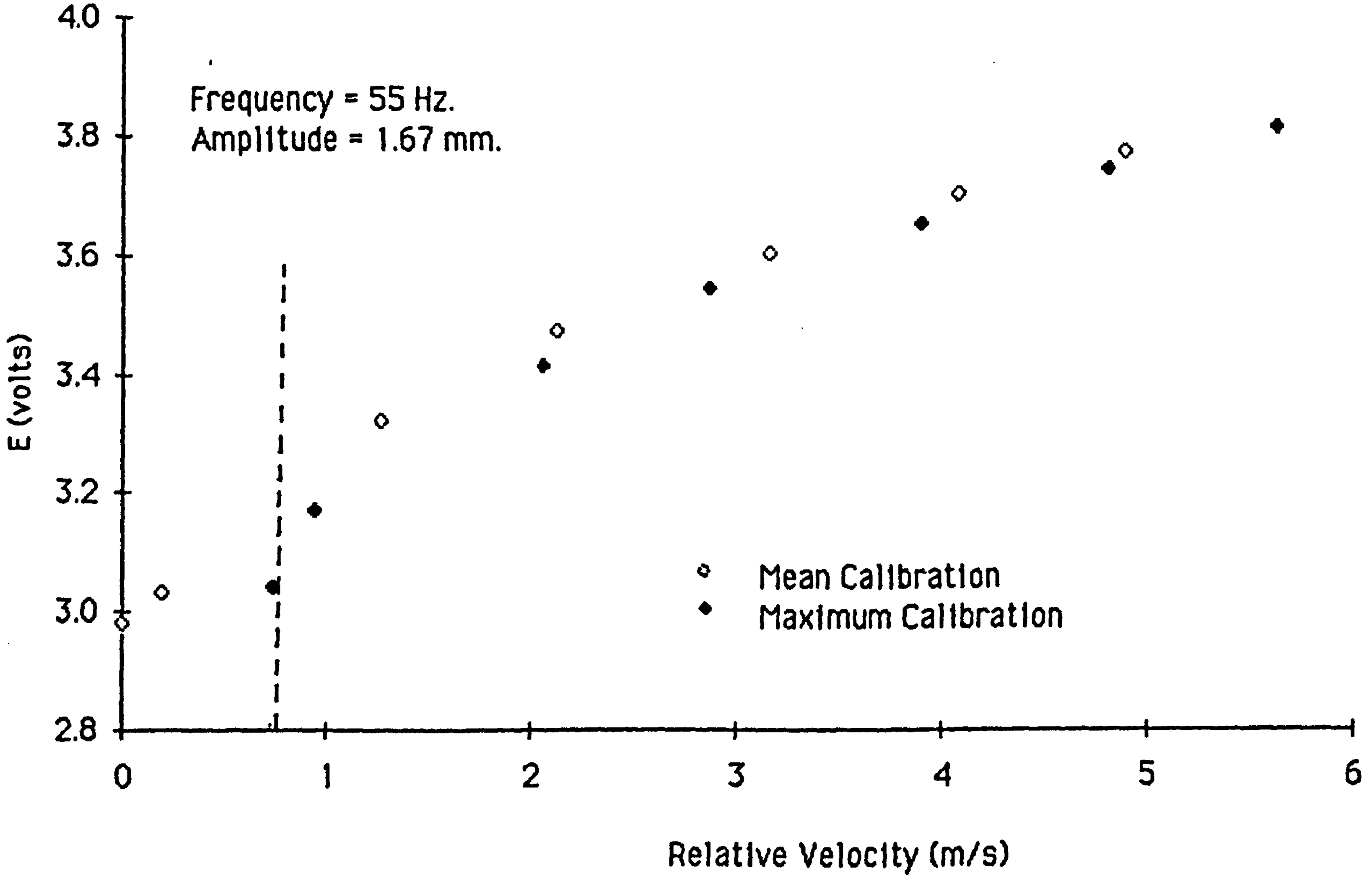


Figure 5.21 Dynamic Calibration.

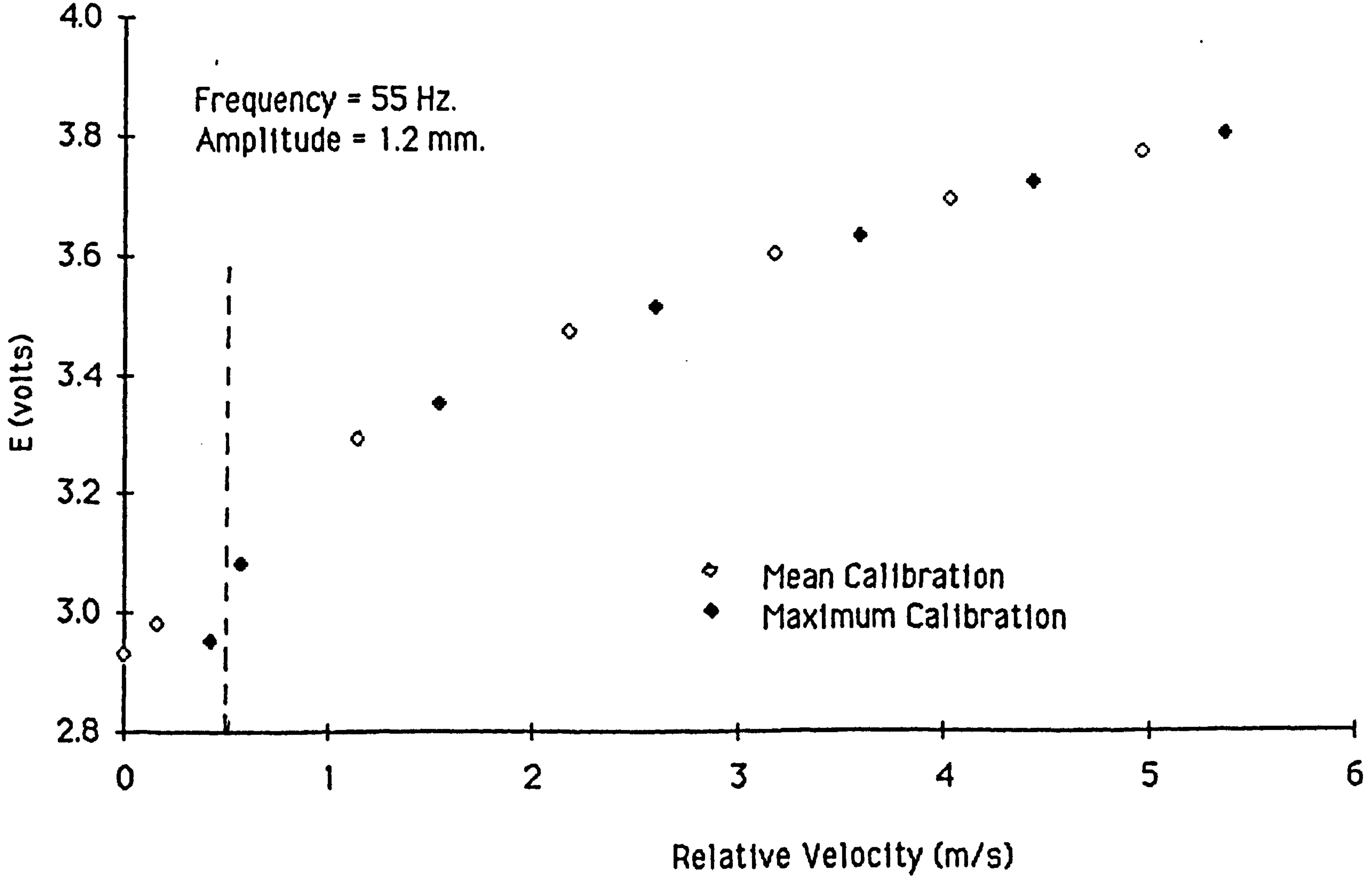


Figure 5.22 Dynamic Calibration.

