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THE TRANSMISSION OF VERTICAL VIBRATION TO THE HEADS AND SHOULDE--ETC(U)
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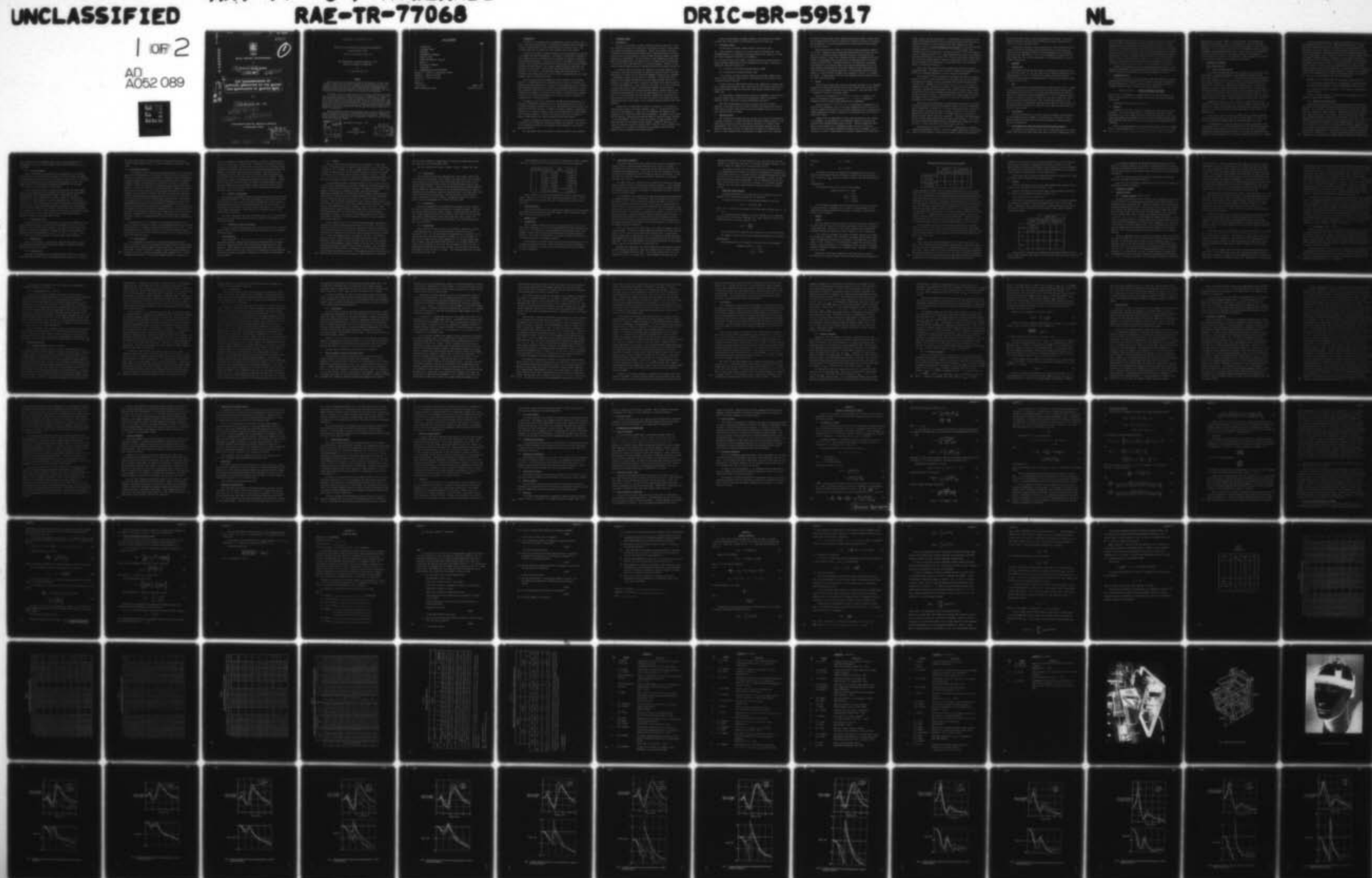

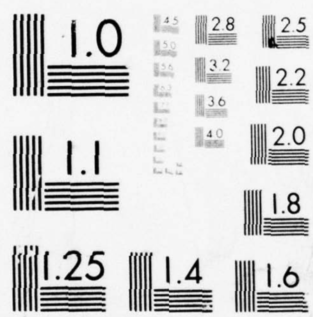
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THE TRANSMISSION OF VERTICAL VIBRATION TO THE HEADS AND SHOULDERS OF SEATED MEN

by

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SUMMARY

Modern forms of transportation can impose high levels of vibration upon occupants. These levels can cause discomfort to the passengers or loss of performance by pilots or drivers. To determine the effects of vibration, it is necessary to define the vibration levels experienced by such people. This definition should preferably quantify not only the input levels, but also those at the parts of the body most likely to be affected by the vibration.

This Report covers an investigation of the frequency response of the human body to vertical vibration, using six subjects on a rigid seat. The input used was a swept sine acceleration, where the frequency of the vibration varied linearly with time between an upper and lower value, at a fixed amplitude. The use of such an input facilitated measurements of amplitude ratio and phase angle plots of the ratio of head and shoulder acceleration to seat acceleration against frequency, to be made for various postures and limb positions. Resting the back against the seat and putting the legs forward, were both found to have a major effect on transmission.

Attempts are made to model these response curves so that by simply monitoring floor vibration in vehicles and assuming the seat response is known, one can predict the range of vibrations present at the head and shoulders. Theoretical analysis is used to demonstrate that the response of cushions is directly related to the human frequency response.

Departmental Reference: FS 55

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1 INTRODUCTION

Vibration is a phenomenon which accompanies man from the cradle to the grave. From early childhood man is conditioned to vibration from the rocking of a pram or in more primitive times from being carried on mother's back. The ultimate experience of vibration has been quoted as that in the hearse!

Vibration is normally an undesirable part of the environment, and can lead to discomfort and loss in performance. Performance can sometimes be degraded to such a degree that the environment has to be modified to reduce the vibration - by reducing speed perhaps - or the vehicle has to be re-designed. In aviation, vibration can be induced from operation off rough ground, and as take-off speeds increase, what would appear to be a smooth runway can produce high levels of vibration in the aircraft. Low-altitude, high-speed flight can impose a high vibration on the pilot, as can helicopter flight where vibrations due to imbalance of the rotors can be felt in the cockpit, although normally at a higher frequency than for fixed-wing aircraft.

Over the frequency range normally met with in vehicles, the human body behaves in a dynamic manner ie it possesses mass (or inertia), elasticity and damping, essential properties for a system to exhibit phenomena such as resonance and transmission amplification (or reduction) at different frequencies. Therefore to quantify the effects of vibration, specification of the input vibration conditions, for example on the floor of the vehicle, is insufficient to specify the levels at and relative displacements of the parts where the vibration is frequently felt - the head and limbs.

