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# A MECHANICAL IMPEDANCE INVESTIGATION OF HUMA RESPONSE TO VIBRATION



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## FOREWORD

This study was initiated by the Biophysics Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was conducted by the Kentucky Research Foundation, Wenner-Gren Aeronautical Research Laboratory, University of Kentucky, Lexington, Kentucky, under Contract No. AF 33 (616)-7766. The principal investigator for the Wenner-Gren Aeronautical Research Laboratory was Dr. Karl O. Lange, under whose direction this phase of the research was carried out by Mr. Richard G. Edwards, Research Associate. Mr. Richard D. Lowry and Maj Neville P. Clarke, USAF, VC, Vibration and Impact Branch, Biodynamics and Bionics Division of the Biophysics Laboratory, were the technical monitors for the Aerospace Medical Research Laboratories. The work was performed in support of Project No. 7231, "Biomechanics of Aerospace Operations," Task No. 723101, "Effects of Vibration and Impact." The research sponsored by this contract was started in December 1962 and was completed in February 1964.

The assistance of Messrs. V.C. Currens, A.E. Fairbanks, T.D. Sharp, E.W. Vaught and indeed the entire staff of the Wenner-Gren Aeronautical Research Laboratory was invaluable, as was the support from the Aerospace Medical Research Laboratories.

This technical report has been reviewed and is approved.

J. W. HEIM, PhD
Technical Director
Biophysics Laboratory

## ABSTRACT

To help establish the dynamics of the human body the mechanical impedance was measured as two subjects were exposed to vertical sinusoidal motion at frequancies from 1 to 20 cycles per second. The impedance in the supine, lateral, and standing subject positions and its variation due to voluntary change in muscle tone and due to padding the support were determined. In all tests the frequency interval from 4 to 7½ cycles per second was found to contain the initial whole body resonance. Nonlinearity of the response, as established by impedance dependence upon shaketable acceleration level, was observed by altering the peak shaketable acceleration from 0.2 to 0.35 to 0.5 g. The degree of nonlinearity was found to be dependent upon subject position as well as subject physiological differences. Changes in support padding and muscle tone produced substantial alterations in impedance but little variation of resonant frequencies.

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# SECTION I

# INTRODUCTION

So long as the versatility, reliability, and decision making capacity of the human operator remain without inanimate substitute, the environmental limits outside of which human abilities fail must be established. Random vibration is one environmental factor commonly encountered. Critical vibrations beyond which human performance is impaired can be found by determining the response of the human body and mind to subcritical, ordered vibration and then carefully extrapolating to critical conditions represented by random vibration. Design of manned vehicles and devices utilizing results of such investigations will minimize vibration interference with operator performance.

To establish human responses to vibration previous investigators used various techniques. Clark, Lange, and Coermann (ref. 2) reported the response in terms of body deformation while White, Lange, and Coermann (ref. 13) determined internal pressures. Ziegenruecker and Magid (ref. 17) found the subjective tolerance to short time vibration by increasing the shaketable amplitude at each respective frequency until, in the subject's opinion, a further increase would result in bodily harm. Coermann (ref. 3), Hopkins (ref. 7), Wittwer (ref. 15) and Weis, Clarke, and von Gierke (ref. 12) employed the mechanical impedance method while Krause and Lange (ref. 8) and Coermann, Ziegenruecker, Wittwer, and von Gierke (ref. 4) established significant correlations among the various methods.

The determination of the whole body vibration response involves finding resonant frequencies of individual body organs and body subsystems consisting of several organs or body parts. Because many of these organs are inaccessible to direct measurement during vibration, external investigation techniques sensitive to these resonances have to be used. Mechanical impedance offers this advantage and therefore was the technique chosen for the present investigation.

## SECTION II

## THEORETICAL ASPECTS OF MECHANICAL IMPEDANCE

The vibration exciter used in this investigation was the Wenner-Gren Aeronautical Research Laboratory electrohydraulic shaketable shown in figure 1 (ref 9; ref 11). Analogous to the technique used by Coermann (ref. 3), the ratio of the maximum force transmitted per cycle between subject and shaketable to the maximum velocity occuring at the point of force transmission during the cycle is defined as mechanical impedance:

$$Z = F_{max}/V_{max} \angle\theta \qquad (1)$$

where $Z$ = mechanical impedance (lb-sec/in)
$F_{max}$ = maximum force transmitted per cycle (lb)
$V_{max}$ = maximum velocity per cycle (in/sec)
$\theta$ = difference in phase of the maximum force and maximum velocity.

The mechanical impedance for a linear spring-mass-damper system as shown in figure 2 can be expressed as

$$Z \propto (Z_k, Z_c, Z_m) \propto (k/w, c, mw) \qquad (2)$$

where $Z_k$, $Z_c$, and $Z_m$ represent the mechanical impedance values of, respectively, the spring, damper, and mass
$k$ = linear spring constant (lb/in)
$w$ = angular velocity (radians per second)
$= 2\pi f$, where $f$ is the frequency of the shaketable in cycles per second.
$c$ = linear damping constant (lb-sec/in)
$m$ = mass (lb-sec$^2$/in).

For a given frequency, then, (see equation 2) the total impedance of a linear system is a constant with magnitude dependent only upon the existing arrangement of the components of the system.

If the human body is approximated by a finite number of linear systems, then for a given frequency the total whole body impedance will be the sum, depending upon the arrangement of the systems, of the individual system impedance values.

Moreover, if the impedance of each system were constant, the total whole body impedance must be also constant for a whole body system composed of individual linear systems. Whereas, if the total whole body impedance were found to be dependent upon shaketable acceleration at any given frequency, then nonlinearity exists in the whole body system.

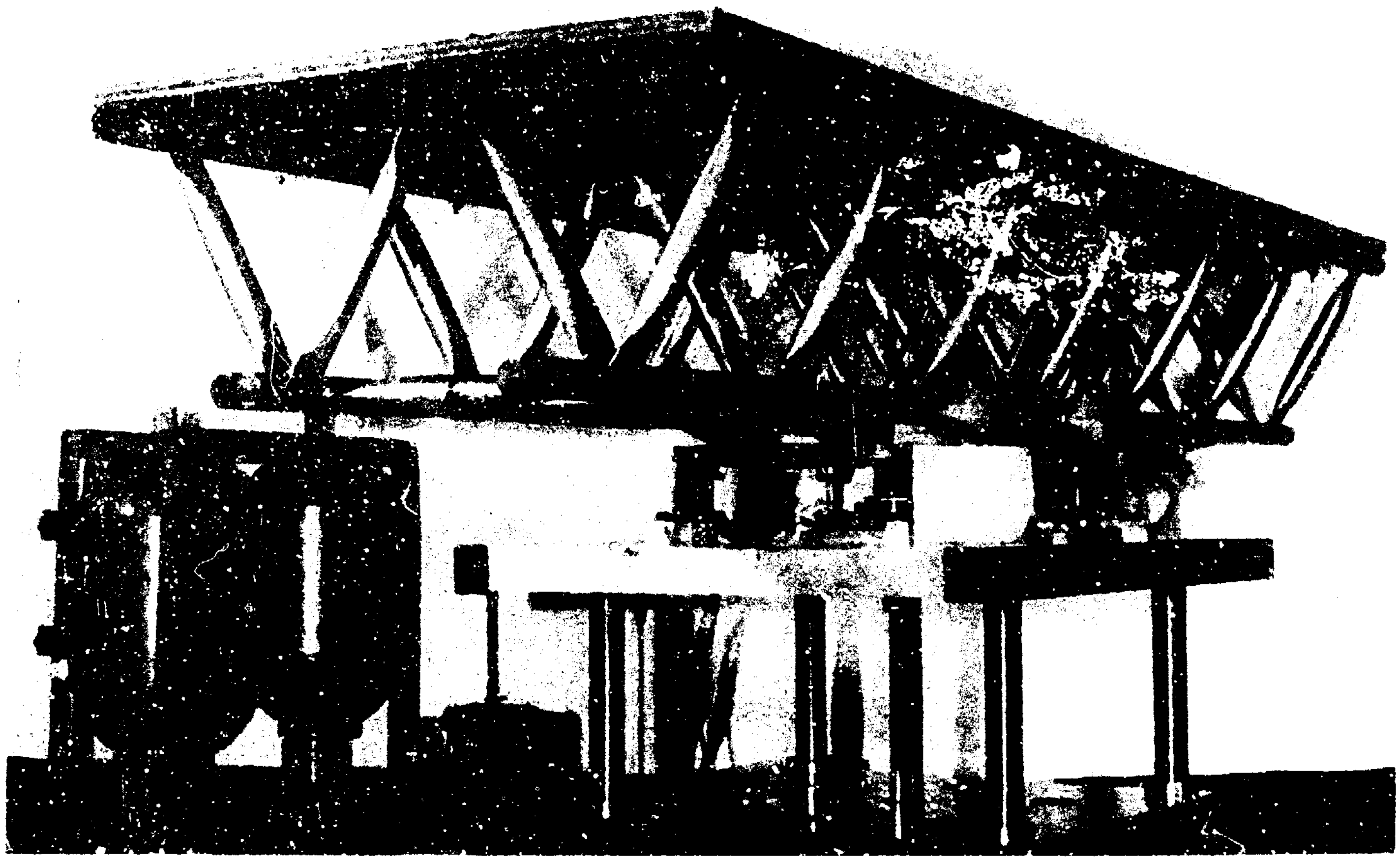


Figure 1. Wenner-Gren Aeronautical Research Laboratory Shaketable

At frequencies below 2 cps the human body responds to vibration similar to a rigid mass, while above 20 cps the harmful effects can be controlled. The 2 to 20 cps interval, however, has been found to contain body resonances; consequently, it is desired to measure the whole body impedance in this critical frequency region. After whole body impedance curves are available, it must be attempted to interpret them. The whole body system should then be further investigated by testing its linearity through variation of the shaketable input, and by having the subjects systematically change parameters over which they have control, such as muscle tone.