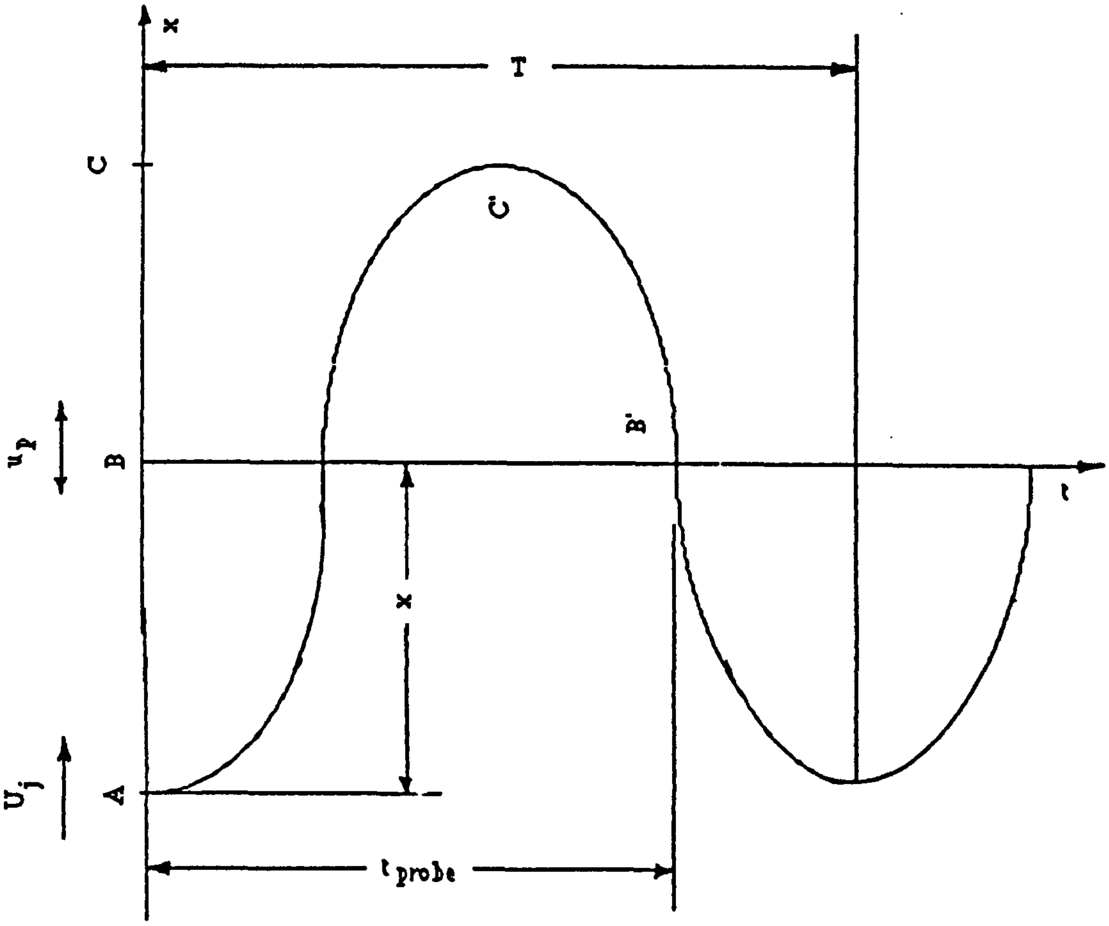


Figure 5.23 Time Variation of Probe Position

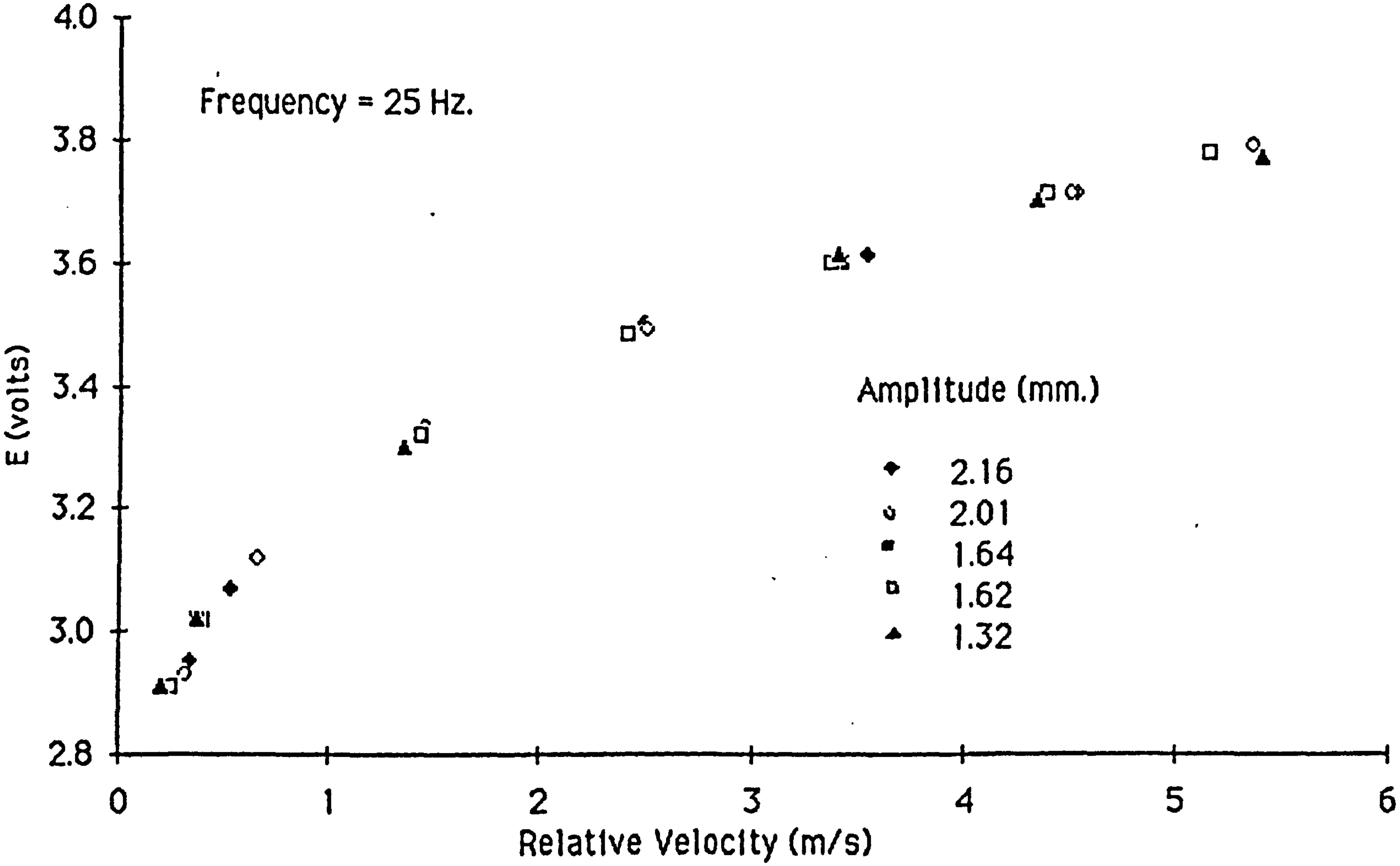


Figure 5.24. Effect of Amplitude on the Maximum Response

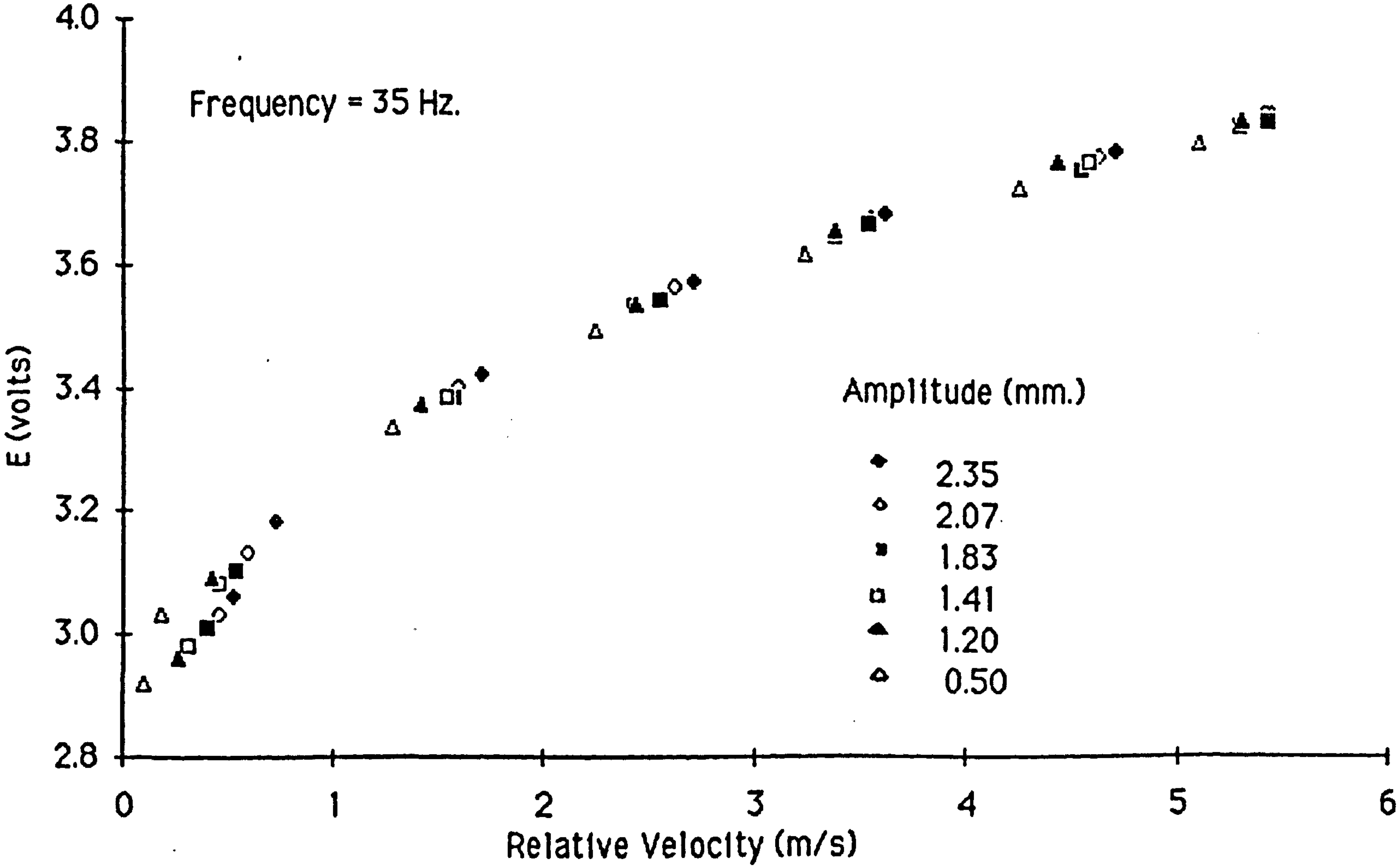


Figure 5.25 Effect of Amplitude on the Maximum Response

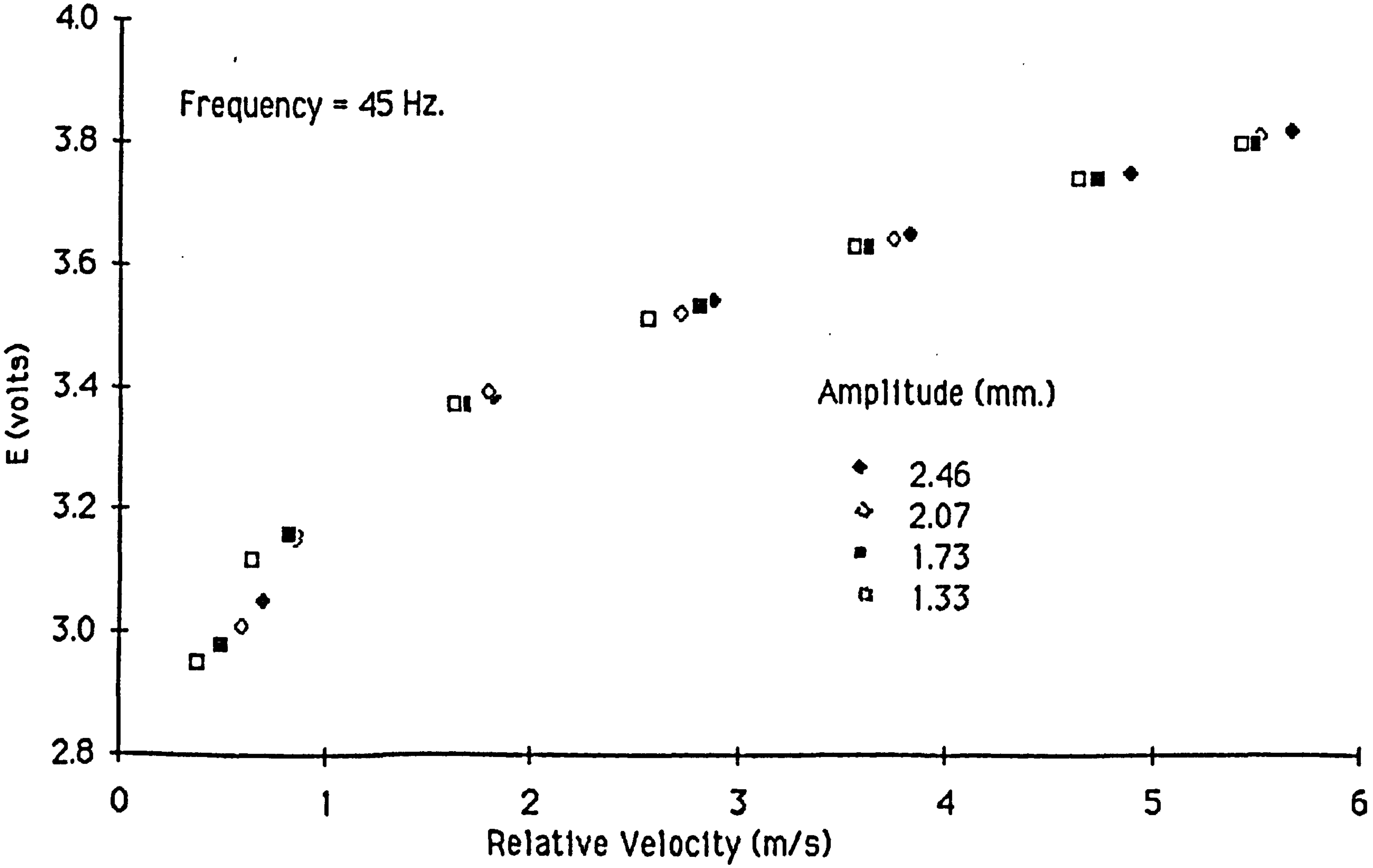


Figure 5.26 Effect of Amplitude on the Maximum Response

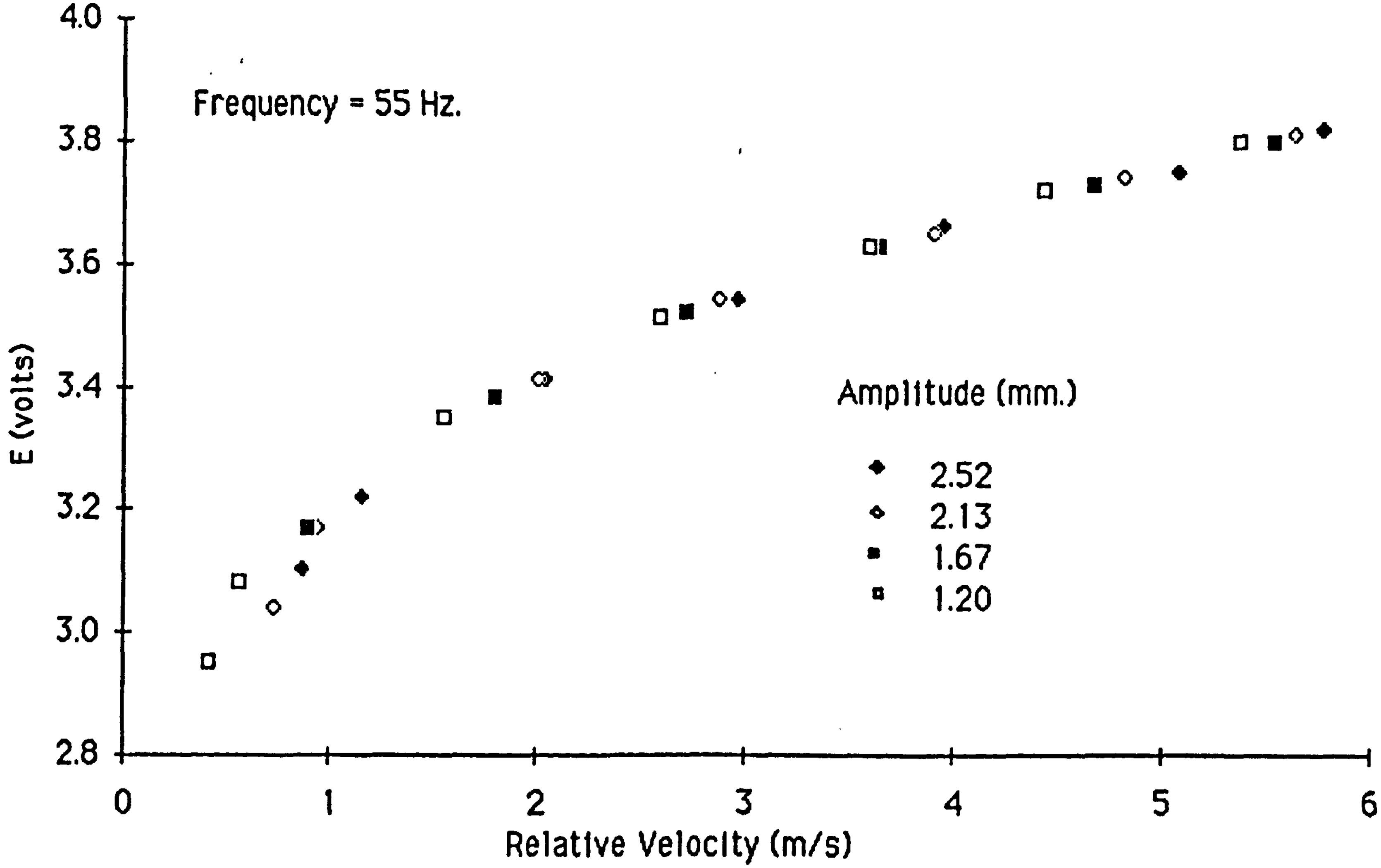


Figure 5.27 Effect of Amplitude on the Maximum Response

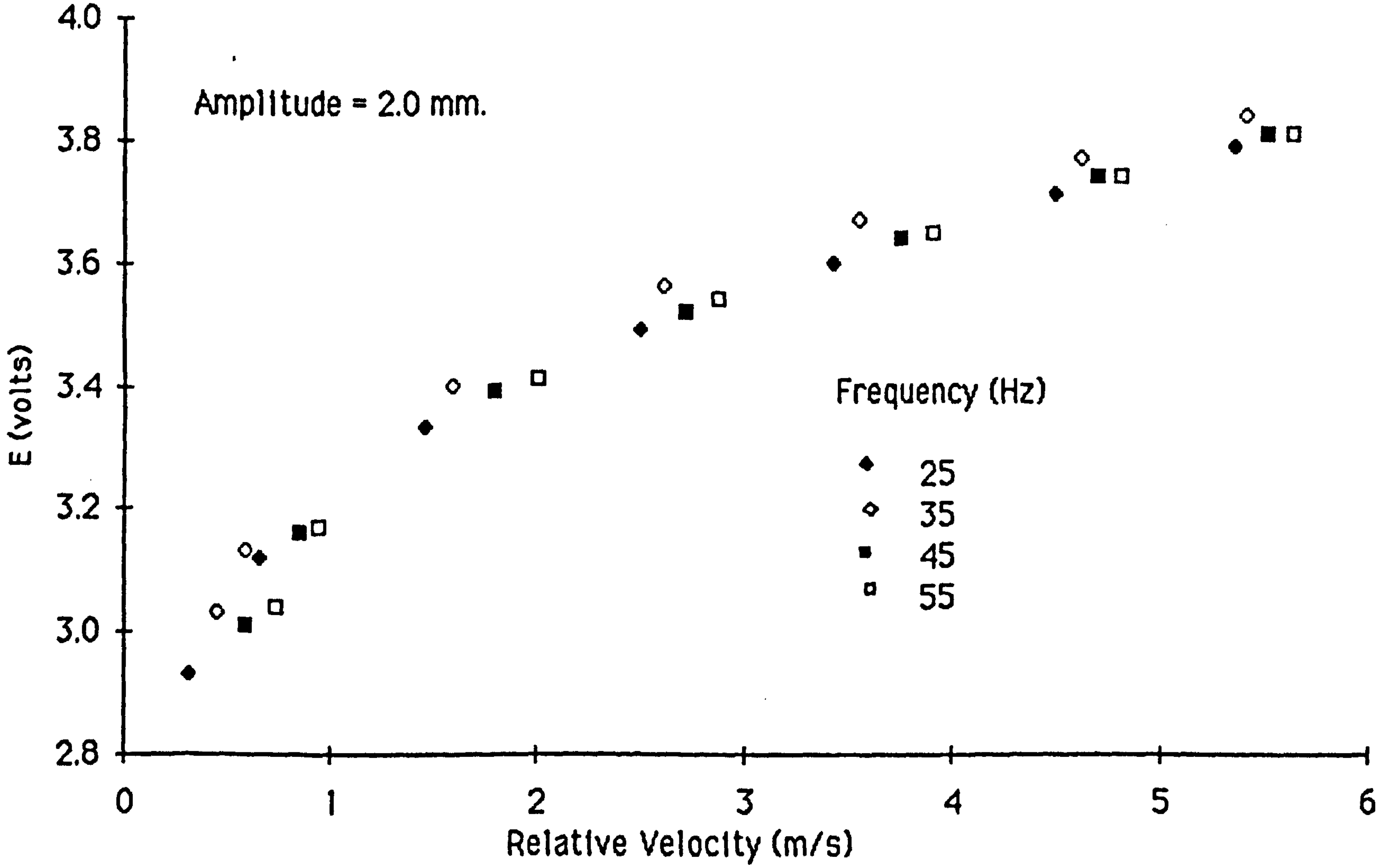


Figure 5.28 Effect of Frequency on the Maximum Response

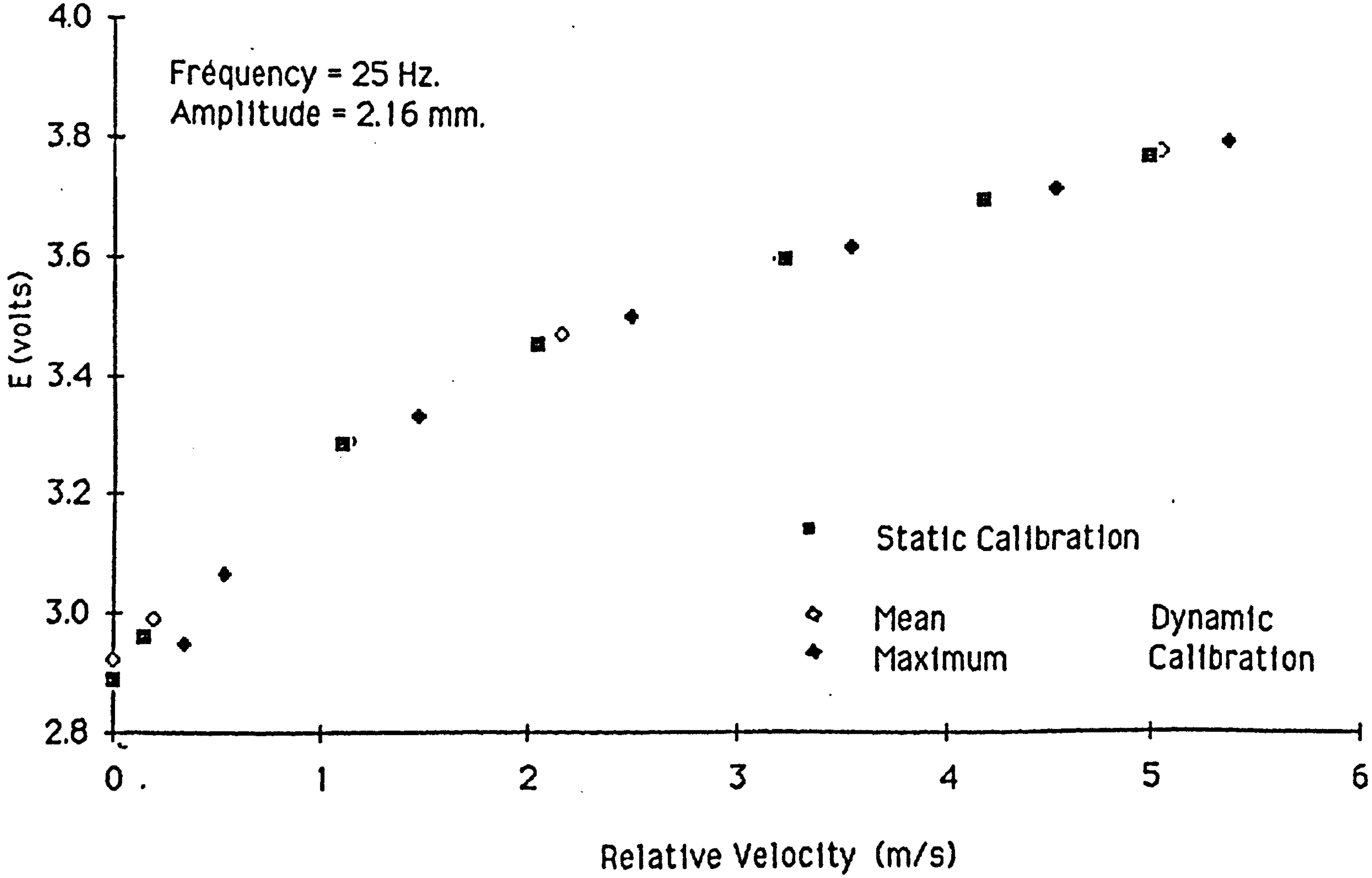


Figure 5.29 Comparison of Static and Dynamic Calibrations.

Table 1

Dynamic Calibration

Frequency of oscillation = 25 Hz.
Amplitude of oscillation = 2.16 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.95	0.34	2.92	0.0
3.07	0.53	2.99	0.19
3.33	1.46	3.28	1.13
3.46	2.49	3.47	2.15
3.61	3.54	3.59	3.20
3.71	4.53	3.69	4.19
3.79	5.37	3.77	5.05

Table 2

Dynamic Calibration

Frequency of oscillation = 25 Hz.
Amplitude of oscillation = 2.01 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.93	0.32	2.91	0.0