This Report, which covers work done at the RAE as part requirement for a Doctorate of Philosophy in Human Sciences at Loughborough University, sets out to define the dynamic characteristics of the body (between the head and seat, and between the shoulders and seat), in terms of frequency response of transmission functions, or in terms of the mass, elasticity and damping factors which produce such a frequency response. Variations in response curves due to changes in posture, limb positions and input acceleration levels are explored.

In order to attempt to explain the variations in the curves found as well as the basic curves themselves, modelling techniques are explored. The effect of the human frequency response on the dynamics of seat cushions is also investigated theoretically.

068 The experimental work is preceded by a critical survey of the literature.

2 LITERATURE SURVEY

2.1 Introduction

The effect of vibration on human activity is basically four fold. First, the vibration can affect the visual sense, resulting in a loss of visual acuity and consequent degradation of performance. Second, the vibration can induce involuntary limb motions which may then result in impaired operation of various controls such as steering wheels, control columns and rudder pedals, and again, degradation of performance. The third factor is that vibration may affect the subject's psychological state in terms of lack (or possibly gain) in motivation or arousal or affect some other motor or conscious response. Fourthly, it may induce fatigue through conscious or subconscious efforts to maintain posture etc.

In order to define the effects of vibration on the human organism, it is necessary to know what accelerations are present at specific parts of the body. Measurements of factors such as total body impedance or mobility are inadequate in attempting to define all the effects of vibration, as these merely give a measure of the 'lumped' characteristics of the system 'loading' the source of vibration, and cannot be refined to quantify the vibrations at specific parts of the body (see Appendix A). Also, as will be seen later, if it is found that man is not a simple series network, as described in Appendix A, but rather a combination of parallel and series spring-mass systems, impedance analysis and frequency response analysis will both be unrepresentative of the total system. But, if one is interested in the accelerations transmitted to and present at a particular part of the body, the fact that the parallel loop prevents any exact simulation does not really matter, as the required absolute quantities have been measured.

Clearly then, to understand the effects of vibration it is desirable to know vibration levels at the head, shoulders, legs etc. Having decided on the positions of measurements, it must still be remembered that changes in body parameters for a subject may affect these measurements. Parameters such as hand and arm position, leg position and posture should be included as major variables in any investigation. As will be seen later mention of these parameters has been conspicious by its absence in past reports. Potemkin[34] sums this up in saying "It should be noted that hitherto (1971) there have been no papers on the investigation of the effects of vibration on the dynamic reactions of man dependent upon the change in his working posture".

Before the experimental programme commenced, the literature was examined to ensure that there would be no unnecessary repetition of past work.

2.2 Literature sources

The following continually updated abstract sources were used -

(a) Human Response to Vibration, A Critical Survey of Published Work, 1970. ISVR Memorandum No.373, published by the Human Factors Unit, Institute of Sound and Vibration Research, University of Southampton.

(b) Aerospace Medicine and Biology - published monthly by the National Aeronautics and Space Administration (first published in July 1964), a selection of appropriate reference announced in,

(i) Scientific and Technical Aerospace Reports (STAR)

(ii) International Aerospace Abstracts (IAA)

In its subject coverage, 'Aerospace Medicine and Biology' (AMBB) concentrates on the biological, physiological, psychological and environmental effects to which man may be subjected.

Initially both the STAR and IAA abstracts were examined for relevant papers, but for papers published after 1964 it was found that the Aerospace Medicine and Biology Bibliography (AMBB) was effectively covering any relevant papers from STAR or IAA.

The sub-headings of AMBB which were used were, Biodynamics, Bioengineering, Cushions, Dynamic models, Human factors engineering, Mechanical impedance, Vibration effects, Vibration isolators and Vibration perception.

When many relevant papers had been collected, and their references examined, it was found that most of these references had already been collected. This situation served to show that the survey was complete and that few if any vital papers had been overlooked.

2.3 Relevant reports

The literature was searched (as per section 2.2) to find the following type of report or reports:- A report defining the transmission characteristics of the human body covering (a) vertical and lateral excitation, (b) frequency range approximately 1 Hz to 30 Hz, covering the main whole-body resonances and the frequency range where the eyes are reported to be affected, (c) measured parameters to cover head/seat and/or shoulder/seat for manual and visual responses,

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(d) effect of various input levels ranging from positively aware to barely aware of the vibration and (e) effect of variations in subjective posture, arm position and leg position. It was not expected that one report would be found covering all the above topics!

Before going into the details of the reports found some general comments are in order. Almost all the reports found covered the vertical axis only, and used nominally sinusoidal inputs, though few referred to the possibility of harmonic distortion. Some of the vibrators used were electrodynamic which were limited in displacement and could only give low vibration levels at the lower frequencies (below 5 Hz). Presumably because of the difficulty in attaching accelerometers to the subjects, many of the reported measurements were of the input impedance characteristics of the body, whereas we were investigating the vibration levels at the head and shoulders. Very few papers mentioned subject posutre as a major variable and fewer still attempted to vary it, to determine its effect. In many reports, the tests were conducted with the subjects sitting on a base, with no back rest.

2.4 Survey

Clearly there are many more reports in existence dealing with the biodynamic response of the human body than the ones to which reference will be made, but it was felt that the papers listed are the most pertinent. They have been listed in alphabetical order of the authors' names.

Some of the references[15,16,17,20,32,42] provided an overview of the field of biodynamics; two bibliographies[24,49] of reports dealing with biodynamics were also found, which together were of assistance.

Several reports[9,10,13,28,45,47] on the measurement of impedance of the body have been considered, as it is felt that although they do not include the required parameters the values of the resonant frequencies will be applicable and trends regarding non-linearity, postures etc, should read across to the transmissibility results.

Compared with the measurement of other vibration effects such as comfort or performance, the measurement of the biodynamic response to vibration has produced better agreement among research results. Various attempts have been made to model response, but a comprehensive model does not yet exist due primarily to the wide range of important variables, such as frequency, level, duration etc as well as anthropometric and postural variables such as body size, weight, posture, age and limb positions. Unfortunately even though most of the reports found agreed moderately well as regards the frequency and amplitude of whole-body resonances, little information was found regarding the other variables. There is general agreement on the existence of a vertical whole-body resonance around 5 Hz [5,9,11,13,19,25,28,35,40,41 and 48]. As far as the horizontal axes are concerned there are fewer reports[10,27,48] but these agree on a major resonance at around 1.5 Hz. The transmissibility ratios to the shoulder have been investigated by two authors[7,48]. There is conflicting evidence about the presence of resonant peaks at frequencies higher than 4 Hz to 5 Hz (eg Refs 7 and 10 as against Ref 9) perhaps due to unreported factors such as seating, posture, individual variations etc.

Most of the papers mentioned so far reported the effects of nominally sinusoidal inputs. Two authors used 'real-life' vibration, a helicopter environment[19] and a simulated high-speed, low-level aircraft environment[25].

Three authors[9,14,34] had attempted to investigate the effects of varying posture. In one[9], no back rest was used for the tests, and the slumped posture was produced by bending the spine considerably with the head falling forward onto the chest - completely unrepresentative of real life, except perhaps of sleeping on a bench! The other two authors[14,34] dealt with the transmission of vibration to the head for three postures, none of which could be said to apply to real-life, but at least an attempt had been made to find the effects of the extremes of posture variations. Unfortunately the frequency range chosen was very large (2-200 Hz) and the analysis was in 6 Hz bands, providing little information at low frequencies.