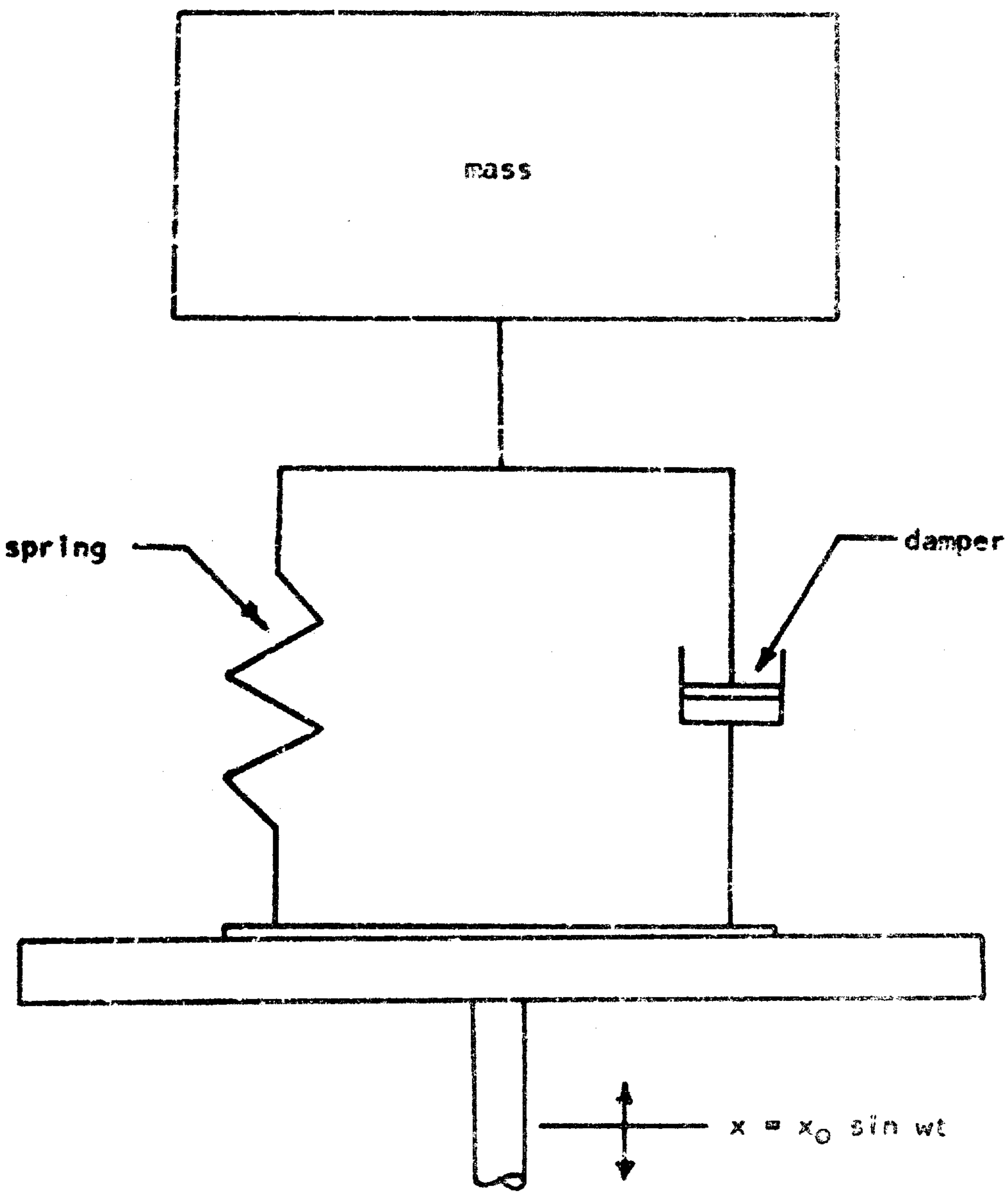



Figure 2. A mechanical system undergoing sinusoidal motion

## SECTION III

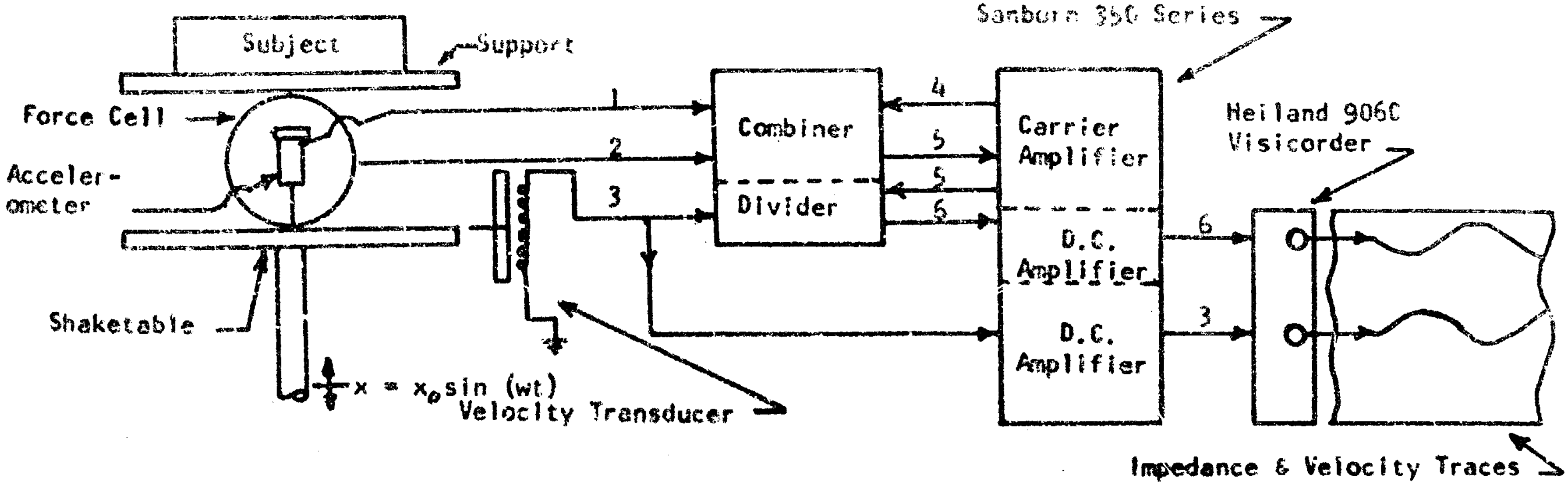
## IMPEDANCE MEASUREMENT TECHNIQUE

Figure 3 illustrates the instrumentation and also shows a subject in the supine position atop the shaketable. Figure 4 is a block diagram of the instrumentation used for the impedance measurements.

Figure 3. Supine subject with related impedance instrumentation set-up

The electrohydraulic shaketable (ref. 11) is capable of producing continuously variable motion within the limits of 10 inches of amplitude, frequencies to 100 cycles per second, and velocities to 80 inches per second. These limits correspond to accelerations up to 12 g and vector force outputs up to 3000 pounds.

A custom built force cell-accelerometer arrangement for direct




Note: Numbers refer to the corresponding signal as follows:

1. Support Force
2. Total Force
3. Velocity
4. Excitation
5. Net Force
6. Impedance

Figure 4. A block diagram of the instrumentation used for impedance recording

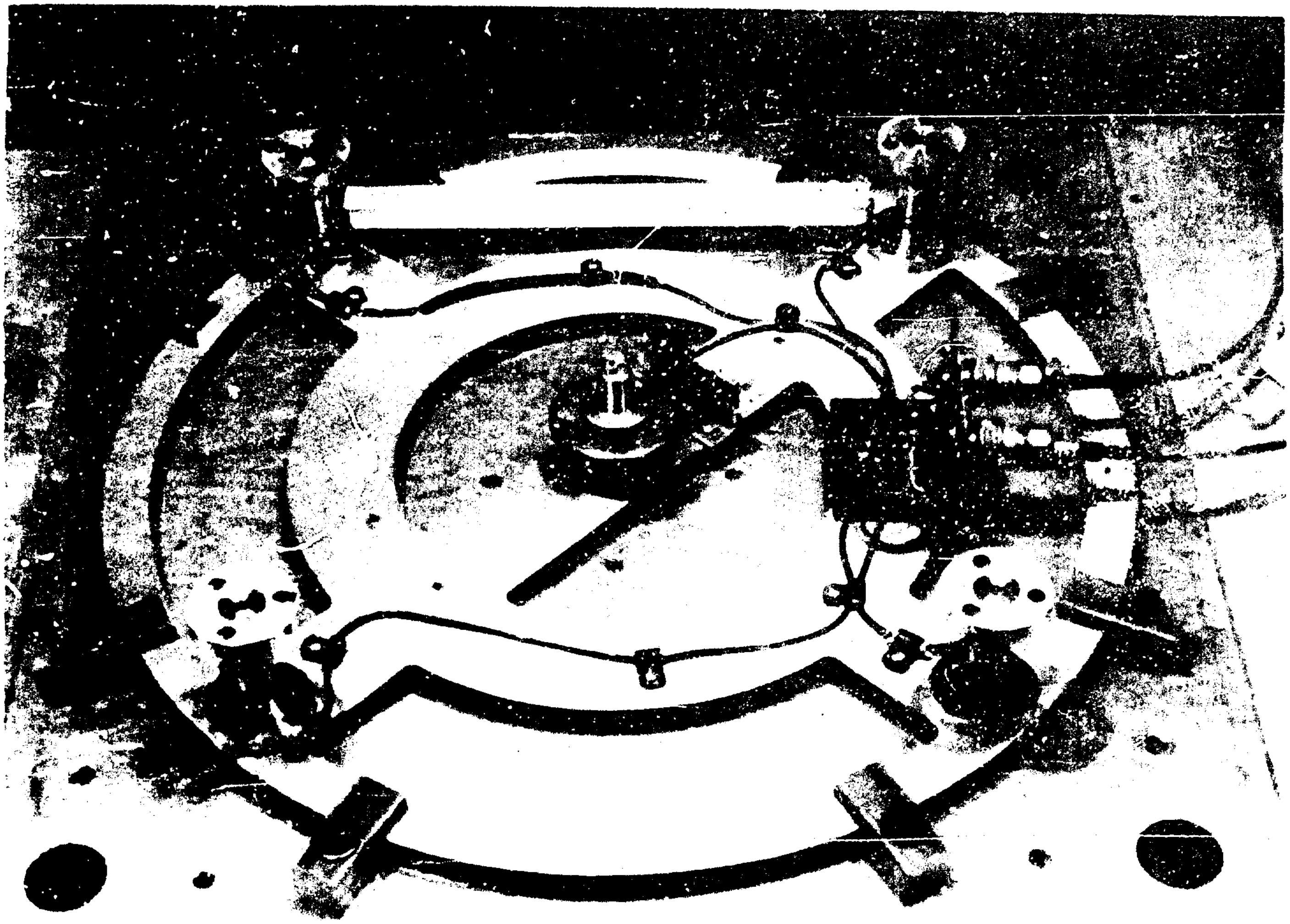


Figure 5. Partially disassembled impedance force table showing the four force cells symmetrically located around accelerometer unit.

impedance measurement is located between the support and the shaketable (ref. 9). Figure 5 is a view of this unit partially disassembled. The spring type deformation response of the cylindrical force cells to force transmission through them is sensed by semiconductor strain gages attached to the walls. Upon vibration an accelerometer mounted as shown on the shaketable produces an electrical signal proportional to the force transmitted from the subject support, which is sturdy enough to be considered an inert mass. This signal is then electrically subtracted in a combiner from the total force signal to yield the "live load"; namely, the net force of the subject alone. In the divider this net force is divided by a constant equal to the peak velocity at any one frequency, this yields another vector whose peak value equals the magnitude of impedance. This signal along with that of the shaketable velocity, was fed to a Heiland Visicorder for recording of the traces on photosensitive paper. From these two traces the phase angle of the impedance was measured. Thus, both the impedance magnitude and phase angle were obtained.

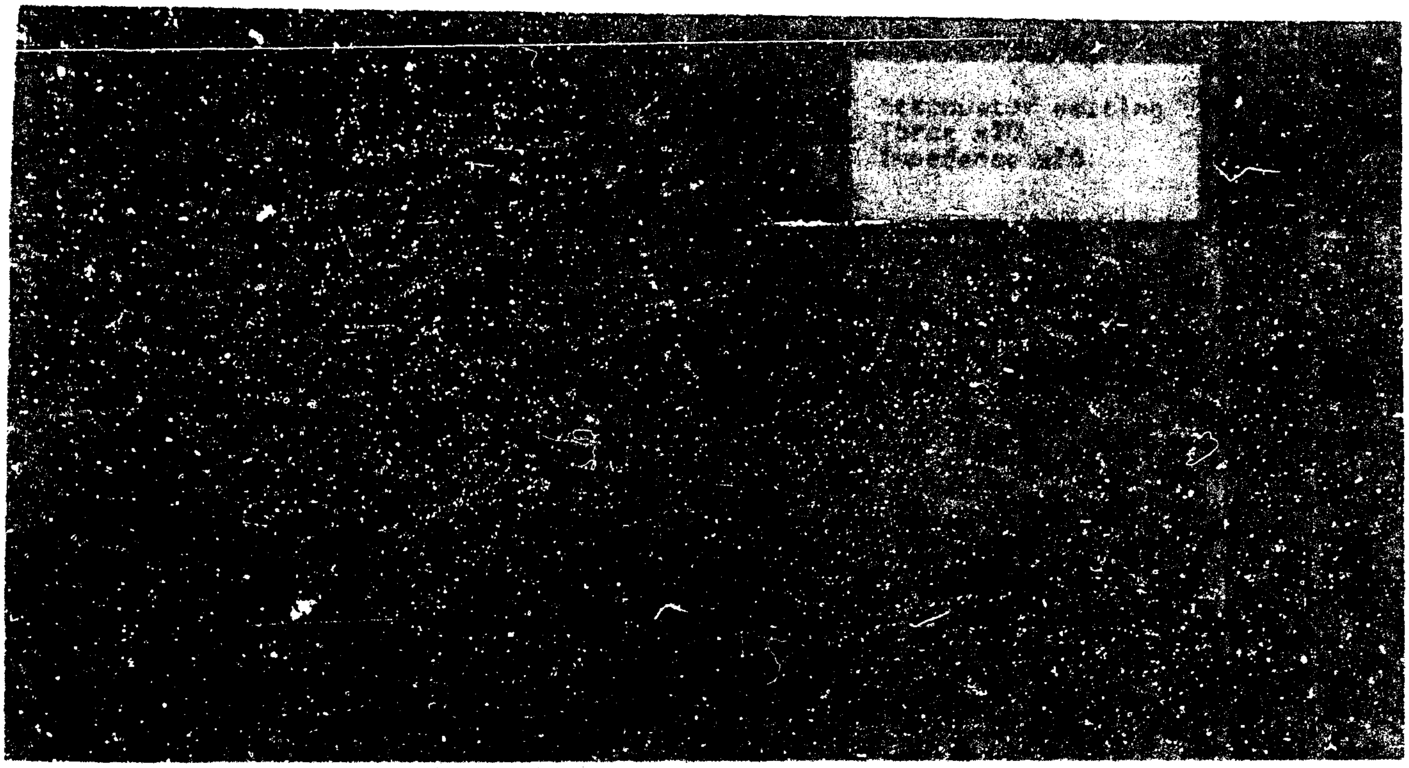


Figure 6. Impedance calibration trace from Visicorder

The test procedure for a given subject attitude, frequency range, and table acceleration level consisted of (1) pretest calibrating, (2) positioning the subject on the support, (3) bringing the shaketable motion up to the required intensity for each frequency, (4) recording the impedance and velocity traces from the Visicorder, and (5) recalibrating after the completion of testing.

Impedance calibration was accomplished by setting the velocity divisor to unity and then successively placing three 25 pound weights on the table and removing them again one by one, and finally applying a 162 pound weight. The trace thus obtained, figure 6, represents impedance values equal to those of the weights applied to the table. Measurements of these traces showed that the force cells are linear. The velocity calibration was accomplished at a table frequency of 1 cps with 2 inches amplitude, resulting in a peak velocity of 12.55 inches per second. Figure 7 illustrates a typical recording of V and Z. From such curves and the respective calibration data the desired impedance values and phase angles were obtained.

Two supports were developed for the different subject positions to be tested. Figure 8 shows the support used for the supine and lateral positions.

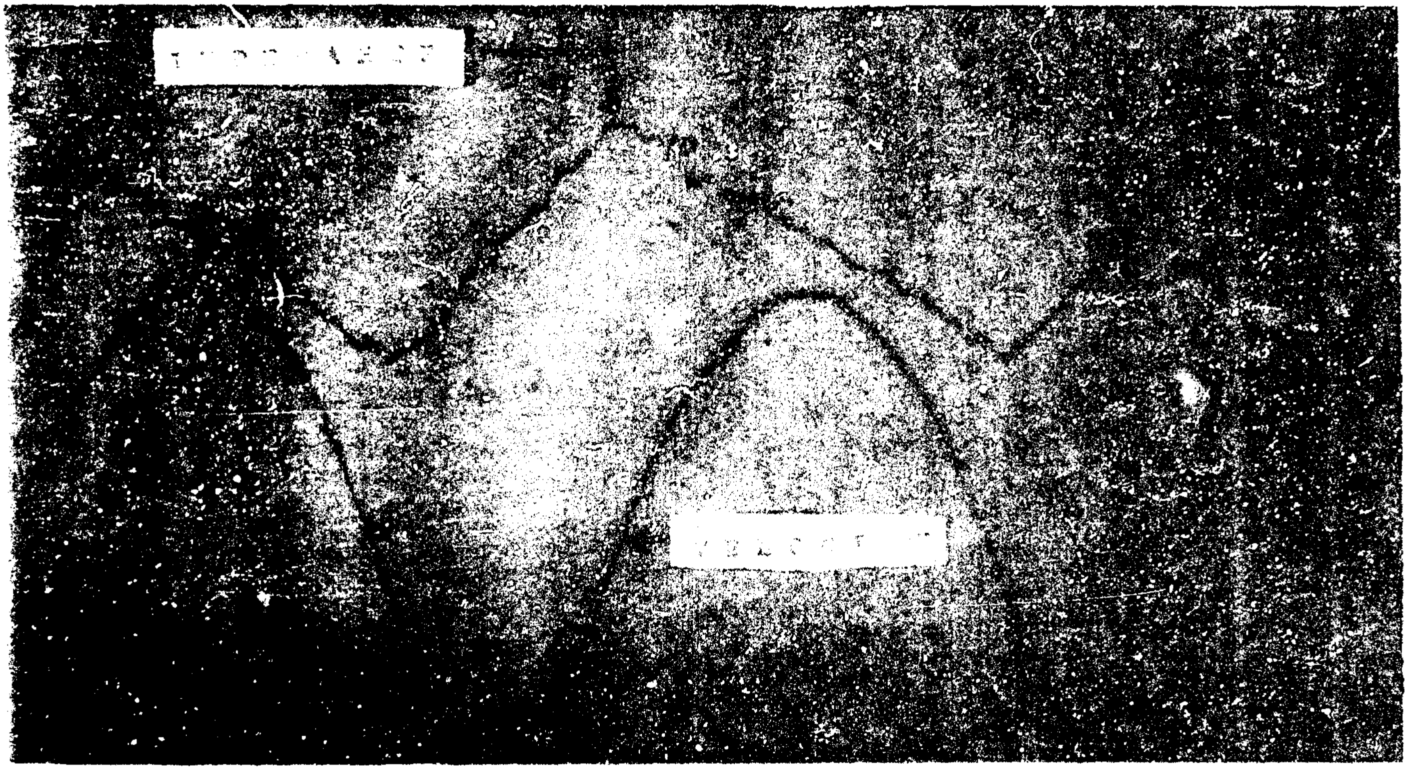


Figure 7. Impedance and velocity traces from Visicorder

A plywood surface with steel underbracing was used to make this support a rigid structure. The support for the standing position consisted of a 12" by 15" reinforced steel surface.