3.12	0.65	3.04	0.34
3.33	1.46	3.29	1.14
3.49	2.50	3.47	2.19
3.60	3.42	3.58	3.11
3.71	3.49	3.70	4.18
3.79	5.36	3.77	5.05

Table 3

Dynamic Calibration

Frequency of oscillation = 25 Hz.
Amplitude of oscillation = 1.64 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.91	0.26	2.90	0.0
3.02	0.40	2.67	0.14
3.32	1.44	3.29	1.18
3.48	2.41	3.46	2.16
3.60	3.41	3.59	3.15
3.71	4.40	3.69	4.14
3.78	5.15	3.77	4.90

Table 4

Dynamic Calibration

Frequency of oscillation = 25 Hz.
Amplitude of oscillation = 1.62 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.91	0.25	2.90	0.0
3.02	0.38	2.97	0.14
3.32	1.43	3.29	1.18
3.48	2.41	3.46	2.16
3.60	3.37	3.59	3.15
3.71	4.39	3.69	4.14
3.78	5.15	3.77	4.90

Table 5

Dynamic Calibration

Frequency of oscillation = 25 Hz.
Amplitude of oscillation = 1.32 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.91	0.21	2.90	0.0
3.02	0.38	2.97	0.17
3.30	1.36	3.28	1.15
3.61	3.39	3.59	3.19
3.70	4.35	3.69	4.14
3.77	5.39	3.76	5.19

Table 6

Dynamic Calibration

Frequency of oscillation = 35 Hz.
