Development of equipment and techniques for experimental determination of dynamic response of the human forearm

by Michael Dennis Harrigan

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mechanical Engineering
Montana State University

Abstract:
The need to determine the dynamic response of a human biological system has been well established., It is the purpose of this study to design, construct, and test sophisticated equipment for determining the dynamic response of the human forearm. Specifically, equipment was designed to experimentally determine the response of the human forearm to a sinusoidal forcing function. The frequency of the forcing function was swept between 50 and ' 1000 Hertz, The forcing function was applied at the olecranon process. The response was measured by an accelerometer at different locations on the forearm, then recorded on an X-Y plotter, thus obtaining a frequency response plot.

In order to determine which configuration of arm position and transducer location offered the most repeatable results, a parametric study was undertaken.

Four parameters were investigated; they were: 1) longitudinal position of the response transducer, 2) angular position of the response transducer, 3)static force between the response transducer and the skin surface, and 4) rotational position of the forearm.

Two test subjects were used. Three tests were conducted at each of the twenty-four configurations, which yielded 144 experiments conducted.

It was concluded that four of the configurations were significantly more repeatable than the other twenty. It was also suggested that the first resonance observed in this study, occurring near 100 Hz,, is a rigid body mode of the ulna, while the second resonance observed, occurring near 250 Hz,, is the first bending mode of the ulna.

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Montana State University, I agree that the Library shall make it freely available for inspection. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by my major professor, or, in his absence, by the Director of Libraries. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature Michael D. Hanegan

Date April 30, 1974

DEVELOPMENT OF EQUIPMENT AND TECHNIQUES FOR EXPERIMENTAL DETERMINATION OF DYNAMIC RESPONSE OF THE HUMAN FOREARM

by

MICHAEL DENNIS HARRIGAN

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Mechanical Engineering

Approved:

Dennis O. Blackketter
Head, Mechanical Engineering

Dennis O. Blackketter
Chairman, Examining Committee

Henry L. Parsons
Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

August 1974

ACKNOWLEDGEMENT

The author is indebted to Dr. D.O. Blackketter and Dr. E.R. Garner for their valuable assistance in this work.

The support of the Department of Mechanical Engineering at Montana State University for this research is greatly appreciated.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figures 13-20 are Frequency Response Plots for the Candidate Configurations.

LIST OF FIGURES (CONT.)

ABSTRACT

The need to determine the dynamic response of a human biological system has been well established. It is the purpose of this study to design, construct, and test sophisticated equipment for determining the dynamic response of the human forearm. Specifically, equipment was designed to experimentally determine the response of the human forearm to a sinusoidal forcing function. The frequency of the forcing function was swept between 50 and 1000 Hertz. The forcing function was applied at the olecranon process. The response was measured by an accelerometer at different locations on the forearm, then recorded on an X-Y plotter, thus obtaining a frequency response plot.

In order to determine which configuration of arm position and transducer location offered the most repeatable results, a parametric study was undertaken. Four parameters were investigated; they were: 1) longitudinal position of the response transducer, 2) angular position of the response transducer, 3)static force between the response transducer and the skin surface, and 4) rotational position of the forearm.

Two test subjects were used. Three tests were conducted at each of the twenty-four configurations, which yielded 144 experiments conducted.

It was concluded that four of the configurations were significantly more repeatable than the other twenty. It was also suggested that the first resonance observed in this study, occurring near 100 Hz., is a rigid body mode of the ulna, while the second resonance observed, occurring near 250 Hz., is the first bending mode of the ulna.

INTRODUCTION

Previous works have dealt with dynamic response to human biological systems. Dr. Jurist (1) attempted to correlate several physical factors of test subjects forearms with the determined resonant frequency, and the ulna length. The investigator found in a study of children that the product of resonant frequency and ulna length was significantly correlated with height, weight, upper arm circumference, and bone mineral content. He also concluded that the resonant frequency was not significantly correlated with ulna length for boys of age 6-11 years.

R. Matz (2) did a parametric study to correlate biological parameters of the human forearm with natural frequency. He found that the four parameters he investigated, ulna length, bone diameter, fleshiness, and muscle development were significantly correlated with resonant frequency. Dr. E. R. Garner modeled the forearm mathematically and solved for macroscopic material properties using digital computation techniques (4).

The intent of this study was to develop sophisticated instrumentation which could provide repeatable data for dynamic response of the human forearm. In addition to development of the equipment, a study was undertaken to demonstrate the repeatability of results obtained with the equipment for different transducer configurations. This study entailed four parameters:

1) Longitudinal position of the response transducer. Two locations were investigated: a point near the elbow, and a point located midway between the elbow and the styloid process. See figure 1.

2) Rotational position of the forearm. Two positions were investigated: a position with the right forearm rotated fully counter-clockwise (viewing from the hand toward the elbow). This is called the AP position. The second position was with the right forearm rotated 90 degrees clockwise from the AP position. See figure 2.

3) Force with which the response transducer was held against the forearm. Two values were investigated: a relativly light force and a relativly heavy force. The force was controlled by the strength of the spring used to hold the response transducer against the forearm.

4) Rotational position of the response transducer about the longitudinal axis of the forearm. The response transducer is always maintained normal or perpindicular to the skin surface, but may be aligned in a plane with the input transducer or may be rotated to other positions. These positions were analyzed: a position aligned with the input transducer, a position 30 degrees clockwise from alignment with the input transducer, and a position 30 degrees counter-clockwise from alignment with the input transducer. See figure 3.

The combination of the four parameters yields twenty-four permutations (three parameters have two positions, one parameter has three positions). Each permutation was given six trials; three trials on each of two volunteer subjects. Thus a total of 144 experiments were conducted.

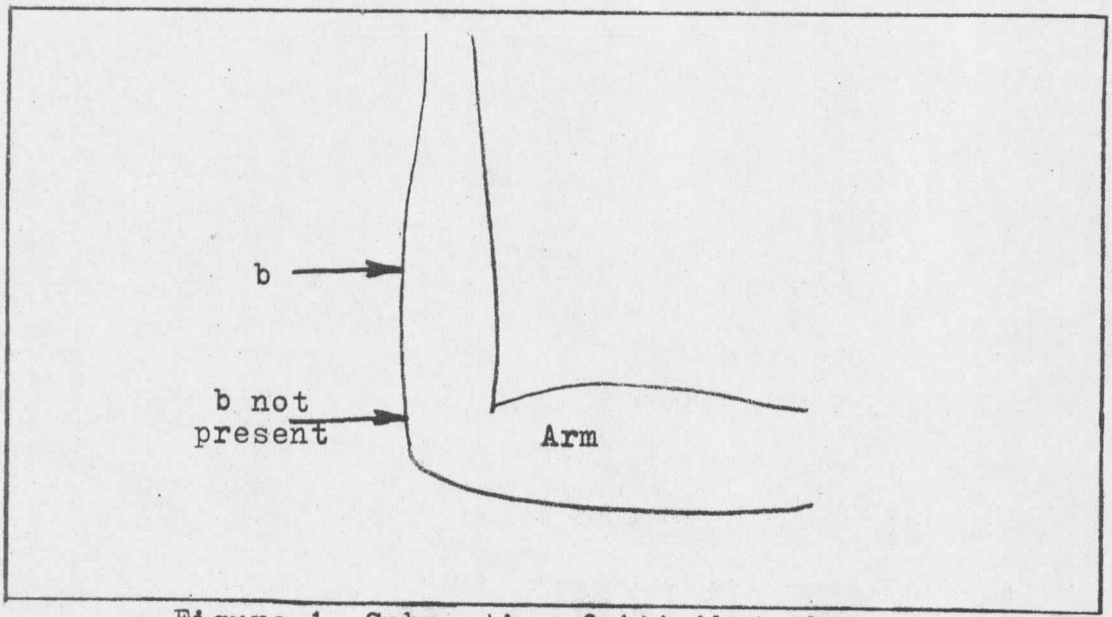
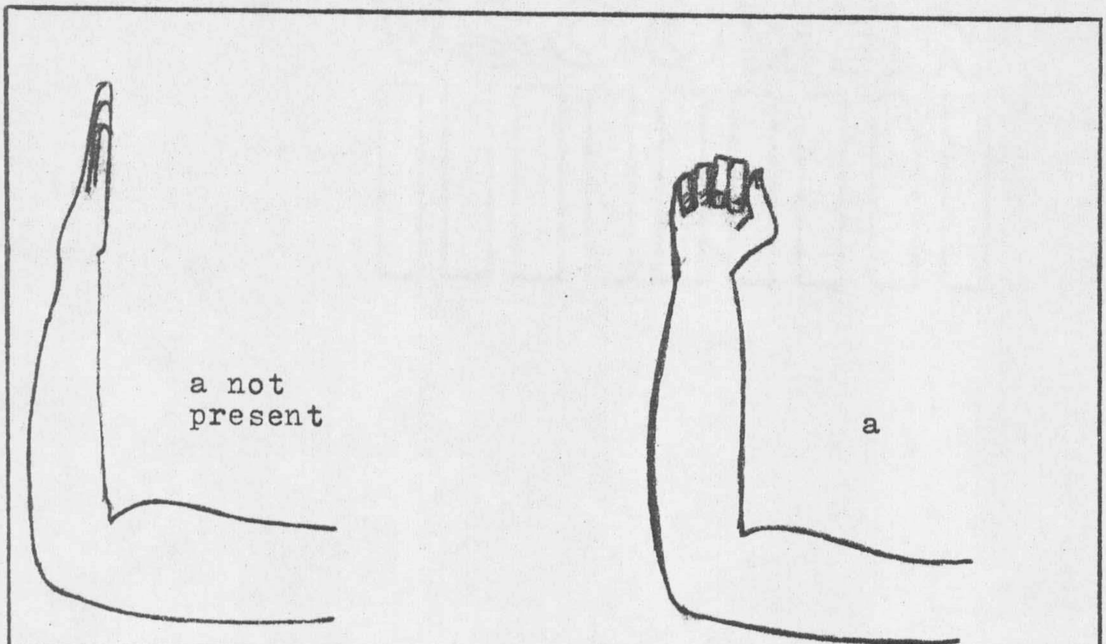


Figure 1 Schematic of Attribute b



<u>Figure 2</u> Schematic of Attribute a

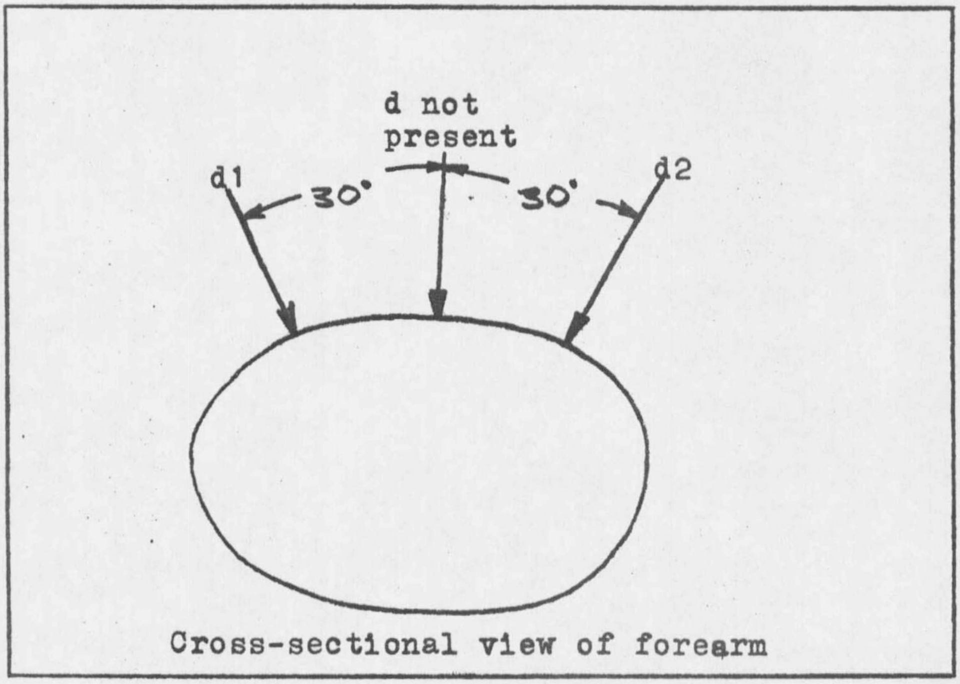


Figure 3 Schematic of Attribute d

The resulting data was reduced using statistical techniques.

CHAPTER 1

THE FREQUENCY PRESPONSE PLOT OF THE HUMAN FOREARM

The prupose of this study is to develop equipment to obtain a frequency response plot of the human forearm. The frequency response plot is an indication of the dynamic response of a system.