For each test point, the proper table frequency and amplitude, and therefore acceleration level, were achieved by adjusting the shaketable controls, and the traces were then recorded for approximately 10 seconds. A constant acceleration level was maintained throughout the 1 to 20 cps test interval.

The two subjects used for these tests were AEF and RGE:

| Subject | Age | Height | Weight |
|---|---|---|---|
| AEF | 26 | 5'11" | 171 lbs. |
| RGE | 23 | 6'3" | 185 lbs. |

Figure 8. Support used for impedance tests of supine and lateral subjects

## SECTION IV

## THE MECHANICAL IMPEDANCE OF TWO HUMAN SUBJECTS

### Supine Position, Varied Muscle Tone

Figures 9 and 10 are the graphs of impedance versus frequency for AEF and RGE, respectively, with muscle tone as a parameter. In these tests the impedance was recorded at each frequency, first with the subject tensing his muscles as much as possible and then, without altering the shaketable motion, with the subject relaxing. This procedure was followed throughout the frequency range.

The dependence of impedance on muscle tone is apparent. For each subject a 40-50% systematic difference in impedance exists over extended frequency ranges. Sudden fluctuations of impedance during any one measurement may very well be caused by the inability to maintain the same muscle tone long enough or by sporadic muscular changes. The impedance of the relaxed subjects is smaller than that of the tensed subjects up to approximately 11 cps and vice versa beyond this frequency. It is postulated that this is the result of decreased damping and increased stiffness due to tensing the muscles, the impedance of the tensed subjects at low frequencies consisting predominatly of elastic and mass components while damping effects predominate at high frequency.

The phase angle curves for both subjects substantiates this analysis. Up to approximately 7 cps the phase angle of the tensed subject is greater than that of the relaxed. Beyond about 7 cps the increased elastic component of the tensed subject is characterized by a lower phase angle than that of the relaxed subject.

Resonances of each subject appear at 6 cps and in the 8-10 cps interval. The effect of changing the muscle tone is not reflected by a significant corresponding change in resonant frequency as one would expect. Another resonance is recorded in the 16-19 cps range; however, a resonance of the support structure was detected at approximately 18 cps and consequently little significance can be attached to the impedance in this region.

### Supine and Standing at Three Different Shaketable Accelerations

Figures 11 through 14 are impedance curves at shaketable acceleration levels of 0.2 g, 0.35 g, and 0.5 g. Figures 11 and 12 represent AEF and RGE, respectively, in the relaxed

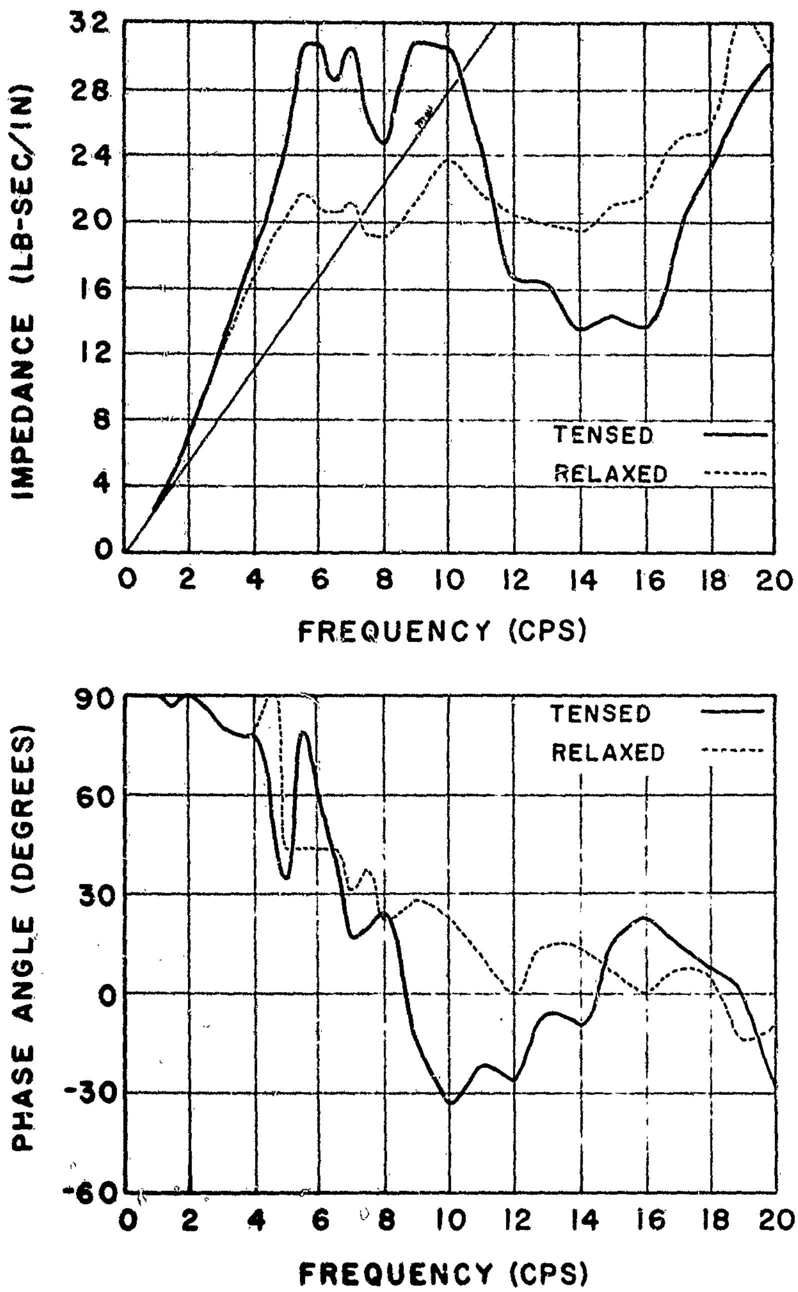



Figure 9. Whole body mechanical impedance versus frequency, subject AEF, supine tensed and supine relaxed.

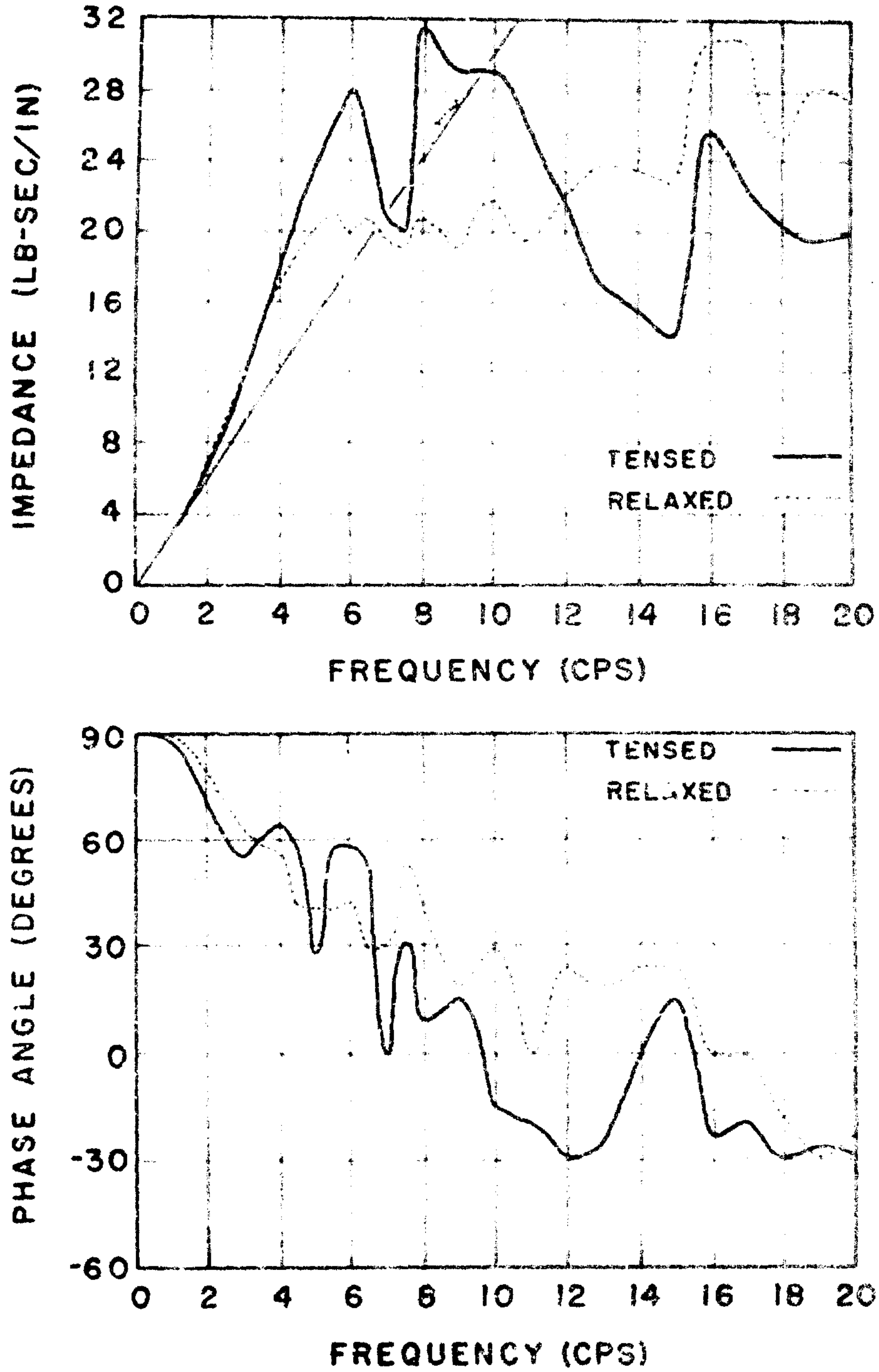



Figure 10. Whole body mechanical impedance versus frequency, subject RGE, supine tensed and supine relaxed.