Amplitude of oscillation = 2.35 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.06	0.52	3.01	0.0
3.18	0.72	3.05	0.21
3.42	1.69	3.34	1.18
3.57	2.70	3.51	2.19
3.68	3.61	3.63	3.10
3.78	4.70	3.74	4.18
3.84	5.44	3.81	4.93

Table 7

Dynamic Calibration

Frequency of oscillation = 35 Hz.
Amplitude of oscillation = 2.07 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.03	0.46	2.99	0.0
3.13	0.59	3.02	0.13
3.40	1.58	3.32	1.13
3.56	2.61	3.50	2.16
3.67	3.55	3.62	3.10
3.77	4.63	3.74	4.18
3.84	5.41	3.81	4.95

Table 8

Dynamic Calibration

Frequency of oscillation = 25 Hz.
Amplitude of oscillation = 2.16 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.01	0.40	2.98	0.0
3.10	0.53	3.00	0.13
3.38	1.57	3.32	1.17
3.54	2.55	3.50	2.15
3.66	3.54	3.62	3.15
3.75	4.55	3.72	4.16
3.83	5.42	3.80	5.02

Table 9

Dynamic Calibration

Frequency of oscillation = 35 Hz.
Amplitude of oscillation = 1.41 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.98	0.31	2.95	0.0
3.08	0.45	3.00	0.14
3.38	1.53	3.33	1.21
3.53	2.42	3.49	2.11
3.64	3.38	3.62	3.07
3.76	4.58	3.74	4.27
3.82	5.29	3.80	4.99

Table 10

Dynamic Calibration

Frequency of oscillation = 35 Hz.