Paper (10) covers some results for standing and sitting subjects and shows a vertical resonance at the head and shoulder of about 1.15 and 1.70 amplitude ratios respectively, at around 5 Hz. The head results show slight evidence of a higher frequency resonance but only as a point of inflexion in the curve the amplitude ratio being less than unity. No definitions of or variations in posture are given and the input was 'sinusoidal'. Two graphs are included which show the elliptic head motions induced by input linear sinusoids. This clearly could be of considerable importance in any experiment which attempts to define the ratio of linear vibration at the head to that at the seat.

Several papers were found[5,6,12,31,40 and 44] dealing with the frequency response characteristics of seats. Few of the authors appreciated that the peaks
068 around 4 Hz were probably a reflection of the body's response (see Appendix A)

and that these peaks could be reduced by modifying the cushions. Also little work had been done on the lateral characteristics of seats, especially with respect to the seat structure itself.

Following the literature survey described here, it was concluded that the required work had not previously been covered and there is still a need for research into the frequency response of the seated human and of its variation with posture and limb position. Ideally this information is required for all three linear axes, but in this investigation it was only possible to cover the dominant vertical mode.

3 EQUIPMENT

3.1 Vibration rig

The vibrator used was the RAE two-axis electrohydraulic facility which is fully described in Ref 39. The rig, shown in Fig 1 consists basically of a flat aluminium table (1.83 m × 1.22 m) which can vibrate in the vertical and/or horizontal direction with a maximum amplitude of ±250 mm, and a frequency range of about 0.5 Hz to 40 Hz.

3.2 Seat

The seat used was a rigid wooden structure fitted with arm rests. A sketch of the seat (which is one of a pair fitted on the rig) showing various angles and dimensions is given in Fig 2. A rigid seat was chosen because the characteristics of a cushion have been shown (Appendix A) to be very complicated and to reflect the response of the man. Clearly at a later date it would be useful to check the results found here against those obtained when cushions are used. There will clearly be differences, especially with respect to back cushions, but the research into the subject on a hard seat should come first and provide the basis for future studies.

3.3 Seat harness

To prevent modification of the man's inherent biodynamic characteristics no seat harness was used, although the subjects wore a lap strap, so that it did not normally exert any load on the body but acted as a safety precaution against rig malfunction.

3.4 Accelerometers and associated amplification/recording equipment

The miniature accelerometers (6 mm × 8 mm × 14 mm) used were of the strain-gauged, cantilever type, model number BLA2 made by the Ether Engineering Co Ltd.

The strain gauges formed one half of a bridge network, the output of which was fed into an SEL ac carrier amplifier, which contained the other half of the bridge together with a balancing potentiometer which was used as a calibration facility. The demodulated output from the amplifier was then fed into a filter (with roll-off frequency of 100 Hz, thus cutting out the accelerometer resonance at 180 Hz) and then into a Tannberg type 100, frequency-modulation, 4-channel, magnetic tape recorder. This tape recorder has a voice track which was used to provide a check of run number, level, subject etc, so that the three other channels could be used to record accelerations simultaneously. For details concerning the mounting and positioning of the accelerometers see section 4.2.

A swept sine generator was used for generating the input function. This was made by Southampton University and provides sine wave of constant amplitude with the frequency varying linearly with time (see sections 4.1 and 5).

3.5 Computing facility

For analysis purposes, the tape recorder output was connected to a Hewlett Packard type 5451A Fourier Analyser, which performs a Fast Fourier Transform on any time-varying input or output function or both. The transfer function (or frequency response) between output and input can be defined as -

$$\text{Transfer function} = \frac{\text{Fourier transform of the output}}{\text{Fourier transform of the input}} .$$

This function is calculated as a complex quantity, ie it has both modulus and phase. As the computer has a two-channel simultaneous input phase information is preserved.

The analysis theory is given in Appendix C.

3.6 Subjects

Six subjects were used, selected to represent the normal range of aircrew population. It could be argued that six is a small sample from which to draw conclusions, but it was strongly felt that it would be preferable to test a few subjects thoroughly and establish the variation in their responses under several body conditions rather than to test a lot of subjects under relatively few test conditions.

Prior to any experimentation, all subjects were asked to fill in a 'Subject File'. It was stressed that the information given would be kept strictly confi-
068 dential unless the subject permitted disclosure and any reference to a subject

would be made by a subject number - never by his name. The proforma used (Appendix B) was drawn up on the lines recommended by a British Standards Institute Draft for Development[3] covering the safety aspects of human vibration experiments. The acceleration levels used in this experiment did not exceed the recommended 'fatigue/decreased proficiency' levels set out by the International Standards Organization and BSI[4], and hence following the safety guide's recommendations for schedule 1 type vibration, so that no medical certification, other than that contained in the proforma, was necessary.

4 EXPERIMENTAL TECHNIQUES

4.1 Input characteristics

4.1.1 Choice of input function

Of the reports found dealing with the transmission of vibration across the body, almost all describe experiments using nominally sinusoidal forcing functions as input[5,9,11,21,41,48]. It is well known that although one may start with a pure sine wave output from an oscillator, by the time the signal reaches the floor of the vibrator, a large amount of harmonic distortion may well be present[37,38]. Clearly this distortion can introduce errors. In many of the reported experiments, subjects were exposed to several minutes of sinusoidal oscillation, whereas in real life one rarely finds records showing more than ten or so repeated oscillations - the exception being helicopter vibration. Also subjects are unable to maintain the same posture, muscle tone, arm, leg and head positions for such a period, so conditions must have varied across the tests.

Dieckmann[11] has shown that under vibration of a sinusoidal type, man exhibits an elliptic motion at the head. It can be argued or surmised that this rotation is a steady state phenomenon and thus needs time to build up, so that the use of a non-sinusoidal input function would reduce rotation and all its implied errors.

If one rejects the use of 'pure' sinusoids for the foregoing arguments, one is left with the choice of using either a random signal, or a 'swept sine' or other deterministic (quantifiable and repeatable) form, as an input.

If a random signal is used the question of statistical reliability and random error arises. It can be shown (Bendat[2]) that for reasonable random and bias errors, record lengths of the order of 100 to 200 s must be considered. Even then the functions generated can never by definition be completely deterministic, and some frequencies in the nominal frequency range may not be included.

A swept sine signal however is completely deterministic (see Appendix C) and sweep need last only 10 s or so. Thus using the swept sine, the same posture and limb positions need to be preserved for only approximately 10 s, after which they may be changed in a controlled manner and another test begun. The swept sine technique, although favoured in the preceding paragraphs, has several disadvantages. First, analysis is difficult, a digital computer complete with Fourier transform software is desirable, if not essential, whereas for sinusoidal work, only an rms meter and filter are necessary. Secondly there is the problem of non-linear response. If the response of the body to vibration inputs is grossly non-linear the only technique which can be used to give a general solution is that of sinusoidal input. Even this technique is suspect as, by definition of non-linearity, an input sinusoid of frequency f_1 can generate super (or sub) harmonics in the output of a non-linear system, of frequencies $2f_1$, $3f_1$, $f_{1/2}$ etc, depending on the type of non-linearity.