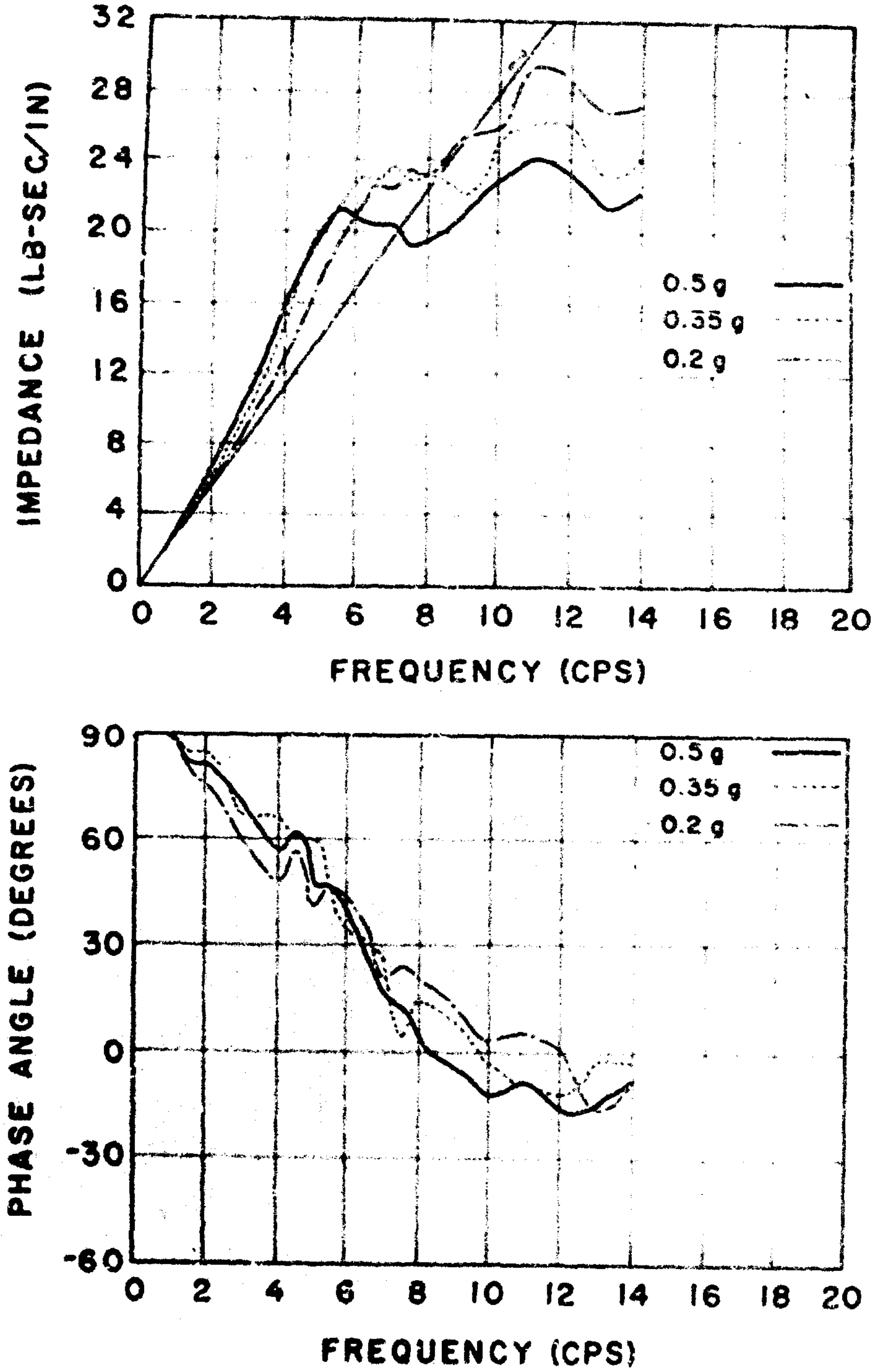



Figure 11. Whole body mechanical impedance versus frequency, with table acceleration level as a parameter, subject AEF, supine relaxed

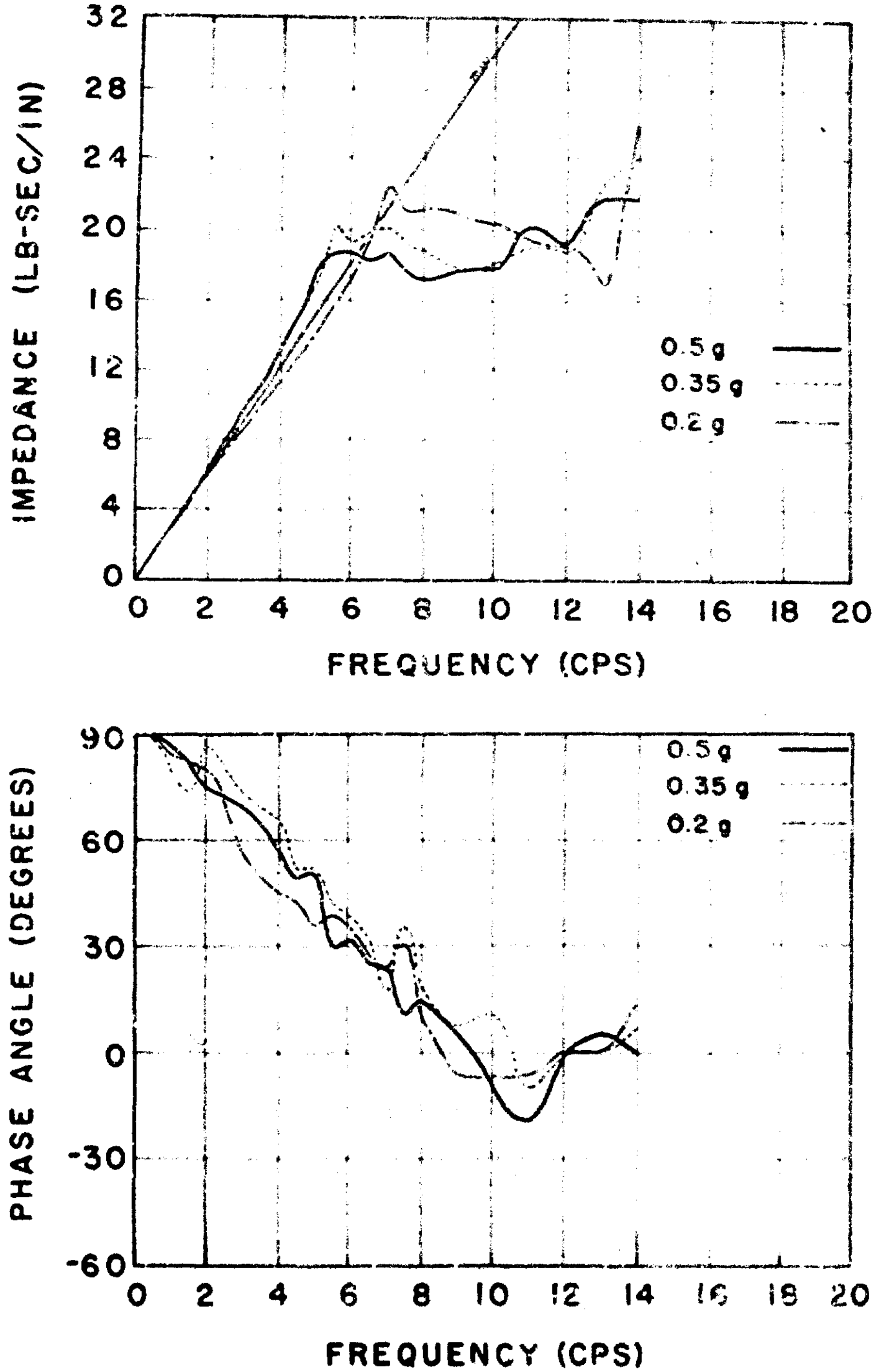



Figure 12. Whole body mechanical impedance versus frequency, with table acceleration level as a parameter, subject RGE, supine relaxed