Amplitude of oscillation = 1.2 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.96	0.26	2.94	0.0
3.09	0.42	3.01	0.15
3.37	1.41	3.33	1.14
3.53	2.43	3.51	2.17
3.65	3.38	3.63	3.13
3.76	4.44	3.74	4.18
3.83	5.30	3.82	5.04

Table 11

Dynamic Calibration

Frequency of oscillation = 35 Hz.
Amplitude of oscillation = 0.50 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.92	0.11	2.91	0.0
3.03	0.18	2.30	0.17
3.33	1.28	3.31	1.17
3.49	2.24	3.48	2.12
3.61	3.23	3.61	3.13
3.72	4.25	3.71	4.14
3.79	5.10	3.78	4.99

Table 12

Dynamic Calibration

Frequency of oscillation = 45 Hz.
Amplitude of oscillation = 2.46 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.05	0.69	2.99	0.0
3.15	0.85	3.03	1.15
3.38	1.82	3.29	1.13
3.54	2.87	3.47	2.18
3.65	3.83	3.60	3.14
3.75	4.89	3.71	4.20
3.82	5.67	3.78	4.96

Table 13

Dynamic Calibration

Frequency of oscillation = 45 Hz.
Amplitude of oscillation = 2.07 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.01	0.59	2.97	0.0
3.16	0.85	3.04	0.26
3.39	1.79	3.31	1.21
3.52	2.72	3.47	2.13
3.64	3.75	3.59	3.16
3.74	4.70	3.70	4.12
3.81	5.52	3.77	4.94