Summing up, it is felt that many of the previous reports suffer from

(i) the relatively long duration of experimentation, imposing unnatural constraints on the subjects in terms of maintaining posture etc, and

(ii) a lack of distortion information - and a failure to acknowledge its possible effects.

The use of a swept technique is therefore to be recommended, and it was used for the experiments reported here.

4.1.2 <u>Duration of transient input</u>

Theoretically the duration of swept sine function should not affect the calculation of the frequency response as both input and output will be equally affected. In the extreme, of course, the input reduces to an impulse and the output then becomes the impulse response. However the input has to be applied via a high inertia system - the vibrator - and this needs an input signal of finite length otherwise the signal level on the table is very small. Also although it has been argued that swept sine waves rarely exist in the real world (nor for that matter do sinusoidal or purely random signals), some reference to what happens in reality must be preserved, and it is quite common for 'burst' of vibration to be encountered lasting about 20 s, eg a car traversing a rough patch of road, slowing down at the same time to give a variation in frequency, an aircraft in turbulence, etc. Previous researchers who had used swept sine
068 techniques for testing moderately damped systems[45] established an empirical law

which stated that for a reasonable output response, signal sweep rates of approximately 1 Hz/s (for the low frequency end of the spectrum) were to be recommended.

4.1.3 Frequency ranges

After it was found in an unreported pilot experiment that the vibrator could not give a flat response over the range 1-25 Hz in one sweep, two ranges of frequency were used, (a) 1-10 Hz in 10 s and (b) 2-25 Hz in 25 s. The results were then superimposed to give an overall frequency range of 1-25 Hz. This range covers all the body's major resonances including those in the range 10-25 Hz which is least covered in the literature.

As will be seen the results in general indicated that the total response curves could be drawn by firstly following the 1-10Hz curve and then smoothly changing across to the higher frequency range, ie there were no sharp discontinuities due to a difference in response caused by a change in the duration of the input transient. Due to the characteristics of the hydraulic vibrator used - even though the input electrical function had constant amplitude - the amplitude of the acceleration waveform on the table at the low frequency end of the 2-25 Hz range was not constant. Therefore the ranges analysed were 1-10 Hz and 8-25 Hz. Fig 22 shows a typical set of results - from which the final curves were taken. It can be seen that the two frequency ranges merge in together for amplitude and phase, around 6-8 Hz.

4.1.4 Acceleration levels

In order to check for non-linear effects, the tests were conducted at three input acceleration levels, this level being held constant (for 25 s or 10 s) amplitude of the frequency varying function. The peak levels chosen were those usually associated with decrement in performance, rather than with comfort or perception, and were approximately ± 4.0 m/s^2, ± 2.8 m/s^2 and ± 2.0 m/s^2. These levels are typical of those measured in vehicles under rough conditions.

4.1.5 Repeatability

Two runs per subject per condition were conducted and analysed, a pilot experiment having indicated that each subject was able to repeat a 'condition' within narrow limits (see Fig 23).

4.1.6 Vibration axis

Ultimately the measurement of the human frequency response for all three linear and rotational axes and for the standing and sitting man will be required.

The scope of this paper is however limited to the seated man subjected to vertical linear vibration (which is the main circumstance encountered in real life).

4.2 Accelerometer positions

It is generally agreed that whole body vibration mainly effects visual and manual (or foot) dexterity, the third possible effect is the psychological one which is not considered for this experiment. Therefore it would seem important to measure hand/arm vibration and eye vibration and thus be able to determine frequency response curves between those points and the input - the seat/man interface. However the measurement of both hand and eye vibration poses many problems. It has been found to be virtually impossible to measure the acceleration levels at the eye especially in the frequency region where the eyes are thought to be most sensitive (around 20 Hz), due to the very small amplitudes involved, even at moderate acceleration levels of ± 5.0 m/s^2 at about 20 Hz, a level which would excite adverse comment from a pilot or driver, is equivalent to an amplitude of only ± 0.4 mm. Most previous researchers in the field have compromised by measuring head vibration with an accelerometer attached to a harness, and this method was followed for this experiment. It can be argued that the vibration levels on the head are as important as at the eyes, as the skull will effectively transmit the vibration to the brain and to the loose tissues on the head. Thus measurement on the hard part of the head provides a suitable first step, though it is recognised that the eye itself may have a superimposed response.

The measurement of hand vibration is equally difficult because of the possible rotational components involved in any hand/arm movement and also because of the difficulty in attaching a harness and accelerometers to the hand. It was eventually decided to construct a harness to hold an accelerometer(s) against the acromion, ie the top of the shoulder, and to use this as a definition of the input to the hand/arm systems.

4.2.1 Head vibration

The accelerometer was attached to a specially designed head harness (Fig 3). The main structure of the harness was a plastic insert from a standard safety helmet which could be adjusted by each subject until it was tightly held on his head. A strip of male Velcro 'adhesive' was sewn and glued around the
068 outside of the insert, providing a reasonably rigid attachment area. In order to provide some latitude in accelerometer mounting position, a cruciform of

25mm wide dressmaker's elastic was constructed, at each end of which was sewn and glued a small strip of female Velcro. A 25mm cube of aluminium, grooved to accept the accelerometer, was then stuck to the centre of the cruciform, and by spreading the cruciform across the top of the head and pressing the Velcro parts together, a reasonably rigid harness was constructed. The position of the accelerometer itself on the top of the head could be varied by adjusting the point at which the Velcro on the insert met the Velcro on the harness. Within the limits of comfort, the harness was tensioned as tight as possible. A short series of runs were carried out where the output of the head harness accelerometer was compared with an accelerometer rigidily held (via a dental bite) in the mouth. This was to check the response of the head harness accelerometer, and is discussed in section 8.8.

4.2.2 Shoulder accelerometer

The harness used to measure shoulder acceleration was the same as that used in a previous experiment[38]. Two loops of dressmaker's elastic were used to hold the accelerometer, first a torso loop under the armpits and second a vertical loop folded around the first loop and passing over the top of the shoulder. The accelerometer was attached to the second loop and held down by it. The tension of the elastic was adjusted to ensure that the accelerometer would not lift under vibration conditions.

The elastic loops were worn over the clothing (shirt only), but the tension was such that it was assumed that the measured response was independent of the interposed clothing.

4.2.3 Seat/man interface accelerometer

The seat acceleration was measured with a RAE seat bar attached to the seat pan by a strip of Velcro, similar bars have been used extensively by the RAE for field measurements.

4.3 Body parameters

Previous work[36,37] has indicated that, apart from the obvious anthropometric and seating variables, the main body parameters which might affect the transmission of vibration across the body are variations in posture and in limb positions. Clearly there are other parameters which might affect the results such as clothing, activity, time of day etc, but posture and limb positions were selected as the major intra-subject variables, all the others being assumed to be second order. 068

4.3.1 Posture

There are three main descriptions of posture, 'slumped', 'normal' and 'erect'. The problem is how to quantify these variables, that is 'how slumped is slumped?' and 'is subject 2's idea of slumped the same as subject 6's?'. Any variation in posture must be associated with an increase or decrease in muscle activity and, as a corollary, muscle activity dictates the posture. However this report deals with the practical aspects of vibration measurements and it was felt that any attempt to enter the field of electromyography would be unwise.