The dynamic response of any mechanical system can be illustrated using a frequency response plot. As an example, consider the simple beam pinned at each end shown in figure 4. Analysis of the system demonstrates that such a beam has an infinite number of natural frequencies; associated with each of the natural frequencies is a particular mode shape. The natural frequencies of such a beam can be found experimentally by exciting the beam at or near one of the natural frequencies, and measuring the amplitude of the displacement of the beam. As the excitation frequency approaches the natural frequency of the beam, the amplitude of the displacement at a particular non-nodal point will increase. An accelerometer can be used to measure response acceleration at various points on the beam. By plotting response amplitudes versus input frequency, the natural frequencies will appear as peaks on the frequency response plot as shown in figure 5. The positioning of the accelerometer

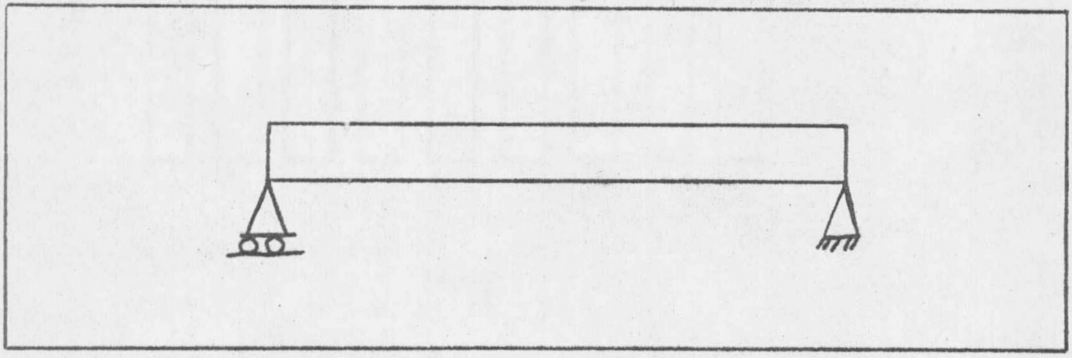


Figure 4 Pinned End Beam

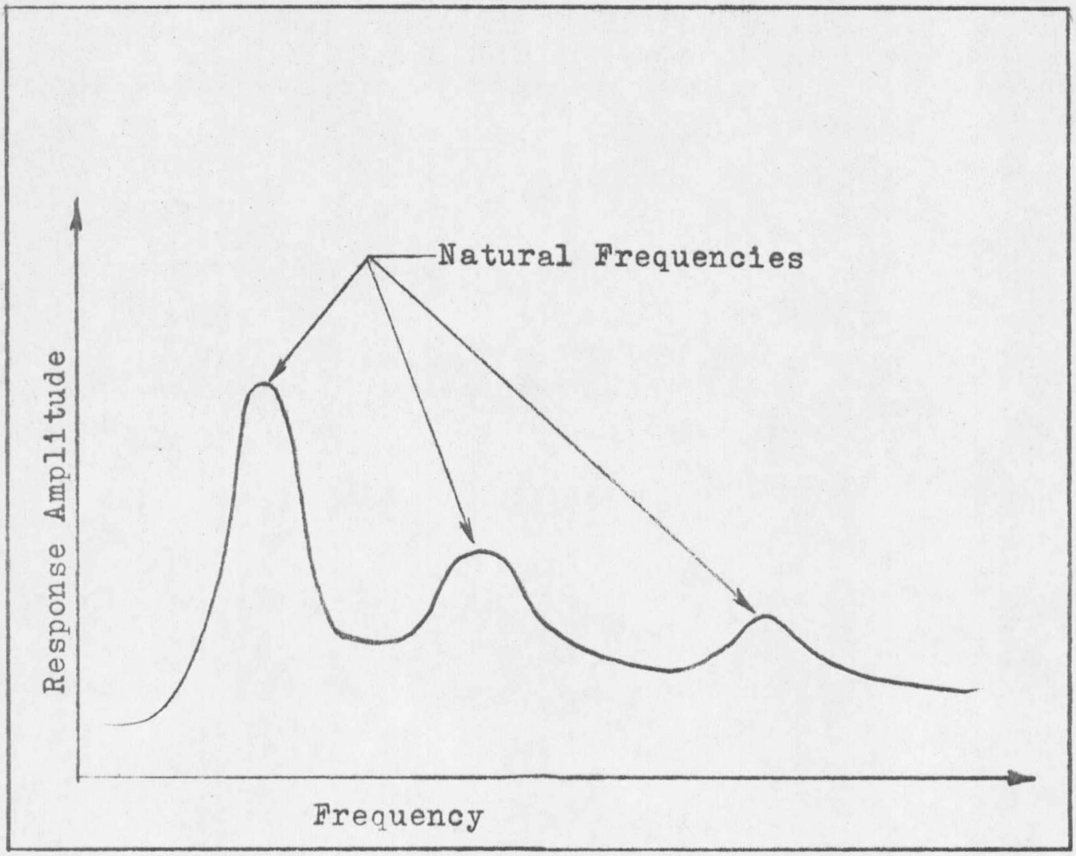
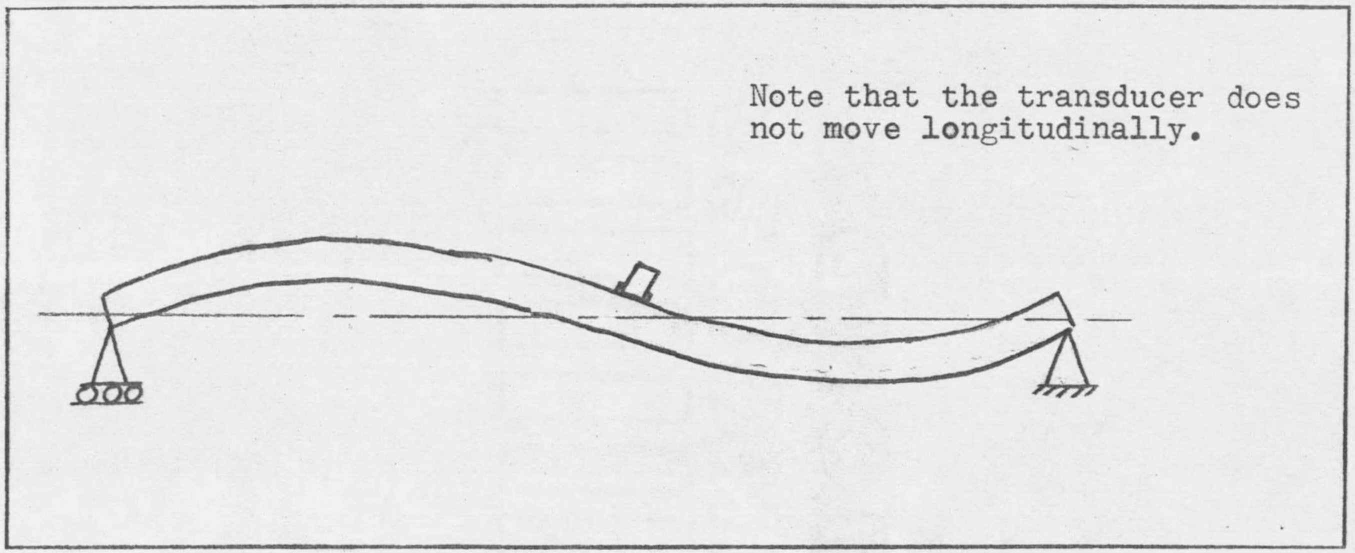


Figure 5 Example of a Frequency Response Plot

is important because of the nodes that may be associated with a particular natural frequency. This is illustrated in figure 6.

The human forearm can be compared to the beam in the example above in that both are examples of a continuous system. It is expected that the forearm will have an infinite number of natural frequencies and a particular mode shape associated with each of the frequencies. In the experimental work, small amplitude displacements must be maintained to avoid pain and possible damage to the biological system. Thus very sensitive response equipment is required. Further, the major structural elements of the forearm are the bones, and the bones are insulated from the instrumentation by the soft tissue of the flesh. Ideally, the response accelerometer should be attached directly to the bone. Since this is physically difficult, as an alternative, the transducer can be pressed against the skin surface at a point where the skin and flesh are thin, thus allowing the transducer to be in close proximity to the bone. Even a small layer of skin and flesh will attenuate the transducer displacement at the skin surface. The location of the response accelerometer is important; when the response accelerometer is located



Note that the transducer does not move longitudinally.

<u>Figure 6</u> Schematic of Pinned End Beam Resonating in Second Bending Mode with Accelerometer Located at a Nodal Point

at or near a nodal point of the mode being excited, there will be little or no response for the associated natural frequency. Also, since the forearm is a three-dimensional system, the plane of vibration is not known. For identification of the plane of vibration it is necessary to position the response accelerometer at several locations on the forearm.

The evaluation of the system for determining the dynamic response of the human forearm to a sinusoidal forcing function is accomplished with a parameter study. The four parameters that were varied are:

1) Longitudinal position of the response transducer.
2) Rotational position of the forearm.
3) Force with which the response transducer was held against the forearm.
4) Rotational position of the response transducer about the longitudinal axis of the forearm.

CHAPTER 2

EQUIPMENT DEVELOPMENT

Development of equipment was accomplished in several phases. They were: 1) the electronics to provide the necessary signal to the input transducer, 2) the electronics to detect the signal from the response transducer and record the results, 3) the design of the input and output transducers, and 4) the design of a fixture to position the human forearm and transducers. The system is shown schematically in figure 7.

Some basic decisions on transducer design were required as a first step. There are several highly sensitive piezo-electric accelerometers available on the commercial market. An accelerometer manufactured by MB Electronics was selected for a response transducer. For analysis of the data, it is desirable to have the input system exert a force on the arm that varied sinusoidally such that the amplitude of acceleration was constant for the frequency range of 50-1000 Hz. In order to obtain an appropriate input system, a control system was designed and assembled. The details of the control system appear in Appendix B. The input system was, thus, composed of an accelerometer and a control circuit with the function generator, power

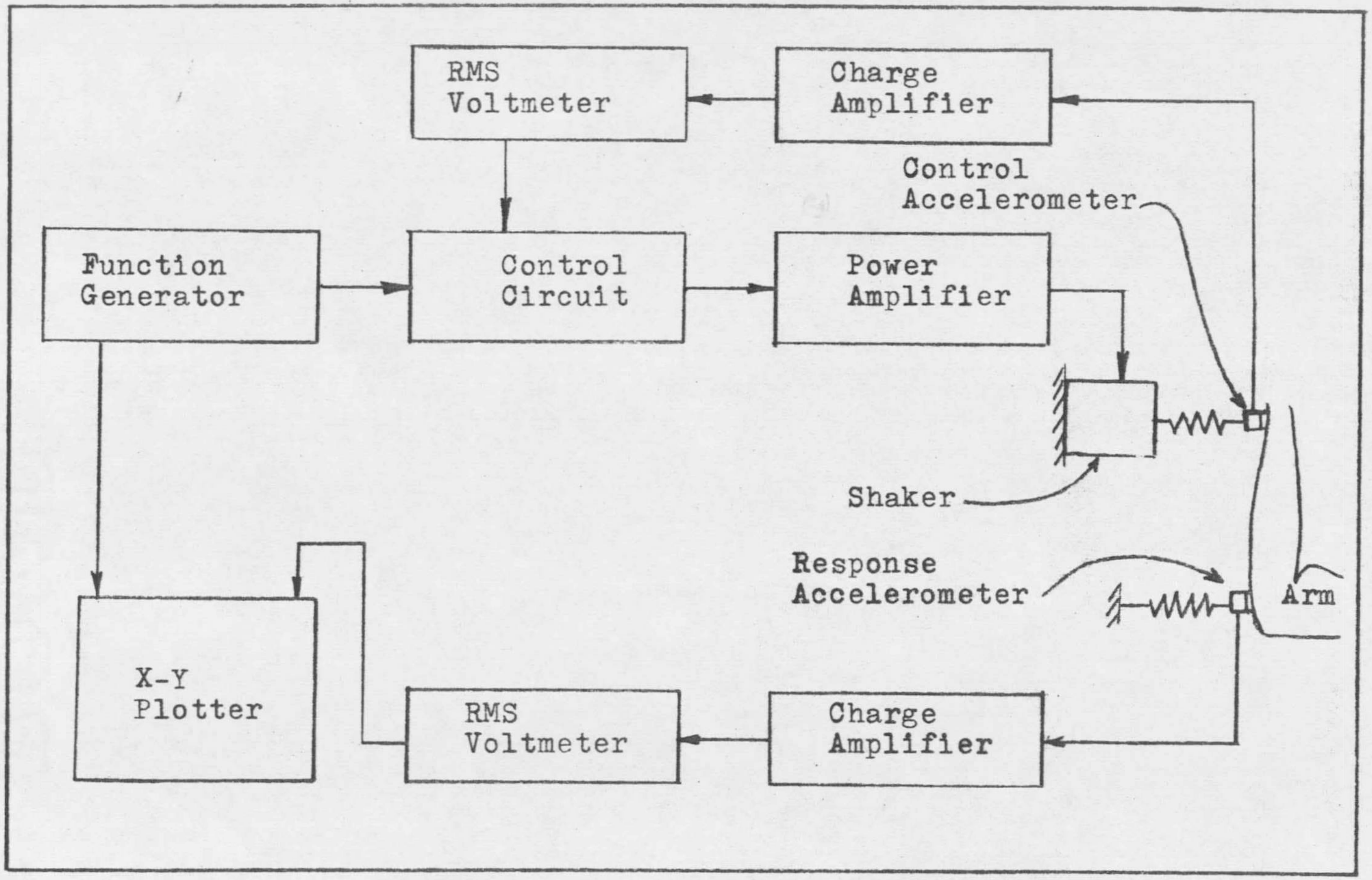


Figure 7 Schematic of Equipment

amplifier, and electromagnetic vibrator. It is noted that except for the interface between the control circuit and the other devices, development of the components was done independently.