Table 14

Dynamic Calibration

Frequency of oscillation = 45 Hz.
Amplitude of oscillation = 1.73 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.98	0.49	2.94	0.0
3.16	0.82	3.05	0.33
3.37	1.67	3.31	1.18
3.53	2.80	3.49	2.31
3.63	3.62	3.59	3.13
3.74	4.73	3.71	4.24
3.80	5.48	3.77	4.99

Table 15

Dynamic Calibration

Frequency of oscillation = 45 Hz.
Amplitude of oscillation = 1.33 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.95	0.38	2.93	0.0
3.12	0.64	3.03	0.26
3.37	1.63	3.32	1.25
3.51	2.56	3.48	2.19
3.63	3.56	3.60	3.19
3.74	4.64	3.71	4.27
3.80	5.42	3.78	5.05

Table 16

Dynamic Calibration

Frequency of oscillation = 55 Hz.
Amplitude of oscillation = 2.52 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.10	0.87	3.02	0.0
3.22	1.15	3.06	0.28
3.41	2.04	3.29	1.17
3.54	2.96	3.46	2.09
3.66	3.95	3.59	3.08
3.75	5.08	3.69	4.21
3.82	5.77	3.77	4.90

Table 17

Dynamic Calibration

Frequency of oscillation = 55 Hz.
Amplitude of oscillation = 2.13 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.04	0.74	2.98	0.0
3.17	0.94	3.03	0.20
3.41	2.01	3.32	1.27
3.54	2.87	3.47	2.13
3.65	3.91	3.60	3.17
3.74	4.82	3.70	4.09
3.81	5.64	3.77	4.90

Table 18

Dynamic Calibration

Frequency of oscillation = 55 Hz.
Amplitude of oscillation = 1.67 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
3.17	0.89	3.04	0.31
3.38	1.79	3.31	1.21
3.52	2.72	3.46	2.14
3.63	3.64	3.58	3.06
3.73	4.67	3.69	4.10
3.80	5.54	3.77	4.96

Table 19

Dynamic Calibration

Frequency of oscillation = 55 Hz.
Amplitude of oscillation = 1.20 mm.

Maximum Hot-wire Voltage in Volts	Relative Velocity in m/s	Mean Voltage in Volts	Jet-Velocity in m/s
2.95	0.42	2.93	0.0
3.08	0.57	2.98	0.16
3.35	1.55	3.29	1.14
3.51	2.59	3.47	2.17
3.63	3.59	3.60	3.18
3.72	4.44	3.69	4.03
3.80	5.37	3.77	4.96

Table 20

Static Calibration

Output Voltage in volts	Velocity in (m/s)
2.89	0.0
2.96	0.15
3.28	1.10
3.45	2.04
3.59	3.22
3.69	4.18
3.76	4.99

APPENDIX A

UNCERTAINTY ANALYSIS

The jet velocity is given by

$$U = 4*m/\pi\rho D^2 t \tag{A.1}$$

The uncertainty in U is given by

$$\omega_U = \{((\partial U/\partial m)\ \omega_m)^2 + ((\partial U/\partial D)\ \omega_D)^2) + ((\partial U/\partial t)\ \omega_t)^2\}^{1/2} \tag{A.2}$$

where

$$\partial U/\partial m = 4/\rho\pi D^2 t, \tag{A.3}$$

$$\partial U/\partial D = -8m/\rho\pi D^3 t, \tag{A.4}$$

$$\partial U/\partial t = -4m/\rho\pi D^2 t^2, \tag{A.5}$$

and the percentage uncertainty in U is given by

$$(\ \omega_U/U)*100 = \{\ (\ \omega_m/m)^2 + (\ \omega_D/D)^2\ + (\omega_t/t)^2\}^{1/2}*100 \tag{A.6}$$

for table 5, row 3

$m = 13.61$ kg

$\omega_m = 0.045$ kg

$D = 19.05$ mm

$\omega_D = 0.01$ mm

$t = 42.0$ secs

$\omega_t = 0.5$ secs

The estimated uncertainty in U is 0.01 m/s.

The uncertainty in the hot-wire voltage measurements is given by 0.024 percent of the range. The uncertainty in the voltage (voltage range was 5 volts) measured was

$\omega_v = 5*0.24/100 = 0.01$ volts.

The probe velocity amplitude is given by

$$u_p = k * v_a/2\pi f \tag{A.7}$$

where v_a is the output voltage from the charge amplifier

$$\partial u_p/\partial f = - k * v_a/2\pi f^2 \tag{A.8}$$

$$\partial u_{p/}\partial v_a = k/2\pi f \tag{A.9}$$

the uncertainty in u_p is given by

$$\omega_{up} = \{((\partial u_p/\partial f)\ \omega_f)^2 + ((\partial u_{p/}\partial v_a)\ \omega_{va})^2\}^{1/2} \tag{A.10}$$

for table 5, row 3

$v = 0.11132$ volts

$f = 35$ Hz

$\omega_{va} = .00048$ volts

$\omega_f = 0.1$ Hz

The estimated uncertainty in u_p is 0.0001 m/s

The relative velocity is given by

$$\text{Relative velocity} = U - u_p \tag{A.11}$$

The uncertainty in the relative velocity is given by

$$\omega_{\text{relative velocity}} = \{ ((\partial rv/\partial U)\ \omega_U)^2 + ((\partial rv/\partial u_p)\ \omega u_p)^2\}^{1/2} \tag{A.12}$$

for the above data the estimated uncertainty in the relative velocity is 0.01 m/s.

B.1 Data Acquisition Program in Basic

```
]LIST

100  HIMEM: 38144: REM  SET UP GE
     TAI13 ADDRESS
200  DIM A%(1,2000):A%(1,0) = 0
300  HOME : HTAB 12: INVERSE : PRINT
     "DATA ACQUISITION": NORMAL :
      PRINT
400  PRINT : PRINT "THIS PROGRAM
     MAKES A SERIES OF READINGS E
     ACH TIME IT IS CALLED"
500  PRINT "IT TAKES 4000 READING
     S ON EACH CHANNEL ": PRINT "
     WITH THIS PROGRAM YOU CAN": PRINT
     ". CREATE A FILE": PRINT ".R
     UN TO COLLECT": PRINT ". AD
     THEN STORE IT."
600  PRINT  CHR$ (4)"BLOAD GETAI1
     3,A$9500"
700  PRINT : PRINT "ENTER YOUR CH
     OICE: (C,R,S)"
710  GET A$
720  IF A$ = "C" THEN 1000
730  IF A$ = "S" THEN 2000
740  IF A$ = "R" THEN 3000
750  IF  ASC (A$) = 13 THEN  PRINT
     : PRINT  CHR$ (4)"RUN HELLO"

760  GOTO 700
1000  PRINT : INPUT "ENTER DATE?
     ";D$: PRINT : INPUT "TIME? "
     ;T$: REM  CREATE A FILE
1100  PRINT : INPUT "CARD IN SLOT
      NUMBER? ";SLOT
1200 A%(0,0) = SLOT:A%(1,0) =  -
     2000
1300  PRINT : INPUT "CHANNEL A? (
     0-15 OR RETURN) ";CA$:CA =  VAL
     (CA$): IF CA$ = "" THEN 700
1400  PRINT : INPUT "CHANNEL B? (
     0-15 OR RETURN) ";CB$:CB =  VAL
     (CB$): IF CB$ = "" THEN 700
```

```
1500  PRINT : PRINT "0=0 TO 5V
        4=-5 TO +5V": PRINT "1=0 T
     O 1V      5=-1 TO +1V": PRINT
     "2=0 TO .5V      6=-.5 TO +.5
     V": PRINT "3=0 TO .1V       7
     =-.1 TO +.1V"
1600  PRINT : INPUT "GAIN SETTING
                  ? (CHANNEL A) ";
     GA
1700  PRINT : INPUT "GAIN SETTING
     ? (CHANNEL B) ";GB
1800 K = 1
1810  FOR I = 1 TO 2000
1820  IF (I / 2 - K) = 0 THEN  GOTO
      1865
1840 A%(0,I) = CA + 16 * GA
1860  GOTO 1900
1865 K = K + 1
1870 A%(0,I) = CB + 16 * GB
1900  NEXT I
1999  GOTO 700
2000  REM  STORE DATA
2100 CD$ =  CHR$ (4)
2200  INPUT "FILENAME? ";F$
2300  PRINT CD$;"OPEN ";F$
2400  PRINT CD$;"DELETE ";F$
2500  PRINT CD$;"OPEN ";F$
2550  PRINT CD$;"WRITE ";F$
2600  PRINT D$,T$,SLOT,CA$,CB$,GA
      ,GB
2700  FOR K = 1 TO 2000: PRINT A%
      (1,K): NEXT K
2800  PRINT CD$;"CLOSE ";F$
2999  GOTO 700
3000  REM  RUN
3100  IF A%(1,0) = 0 THEN 700
3200  HOME
3510  POKE 8,1: CALL 38144
3520 K = 2
3550  FOR J = 1 TO 500 STEP 2
3600  PRINT A%(1,J),A%(1,K)
3610 K = K + 2
3650  NEXT J
3999  GOTO 700
```