It was therefore decided to allow each subject to act as his own control, in selecting his interpretation of posture. During the initial briefing of each subject, he was invited to sit on the vibrator in a normal posture with his back against the back rest, not slumped, not erect, just sitting normally. Immediately following this, the subject was told to assume a slumped posture, to allow himself to relax in the seat, without letting his head fall forward and without letting his back come off the back rest. Then he was asked to sit at attention. Thus the subject had adopted the three required postures, and he was told he would be required to assume these postures in later experiments - postures which he had himself interpreted as 'slumped', 'normal' and 'erect'. This experiment was not aimed at defining the average man, in fact in the field of human engineering there is no such thing, we are all for some dimensions, anthropometric freaks. Thus as long as each subject maintains his concept of these posture conditions, it does not matter if subject 2's idea of slumped differs from subject 6's.

A chance remark by one of the subjects during preliminary experiments had indicated the need for another posture variable to be included. This subject reported that during the vibration sweeps, especially at the high frequency end of the spectrum, he was able to reduce the vibration he felt in his head region (described as a tingling of the scalp and neck) by leaning forward off the back rest. He had thus eliminated one of the inputs to the body - the vibration input at the back - thereby reducing the vibration felt on the head. In the experiment it was stressed to all the subjects, that for one of the conditions they should bring themselves slightly forward off the back rest - but without altering their posture from what had been decided as normal. This may sound a contradiction in terms in that it is impossible to lift off the back without altering muscle tone and hence posture. The assumption was however made that the
068 muscle activity used to lift off the back is a small proportion of the muscle

activity used to maintain a normal posture, and that the change between normal and erect posture has the dominant effect.

Thus four postures were tested, 'normal', 'erect', 'slumped' and 'back off'.

4.3.2 Arm position

The variations used for this experiment were 'arms folded', hand in lap (left hand on left thigh etc) called 'normal', and arms straight out, the hands resting lightly on the controls of an oscilloscope which was in front of the seat and rigidly mounted on the vibrator and therefore vibrated with the seat (called 'hands on scope'). Again it can be argued that these variables should be rigidly controlled. Again the answer is one of impracticabilities in terms of measuring muscle activity and also that each subject acts as his own control with little final inter-subject averaging. Thus the selection of arm positions covered situations of a pilot or driver, viewing dial controls etc, and of a subject actually manipulating such controls in front of him.

4.3.3 Leg position

An earlier experiment[38], had indicated that leg position could influence the level of vibration reaching the shoulder to a significant degree. Thus leg position was included here as a major variable, and the variations chosen were, legs 'normal' (again decided upon by the subject), legs 'back' (so that the shin/femur angle was approximately a right angle) and legs 'right forward' (the subject's leg length dictating the exact position). All leg positions had the feet flat on the floor.

4.3.4 Overall plan

Thus we have arrived at the final set of variables, namely four postures × three arm positions × three leg positions and a possible test pattern containing 36 runs. If all these possible combinations were tested then (a) the analysis time and effort involved would be enormous, to cover the number of subjects, acceleration levels, ratios measured etc, and (b) each subject would have to spend a long time being vibrated and hence it is doubtful whether his posture at the beginning of such a run would correspond to that at the end. It was therefore decided to limit the runs to eight - one variation of each parameter when the other two are held 'normal'. The following table lists the eight runs which made up one test.

This programme took about 25 min for each subject (see section 5) compared with the 2 h which would have been necessary for all the tests suggested.

Run number	Posture	Arms	Legs
1	Normal	Normal	Normal
2	Erect	Normal	Normal
3	Slumped	Normal	Normal
4	Normal	Folded	Normal
5	Normal	Normal	Forward
6	Normal	Normal	Back
7	Normal	'Hands on scope'	Normal
8	Back off	Normal	Normal

Normal condition is defined as normal posture, hands in lap and legs in middle. Thus runs 1, 2, 3 and 8 give variations in posture, runs 1, 4 and 7 give variations in arm position, and runs 1, 5 and 6 give variations in leg positions.

4.4 Output parameters

The results required from this experiment are head/seat (h/st) and shoulder/seat (sh/st) acceleration ratio/frequency response curves, giving modulus and phase, for all the conditions tested.

5 METHOD OF TEST

5.1 Preliminaries

After a suitable warming up period for rig and electronics the accelerometers were calibrated by rotating them through 360° around their operating axis to give ± 1 g. By comparing the voltages generated with standard values it was possible to ensure that the complete measuring system was functioning satisfactorily. The signal corresponding to ± 1 g was then recorded and served as a calibration signal for the subsequent analysis.

A low-frequency, sinusoidal signal was then fed into both axes on the rig to ensure full and free movement. Some time during the check the emergency buttons, including the one mounted on the vibrator table itself, were checked for correct operation.

5.2 Instructions to subject

The subject (who had previously completed the pro-forma in Appendix B) was brought into the vibrator room and shown the overall system. The safety precautions built into the rig were explained to him, and the actions of the emergency buttons demonstrated. It was stressed that if an emergency did occur then under no circumstances should he attempt to jump off the platform. It was also made clear that the complete system had been 'man-rated' and contained adequate safety circuits.

The subject then sat in the seat on the vibrator and fastened his seat lap harness, loosely so that it constituted no physical restraint. It was explained that the purpose of the harness was simply to prevent him from suddenly leaving the vibrator should a fault occur and also to secure him if the table tilted as a result of any such fault.

The experimenter then switched on the swept sine generator and demonstrated the highest amplitude input to the subject, effectively saying "This is all you are going to feel!". Then, following the procedure laid down in section 4.3.1, the subject adopted the different postures, first under no vibration and then under vibration. The arm and leg position variations were then explained to and practised by the subject (sections 4.3.2 and 4.3.3). The accelerometer harnesses were then attached to the subject, as described in sections 4.2.1 and 4.2.2. It was explained that, during the vibration runs, the subject would be required to keep his head and shoulders in the same vertical plane throughout the tests. Since any deviation from the vertical would be sensed by the accelerometers as a dc change in the signal and displayed on the output amplifiers, a check on this was maintained by the experimenter.

Due to the presence of the head harness, the subject was unable to wear an intercom headset. In order to provide communication between the subject and the 'driver', at the control console outside the vibration room, a second experimenter equipped with an intercom set, sat in the vibration room thus satisfying a recommendation of the safety guide[3], that a second observer be present during human runs. This second experimenter also instructed the subject on the required posture, arm and leg positions for the particular run.

Recorded tests then began, the subject being instructed on posture etc by the observer through the sequence of eight runs (making one test), set out in section 4.3.4, at the highest vibration level. If the sweep duration was 25 s, a test took about 4 min; if 10 s, about 2 min. Then followed a brief rest and the sequence was repeated at the same vibration level. The input level was then reduced to the medium and then lowest level and the procedure repeated. In all, for one subject the complete set of runs took about 25 min.