The development of the electronics for producing the input signal was accomplished using commercial equipment. A Hewlett-Packard function generator was used for producing the input signal, for sweeping the signal over the desired range of frequencies, and for controlling the sweep rate.

An X-Y plotter, also manufactured by Hewlett-Packard, was used to construct a graph of input frequency versus output response amplitude, the frequency response plot. The signal produced by the Hewlett-Packard function generator was transmitted to the amplifier through the control circuit. The power amplifier served to convert the voltage signal to a power signal which was then used to drive the input transducer. A piezo-electric accelerometer was used to detect the acceleration amplitude of the mechanical signal at the interface between the input transducer and the skin surface. The signal from the control accelerometer was then amplified through a calibrated charge amplifier, and the signal is detected by a RMS voltmeter.

The RMS voltmeter also provided a D.C. voltage which was proportional to the RMS value of the signal provided by the control accelerometer to the charge amplifier. This proportional D.C. signal was used in the specially designed control circuit to control the feedback loop of the operational amplifier. The operational amplifier was located between the function generator and the power amplifier. Thus, the signal to the power amplifier was controlled.

The circuitry for reading and recording the response signal was assembled from commercially available equipment. A calibrated charge amplifier was necessary to amplify the signal from the response transducer, a piezoelectric accelerometer. This amplified signal was then transmitted to another RMS voltmeter which detected the signal and provided an analogous D.C. output voltage. This voltage is proportional to the response signal, and is used to drive the Y-axis of the X-Y plotter.

The problem of fixture design, and input transducer design still remained. The transducers and fixture were interrelated since the fixture had to locate the arm and transducers in positions that could be repeated at a later date. The fixture is shown in figure 8, and a detail drawing of the fixture appears in Appendix C. After

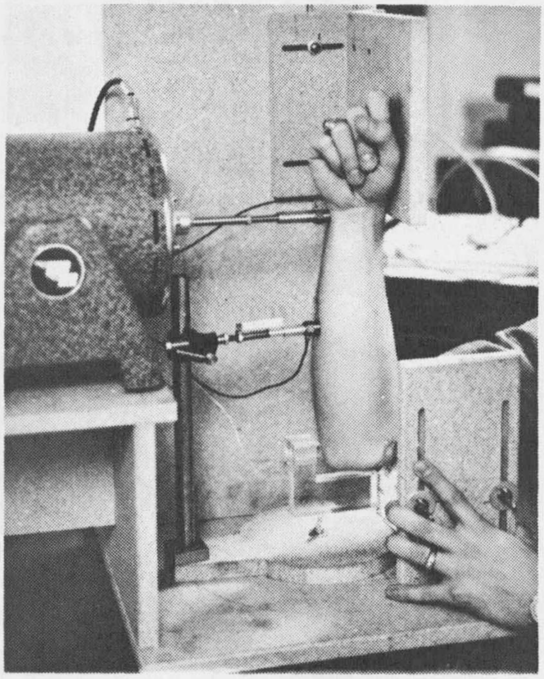


Figure 9 Positioning Fixture

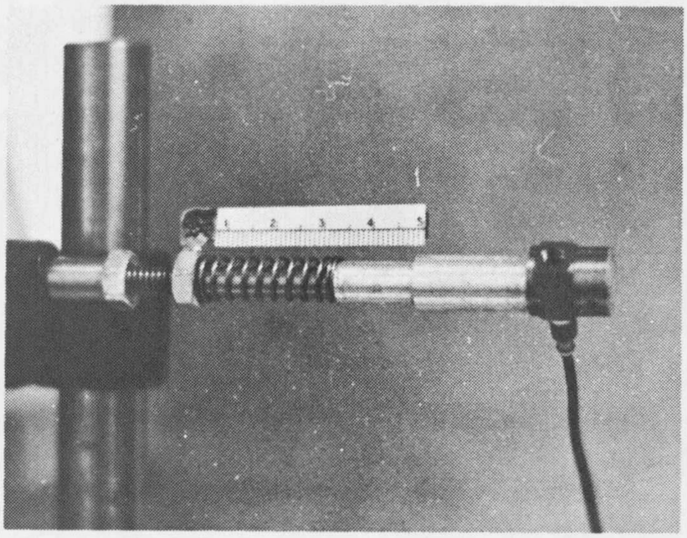


Figure 10 Response Transducer

several experiments with low powered loudspeakers for use as an input device, it was concluded that the loudspeakers were too delicate and inconsistent for use as an input device. Also, the small loudspeakers could not produce the power necessary at the lower frequencies. The low powered loudspeakers were not suitable as input devices. Experimental analysis of a small MB Electronics electromagnetic vibrator indicated that this device would be satisfactory as a component of the input transducer. Attached to the head or table of the vibrator is a rod with a slider on it. The slider is held in position with a coiled compression spring as shown in figure 9. On the slider is the control accelerometer. The slider pressed the accelerometer against the skin surface of the forearm under the force of the compression spring.

Thus the static force on the forearm was transmitted through the spring. The natural frequency of the slider spring system is considerably lower than the frequency range under consideration. The spring is a long spring with a small spring constant, such that when it is compressed to the length used in the transducer, it produces a nearly constant force over a displacement of about

±¼ inch. This was done so that the small movements of the forearm, which were expected, would not significantly affect the force with which the transducer was pressed against the forearm.

The response transducer is somewhat similar to the input transducer. A similar slider-spring mechanism was used, but the rod was mounted to a base which was adjustable so that the response could be taken at various positions. This adjustment was accomplished by rotating the transducer parallel to the longitudinal axis of the forearm. Also, there were fine adjustments available to insure that the response transducer was located properly in the desired location.

The right forearm was held in the fixture with the forearm in a verticle position and the upper arm horizontal forming a right angle at the elbow. The upper arm rested in an adjustable cradle. The wrist and hand were positioned by an adjustable plate which the hand rested against. In order to have the forearm as free as possible from external constraints, the points of contact between the positioning fixture and the arm were not in the vicinity of the forearm being studied.

CHAPTER 3

PARAMETRIC EVALUATION OF TRANSDUCER LOCATION

It has been previously noted that transducer location is an important aspect of experimentally determining the dynamic response of the human forearm. Several factors affect the ability of the response transducer to detect natural frequencies of the forearm system. Primarily, the location of the response transducer on the forearm is critical. It must be located at a point on the forearm which is not a nodal point. Also, as has been previously noted, the response amplitudes are a function of the angular position of the response accelerometer relative to the longitudinal axis of the forearm. Another problem which has already been mentioned is the fact that the transducer cannot be attached directly to the bone. Since it cannot be directly attached to the bone, it is necessary to find a location which puts the response transducer in close proximity to the bone. The pressure between the transducer and the skin is an important parameter. If this force is very large, the transducer may be uncomfortable for the test subject; also a large force applied to the system at a point will affect the dynamic response of the system.

These being the factors to be considered, a parametric evaluation of the equipment was undertaken. Four independent parameters were considered. Two of the independent parameters are concerned with location of the response transducer on the forearm. Another independent parameter is concerned with the static force between the response transducer and the skin surface. The final independent parameter is concerned with the position of the forearm.

The first independent parameter is rotation of the forearm as shown in figure 2. Since the forearm can rotate about its longitudinal axis, it changes geometry and hence the dynamic response will change. Also, rotation of the forearm moves the bones, the ulna and the radius, in relation to each other and in relation to the skin surface. Hence som position may be preferable due to the bones being more accessible for the response transducer. It was desired to test the sensitivity of the frequency response plot to the rotation of the forearm. Therefore, two positions were chosen for this independent parameter. Viewing the right forearm from the hand towards the elbow along the longitudinal axis, the hand is rotated fully counter-clockwise. This describes the AP position and is the first position. Rotating the hand and wrist 90 degrees clockwise from the AP position describes the second position.

The second independent parameter is location of the response transducer along the longitudinal axis of the forearm as shown in figure 1. This parameter was varied in an attempt to avoid locating the response transducer at a nodal point for the modes which are being excited. The response transducer always measure acceleration in the horizontal plane, but can be moved vertically to various points on the longitudinal axis of the forearm. Two positions on the longitudinal axis were chosen as test points. One position was just above the elbow on the olecranon process. The other is a point midway between the olecranon process and the styloid process.

The third independent parameter which was considered is the force with which the response transducer was held against the forearm. A small force may not cause the response transducer to be in close enough proximity with the bone. A large force may be painful for the test subject and may affect the response of the system to a large degree. Two forces, which were provided by coil springs, were tried: a relativly light 2.5 pound force, and a relativly strong 5.0 pound force.

The fourth independent parameter was the angular location of the response transducer about the longitudinal axis of the forearm as shown in figure 3. Three different angular positions were used. This parameter was varied in order to locate the appropriate plane for the transducer location. Also, angular position about the longitudinal axis of the forearm affects the relative position of the bones to the skin surface, so one position may allow the response transducer to be in closer proximity to the bone. The three positions that were tried are: 1) aligned with the input transducer, 2) 30 degrees clockwise from alignment with the input transducer, and 3) 30 degrees counter-clockwise from alignment with the input transducer.

Since each of the four aforementioned parameters could have been varied independently, a conventional statistical code was used to describe the state of each parameter. A code containing four letters (a,b,c, and d) was used. The presence of a letter in the code indicates one state of a given parameter. The absence of a letter indicates the other state of the given parameter. In the case of the fourth parameter, where there were three states, the symbols d1 and d2 were used. Thus d1 indicates one state, and d2 indicates another state, while the absence of d1 and d2 indicates the third state. This code is summarized in Table 1.

Several other independent parameters could have been varied, but were held constant. These are listed below and may be considered in future studies.

1) The response transducer was always measuring vibration in a horizontal plane, and the forearm was always held in a verticle position.

2) The input vibration was aligned horizontally and in the same verticle plane that is described by the upper arm. The input force was applied at the styloid process.

3) The input signal was maintained at a constant force at the skin surface.

In this study, only two dependent parameters were considered. They were: 1) the frequency location of the lowest frequency peak, and 2) the peak amplitude of the lowest frequency peak. Analysis of the data related to these two dependent parameters allowed several configurations to be selected as condidate configurations. Candidate configuration is a term used in this paper to denote a particular combination of the four independent parameters

TABLE 1 Summary of Parameter Code

	Independent Parameter	Symbol	Presence	State
1	Rotation of forearm	a	Not Present	Rotated full counter-clockwise
			Present	Rotated 90° clock-wise from above position
2	Longitudinal position of response transducer	b	Not Present	Located at olecranon process
			Present	Located mid-way between olecranon process and styloid process
3	Force on response transducer	c	Not Present	Relatively light force (2.5 lb.)
			Present	Relatively strong force (5.0 lb.)
4	Angular position of response transducer	d	Not Present	Aligned with input transducer
			d1	30° counter-clockwise from alignment with input transducer
			d2	30° clockwise from alignment with input transducer

which yields consistent results for the two dependent parameters.

CHAPTER 4

DISCUSSION OF DATA REDUCTION

The data was reduced by averaging values for the lowest natural frequencies and for the amplitude of the response associated with the lowest frequency for the three trials at each of the twenty-four configurations for each of the two test subjects. This computation yielded a mean frequency and a mean amplitude for the first resonant peak for each of the twenty-four configurations on each of the two test subjects.

In order to have an indication of how repeatable the data taken at each configuration was, the percent standard deviation at each configuration was calculated for both the amplitude and frequency of the first resonant peak. The following formulae were used to calculate the percent standard deviation of the frequency and amplitude (5).

$$\%DEV=\frac{\Sigma(X-\overline{X})^2}{N-1} \quad \frac{100\%}{\overline{X}}$$

where

$\overline{X}$=mean value= $\frac{\Sigma X}{N}$
X=experimentally obtained values
N=number of trials (in this case 3)

The percent standard deviation was calculated for each position on each subject; these values were then arranged in order of decreasing percent deviations, as presented in tables 2 and 3. The decreasing order was determined by averaging the mean values for each subject and using that average value to arrange the decreasing order. This same information is presented graphically in figures 10 and 11.

There are four positions which have frequency deviations of less than 8% and amplitude deviations of less than 22%. These were considered candidate configurations and are presented in table 4.

By virtue of the high percent deviations for frequency or amplitude of the other twenty configurations, which indicates a lack of consistency at each of these configurations, these twenty configurations were rejected for consideration as candidate configurations. The four candidate configurations are ab, abd1, abd2, and c.

It is interesting to note that three of the four candidate configurations have attributes a and b. Also, it is interesting to note that all four candidate configurations show a definite secondary peak(see appendix), which is not the case for many of the other configurations.

