Parameter investigation for low frequency vibration of the forearm

by Roger Edward Matz

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Aerospace and Mechanical Engineering
Montana State University

Abstract:
The need to be able to predict the response of portions of the human body to dynamic loading has been well established, and it is the purpose of this study to experimentally investigate the effects of several independent parameters as they relate to the frequency response of a biological system. Specifically, the forearm of volunteer subjects was excited by a very small amplitude, sinusoidal forcing function at a position near the styloid process, and the response of the arm was measured with an accelerometer located near the olecranon process. The input forcing function frequency was automatically swept through a frequency range of 80 to 600 Hz, and the resultant output frequency response was recorded as a power spectral density curve by means of a wave analyzer. The natural frequencies of the arm were considered to be the frequencies at which relative peak amplitudes occur in the power spectral density curve. For each subject, four independent parameters, as well as the dependent variable (natural frequency), were measured. These four independent parameters were r (1) arm length as measured from elbow to wrist, (2) bone size as indicated by wrist size, (3) muscle development as indicated by the per cent increase in upper arm circumference from unflexed to flexed position, and (4-) fleshiness as indicated by the ratio of unflexed upper arm circumference to wrist width. The subjects utilized were approximately 250 college-age males.

The significance of the effects of each of the foregoing parameters, and of the interactions between these parameters, on the dependent variable was examined via a 2n fixed factor, factorial experiment. The experimental results indicated all of the four factors significantly affected the resonant frequency at the 99% level of confidence. It was further determined that each of these factors had significant interactions, with all two way interactions except arm length-bone size and muscle development-fleshiness significant. All three way interactions were significant.

No general trend was determined for any factor except bone size, for which an increase in level tended to cause a decrease in natural frequency.

It was concluded that although other parameters may be found which affect the resonant frequency, these four were the ones of most importance.

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Signature Roger E. Motz

Date August 4, 1972

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Head, Major Department

Chairman, Examining Committee

Graduate Dean

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ABSTRACT

The need to be able to predict the response of portions of the human body to dynamic loading has been well established, and it is the purpose of this study to experimentally investigate the effects of several independent parameters as they relate to the frequency response of a biological system. Specifically, the forearm of volunteer subjects was excited by a very small amplitude, sinusoidal forcing function at a position near the styloid process, and the response of the arm was measured with an accelerometer located near the olecranon process. The input forcing function frequency was automatically swept through a frequency range of 80 to 600 Hz, and the resultant output frequency response was recorded as a power spectral density curve by means of a wave analyzer. The natural frequencies of the arm were considered to be the frequencies at which relative peak amplitudes occur in the power spectral density curve. For each subject, four independent parameters, as well as the dependent variable (natural frequency), were measured. These four independent parameters were: (1) arm length as measured from elbow to wrist, (2) bone size as indicated by wrist size, (3) muscle development as indicated by the per cent increase in upper arm circumference from unflexed to flexed position, and (4) fleshiness as indicated by the ratio of unflexed upper arm circumference to wrist width. The subjects utilized were approximately 250 college-age males.

The significance of the effects of each of the foregoing parameters, and of the interactions between these parameters, on the dependent variable was examined via a 2^n fixed factor, factorial experiment. The experimental results indicated all of the four factors significantly affected the resonant frequency at the 99% level of confidence. It was further determined that each of these factors had significant interactions, with all two way interactions except arm length-bone size and muscle development-fleshiness significant. All three way interactions were significant.

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Chapter 1

INTRODUCTION

Previous investigations have dealt with in vivo measurement of resonant frequencies of the bone-flesh structure of the forearm (1,2)* Dr. Jurist (2) attempted to correlate several physical factors of the subjects 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.

The intent of this study was to explicitly define several physical factors, including some investigated by Jurist and to determine if these factors significantly affect one resonant frequency of the forearm. The parameters studied were:

A) Ulna length
B) Bone size--as indicated by wrist width

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*Numbers in parentheses refer to corresponding entry in Bibliography.

C) Muscle development--defined by per cent increase in upper arm circumference between unflexed and flexed position
D) Fleshiness--as indicated by ratio of unflexed upper arm circumference to wrist width.

The investigation of the effects of these factors was accomplished by the theory of experimental design (3,4,5). Experimental design is a widely used industrial tool (5), allowing efficient collection, organization, and analysis of experimental data.

Chapter 2

METHOD OF ANALYSIS

2.1 Experimental Design

The experiment was designed and the data analyzed using the principles of experimental design.

Experimental design gives one reasonable assurance that the results of an experiment will provide definitive answers to the questions under investigation.