The subjects received the test conditions in exactly the same sequence, ie no attempt was made to balance the design of the experiment to eliminate any order effects (see 4.3.4). The basic objective of balanced experiments is after all that, for a set of tests which may be time-dependent in nature, the time factor and learning should be eliminated. For the experiments reported here, where the only time effect involved can be fatigue, it is extremely unlikely that the 3 min could cause enough fatigue to alter the subject's biodynamic response.

6 THEORY AND METHOD ANALYSIS

A detailed discussion of the theory and method of analysis is given in Appendix C, but some general comments will be given here.

The swept sine input used for this experiment defined in the form,

$$y(t) = A \sin \left\{ \omega(t) t \right\}$$

where $\omega(t)$ is such that the frequency of the wave varies linearly from ω_1 to ω_2 in T s.

The required frequency response of the body $[H(f)]$ is then calculated from the ratio of the Fourier transform of the output $[S_y(f)]$ divided by the Fourier transform of the input $[S_x(f)]$, thus

$$H(f) = \frac{S_y(f)}{S_x(f)} .$$

This then provides the amplitude ratio and phase of the response function.

The computer settings for the various analyses performed were as follows:

<u>1-10 Hz in 10 s</u>

Anti-aliasing filters (see Appendix C) set at 10 Hz for both channels

$$\text{Computer block size} = 256$$
$$T = 10 \text{ s}$$
$$F_{max} = 12.8 \text{ Hz} .$$

Therefore $\Delta t = 0.039$ s

and

$$\Delta f = 0.1 \text{ Hz} \quad .$$

Even though the input data contained no information above 10 Hz (this being the upper frequency set for the swept sine wave), the necessary period T of 10 s meant that F_{max} had to be 12.8 Hz in order to fill the selected block size.

2-25 Hz in 25 s

Anti-aliasing filters set at 25 Hz for both channels

$$\begin{aligned} \text{Computer block size} &= 1024 \\ T &= 20 \text{ s} \\ F_{max} &= 25 \text{ Hz} \\ \Delta t &= 0.020 \text{ s} \\ \Delta f &= 0.05 \text{ Hz} \quad . \end{aligned}$$

A small keyboard programme was written which took in the data, performed the Fourier analysis, eliminated the dc components (corresponding to 0 Hz), converted the frequency domain data into polar co-ordinates, and plotted the results on an X-Y plotter.

7 RESULTS

7.1 Summary

The total number of graphs required to cover all the results (ignoring for the moment the fact that all the runs were duplicated) is given by six subjects × eight conditions × three levels × two ratios (head/seat and shoulder/seat) each graph showing both amplitude and phase response, a total of 288 graphs.

If the results are grouped into posture variables, arm position variables and leg position variables (three instead of the maximum eight possible conditions), and amplitude and phase can be presented on the same sheet, the figure reduces to 108. Clearly it is not practicable to present all the results and equally, as discussed earlier, it is undesirable only to calculate the average response of subjects and present as a 'standard' value. Therefore a compromise has to be reached.

Inspection of the results summarized in the table below, in general indicates that the primary features of both the head and shoulder responses are

Approximate transmission ratios at resonance

	Head/seat		Shoulder/seat	
	Normal	Back-off	Normal	Back-off
Transmissibility at first (4 Hz) peak	1.3	1.4	2.2	2.3
Transmissibility at second (13 Hz) peak	1.7	0.8	0.7	0.4

a peak (resonance) at about 4 Hz and a second peak around 13 Hz, with a dip at about 8 Hz. For the head, the transmissibilities for the two peaks are about 1.3 and 1.7 respectively for the normal posture and for the back-off posture the higher frequency peak was reduced to about 0.8 with a slight increase in the amplitude for the first peak. The results for the shoulder are 2.2 and 0.7 for the normal posture, whilst back-off gives a reduction at the higher frequency to about 0.4 with again a slight increase in amplitude ratio for the lower peak. The phase lag curves showed an increase from 0 to π as the frequency increase for the highest input level, whilst for the lower levels, in general, the increase was from 0 to 3π. Clearly these are only generalised comments, variation in subject, condition, level etc producing slight variations. However the pattern described above was consistent for all the subjects and all conditions, except for condition 8 where the subject leaned slightly forward off the seat back.

On the assumption therefore that this pattern describes the important results, Tables 2 to 5 were constructed giving for every subject, every condition and every input level the values of the maximum and minimum amplitude ratios on the frequency response curves, together with the frequency and phase lag at which these values occur.

7.2 Tables

Table 1 gives some basic anthropometric data. Tables 2 and 3 give the values of the maximum and minimum amplitude ratios and the frequencies at which they occur for all six subjects and for all conditions and levels, for the head/seat tests. Tables 4 and 5 give similar results for the shoulder/seat responses. The tables are presented in this way as it is felt that the important parameters
068 of the results, both in assessing the results and trying to provide a theoretical explanation, are the maximum and minimum transmissibility ratios and the

frequencies at which they occur. The average responses for every condition and level are given in Table 6. Comparison of the values in Tables 2 to 5 and Table 6 gives an indication of variability within subjects as far as the maximum and minimum points are concerned. Table 7 gives an indication of the variability between subjects averaged across the three input levels.

Table 8 gives the correlation coefficients between the subject's age, weight and height and his vibration response characteristics.

7.3 Figures

Subject 2 was found to give the most nearly average head response, and his results for all conditions are given in Figs 4 to 12.

Subject 1 was found to give the most nearly average shoulder response and his results for all conditions are given in Figs 13 to 21.

The table gives a key to Figs 4 to 21.

These results are presented in detail, as most of the discussion regarding the variation in response for different parameters will centre around these curves. Comparisons will be made between the trends observed for these particular subjects and the trends for the other subjects, whose complete response curves are not given.

		Figure number	
	Vibration level	Head/seat (subject 2)	Shoulder/seat (subject 1)
Posture	H(igh)	4	13
	M(edium)	7	16
	L(ow)	10	19
Arms	H	5	14
	M	8	17
	L	11	20
Legs	H	6	15
	M	9	18
	L	12	21

Figs 22 and 23 illustrate the variability in the results obtained (for one subject, same condition, same level) for the two input durations and for identical 068
runs respectively.

In an attempt to quantify and explain any possible non-linear effects Figs 24 to 33 present graphs of the variation in the amplitude of the resonant peaks with the frequency at which they occur. Visual inspection of such information can often provide a better grasp of non-linearity effects than mathematical explorations.

Figs 34 and 35 give plots of the correlation between age and resonant frequency, and weight and resonant frequency.

Figs 36 to 40 are included in connection with the theoretical arguments and explanations covered in Appendix A.