Figure 12 shows the variation of the first resonance

TABLE 2 Configurations in Order of Decreasing Amplitude Percent Deviation

Configuration	Subject #1		Subject #2	
	Amplitude	% Dev.	Amplitude	% Dev.
(1)	2.3670	56.740	2.1000	42.320
b	2.3000	49.380	.7333	43.830
a	3.5000	60.000	5.4330	13.060
bc	3.9670	43.470	1.8670	16.370
abcd2	5.7000	21.270	5.1330	37.030
d2	1.1000	31.490	1.2670	25.380
bcd2	1.3330	30.310	1.0000	26.460
cd1	2.7670	24.600	1.8000	30.930
abcd1	4.9330	25.670	3.7000	29.230
bd2	.6433	7.977	1.9000	43.080
ad1	2.5330	4.558	2.9670	44.890
acd2	1.4330	17.560	2.6670	27.640
d1	1.2670	9.116	1.0000	36.060
ad2	1.5670	25.800	2.7670	17.830
abc	8.1670	24.770	6.7670	13.730
ac	7.4000	7.524	5.2000	27.130
abd1	4.9670	11.090	3.7000	21.450
bd1	4.2670	9.758	2.0670	21.820
ab	3.6000	10.020	4.2000	20.620
c	3.9670	21.440	4.8000	8.333
cd2	2.0670	16.990	3.1670	12.760
bcd1	5.8000	9.123	4.1000	15.990
abd2	3.6670	9.578	2.7330	12.850
acd1	5.0670	14.000	2.1670	7.050

Figure 10 Mean Amplitude and Percent Amplitude Deviation vs Configuration

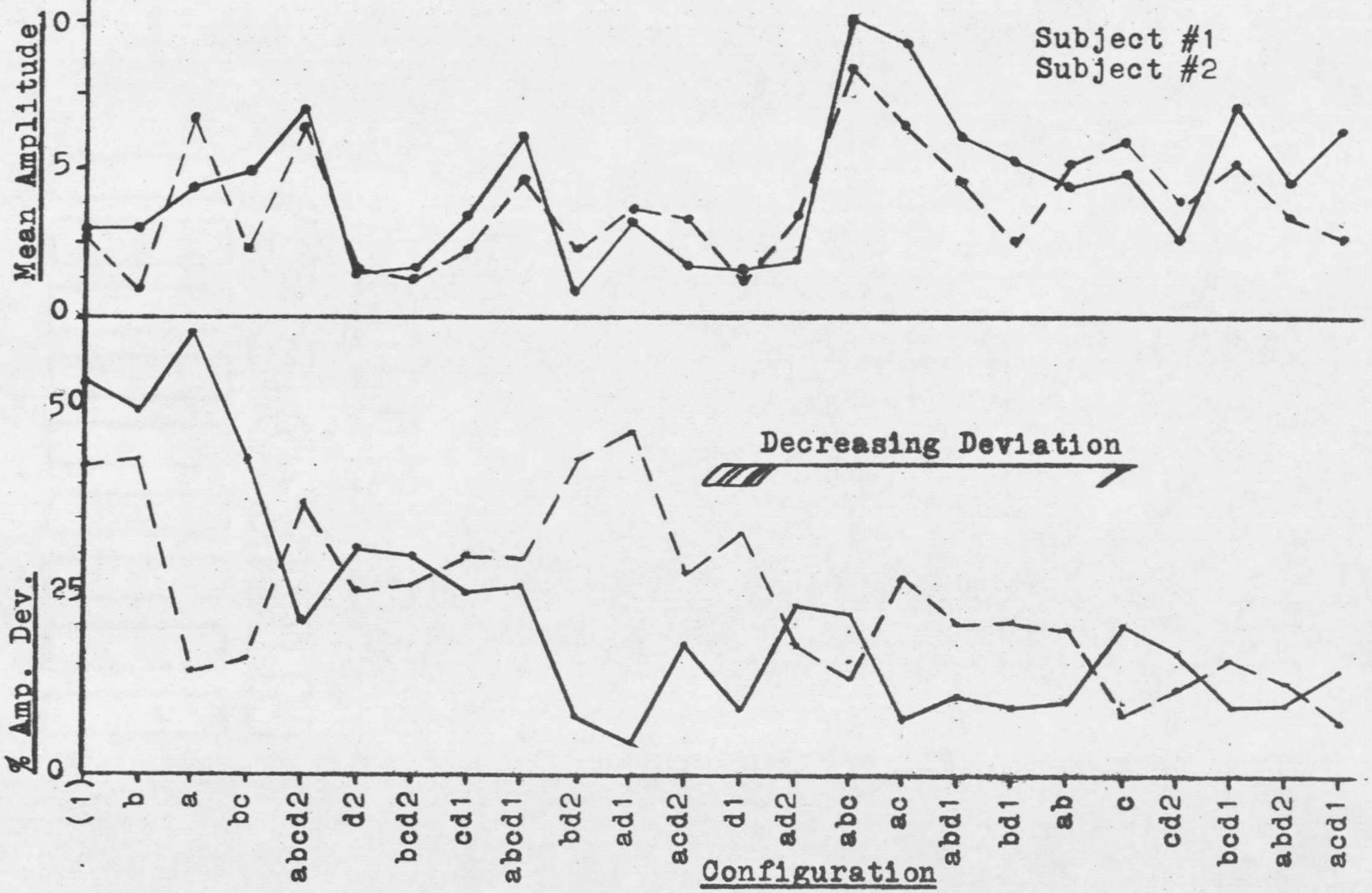
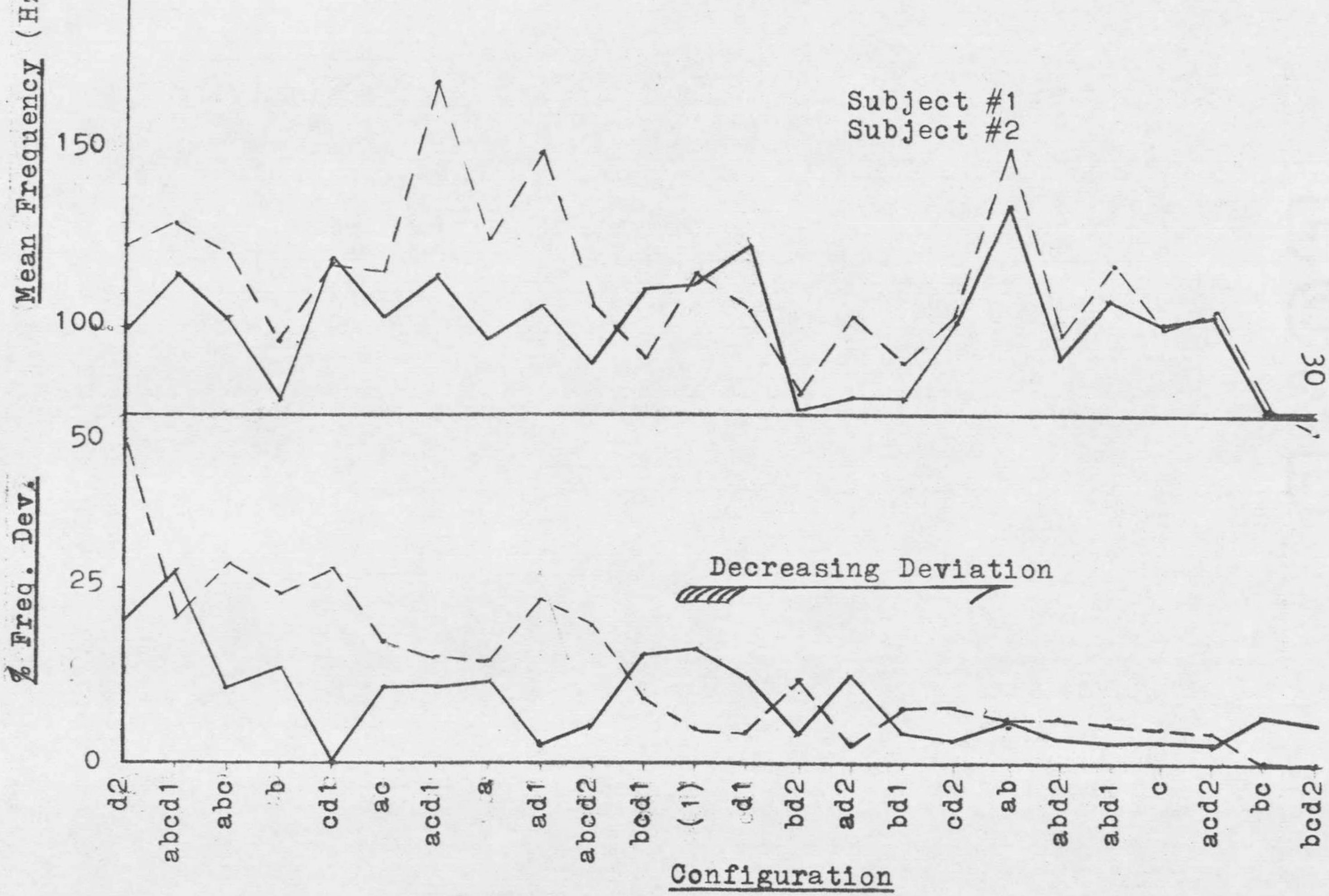


TABLE 3 Configurations in Order of Decreasing Frequency Percent Deviation

Configuration	Subject #1		Subject #2	
	Frequency	% Dev.	Frequency	% Dev.
d2	100.00	21.790	123.30	46.990
abcd1	115.00	27.150	130.00	20.350
abc	103.30	11.170	121.70	31.920
b	78.33	13.290	96.67	23.320
cd1	120.00	.000	118.30	30.570
ac	103.30	11.170	116.70	17.840
acd1	115.00	11.500	170.00	15.560
a	96.67	11.950	125.00	14.420
ad1	106.70	2.706	150.00	23.330
abcd2	90.00	5.556	106.70	19.520
bcd1	111.70	15.720	91.67	8.332
(1)	113.30	16.700	116.70	4.949
d1	123.30	12.390	105.00	4.762
bd2	76.67	3.765	86.67	12.010
ad2	80.00	12.500	103.30	2.794
bd1	78.33	3.685	90.00	11.110
cd2	101.70	2.839	103.30	11.170
ab	135.00	6.415	151.70	6.863
abd2	91.67	3.149	98.33	7.767
abd1	108.30	2.665	118.30	6.454
c	101.70	2.839	100.00	5.000
acd2	103.30	2.794	105.00	4.762
bc	74.00	7.151	75.00	.000
bcd2	75.00	6.667	70.00	.000

Figure 11 Mean Frequency and Percent Deviation versus Configuration



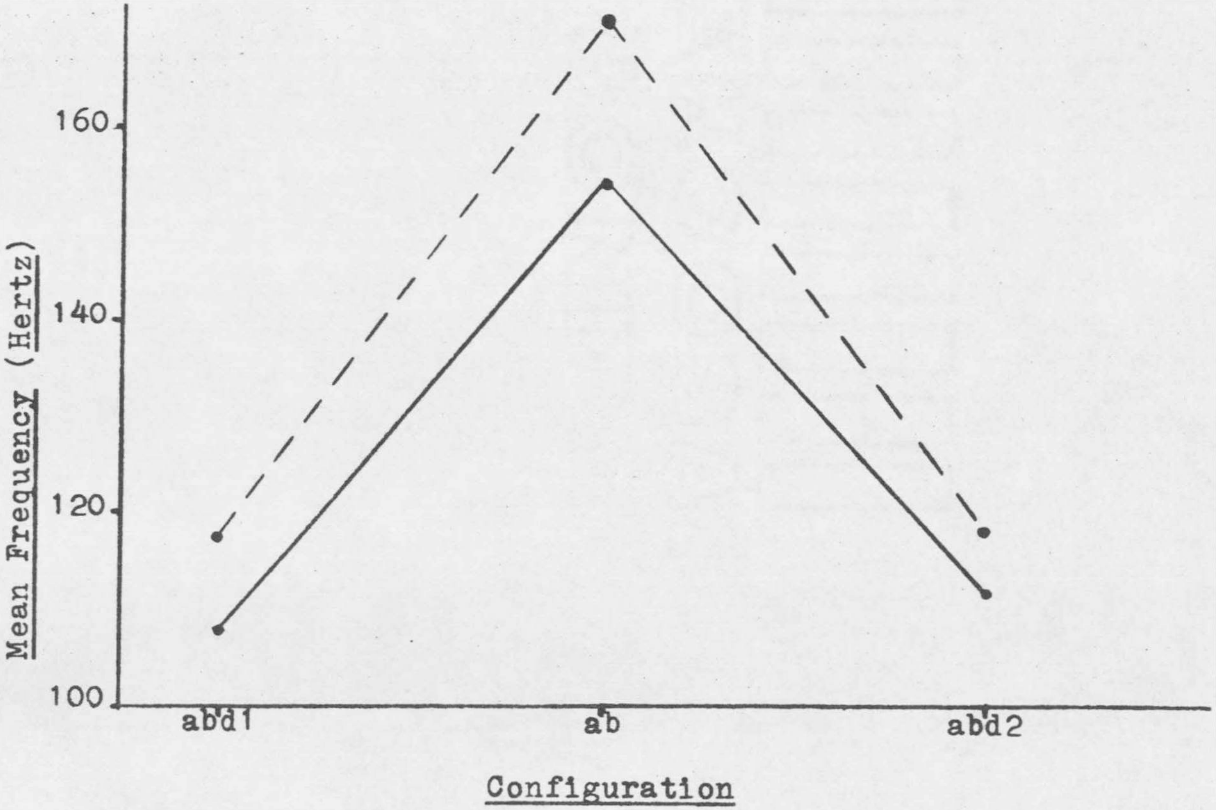


Figure 12 Change in First Resonance Peak with Angular Position of Response Transducer

peak frequency location with attribute d (angular position of the response transducer about the longitudinal axis of the forearm), for both test subjects. Note that all the first natural frequencies for subject number two are consistently higher than the natural frequencies for subject number one. This is most likely due to either material or geometrical differences between the two subjects. Also note that the variation in frequency with parameter d is the same for each subject. Both of these facts indicate that the tests are valid and repeatable.