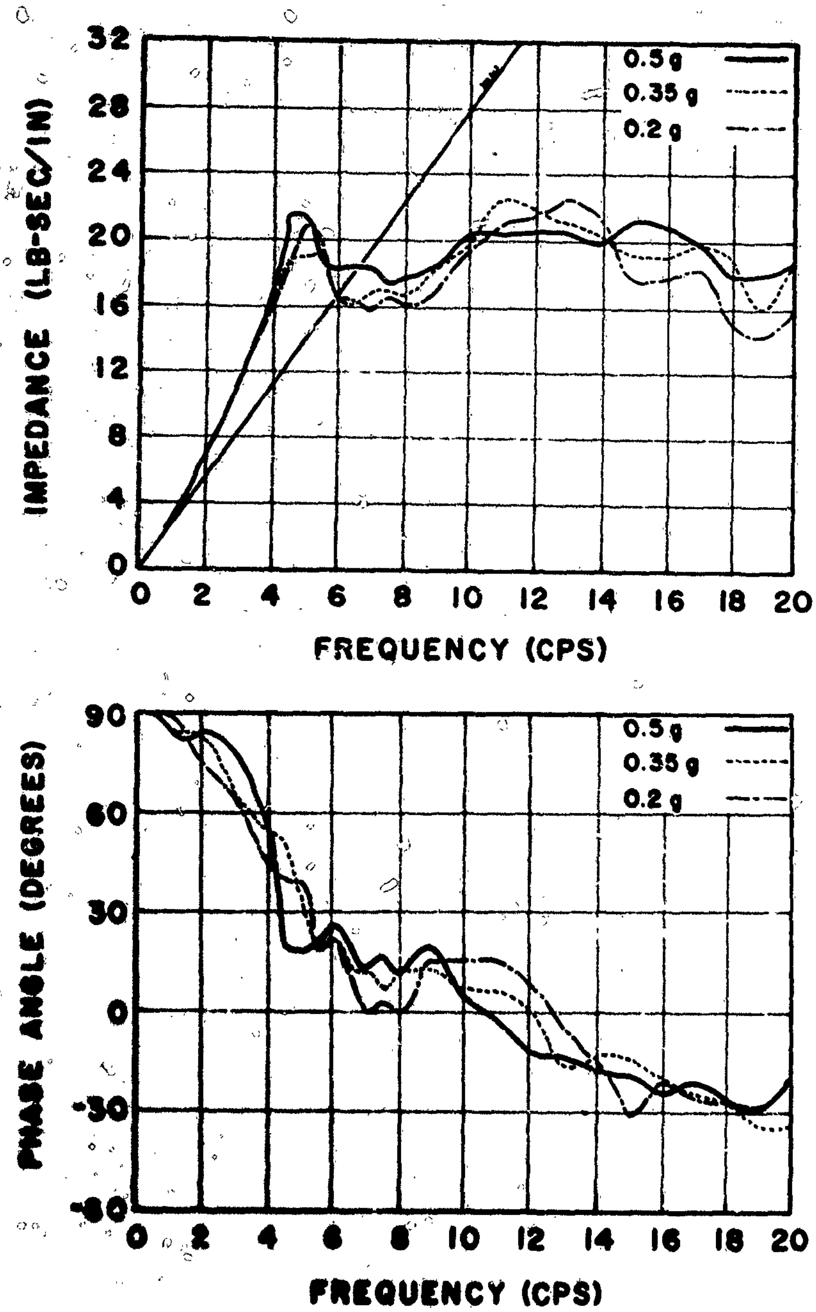



Figure 13. Whole body mechanical impedance versus frequency, with table acceleration level as a parameter, subject AEF, standing relaxed

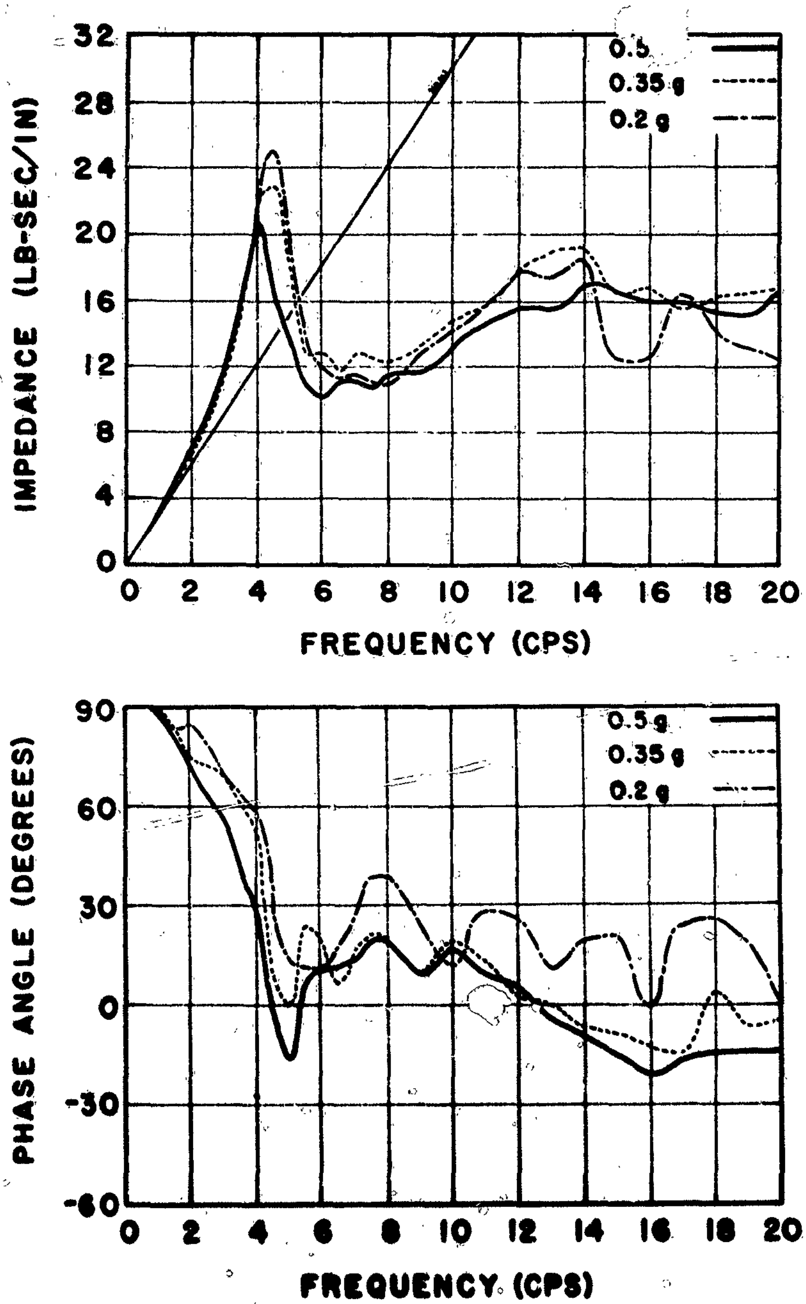



Figure 14. Whole body mechanical impedance versus frequency, with table acceleration level as a parameter, subject RGE, standing relaxed

supine attitude, figures 13 and 14 represent the same subjects in the relaxed standing attitude. These particular tests had a twofold purpose: (1) to determine the impedance in the two attitudes and (2) to investigate the dependence of impedance on the intensity of the vibrations as expressed by the acceleration level of the shaketable, i.e., the linearity.

From the curves of the supine position it is evident that the impedance decreases with increasing shaketable acceleration level. The first resonant frequency also depends upon acceleration level. It occurs in the $5\frac{1}{2}$ to $7\frac{1}{2}$ cps interval decreasing with increasing acceleration. A second resonance appears at 11 cps for AEF and 14 cps for RGE. At this resonance, impedance also decreases with increasing intensity levels, but the frequency shift due to intensity is not clearly expressed.

In the standing position a very prominent resonance occurs in the 4-5 cps frequency interval. The measurements on RGE (fig. 14) again show that impedance value and resonant frequency shift downward when the shaking intensity is increased, but the effect on AEF, if present at all, is within the limits of accuracy of measurement.

## Supine on Padded Support

Figures 15 and 16 contain the impedance curves of subject AEF in the supine, relaxed attitude the same as those shown in figure 11. In addition there are curves for the total impedance of this subject plus a foam rubber pad or plus a cotton mattress, respectively. The purpose of these tests was to gain some insight into the effects of cushioning. To be emphasized is that the impedance without padding represents the impedance of the subject alone while the other curves represent the impedance of the subject plus the padding. The comparison is therefore not one of the subject's impedance as recorded with and without padding, but rather that of the impedance of the subject to that of the subject and pad.

An ambulance stretcher foam rubber pad and a standard cotton mattress (no springs) were used. They were positioned on the support structure used for the previous supine position tests, and the subject then assumed the supine relaxed attitude atop the padding. Figure 15 contains the impedance versus frequency plots at an acceleration level of 0.5 g throughout the frequency range and at 0.35 g from 1 to 10 cps. Figure 16 is the impedance versus frequency graph with the cotton mattress at 0.5 g. From static tests made on the two paddings the foam rubber pad was found to have lower coefficient of elasticity (and apparently lower damping) than the cotton mattress.

Note the shift in resonant frequencies due to the rubber pad and lack of this characteristic with the mattress.