The method includes preplanning of the experimental method, provides the manner or order in which the experimental data is to be collected, and provides the means of analyzing the data and drawing valid conclusions.

2.2 2^n Design

There are many choices of possible experimental designs using the four factors presented as independent variables and resonant frequency as the response variable (3,4). The nature of the current interest in these factors, however, indicated the likely choice to be a 2^n factorial design. A 2^n factorial design (Appendix A) is used as a screening experiment--as a prelude to detailed study of a particular situation. This design allows one to selectively determine which of the chosen independent variables significantly affect the response variable, and also whether possibly the independent variables affect the response variable differently for different level combinations of the other independent variables (interaction effects). This allows screening of those factors which need not be included in the detailed study.

For the 2^n design two levels are selected for each of the n factors (usually chosen at the extremes of possible levels.) Thus, for the experimental conditions all possible combinations of the levels of the n factors are used, hence a factorial design. For this 2^4 design there are 16 possible experimental conditions. If the extremes of the factors are chosen as follows:

	Factor	Levels
A:	arm length	long arm, short arm
B:	bone size	big wrist, small wrist
C:	muscle development	large muscle increase, small muscle increase
D:	fleshiness	very fleshy, slightly fleshy

then one possible experimental condition would be a resonant frequency determination for a person fitting in the category of short arms, big wrists, large increase in muscles and very fleshy (bcd). Similarly there are 15 other possible combinations. These levels would be specified at appropriate numerical values, based on a survey of possible variations.

In general, the experiment is replicated (performed for each of the 16 possible conditions more than once) in order to increase the degrees of freedom for experimental error. With two replicates there are a total of 32 experimental determinations.

2.3 Desired Results

The desired results from the 2^n design were:

1) justifiable conclusions as to whether:

   a) the selected independent factors significantly affect the response variable,
   b) there is interaction between the independent variables; that is, whether the factors affect the resonant frequency differently at different levels of other factors,

2) general trends in the effect on the resonant frequency of a change in the level of a certain factor.

The 2^n design does not allow a determination explicitly of the nature of the factor effect on the response variable, i.e., linear, quadratic, cubic, etc., but does allow a postulation of trends.

3) a postulate as to whether or not all significant factors have been included in the experiment.

Number 3 may be possible by some consideration of the experimental error.

2.4 Methodology

For this experiment the collected data were analyzed by the application of analysis of variance techniques. In the calculation of any variance, the analysis begins by finding the total sum of squares of the deviations of each experimental value from the overall mean. This total sum of squares of the deviations then is segmented into the sums of squares of deviations due to the effects of each of the factors, the sums of squares of deviations due to the interaction effects, and the sum of squares of deviations due to random error. (Appendix B)

Dividing each of these sums of squares by its appropriate degrees of freedom yields unbiased estimates of the experimental variance. If the null hypothesis is true, that the factors or interactions do not significantly affect the response variable, then each of these segmented variances is a chi-square distributed, unbiased estimate of the variance due to random error σ_e^2. The critical region of an F distribution formed by taking the ratio of the various segmented variances to the sample error variance is then used to test the null hypothesis at a chosen level of confidence, α, where α x 100 represents the per cent rejection of a true hypothesis. For this investigation α was chosen at .01.

The critical region is generally taken as the upper tail of the F distribution, (Figure 4) rejecting the null hypothesis in any test if $F > F_{1-\alpha}$, where α is the area of the upper tail.

Having determined the significance of the various factors and interactions, the experimental data are then plotted in a manner which may indicate general trends.

Chapter 3

EXPERIMENTAL PROCEDURE

3.1 Instrumentation

The instrumentation utilized to introduce and detect the vibrations in the arm was required to have the following properties:

1) The transducers must be sufficiently small such that they do not significantly change the response of the system.

2) Instrumentation error must be small in the low frequency range.

3) The excitation source must allow a sweep through a wide frequency range in search of resonant frequencies, and yield visual representation of the system response.

4) The amplitudes of vibration must be relatively small and thus the input and pickup transducers must be relatively sensitive.

5) The transducers must be positioned on the arm in nearly identical positions for each of the subjects.