In table 5, the mean bandwidth as defined by the width of the peak at the half-power points, of the first and second resonant frequencies are tabulated. Tabulated in table 6 are the mean frequencies and mean amplitudes of the second resonant peak. This information is tabulated for the four candidate configurations only. The frequency response plots for the four candidate configurations appear in Appendix A.

TABLE 4 Summary of Candidate Configurations

Configuration	Frequency				Amplitude			
	Subject #1		Subject #2		Subject #1		Subject #2	
	Mean	% Dev	Mean	% Dev	Mean	% Dev	Mean	% Dev
abd1	108.3	2.66	118.3	6.45	4.967	11.09	3.70	21.45
ab	135.0	6.41	151.7	6.86	3.600	10.02	4.20	2.06
c	101.7	2.84	100.0	5.00	3.970	21.44	4.80	8.33
abd2	91.7	3.15	98.3	7.77	3.670	9.58	2.73	12.85

TABLE 5 Bandwidth Data

Configuration	Subject	First Resonance		Second Resonance	
		Mean Bandwidth	% Deviation	Mean Bandwidth	% Deviation
ab	1	85.67	20.56	246.00	5.47
	2	110.00	11.88	263.67	3.68
abd1	1	105.00	7.19	217.00	3.32
	2	83.33	15.00	161.33	2.58
abd2	1	51.33	23.80	264.00	6.46
	2	57.33	8.95	186.67	37.49
c	1	65.33	44.60	89.33	20.71
	2	69.00	20.29	44.33	15.55

TABLE 6 Second Resonance Data

Configuration	Subject	Frequency		Amplitude	
		Mean	% Deviation	Mean	% Deviation
ab	1	423	1.37	.95	18.98
	2	403	2.87	1.13	13.48
abd1	1	350	14.28	1.50	0.00
	2	393	1.47	.72	4.20
abd2	1	407	1.42	.72	13.25
	2	377	.77	.50	20.00
c	1	243	4.75	1.72	21.02
	2	258	.02	3.40	11.76

CHAPTER 5

DISCUSSION OF RESULTS

The tables 2 and 3 and figures 10 and 11 show the four candidate configurations which have a lower percent deviation in both frequency and peak amplitude than the other twenty configurations. Moreover, all four candidate configurations have prominent second resonance peaks. The data tabulated for the four candidate configurations is: 1) the mean frequency of the first resonance, 2) the mean amplitude for the first resonance, 3) the mean bandwidth for the first resonance, 4) the mean frequency for the second resonance, 5) the mean amplitude for the second resonance, and 6) the mean bandwidth for the second resonance.

Note that for both the first and second resonant frequencies and for both subjects, configuration ab yields the highest frequency when compared to positions abd1 and abd2. This tends to support theory, since the forearm should be stiffest in the ab plane. This shift in natural frequency as the transducer is moved to the three different positions about the longitudinal axis of the forearm can be more easily understood if the arm is thought of as a pinned end beam of elliptical cross section. The first bending mode along the major axis of the ellipse is at a higher natural frequency than the natural frequency of the first bending mode along the minor axis of the ellipse. Planes in between the minor and major axis would have first natural frequencies between the high and low values of the major and minor axis. Similarly, the forearm is stiffer along one plane and thus values of natural frequency in planes not in the major plane will be lower.

Also of interest is a comparison of previous methods employed to obtain the frequency response plot. R. Matz employed elastic straps to hold the transducers to the arm. This method, in theory, attached a small mass (the transducer) to the forearm. In practice, however, the repeatability of this equipment was limited due to difficulty in locating the transducer at the same point each time and because of the difficulting in repeating the strap tensions each time. There was another drawback, however, that was not apparent at the time. That is the fact that the first natural frequency which has been used extensivly in this study was attenuated by the straps of the method of R. Matz. This was shown by putting a strap on the test subjects forearm, as with the Matz method, but then running the test using the apparatus developed for this study. When this was done, the first natural frequency was attenuated by a factor of at least ten. These first resonance peaks have been neglected in previous works as unimportant, but these results show that the first resonant peak may be as important as the second resonant peak.

It was also noted that the secondary or second resonant peak was higher in peak amplitude when using the strap apparatus. A possible explanation for this is the damping due to friction in the present system of transducers. The damping forces would be greater at the higher frequencies since damping forces are proportional to velocity. If minimizing that friction showed an increase in the amplitude of the second resonant peak, then friction would be demonstrated to be a factor. Note that with the transducers used, no attempt was made to control or measure the damping forces. The damping forces may have been variable, since they are a function of the friction of the slider mechanism, which could change appreciably with wear.

It is also hypothesized that the first natural frequency noted in this study is a rigid body mode of the ulna, while the second natural frequency is the first bending mode of the ulna. This is supported by the fact that the second natural frequency cannot be detected at the elbow (a nodal point for the first bending mode), but can easily be detected at the midpoint (the point of maximum deflection for the first bending mode). The first natural frequency can be easily detected at nearly every longitudinal position, indicating a rigid body motion.

Another interesting point, and one that should be taken into consideration in futre work is muscle development depending on whether the test subject is left handed or right handed. The two test subject were opposite; subject number one was left handed and subject number two was right handed. It was noted that the left handed individual had significantly less muscle development in his right forearm, making it considerably easier to put the response transducer in close proximity to the ulna than on the right handed subject whose muscle development caused the flesh to be quite thick between the transducer and the ulna in many of the configurations. This resulted in significantly more consistent data from subject number one, the left handed subject. It is therefore suggested that future experimental work be conducted on the left arm of right handed subjects and on the right arm of left handed subjects.

CHAPTER 6

CONCLUSIONS

In conclusion, this study has shown that it is possible to develop an instrument for measuring the dynamic response of a human biological system. The equipment developed here determines the frequency response of the human forearm to a sinusoidal forcing function.

In addition, four configurations have been determined that provide reliable data. These four candidate configurations were determined by using statistical methods to determine the standard percent deviation in the frequency and amplitude of the first natural frequency, then choosing those configurations with the smallest percent deviation.

It was determined that elastic straps being previously used to attach the transducers to the arm attenuate the first natural frequency.

It was hypothecized that the first natural frequency in this study is a rigid body mode of the ulna, while the second natural frequency is the first bending mode of the ulna.

It is also suggested that due to muscle development, right handed subjects be tested on the left arm and left handed subjects be tested on the right arm.

APPENDIX

APPENDIX A

Presented in Appendix A are the frequency response plots for each experiment conducted at each of the candidate configurations.

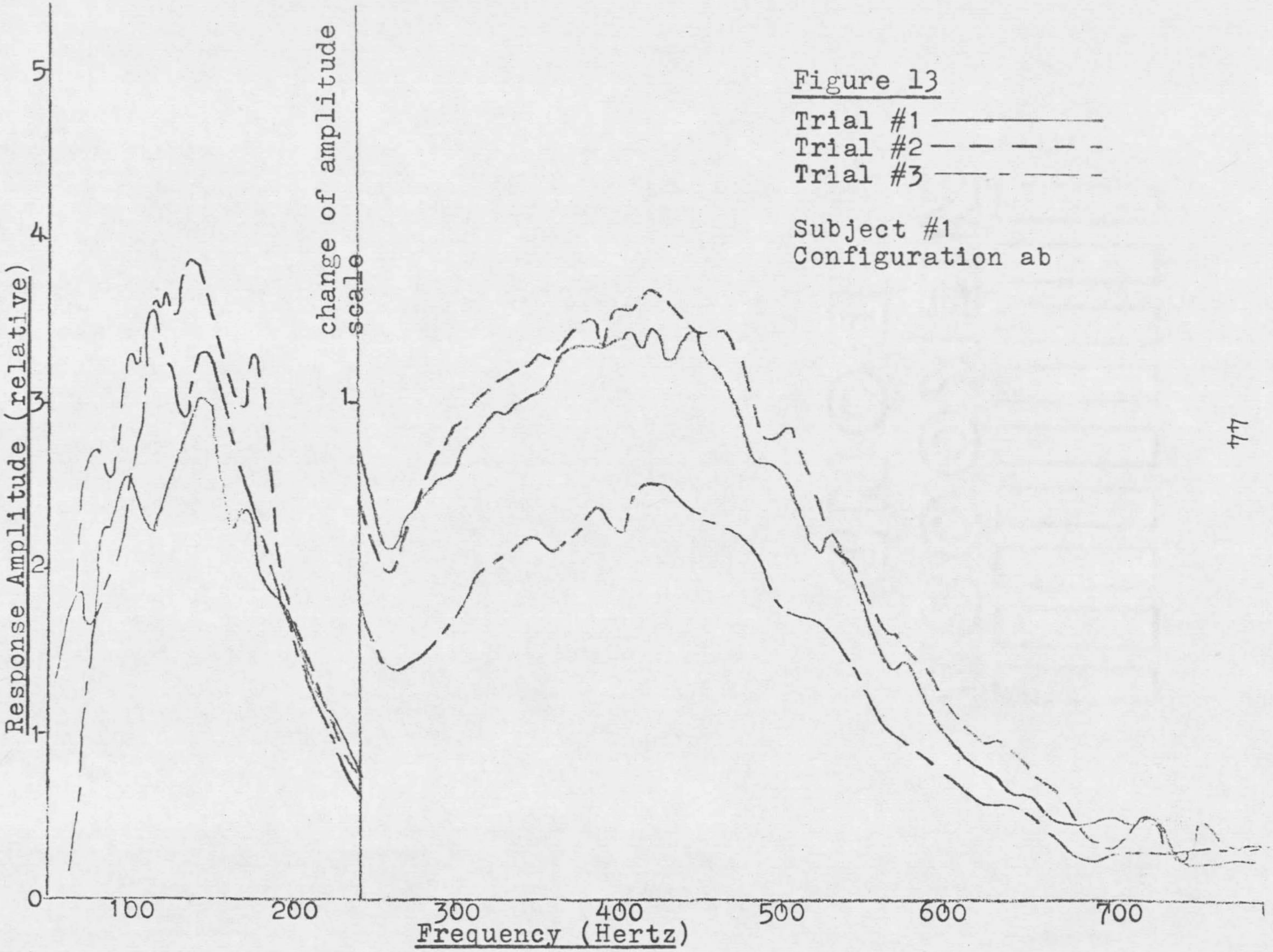


Figure 13

Trial #1
Trial #2
Trial #3
Subject #1
Configuration ab
Response Amplitude (relative)
0
1
2
3
4
5
change of amplitude scale
1
100
200
300
400
500
600
700
Frequency (Hertz)