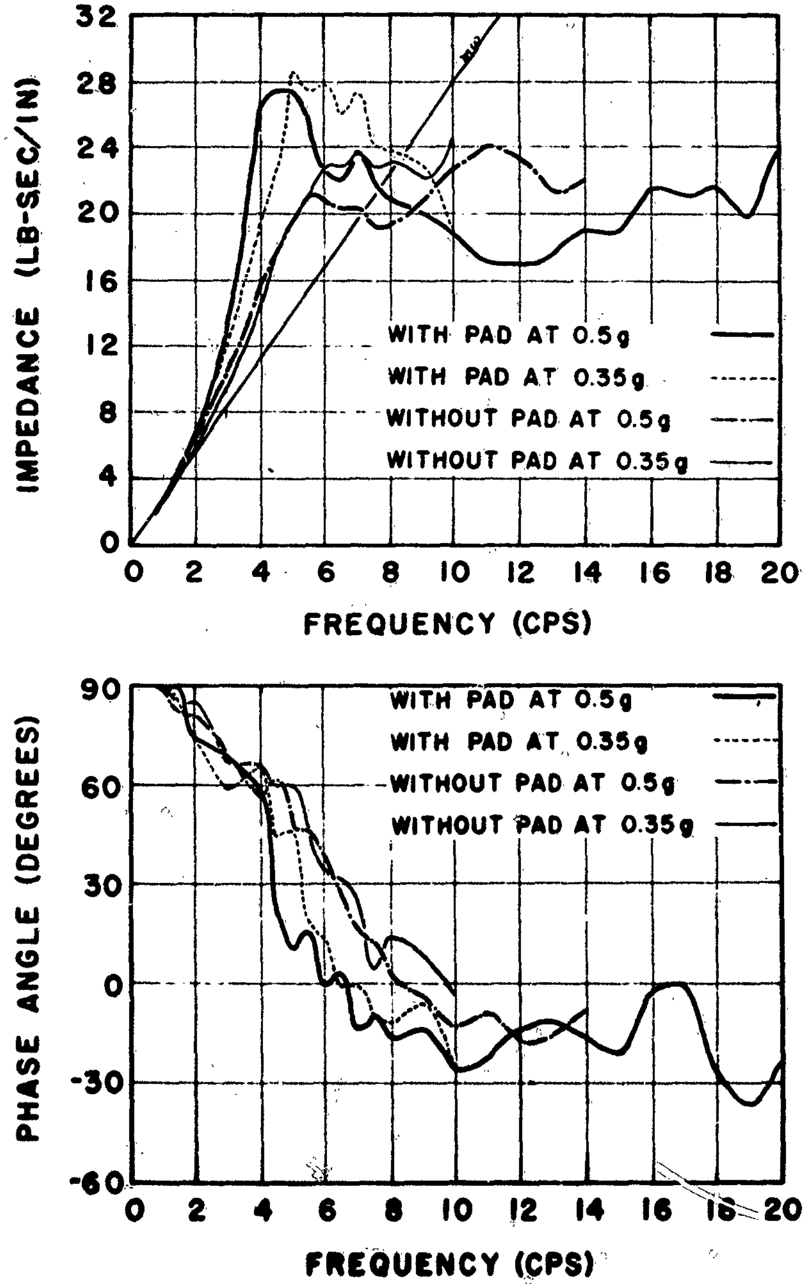



**Figure 15.** Whole body mechanical impedance versus frequency, for two table acceleration levels, subject AEF, supine relaxed with and without foam rubber padding of the support.

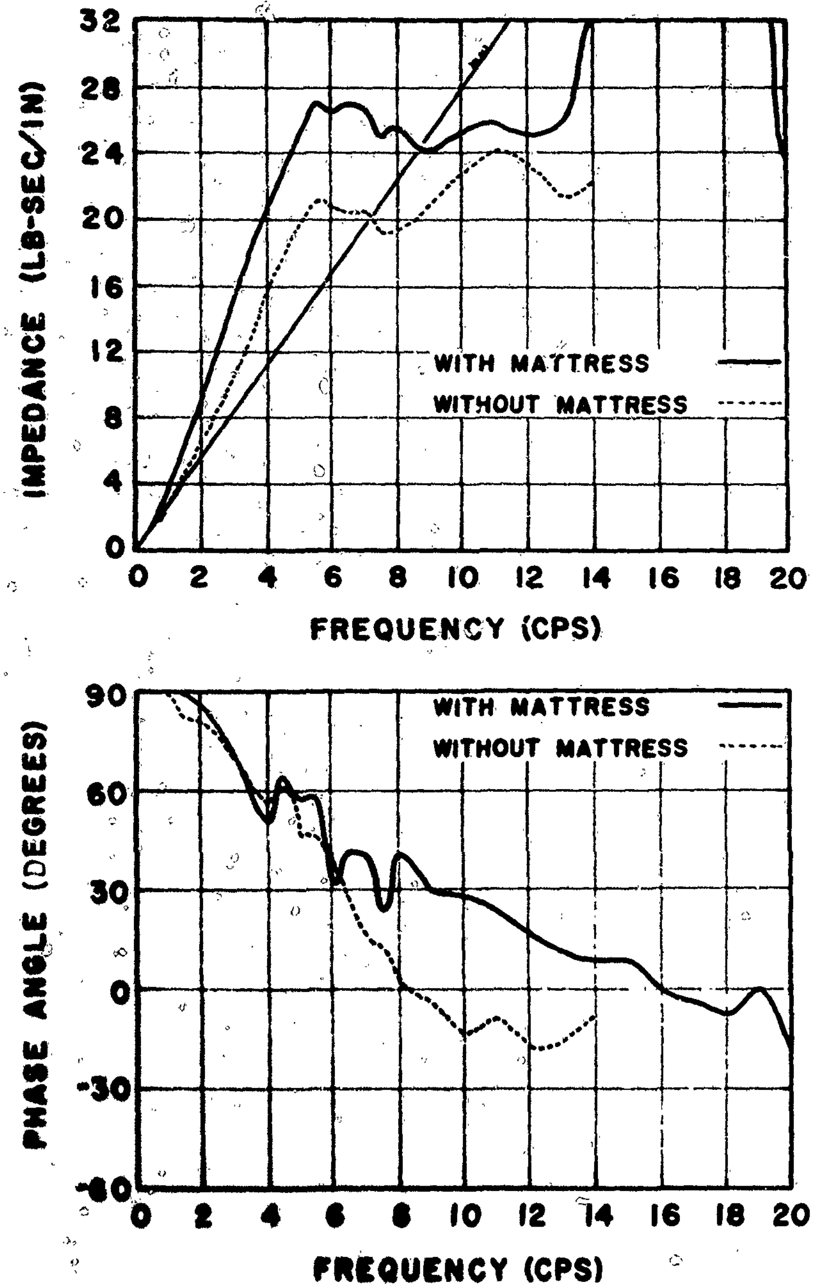



Figure 16. Whole body mechanical impedance versus frequency for subject AEF, supine relaxed, 0.5 g table acceleration level, with and without cotton mattress on the support

Because the shaketable velocity at any one frequency was the same for the subject alone and for subject plus padding, the increased impedance resulting from the padding addition indicates that a higher force is transmitted. Without the pad this force transmission is measured between the support and the subject; with the added pad the measurement is made between the support and the padding. Consequently, no conclusions may be made as to the impedance of the subject when atop the padded support unless the impedance of the padding is somehow computed or measured.

## Lateral Position, Relaxed State

AEF was tested in the lateral position, both on the right and left side. The results are shown in figure 17. RGE's reaction to vibration while lying on his right side is seen from figure 18.

The typical resonance at about 5 to 6 cps occurs in all cases. Another resonance appears to exist at 14 to 18 cps, but it is not certain that this is due to the aforementioned working characteristic of the platform. A slight difference in the location of the subject's center of gravity on the platform might cause this resonance to be or not to be present. See figure 17.

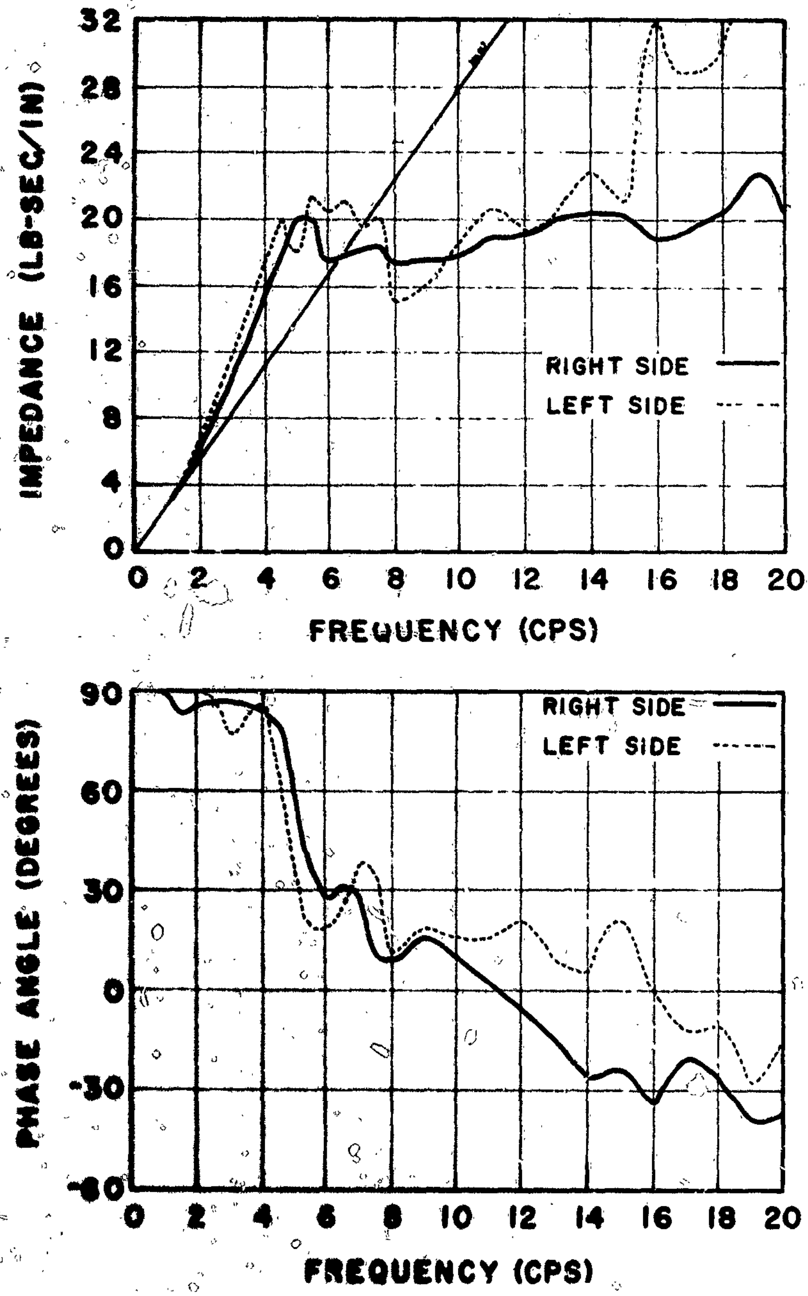



Figure 17. Whole body mechanical impedance versus frequency, subject AEF, lateral relaxed