B.2 Data Acquisition Subroutine in Assembly Language

```
0000:           ;
0000:           ; INTERACTIVE STRUCTURES INC
0000:           ;    DAT DEC '80
0000:           ;
0000:           ;   AI13 TO APPLESOFT ARRAY
0000:           ;


0000:           ;
0000:           ; VARIABLE DEFINITIONS
0000:           ;
C080:           DEV      EQU  $C080     DEVICE SELECT LOCATION
006B:           AARY     EQU  $6B       APPLESOFT ARRAY POINTER
006D:           AARYE    EQU  $6D       APPLESOFT ARRAY END
0006:           PTR      EQU  6
0008:           ARYPTR   EQU  8
003C:           OLDCH    EQU  $3C       LAST CHANNEL/GAIN USED
003D:           DELAY    EQU  $3D       DELAY COUNTER
0006:           DLYVAL   EQU  6         FOR ABOUT 45 MS DELAY
00F9:           STASUB   EQU  $F9       'STA DEV+SLOT*16'



----- NEXT OBJECT FILE NAME IS GETAI13
9000:                    ORG  $9000
9000:           ;
9000:           ; THIS ROUTINE TAKES THE N'TH INTEGER ARRAY
9000:           ;  TO DETERMINE THE SAMPLING SEQUENCE FOR
9000:           ;  THE AI13.  BEFORE USE DIMENSION A YOUR
9000:           ;  ARRAYS AS 1 BY N.  THE (0,0) ELEMENT
9000:           ;  CONTAINS THE SLOT NUMBER FOR THE AI13.
9000:           ;  THE (0,1)'TH ELEMENT CONTAINS THE
9000:           ;   NEGATIVE OF THE NUMBER
9000:           ;  OF SAMPLES TO TAKE (LESS THAN THE
9000:           ;  ARRAY DIMENSION SIZE)
9000:           ;  THEN FILL THE (0,I)'TH ELEMENTS WITH
9000:           ;  THE AI13 ADDRESS/GAIN PARAMETERS.
9000:           ;   IF THIS IS NEGATIVE THIS SAMPLE IS SKIPPED
9000:           ;  AFTER CALLING THE (1,I)'TH ELEMENTS WILL
9000:           ;  CONTAIN THE VALUES.
9000:           ;  TO SELECT THE ARRAY TO USE POKE
9000:           ;  ITS NUMBER INTO LOCATION 8 BEFORE CALLING.
9000:           ;  NOTE: THIS LOCATION IS CLOBBERED!
9000:           ;
9000:           GETAI13  EQU  *
9000:A5 6B               LDA  AARY      GET START OF ARRAY SPACE
9002:85 06               STA  PTR
9004:A5 6C               LDA  AARY+1
9006:85 07               STA  PTR+1
9008:A0 00      GAA1     LDY  #0
900A:B1 06               LDA  (PTR),Y
900C:10 24               BPL  GNARY1
900E:C8                  INY
900F:B1 06               LDA  (PTR),Y
9011:10 20               BPL  GNARY
9013:C6 08               DEC  ARYPTR
9015:D0 1C               BNE  GNARY
9017:C8                  INY
```

```
9018:C8          56          INY
9019:C8          57          INY
901A:B1 06       58          LDA   (PTR),Y     GET NUMBER OF DIMENSIONS
901C:AA          59          TAX               WE WANT TO SKIP OVER THEM
901D:C8          60          INY
901E:C8          61 GAA2     INY
901F:C8          62          INY
9020:CA          63          DEX
9021:D0 FB       64          BNE   GAA2
9023:98          65          TYA
9024:18          66          CLC
9025:65 06       67          ADC   PTR
9027:85 08       68          STA   ARYPTR      NOW GET REAL POINTER
9029:A9 00       69          LDA   #0
902B:65 07       70          ADC   PTR+1
902D:85 09       71          STA   ARYPTR+1
902F:18          72          CLC
9030:90 22       73          BCC   GETOK       GOT THE ARRAY
9032:C8          74 GNARY1   INY
9033:C8          75 GNARY    INY
9034:18          76          CLC
9035:B1 06       77          LDA   (PTR),Y     POINT TO NEXT ARRAY
9037:65 06       78          ADC   PTR
9039:48          79          PHA               CAN'T OVERWRITE JUST YET
903A:C8          80          INY
903B:B1 06       81          LDA   (PTR),Y
903D:65 07       82          ADC   PTR+1
903F:85 07       83          STA   PTR+1
9041:68          84          PLA               NOW WE CAN
9042:85 06       85          STA   PTR
9044:A5 07       86          LDA   PTR+1
9046:C5 6E       87          CMP   AARYE+1     SEE IF PAST END
9048:F0 03       88          BEQ   GNAA2
904A:90 BC       89          BCC   GAA1
904C:60          90 GNAA3    RTS               RETURN WITHOUT DOING ANYTHING
904D:A5 06       91 GNAA2    LDA   PTR
904F:C5 6D       92          CMP   AARYE
9051:90 B5       93          BCC   GAA1
9053:60          94          RTS

9054:            96 GETOK    EQU   *           NOW GOT THE ARRAY
9054:A9 8D       97          LDA   #$8D        'STA' OPCODE
9056:85 F9       98          STA   STASUB      SETUP A STORE SUBROUTINE
9058:A9 C0       99          LDA   #$C0
905A:85 FB      100          STA   STASUB+2
905C:A9 60      101          LDA   #$60        'RTS'
905E:85 FC      102          STA   STASUB+3
9060:A0 01      103          LDY   #1          WANT THE SLOT #
9062:B1 08      104          LDA   (ARYPTR),Y
9064:29 07      105          AND   #7          JUST IN CASE
9066:0A         106          ASL   A           TIMES 16
9067:0A         107          ASL   A
9068:0A         108          ASL   A
9069:0A         109          ASL   A
906A:AA         110          TAX
906B:09 80      111          ORA   #$80
906D:85 FA      112          STA   STASUB+1
906F:C8         113          INY               NOW GET NUMBER OF SAMPLES
```

```
9070:B1 08            LDA  (ARYPTR),Y
9072:85 07            STA  PTR+1
9074:C8               INY
9075:B1 08            LDA  (ARYPTR),Y
9077:85 06            STA  PTR
9079:A9 00            LDA  #0          INITIALIZE OLD CHANNEL/GAIN
907B:85 3C            STA  OLDCH
907D:        GETLOOP  EQU  *
907D:18               CLC
907E:A9 04            LDA  #4          POINT TO NEXT ELEMENT
9080:65 08            ADC  ARYPTR
9082:85 08            STA  ARYPTR
9084:A9 00            LDA  #0
9086:65 09            ADC  ARYPTR+1
9088:85 09            STA  ARYPTR+1
908A:A9 06            LDA  #DLYVAL     INIT DELAY LOOP
908C:85 3D            STA  DELAY
908E:A0 00            LDY  #0          GET HI-ORDER BYTE
9090:B1 08            LDA  (ARYPTR),Y TO SEE IF SKIPPING
9092:30 29            BMI  SKIPTHIS
9094:C8               INY              NOW FOR LO-ORDER BYTE
9095:B1 08            LDA  (ARYPTR),Y
9097:20 F9 00         JSR  STASUB      SETUP ADDRESS/GAIN
909A:48               PHA
909B:C5 3C            CMP  OLDCH       SEE IF SAME AS BEFORE
909D:F0 08            BEQ  SKPDLY      YES, DON'T HAVE TO DELAY
909F:29 02            AND  #2          SEE IF HI-GAIN SETTINGS
90A1:F0 04            BEQ  SKPDLY      NO, LO-GAIN (FASTER)
90A3:C6 3D   WAITLP   DEC  DELAY       NOW TWIDDLE OUR THUMBS
90A5:D0 FC            BNE  WAITLP
90A7:68      SKPDLY   PLA              RESTORE CHANNEL/GAIN
90A8:85 3C            STA  OLDCH       UPDATE OLD
90AA:20 F9 00         JSR  STASUB      TAKES CARE OF OP-AMP SPROING
90AD:48               PHA
90AE:68               PLA
90AF:C8               INY
90B0:BD 81 C0         LDA  DEV+1,X     THIS COMES OUT FIRST
90B3:29 0F            AND  #$F         AND OFF FLAGS
90B5:91 08            STA  (ARYPTR),Y SAVE HI-ORDER
90B7:C8               INY
90B8:BD 80 C0         LDA  DEV,X
90BB:91 08            STA  (ARYPTR),Y AND LO-ORDER
90BD:        SKIPTHIS EQU  *           # ELEMENTS COUNTER
90BD:E6 06            INC  PTR
90BF:D0 BC            BNE  GETLOOP
90C1:E6 07            INC  PTR+1
90C3:D0 B8            BNE  GETLOOP
90C5:60               RTS

*** SUCCESSFUL ASSEMBLY: NO ERRORS
```