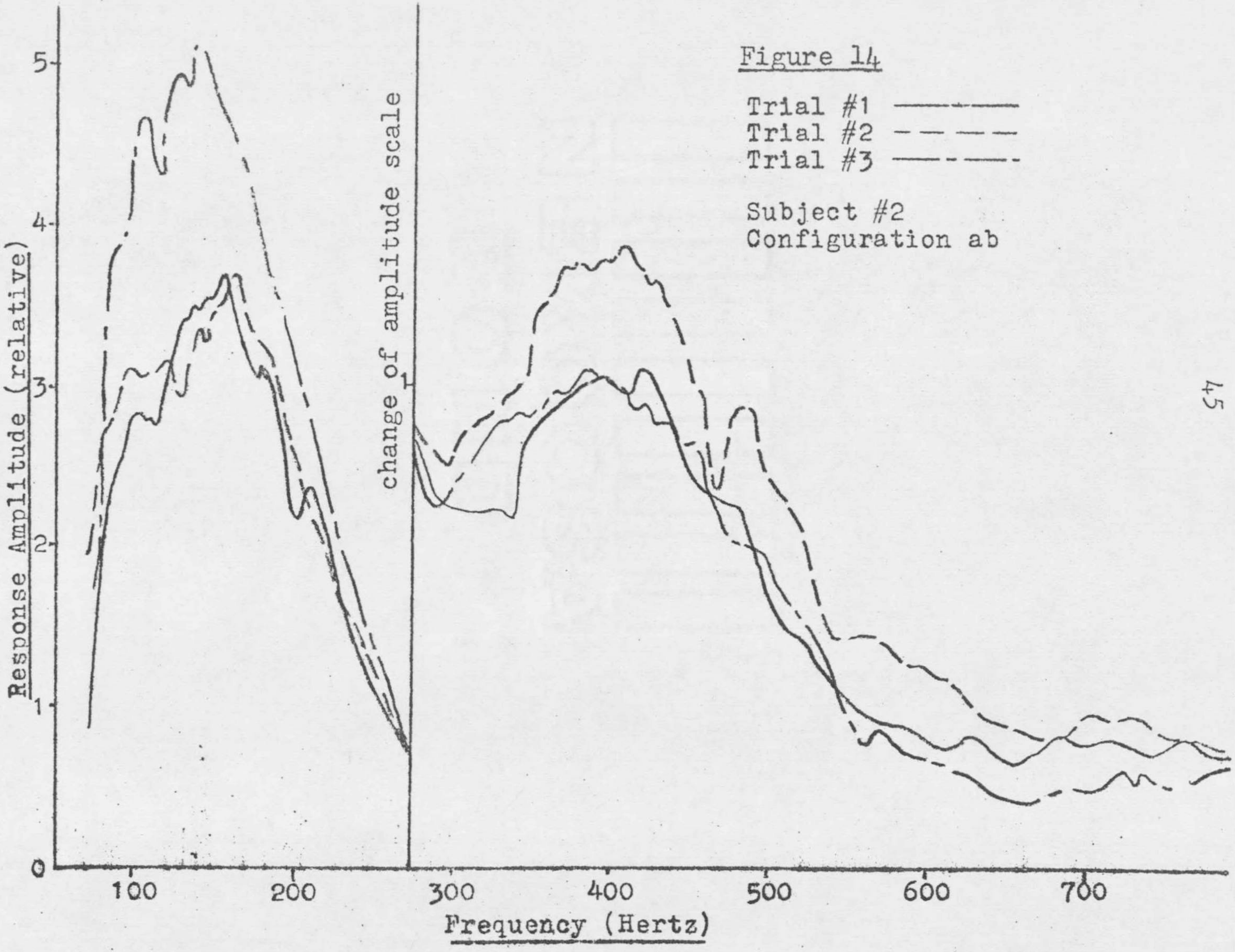


Figure 14

Trial #1
Trial #2
Trial #3
Subject #2
Configuration ab
Response Amplitude (relative)
change of amplitude scale
Frequency (Hertz)
0
1
2
3
4
5
100
200
300
400
500
600
700

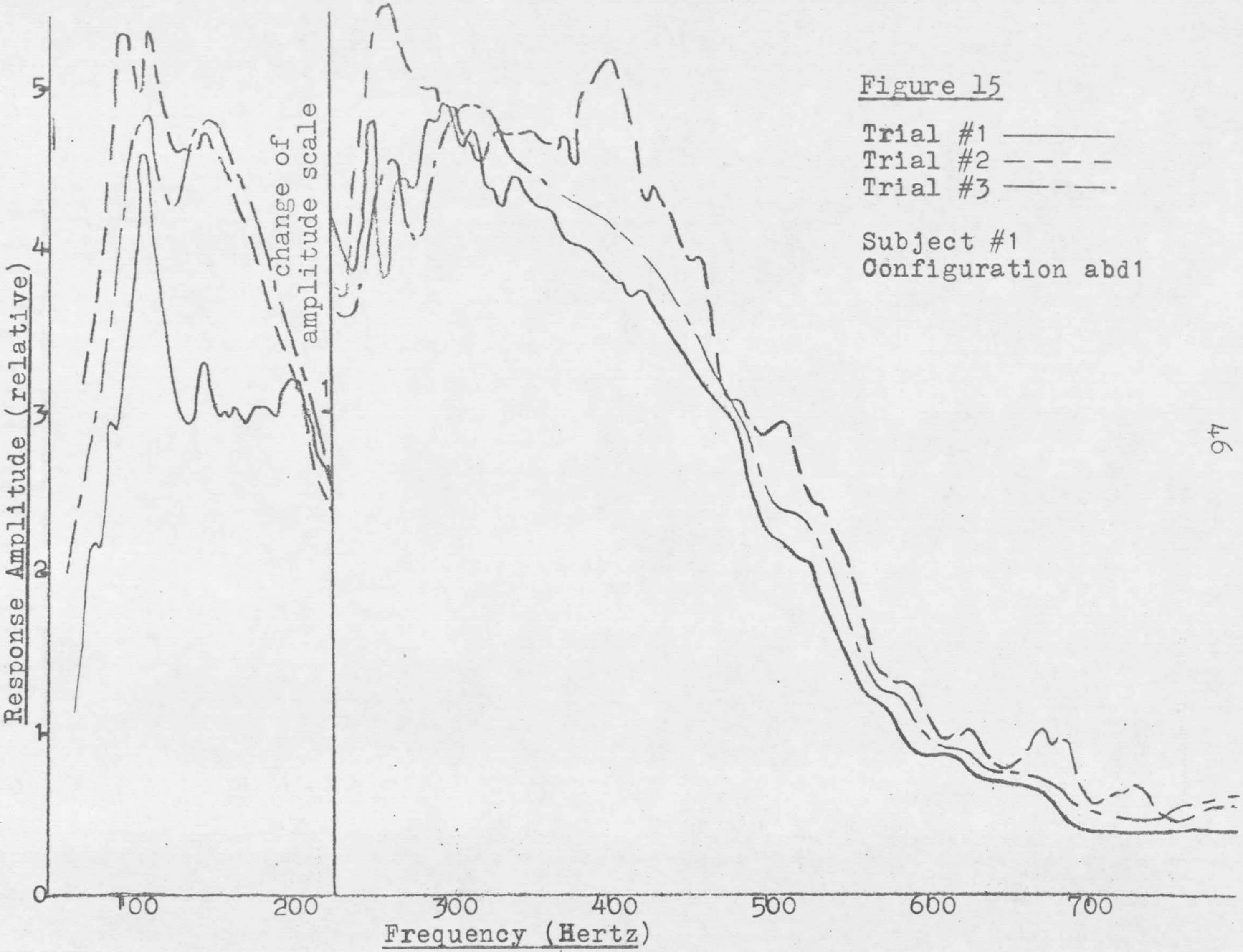


Figure 15

Subject #1
Configuration abd1

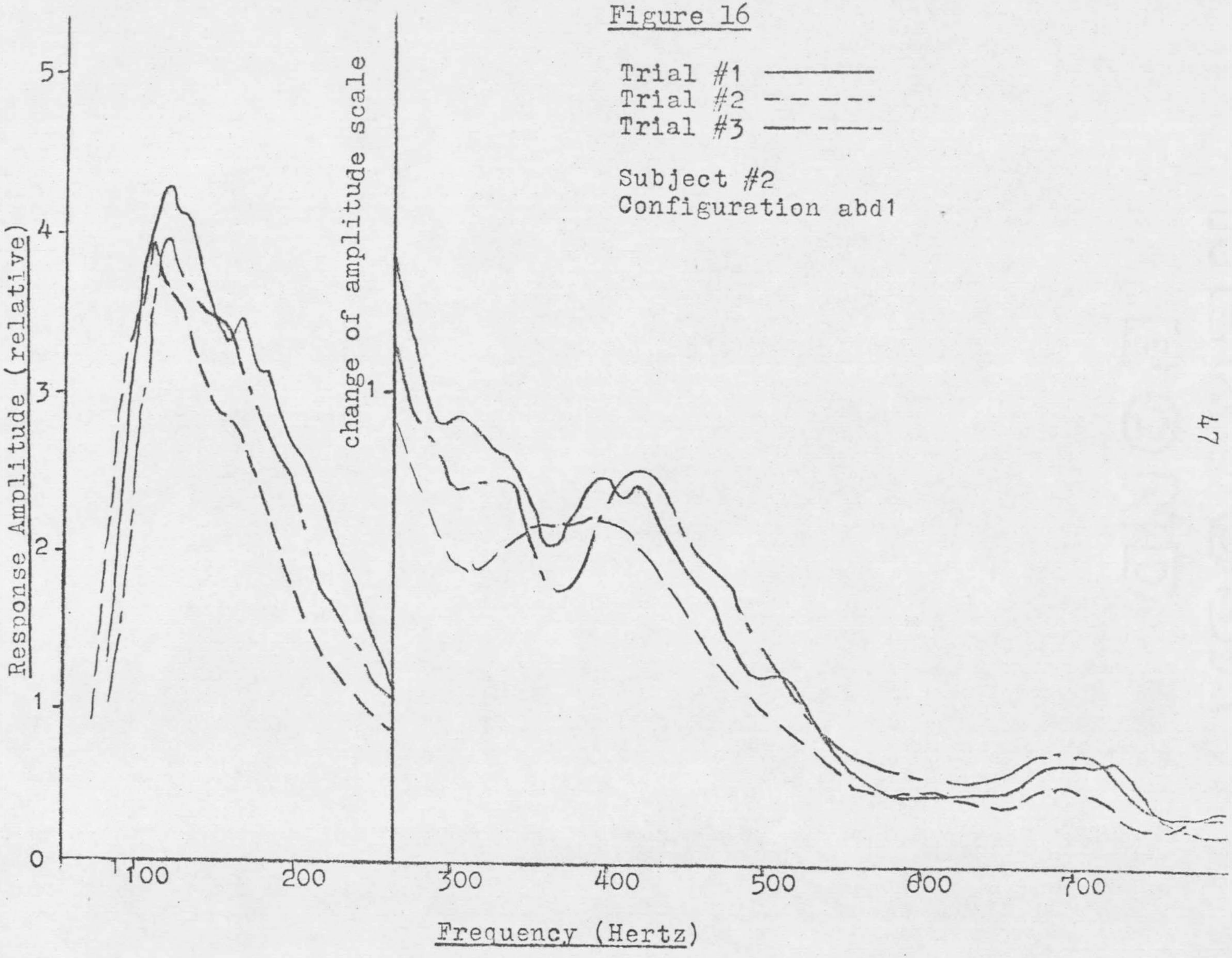
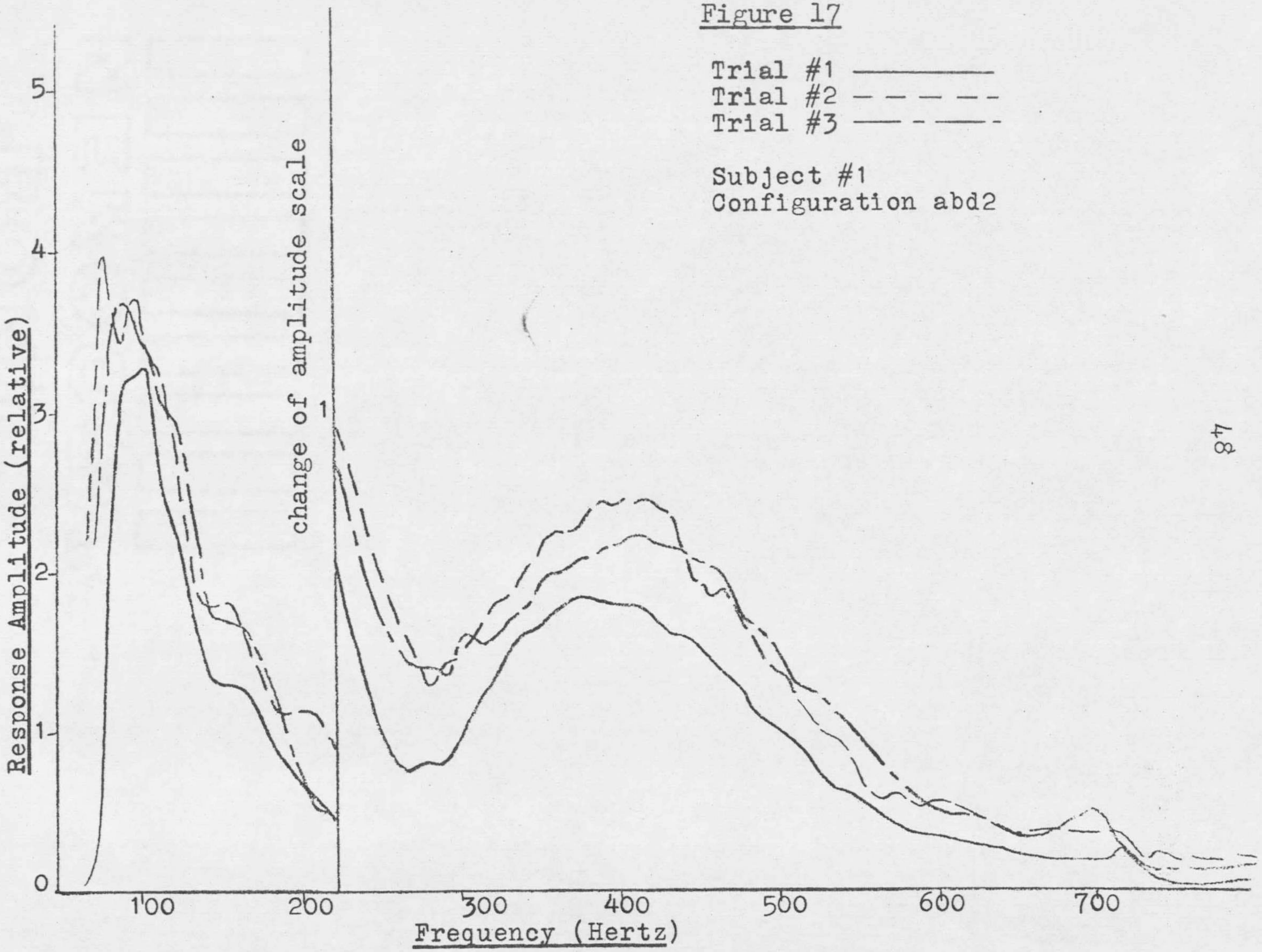