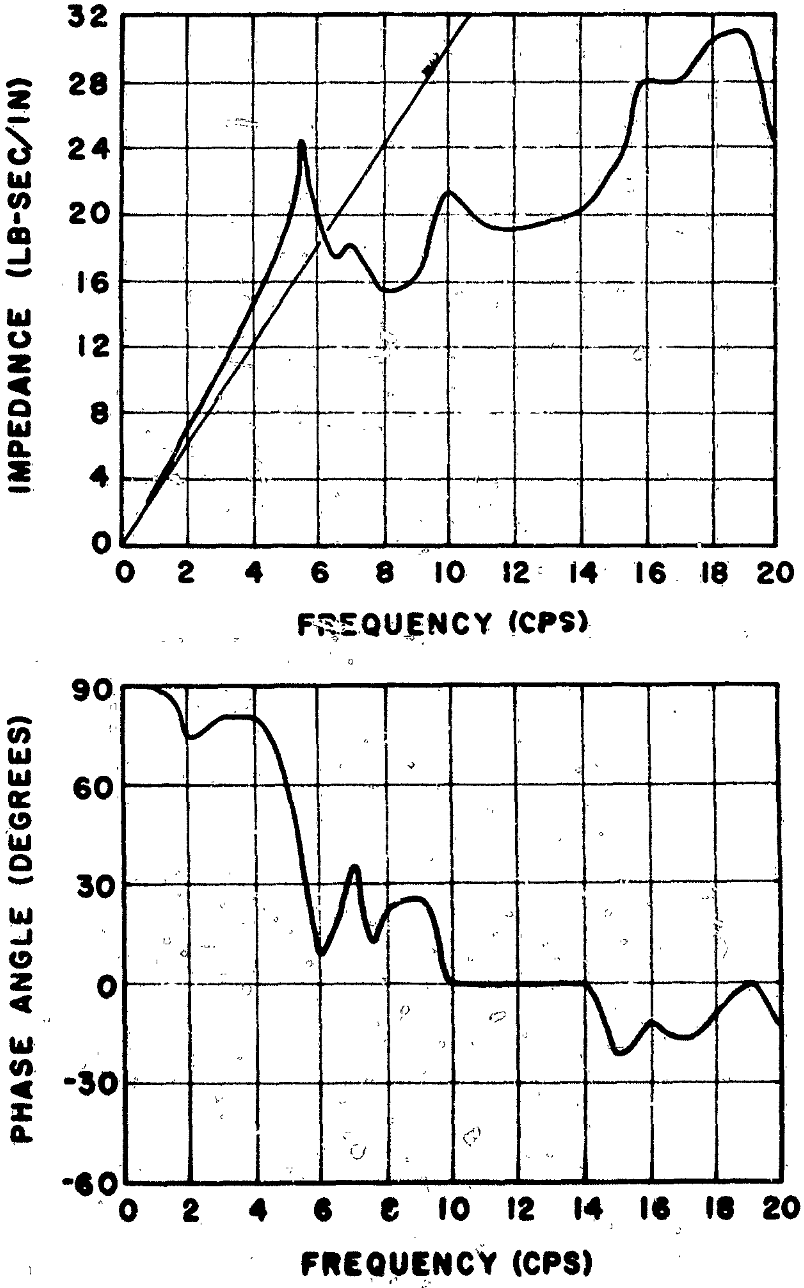



Figure 18. Whole body mechanical impedance versus frequency, subject RGE, lateral relaxed on right side

## SECTION V

## CONCLUSIONS AND CORRELATION TO RELATED INVESTIGATIONS

Prominent resonances like those indicated by impedance peaks represent vibration frequencies which should be of primary interest in protective design of manned vehicles. The question now arises whether or not laboratory results such as those presented in Section IV can be accurately extrapolated to vibrations of very high intensity. This extrapolation would be simple if only sinusoidal vibrations were encountered and if the human body responded to such vibrations in a linear fashion. Then the impedance and the resonant frequencies would be independent of the shaking intensity whether expressed in terms of amplitudes or peak velocity or peak accelerations; or, in other words, the force between subject and support would increase linearly with these parameters. In previous investigations this had been assumed and measurements undertaken on groups of subjects at various shaking intensities had been standardized by linear reduction and averaged. In the present study only two subjects were used individually, but their responses were measured while not only the frequency but also the intensity of the vibration was systematically varied. Figures 11 through 14 show that a degree of nonlinearity exists, i.e., as the shaketable acceleration level is raised the impedance is lowered. The trend of nonlinear response is quite evident even though the acceleration spectrum for the human subjects had to be kept below 0.5 g for safety's sake. Krause and Lange (ref. 8) have investigated the impedance and deformation of a pig at acceleration levels up to 3.0 g. Their studies confirm the existence of a nonlinear response but more extensive testing will be required to establish the exact degree of nonlinearity. White et al (ref. 13) and Clark et al (ref. 2) noticed unexpected fluctuations of colon pressure and body deformation around points of resonance and attributed these to possible nonlinear effects. The present investigation also illustrates nonlinear response being most prominent at resonant frequencies.

To further establish the degree of nonlinearity of the human body to vibration, additional testing is recommended at higher acceleration levels using more subjects than were tested in this investigation.

In the relaxed supine position the frequency range from $5\frac{1}{2}$ to $7\frac{1}{2}$ cps contains the first resonance. From body deformation studies made concurrently with this impedance investigation the frequency interval of $5\frac{1}{2}$ to $6\frac{1}{2}$ cps was also found to contain the peak deformation of chest, upper abdomen, and lower abdomen. Thus, for this attitude frequencies in the range of $5\frac{1}{2}$ to $7\frac{1}{2}$ cps should certainly be avoided (although nonlinear effects could shift this critical frequency interval at higher accelerations).

The impedance in the relaxed lateral position (figures 17-18) does not differ significantly from that of the relaxed supine attitude, except for a slight decrease of the frequency of the primary resonance.

The impedance in the standing position (figures 13-14) shows a resonance between 4 and 5 cps, depending upon table acceleration level and probably, to some extent, upon exact attitude. A second resonance region is noted from 11 to 15 cps. Coermann (ref. 3) reported the impedance peaks of a human subject, standing erect (tensed), (at one table acceleration level only) at 6 and 11.5 cps. The peak impedance magnitude reported by Coermann for a subject standing erect is approximately 30 pounds-seconds per inch compared with approximately 22 pounds-seconds per inch found in this study for a subject, standing relaxed. The increase of the initial resonance impedance due to tensing the muscles in the supine position was found to be 35-40% in the present investigation. This compares favorably to the difference of the impedance of the standing erect position reported by Coermann and the value obtained in the current investigation if tensing the muscles increases the spring properties and decreases body damping.

The results of vibration testing of anesthetized animals should be extrapolated to human vibration response very carefully in view of the dependence of impedance on muscle tone as established by this investigation.

To investigate the effects of padding it is recommended that a technique be developed by which the impedance of the padding may be subtracted from the total impedance to yield that of the subject alone, principally in the same manner in which the impedance of the mass of the support is now subtracted. This value may then be compared to that of the impedance of the subject without padding, and consequently a true measure of the force transmitting characteristics of the padded support may be obtained. The impedance curves of subject plus padding as presented in this investigation show a shift in resonant frequency and an increased impedance compared to the impedance of the subject alone. However, it is not known to what degree this response would be altered by eliminating the impedance of the added pad.

Coermann et al (ref. 3) using the impedance technique found 5 cps to be the resonant frequency for sitting subjects exposed to sinusoidal motion while Wittwer (ref. 15), White et al (ref. 13), and Clark et al (ref. 2) using impedance, colon pressure, and body deformation, respectively, all reported resonant frequencies in the 4 to 7 cps interval. Ziegenruecker and Magid (ref. 17) reported the subjective human tolerance of sitting subjects to vertical vibration and found that from 4 to 8 cps subjects could tolerate less intensity than at other frequencies. New data gained in this investigation show that in the supine and lateral positions impedance peaks occur within this same frequency range.

From this investigation the impedances of the supine, lateral, and standing positions have been reported. The manner in which impedance varies with muscle tone has been illustrated. Nonlinearity of the human body has been shown to exist, and an initial attempt to determine the effects of protective padding has been made.

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13 ABSTRACT

To help establish the dynamics of the human body the mechanical impedance was measured as two subjects were exposed to vertical sinusoidal motion at frequencies from 1 to 20 cycles per second. The impedance in the supine, lateral, and standing subject positions and its variation due to voluntary change in muscle tone and due to padding the support were determined. In all tests the frequency interval from 4 to 7-1/2 cycles per second was found to contain the intital whole body resonance. Nonlinearity of the response, as established by impedance dependence upon shaketable acceleration level, was observed by altering the peak shaketable acceleration from 0.2 to 0.35 to 0.5 g. The degree of nonlinearity was found to be dependent upon subject position as well as subject physiological differences. Changes in support padding and muscle tone produced substantial alterations in impedance but little variation of resonant frequencies.

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| 14. KEY WORDS | LINK A ROLE | LINK A WT | LINK B ROLE | LINK B WT | LINK C ROLE | LINK C WT |
|---|---|---|---|---|---|---|
| Vibration<br>Man<br>Stress, physiological<br>Acceleration<br>Space vehicles<br>Performance<br>Mechanical impedance | | | | | | |

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