8 DISCUSSION OF RESULTS

8.1 Head/seat results

8.1.1 Posture variables (Figs 4,7 and 9)

The most striking feature of the curves is that the amplitude ratio for the back-off condition is consistently much lower than for the other postures, for frequencies greater than about 7 Hz. Below this frequency this condition gives marginally higher amplitude ratios. As far as the other three posture variables are concerned, the slumped posture, like the back-off gives lower values above about 7 Hz and a higher line below about 7 Hz than normal or erect, especially for the two lower input levels. However the difference between normal (1) and slumped (3) postures is much less than the difference between normal and back-off (8). Clearly the slumped condition could have meant that the subject leaned slightly forward so that he approached the condition of back completely off. Inspection of the results at the lower frequency first, peak also supports this theory, in that the highest value is for 'back-off' and the next highest is for 'slumped posture'. The results for normal and erect postures are seen to be virtually identical.

As far as amplitude ratios at resonance are concerned, Tables 2 and 3 give the results, and Figs 24 to 26 give each subject's results for normal posture and back-off. It can be seen that for subject 2, and for normal posture, the amplitude ratio for the first peak varies slightly for the three input levels from about 1.18 to 1.20, and the frequency at which this peak occurs increases from 3.1 to 3.7. For back-off both the maximum amplitude 0.42 to 1.75 and the frequency 3.7 to 4 Hz at which it occurs, increase and with increasing level. The implications of these increases concerning non-linearity are discussed in
068 section 8.5. The dips in the curves all occur around 8 Hz and have an amplitude

ratio of about 0.4. For the second peak at the high level, there is a slight inconsistency in that the slumped results give a higher peak than the normal or erect (2.24 compared with 2.0). However the results at the other levels show the amplitude ratios for slumped posture to be below those for normal and erect posture. The results for other subjects show either that the normal, erect and slumped postures produce very similar results, or that the trend described here of a lower response for slumped is maintained. It is obvious that some of the subjects leaned slightly forward in the slumped position, whilst others were able to slump without leaving the back. [It should be remembered that each subject was allowed to select his own interpretation of slumped, and that each subject showed, on his results, that he was consistent in his selection.]

The amplitude of the second peak for subject 2 with 'back-off' was only 0.82, ie a third of the value for the other postures. At frequencies higher than 13 Hz, 'back-off' tends to give a value of 0.40 whilst the other postures gave ratios which fall with the square of the frequency, ie about 12 dB/octave. At 20 Hz, the 'normal' and 'erect' values are about 1.10 and the slumped, 0.75. These figures are similar for the medium and low input levels. Thus, even at frequencies as high as 20 Hz, we have a factor of 3 between the normal posture and the 'back-off' condition.

Inspection of Tables 2 and 3, which gives the results at the peaks and dip for all the subjects and all the conditions, and Table 6 which gives the averaged data, shows that subject 2 corresponds very nearly to the averaged results. The results for the normal conditions at the first peak and high level show an average of 1.21 with a spread of 1.05 to 1.45 with a spread in frequency of 2.70 to 4.30.

Fig 24 gives plots of all the subjects' results for condition 1 at the first peak, and show clearly the variation in the results between the subjects is probably due to anthropometric variations. The problem of trying to explain inter-subject variability will be discussed in a later section 8.9. The important point to note at this stage is that all the subjects exhibited the same trends so that broad conclusions may be drawn from one subject's results or by the average response.

The results for phase lag for all subjects show an interesting variation with level. At the highest input level, the curves show a gradual increase in phase lag 0 to around π, at about 25 Hz with a hump at about 8 Hz, just above the frequency of the dip in the amplitude ratio plots. Inspection of the phase plots for the lowest input level reveals that an original hump has become extended so that the curves fall to π at 8 Hz and then proceed to fall a further 2π, making a total lag of 3π at 25 Hz. (The plots themselves can only vary between ±π but clearly the curves should be extended continuously from +π phase lag.) The results for the medium level are a mixture of both types of phase response. Some subjects were much more consistent in that results for high levels went from 0 to π and all other levels gave a 0 to 3π response. The section on non-linearity (section 8.4) explains this changeover as a possible result of the change in damping ratio as the level decreases. The results for 'back-off' are again different from the results for the other postures. The phase lag is always of the 0 to π type even at the lowest level. Note that again the slumped posture results lie between the normal and erect variants and the back off.

The results of the variation in posture have thus revealed a very important factor. To minimize head vibration at low frequency (below 6 Hz), and any input level, it is marginally better to sit erect with the back firmly pressed into the seat (to suppress the main body resonance) as opposed to leaning away from the back rest. On the other hand to minimize high frequency vibration (above 10 Hz), the subject should lean forward and allow the body to attenuate the vibration naturally. In this case the reduction in the vibration at the head, as opposed to sitting erect in the seat can be as much as two thirds. It is interesting to note that both kinds of vibration environment occur in aircraft. Low frequency vibration (< 6 Hz) is common in normal fixed wing aircraft, whilst higher frequency (15-25 Hz) vibration is common in helicopters.

8.1.2 Arm position (Figs 5, 8 and 11)

Clearly the effect of various arm positions for subject 2 is very small. At the high and medium input levels, conditions for arms folded and arms on oscilloscope appear to give slightly lower values at the second peak (13 Hz), whilst at the first peak, arms folded gives a slightly higher value (6%) at a slightly higher frequency. These differences are much smaller than the inter-subject differences for the same conditions. Again the slight trend discussed is evident for the other subjects.

The phase angle plots, apart from the low level input, arms touching the oscilloscope, when the phase reverts to the 0 to π type, are almost identical. Results for other subjects again show a consistent effect in that most of the results for high input give 0 to π response, and most of the results for the medium and low inputs give a 0 to 3π response.

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Thus variation in arm position has little effect on the amplitude of vibration transmitted to the head.

8.1.3 Leg position (Figs 6, 9 and 12)

In general, the effect of varying leg position from the normal is to increase marginally the maximum amplitude at the first resonance point especially when the legs are outstretched, and to provide slightly more attenuation (compared with the normal condition) at frequencies greater than about 15 Hz. Comparing the curves for each level, there is little difference, so that the remarks made in 8.1.1 regarding variation in normal posture results for the three levels and the actual values involved, again apply. The results at the high level show an increase in the first peak amplitude when the legs were in the forward position compared with normal. The amplitude increases from 1.22 to 1.56 and the frequency rises from 3.0 Hz to 3.6 Hz. When the legs are brought right back, the amplitude again rises, but only to 1.27 and the peak frequency falls to 2.75 Hz. At the other levels the same trend is apparent except that condition 6 - legs right back - has a higher maximum value.

At other frequencies the leg position curves are 10% lower than the normal (high input), and coincide except at the actual second peak frequency (medium level). Inspection of other subjects' results indicates that the increase in amplitude at the first peak, when the legs are outstretched, is maintained but the figure of 40% is too high to take as an average value for the low level input.