The input device developed was a modified 0.1 watt one-inch Calectro speaker, illustrated in Figure 1. The piston, fixed in the speaker cone, allowed a

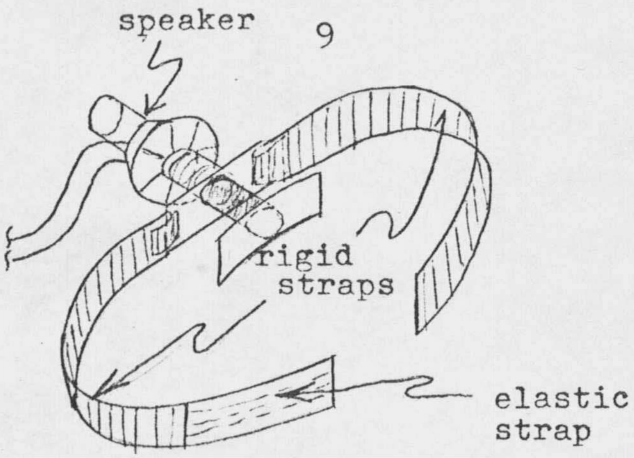

Figure 1. Vibration Input Device

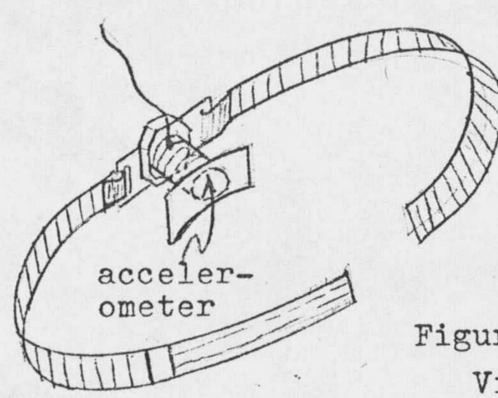

Figure 2. Vibration pickup device

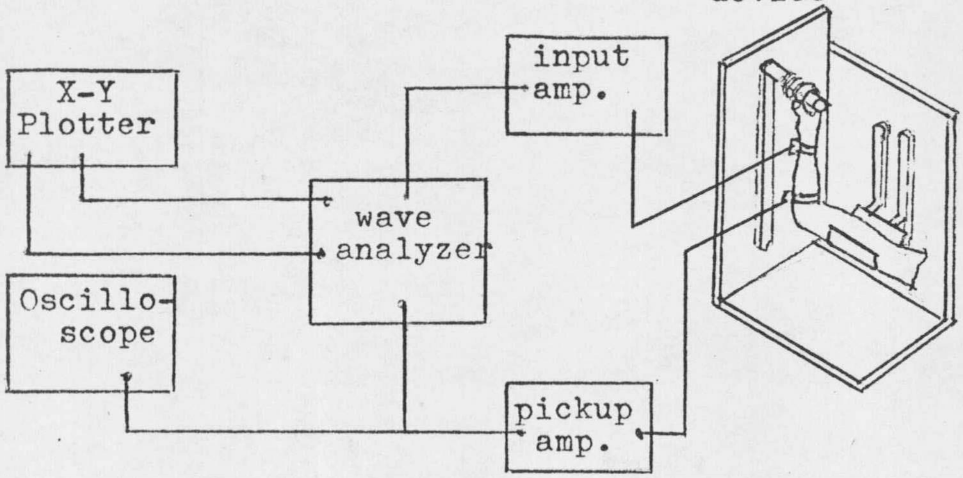

Figure 3. Experimental Schematic

small-area contact for signal input. The particular strap arrangement chosen allowed approximately constant contact pressure. Early work indicated pressure variations would significantly contribute to experimental error.

The pickup device, Figure 2, was a modified accelerometer, with the same strap arrangement as for the speaker.

The input device was strapped to the arm at a distance of 1/8 of the total ulna length above the styloid process, and the pickup at 5/16 of the ulna length from the olecranon process tip. These particular locations were chosen because of the proximity of the ulna to the flesh surface, allowing more nearly direct input to and pickup from the bone itself, which should be the major system component.

The apparatus used in the experiment is presented schematically in Figure 3. The wave analyzer acted both as a source for the input signal and as a means of comparing the input and pickup signals in the arm. It automatically swept through the desired frequency range with approximately constant input power. The recorder allowed plotting the spectral density curve for use in determining natural frequencies (Figure 9, Appendix C). The arm support device was constructed to allow nearly repeatable positioning of the subjects' arms and the transducers attached to the arms.

3.2 Procedure of Testing

Tests were run on approximately 250 volunteer, male college students in the age range of 19-24 years.

For each subject the quantities recorded were:

a) arm length
b) wrist width
c) flexed and unflexed upper arm circumference
d) height
e) weight
f) age
g) previous history of illnesses which might affect vibration response
h) spectral density curve.

Each subject was categorized according to the defined 2^n experimental conditions to determine his fit within any category. Since, as mentioned, the factor levels were defined at the extremes for the 2^n design, the major portion of the subjects did not properly fit within the defined categories and were not useable. The maximum number of replicates was limited by the minimum number of subjects in any one of the 16 categories, since for the analysis it is desirable to have the same number in each group. This number was two.