Figure 16

Trial #1
Trial #2
Trial #3
Subject #2
Configuration abd1
Response Amplitude (relative)
change of amplitude scale
0
1
2
3
4
5
1
100
200
300
400
500
600
700
Frequency (Hertz)

Figure 17



Subject #1
Configuration abd2

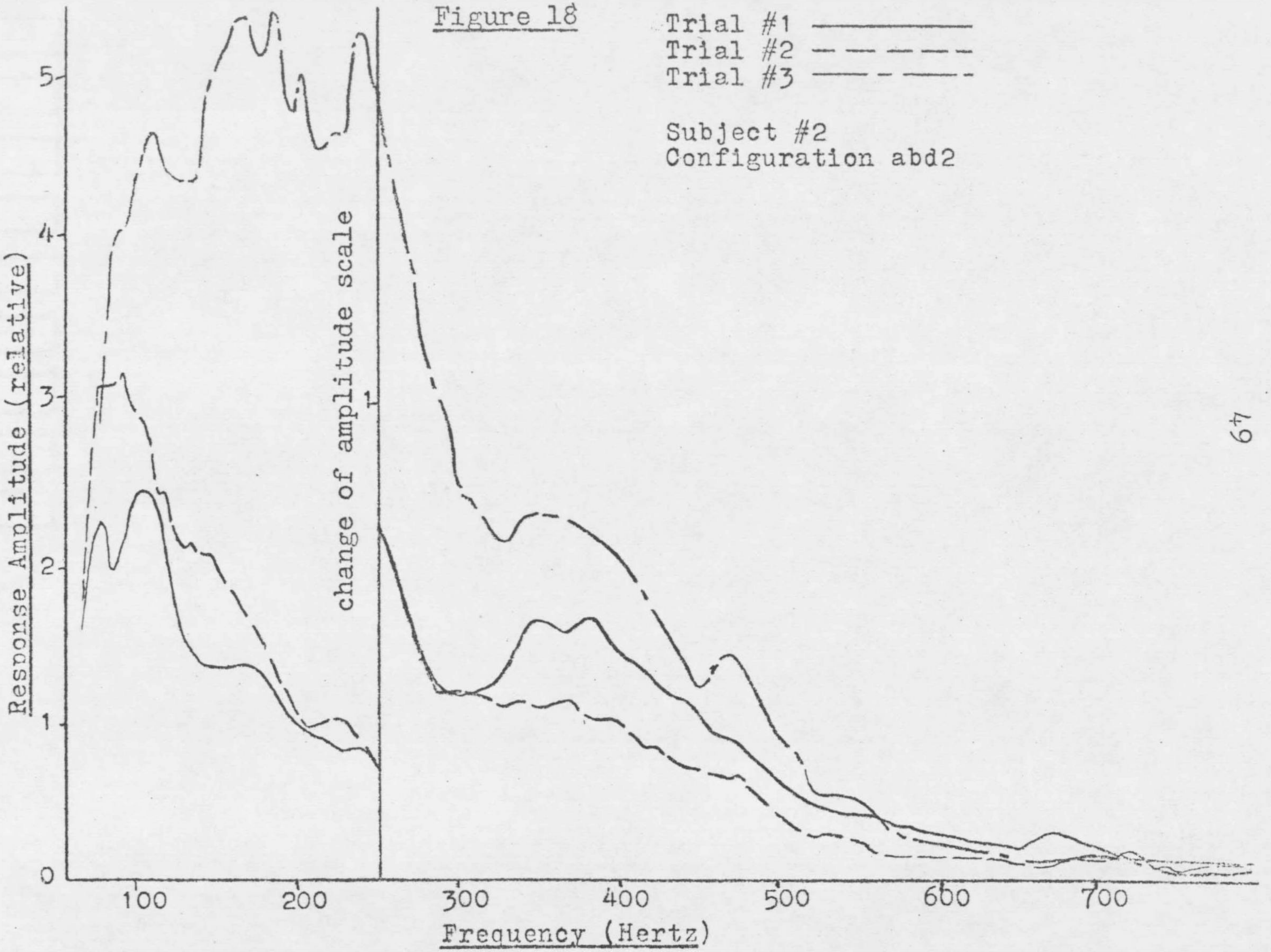


Figure 18

Trial #1
Trial #2
Trial #3
Subject #2
Configuration abd2
Response Amplitude (relative)
change of amplitude scale
5
4
3
2
1
0
1
100
200
300
400
500
600
700
Frequency (Hertz)

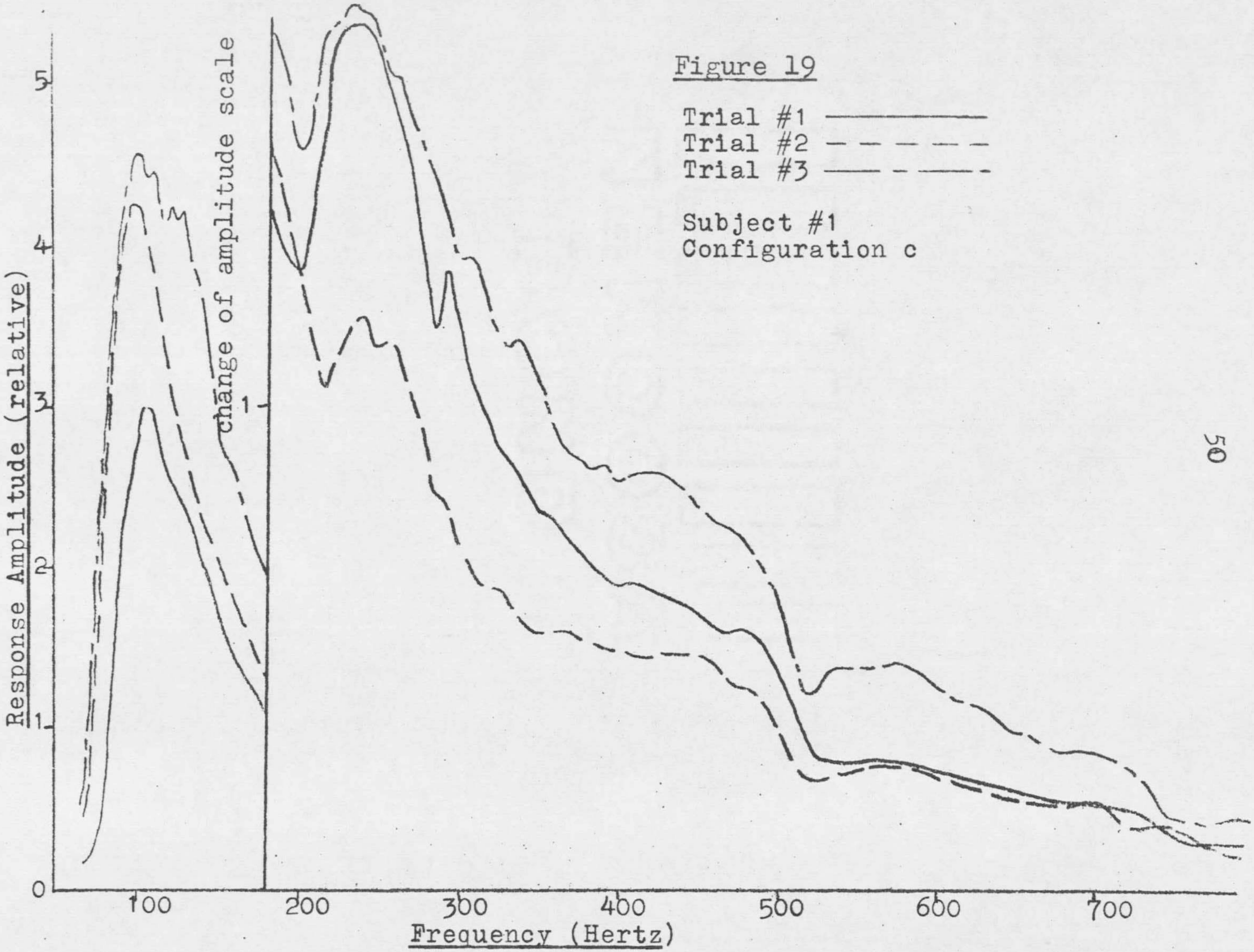


Figure 19

Subject #1
Configuration c

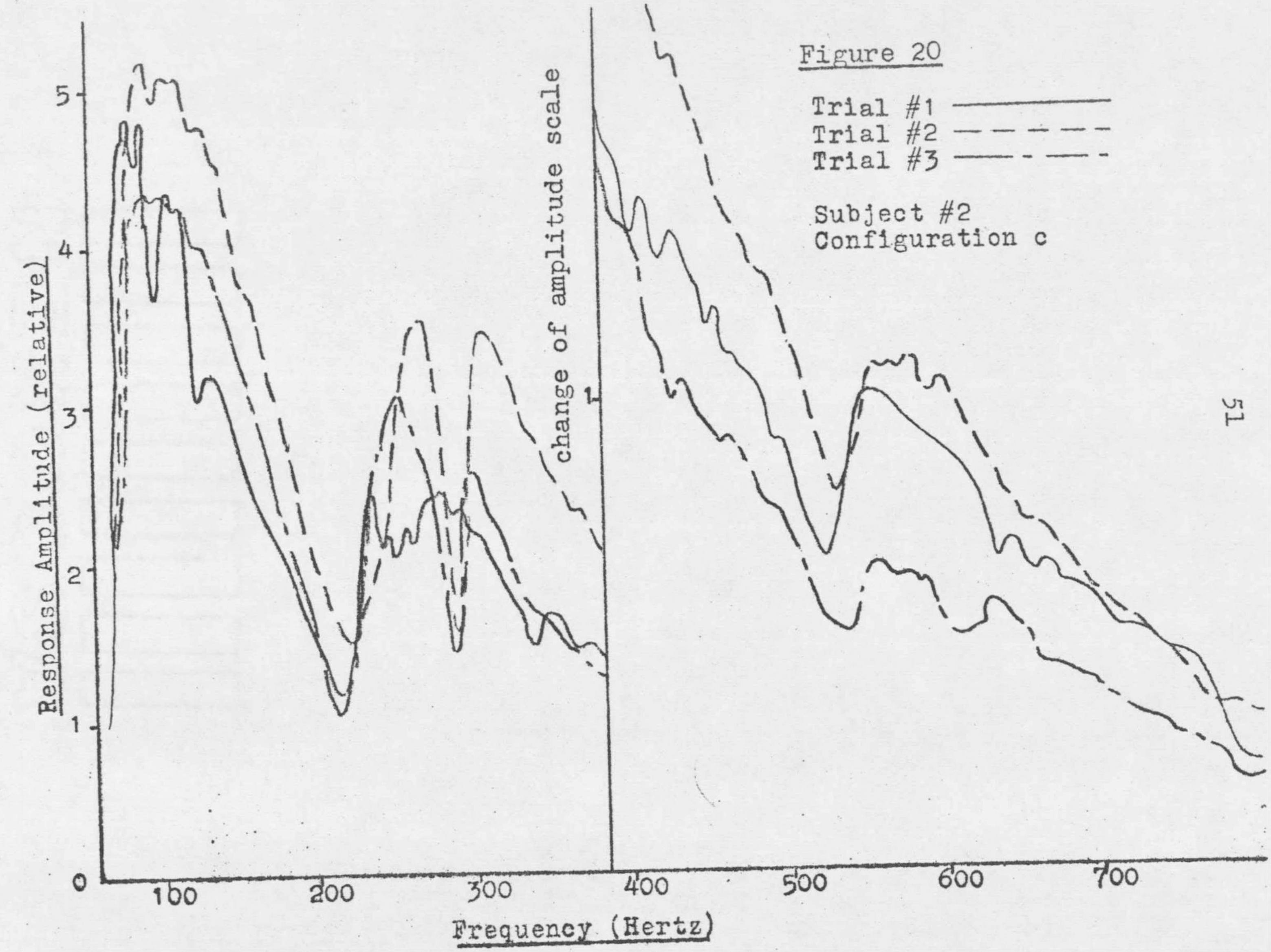


Figure 20

Trial #1
Trial #2
Trial #3
Subject #2
Configuration c
Response Amplitude (relative)
change of amplitude scale
Frequency (Hertz)
0
1
2
3
4
5
1
100
200
300
400
500
600
700

APPENDIX B

FEEDBACK CONTROL CIRCUIT

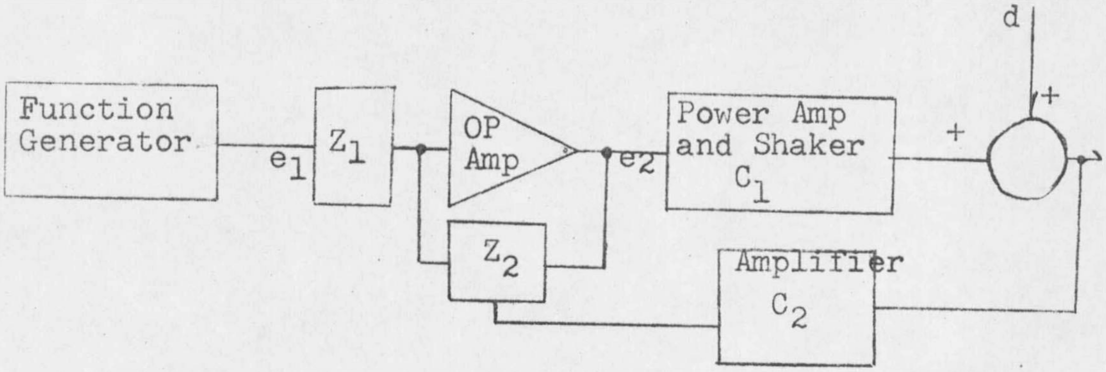
The feedback control circuit was used to control the amplitude of the sinusoidal signal which excited the electro-magnetic vibrator. A control accelerometer at the skin surface was used to obtain a feedback signal, thus acceleration at the skin surface was held constant.