B.3 Data Processing Program in Basic

```
]LIST

200  DIM A%(1,2000),APM%(1,30):A%
     (1,0) = 0
250  DIM ANM%(1,30),HPTN%(1,30),H
     NTP%(1,30)
260  DIM VNM(30),ENTP(30),VPM(30)
     ,EPTN(30),XA(20),YA(20),ZX(2
     0),ZY(20),EM(20)
270  DIM VM(20)
275  INPUT "FREQUENCY OF OSS = ?"
     ;FC
276  INPUT "SUPRESSED VOLTAGE = ?
     ";EC
280 N = 0.0:M = 0.0
290 VC = 47.743209
700  PRINT : PRINT "ENTER YOUR CH
     OICE:(R,U,S)"
710  GET A$
720  IF A$ = "R" THEN 1000
730  IF A$ = "S" THEN 2000
740  IF A$ = "U" THEN 3000
750  IF  ASC (A$) = 13 THEN  PRINT
     : PRINT  CHR$ (4)"RUN HELLO"

760  GOTO 700
1000  REM  LOAD DATA STORED EARLI
     ER
1010  INPUT "TIME IN SECS = ?";SE
     CS
1020 MV = VC / SECS
1110  INPUT "FILENAME?";F$
1120 CD$ =  CHR$ (4)
1130  PRINT CD$;"OPEN";F$
1140  PRINT CD$;"READ";F$
1150  INPUT D$,T$,SLOT,CA$,CB$,GA
     ,GB
1160  FOR J = 1 TO 1998
1170  INPUT A%(1,J)
1180  NEXT J
1190  PRINT CD$;"CLOSE";F$
1200 K = 2
```

```
1210  FOR J = 1 TO 500 STEP 2
1220  PRINT A%(1,J),A%(1,K)
1230 K = K + 2
1240  NEXT J
1250  GOTO 4000
2000  REM  STORE DATA
2050 R = VP(N) / W
2100 CD$ =  CHR$ (4)
2200  INPUT "FILENAME? ";F$
2300  PRINT CD$;"OPEN ";F$
2400  PRINT CD$;"DELETE ";F$
2500  PRINT CD$;"OPEN ";F$
2550  PRINT CD$;"WRITE ";F$
2551  PRINT M
2552  PRINT 0
2600  FOR I = 1 TO M: PRINT XA(I)
     : PRINT YA(I)
2610  PRINT ZX(I): PRINT ZY(I)
2620  PRINT EM(I): PRINT VM(I)
2700  NEXT
2710  PRINT FC: PRINT W
2800  PRINT CD$;"CLOSE ";F$
2999  GOTO 280
3000  REM  UPDATING DATA
3010 M = M + 1
3020 XA(M) = VPM(N) + MV
3030 YA(M) = EPTN(N) + EC
3040 ZX(M) =  ABS (MV - VNM(N))
3050 ZY(M) = ENTP(N) + EC
3060 EM(M) = ((TV * HG) / (4096 *
     999)) + EC
3070 VM(M) = MV
3080  GOTO 700
4000  REM
4002 TV = 0.0
4003 N = N + 1
4005  INPUT "HWGAIN";HG
4006  INPUT "ACCNGAIN";AG
4008 W = FC * 2.0 * 3.14159
4010 I = 1:J = 0:K = 0
4020  IF A%(1,I) > 2048 THEN 4050
```

```
4030 I = I + 2
4040  GOTO 4020
4050  IF I > 1 THEN 4085
4060 I = I + 2
4070  IF A%(1,I) < 2048 THEN 4165
4080  GOTO 4060
4085 TEMP3 = I - 1
4090 AB = A%(1,I)
4100 I = I + 2
4110  IF I > 1998 THEN 4260
4120  IF A%(1,I) < 2048 THEN 4150

4130  IF A%(1,I) > AB THEN 4090
4140  GOTO 4100
4150 L = I - 1:J = J + 1
4160 APM%(1,J) = AB - 2048:HPTN%(
     1,J) = A%(1,L)
4163  GOTO 4170
4165 TEMP1 = I - 1
4170 AC = A%(1,I)
4180 I = I + 2
4190  IF I > 1998 THEN 4260
4200  IF A%(1,I) > 2048 THEN 4230
4210  IF A%(1,I) < AC THEN 4170
4220  GOTO 4180
4230 L = I - 1:K = K + 1
4240 ANM%(1,K) = 2048 - AC:HNTP%(
     1,K) = A%(1,L)
4245 TEMP4 = I - 1
4250  GOTO 4090
4260 X1 = 0:X2 = 0:X3 = 0:X4 = 0
4265 J = J - 1:K = K - 1
4270  FOR I = 1 TO J
4280 X1 = X1 + APM%(1,I)
4290 X2 = X2 + HPTN%(1,I)
4300  NEXT
4310 VPM(N) = (X1 * AG * 9.81) /
     (2048 * 0.01 * W * J)
4320 EPTN(N) = (X2 * HG) / (4096 *
     J)
4330  FOR I = 1 TO K
4340 X3 = X3 + ANM%(1,I)
4350 X4 = X4 + HNTP%(1,I)
4360  NEXT
4370 VNM(N) = (X3 * AG * 9.81) /
     (2048 * 0.01 * K * W)
```

```
4380 ENTP(N) = (X4 * HG) / (4096 *
     K)
4390  PRINT VPM(N),,EPTN(N)
4400  PRINT VNM(N),,ENTP(N)
4405  IF A%(1,1) > 2048 THEN 4410

4406 TEMP1 = TEMP3:TEMP2 = TEMP4
4410  FOR I = TEMP1 TO TEMP2 STEP
     2
4420 TV = TV + A%(1,I)
4430  NEXT
4450  GOTO 700
```

VITA AUCTORIS

1954	Born in Bombay, Maharashtra, India on December 17.
1971	Completed high school at Sacred Heart Boy's High School, Bombay, India in June.
1978	Received the Degree of Bachelor of Mechanical Engineering from the University of Bombay, Bombay, India in June.
1978-1982	Worked as a Production Engineer with Godrej & Boyce Mfg Co Pvt Ltd, Bombay, India.
1986	Currently a candidate for the Degree of Master of Applied Science in Mechanical Engineering at The University of Windsor, Windsor, Ontario, Canada.