Having recorded the natural frequencies for these conditions, an analysis of the results by standard methods of analysis of variance was possible (3,4).

3.3 Equipment Error Analysis

The possible error contributed to the experimental results by the various pieces of equipment is as follows:

Calibrating sine wave generator: ±1%
Wave analyzer: ±1%
Vibration meter: ±1%

Since the amplitude response was relative, the amplitude error is not considered in this analysis.

Chapter 4

DISCUSSION OF RESULTS

4.1 Analysis of Variance

The experimental data and calculations of the various sums of squares are presented in Appendix C. The resulting F tests are summarized by an Analysis of Variance table, Table 1.

At the 99% level of confidence the corresponding F statistic is $F_{1,15} = 8.68$. F values of Table 1 which lie in the rejection region indicated in Figure 4, imply that that particular factor or interaction truly does affect the resonant frequency. It is noted that, except for the AB interaction, the CD interaction, the ABCD interaction, and the replication effect, all other effects are significant at the .01 level.

Higher numbers for these F values indicate greater significance, hence, some of the main factor effects are more significant than are the others. Bone size and fleshiness are much more significant than arm length in affecting the natural frequency, and are also more significant than muscle development. Although

Table 1 Analysis of Variance

Source	degrees freedom	Sums of Squares	F
A: arm length	1	1875.78	8.695
B: bone size	1	16882.03	78.26
C: muscle devel.	1	8417.53	39.02
D: fleshiness	1	15532.03	72.0
2-way interactions			
AB	1	810.03	3.75
AC	1	15708.78	72.82
AD	1	42122.53	195.26
BC	1	8547.78	39.62
BD	1	3180.03	14.74
CD	1	979.03	4.54
3-way interactions			
ABC	1	21580.03	100.03
ABD	1	15975.78	74.05
ACD	1	20757.03	96.22
BCD	1	18963.78	87.91
4-way interaction			
ABCD	1	33.5	<1
Replicates	1	344.5	1.60
Random error	15	3235.97	------

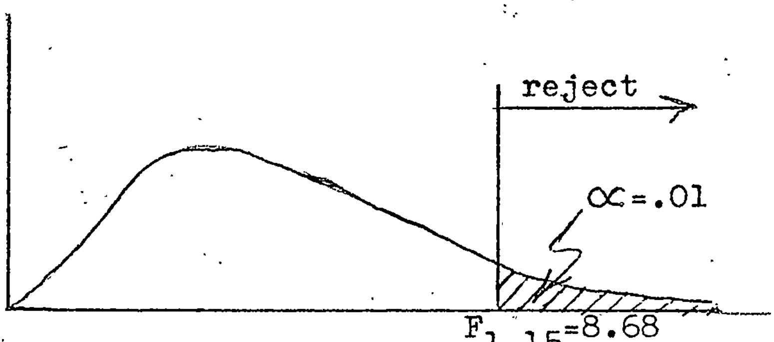

Figure 4. F Distribution

the arm length is just slightly significant at the .01 level, the importance in considering this factor will be seen later in considerations of interactions.

Before proceeding to discussion of interaction effects, some interpretations of interactions may be in order.

A significant two factor interaction indicates that the effect of a particular factor on the response variable is different at different levels of the other factor, where the effect of a factor may be defined as the change in response variable produced by a change in the factor level. These two-way interactions will become clear in the plots presented in section 4.2.

The fact that AD interaction is significant means that the change in resonant frequency between levels of arm length is different for different levels of fleshiness. Similar conclusions are made for arm length-muscle development, bone size-muscle development, and bone size-fleshiness interactions--AC, BC, and BD, respectively. Again the fact that some of these F statistics are much larger than the others indicates that those interactions are much more pronounced than the others.

Similar conclusions may be drawn for the three-way interactions, where three-way interactions indicate that the interaction of two factors is different at different levels of a third factor.

As mentioned before, although the main effect of arm length is only slightly significant, the importance of considering variations in this factor is shown in the significance of many of the interactions of the other parameters with arm length. These factors affect the resonant frequency differently for different levels of arm length.

4.2 Interaction Plots

Figures 5 through 8 are plots of cell totals used in calculating the various two-way interactions versus one of the factors, for each plot.

A given line represents the variation in response variable with the change in level of the abscissa variable at the constant level of the factor indicated on the line. Thus there will be two lines for each of the three remaining factors for each plot. For a given line the effects of the other two factors have been effectively averaged at each endpoint. The straight