The circuit uses an operational amplifier to vary the amplitude of the sinusoidal signal received from the function generator. A photo-resistor is used in the feedback loop of the operational amplifier to control the gain of the operational amplifier, as shown in figure 21. The photo resistor is a photo cell which changes resistance as the light striking it changes; molded into the photo resistor is a small incandescent light bulb. Thus the resistance of the photo resistor is a function of the voltage applied to the light bulb. Note that the resistor is electronically isolated from the light bulb, thus simplifying the associated electronic circuitry.

The system, consisting of the control circuit, power amplifier, shaker, and control accelerometer, was analyzed using techniques of linear control systems (3).

The system is analyzed as follows:

The input system can be represented as



x=acceleration at skin surface
d=disturbing function
C_1=linear constant of Power amp and shaker
C_2=linear constant of Charge amp
e_1=input voltage to control circuit
e_2=output voltage of control circuit
Z_1=input impedance to op amp
Z_2=feedback impedance to op amp

The gain of the operational amplifier is

$$\text{Gain}=e_2/e_1=Z_2/Z_1$$

Impedance Z_2 is found by linearizing the characteristics of the photo resistor to be:

$$Z_2=Z_0-C_2x$$

Therefore, the acceleration amplitude, x, can be written:

$$x=C_1e_2+d$$

From the equation for the gain, e_2 is:

$$e_2=(Z_2/Z_1)e_1$$

Now, x can be expressed as:

$$x=C_1(Z_2/Z_1)e_1+d$$

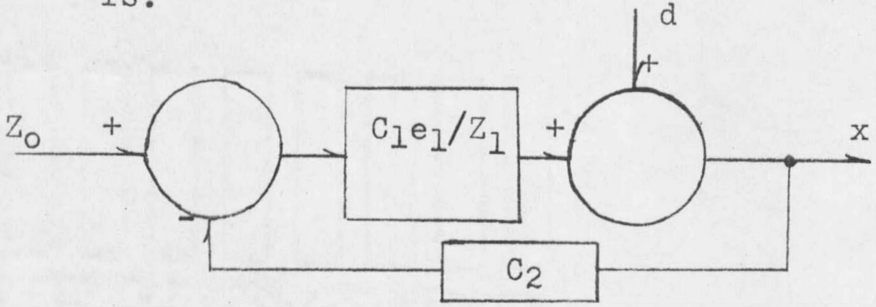
Using the expression for Z_2 in the x equation,

$$x=(C_1e_1/Z_1)(Z_o-C_2x)+d$$

And by rearranging this equation, a transcendental equation is derived:

$$x=(C_1e_1/Z_1)-(C_1C_2e_1/Z_1)x+d$$

The associated block diagram for this equation is:



Making the equation a non-transcendental equation yields the transfer function for the input system:

$$x=(C_1e_1/Z_1+C_1C_2e_1)Z_o + (Z_1/Z_1+C_1C_2e_1)d$$

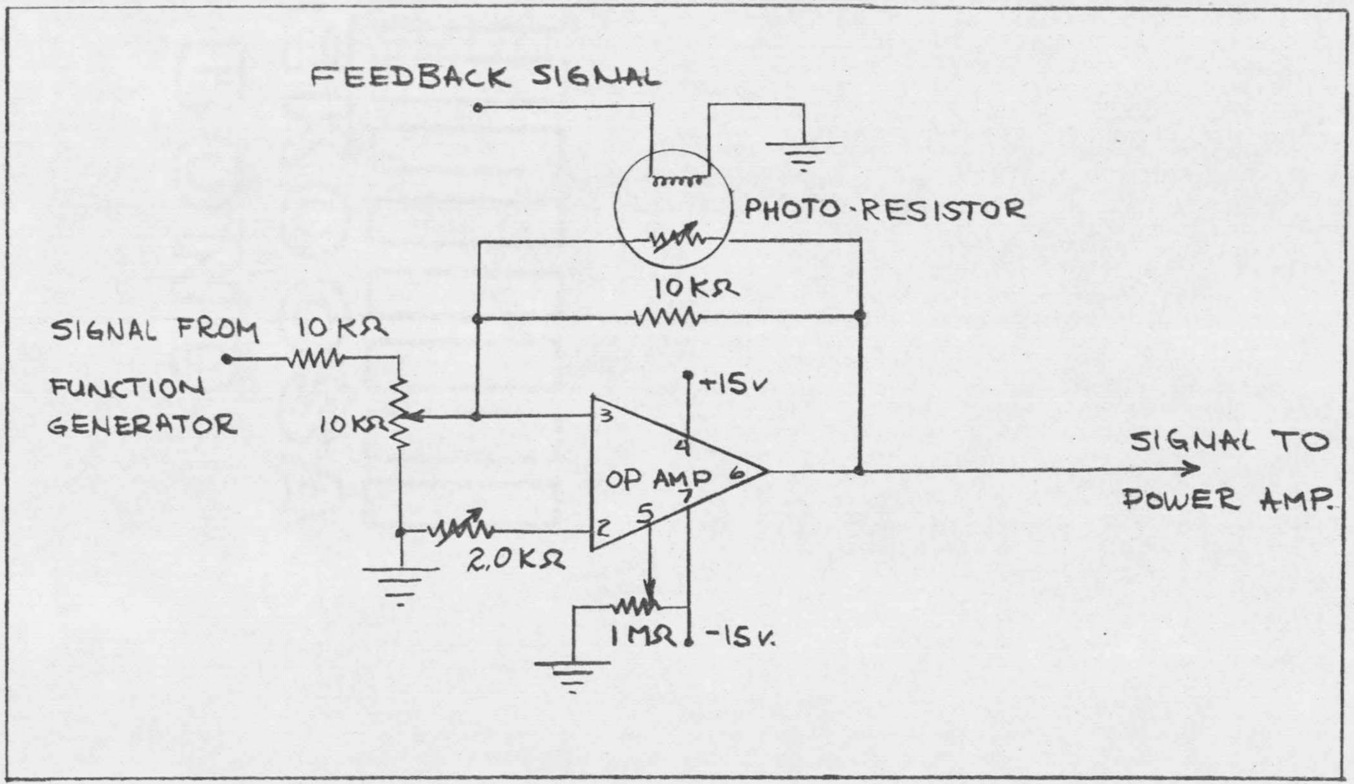
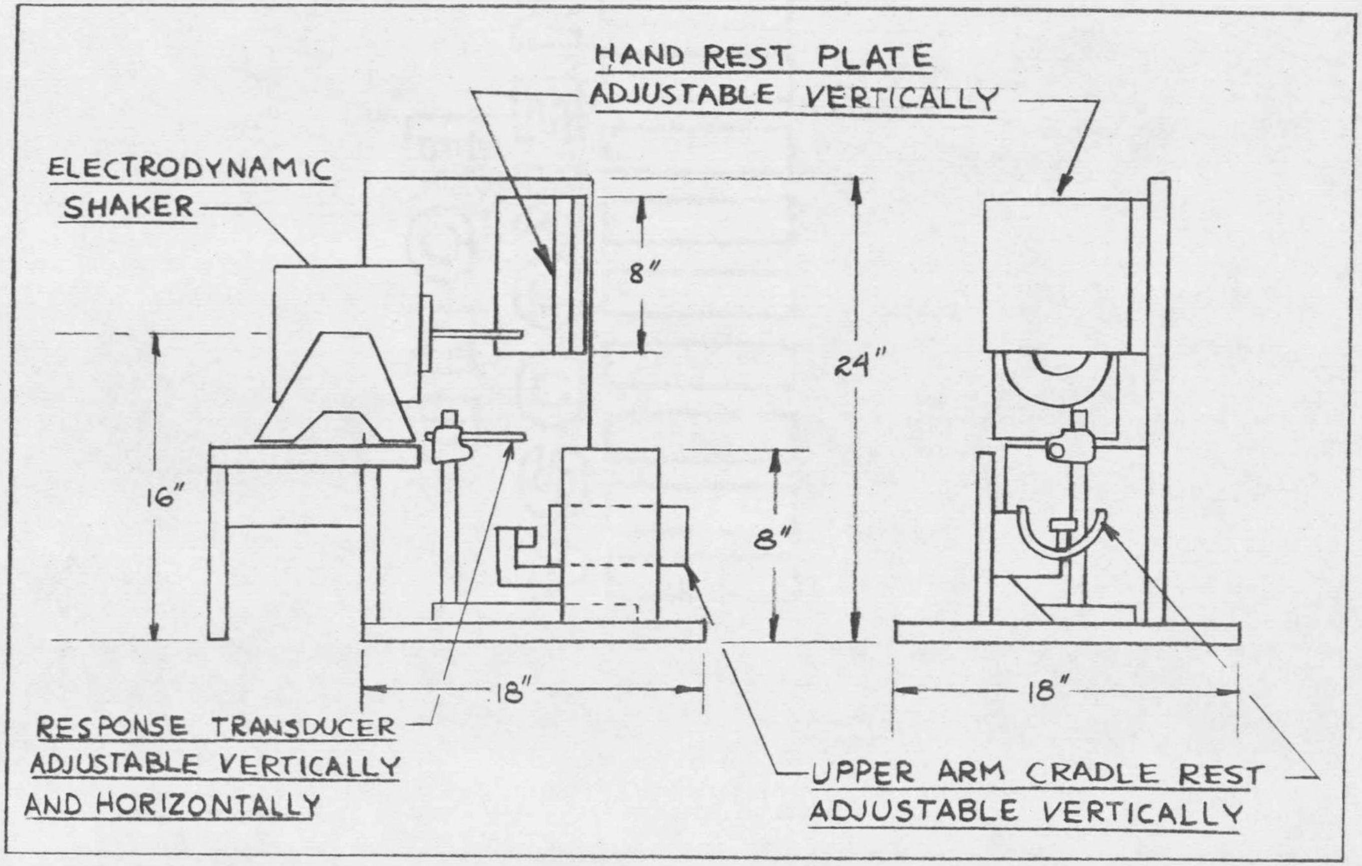


Figure 21 Schematic of Control Circuit

APPENDIX C

DIMENSIONAL DRAWING OF THE ARM POSITIONING FIXTURE



<u>Figure 22</u> Positioning Fixture

BIBLIOGRAPHY

1. Jurist, J.M., "Measurement of Ulnar Resonant Frequency", Orthopedic Research Laboratory, Internal Report No. 36, University of Wisconsin Medical Center, Madison, Wisconsin.

2. Matz, R.E., Blackketter, D.O., Powe, R.E., Taylor, W.R., "Parameter Investigation for Low Frequency Vibration of the Forearm", Proceedings of the 25th ACEMB Conference, 1972.

3. Raven, F.H., Automatic Control Engineering, McGraw-Hill Book Company, New York, 1968.

4. Garner, E.R., "Determination of Macroscopic Biological Material Properties by Dynamic, 'In-Vivo' Testing", Unpublished Doctoral Dissertation, Montana State University, Bozeman, Montana, 1973.

5. Snedecor, G.W. and Cockran, W.G., Statistical Methods, The Iowa State University Press, Ames Iowa, 1971.

6. Anderson, R.A., Fundamentals of Vibrations, The Macmillan Company, New York, 1967.

[redacted] Harrigan, Michael D
N378 Development ofequip-
H235 ment and techniques for
cop.2 experimental determina-
tion of dynamic response
of the human foreman

DATE	ISSUED TO
JAN 2	STEVE JOHNSON ⑥ MC 682-7295 P.O. Box 21 ENNIS