8.2 Shoulder/seat results

8.2.1 Posture variables (Figs 13, 16 and 19)

It is immediately apparent that the curve for condition 8 (back off) is very different above 10 Hz from those for the other three conditions. Also there is again a slight tendency for condition 3 (slumped) to be the nearest of the remaining postures to condition 8, for subject 1. Inspection of the results for the other subjects bears out this trend. For the particular subject shown, we again have two peaks at about 4 Hz and 13 Hz, with normal transmissibility ratios of 2.2 and 0.70; for frequencies higher than about 9 Hz that is the frequency at which the dip occurs, the curve for back off is consistently lower than for the other postures, the difference being greatest at the second peak (0.40 compared with 0.70) and least at the highest frequency tested where the responses in all postures converge. Inspection of the results for other subjects shows a similar reduction of about 40% at the second peak and convergence to the same value at high frequency. The average results show a similar reduction. For frequencies lower than 9 Hz, and the high input level, the slumped condition gives the highest reading - 2.65 as opposed to 2.39 for the back off condition. For the other levels, back off gives the maximum amplitude of about 2.30, as was the case for the head/seat results. Conditions 1 and 2, normal and erect gave very similar curves for all the levels throughout the frequency range. Inspection of the results for the other subjects indicated that in general, back off condition gave the maximum value at the first peak for all levels, followed by slumped. Subject 1 therefore did not follow the overall trend for this particular point but provided a good average response for other trends, and the table of averages clearly shows this effect.

Fig 26 and Tables 2 to 6 indicate that as the input level decreases (high to low level), there is a tendency for the amplitude at the first peak to increase (7%) and the frequency at which it occurs to increase (8%). These differences are well within the intersubject variability. Fig 24 shows the results for the first peak for all subjects and levels for the normal posture, with the maximum amplitude varying between about 1.75 and 2.10 (20%) and the frequency between about 3.40 and 5.30 Hz (55%). The questions of intersubject variability and non-linearity will be covered in later sections (8.6 and 8.4). The variation in the phase angle plots for the shoulder resulting from the posture changes presents a similar picture to that for the head/seat results. At all levels, for the subject illustrated (S1), all the phase plots lie very closely together. At the high level, the curves fall from 0 to 150° at about 8 Hz, then climb back up to a lag of 70° at 9 Hz, then fall steeply to 160° at 15 Hz and are constant from then on. The plot for condition 8 is slightly different having a similar shape, but lags of 165°, 80° and 140°.

At the other levels for this particular subject, there is no such difference between condition 8 and the other postures for the shoulder as there is for the head. The shoulder results are almost identical for all the postures and the two levels of input, medium and low. The lag increase to 180° at 9 Hz, then to 320° at 15 Hz and, again, is flat for higher frequencies. Inspection of other subjects' results show that some back-off results do not show such a large phase lag, but have the 0 to 180° type response even at the lower input levels. The fact that the head results show such a change whereas the shoulder results do not is discussed in the section on non-linearity (section 8.5), and may be
068 explained by saying that the head response is mildly non-linear whereas the

shoulder response is much less so, thus having less change in damping, and producing a different kind of phase lag.

8.2.2 Arm position

Summarizing, the arm positions used made very little difference to the amount of vibration being transmitted to the shoulders. There was however an indication that for high frequency vibration, arms in lap (normal) provides the least transmissibility, whilst for lower frequencies it is preferable to fold the arms or touch the oscilloscope.

Figs 14, 17 and 20 show the plots of the results for the three arm positions. Condition 1 (hands in lap) is again included as a standard so that cross references may be made between the results for posture, arm and leg changes. All arm positions produce a similar plot with two peaks and a dip. Both 'arms folded' (4) and 'hands on the oscilloscope' (7) have higher transmission ratios than 'normal' at frequencies higher than 9 Hz, and the frequency at which the second peak occurs is the same for each condition. This is generally true for all the subjects, the tables of averages giving the best picture perhaps, where it can be seen that at the second peak the frequencies are virtually identical for all the conditions but arms folded gives a peak transmission 50% higher than the normal (0.72-1.10) and arms touching the oscilloscope gives a peak 65% higher (0.72-1.20). The difference in amplitude at the second peak reduces as the frequency rises until at about 25 Hz the other arm position curves converge on the normal line. Below the second peak frequency the trend is for the curves for conditions 4 and 7 to have a higher value (approximately 50%) at the dip frequency compared with the normal condition. It is difficult to deduce a trend from the results of the first peak, as one subject's results appear to contradict another's. Thus in trying to establish a trend in the results for variations which is little influenced by the variations due to different subjects, we are saying that, at the first peak, the variability between conditions is much less than the variability between subjects. Considering the averaged results, these show that the normal position gives a peak transmission value (for every level) higher than the other arm positions (1.89-1.65, 1.98-1.75 and 2.05-1.91 for the high, medium and low levels respectively. This trend appears in some subjects' results but not in others. Tables 4 and 5 give inter-subject variations for the transmission ratios at the first peak covering the range 1.60 to 2.12. The frequencies at which the first peaks occur are similar for the normal and arms-on-oscilloscope case, but for arms folded are 10% lower. As far as the phase lag is concerned, for the medium and lower levels the results with different arm positions are nearly identical with the normal curve. For the high level, the phase curves for conditions 4 and 7 showed a marked difference around the first peak where they only fall to about 100° whereas the normal curve falls to 150°. Apart from this the curves are very similar.

In order to establish any trends for varying arm position, we have been forced, by using the average results, to ignore a basic premise of this Report. It was found that this was the only way of establishing a trend, which ultimately proved to give a variation in amplitude much less than the variation occurring in the normal condition between subjects.

8.2.3 Leg position

Figs 15, 18 and 21 give the results for different leg positions (1 normal, 5 outstretched, 6 right back) for the three input levels. Of all the variables - except the effect of back off in the posture variables - change in leg position gives the most significant effect. Except for frequencies around the first peak, the curve for the three leg variables are very similar for the medium and high levels. However when the legs are stretched out the amplitude at the first peak frequency is 50% greater than for the normal condition (approximately 3.1 instead of 2.05). When the legs are brought right back (condition 6) the peak is fractionally higher (less than 10%) than the normal. This trend is borne out by the average figures in Table 6.

Subject 1's results indicate that there is a slight tendency for the peak values to increase (5%) as the level decreases, for all the leg positions, this trend is also apparent for the frequency of the first peak. All leg variables give the same value of frequency for the first peak at all input levels.

The phase lag curves show little variation with leg position.

8.3 Order of systems involved in response curves

In this section we shall be discussing general conclusions from the detailed analysis of spring mass systems given in Appendix A. One of the simplest, but in some cases most inaccurate, way of deciding the kind of system which gives a particular response curve, is to count the number of peaks in that curve. A single spring-mass-damper system (see Appendix A) has one resonance, unless it is very heavily damped, a two-mass system has at least two resonances, etc. Clearly, however, there are limitations to this argument. One can imagine a two-mass system where the two sub-systems have very similar individual responses
068 (although their components governing stiffness and damping may be markedly

different), and if the coupling term is small, the resulting response curve when the systems are combined will be single peaked. Or if the second system is very heavily damped compared with the first system, and possibly has a higher natural frequency, again only one peak may show.

Inspection of the phase response can also aid in defining the number of orders in a multiple system. One can logically argue that if, in a multiple system, the sub-systems are sufficiently separated as far as their natural frequencies are concerned, and damping is applied high, each part contributes 90° (for $\alpha > 5$ where α is the ratio of the frequency to the natural frequency of the system). If however the natural frequencies are relatively close together (their ratio being two or less) and the systems are lightly damped, then each sub-system contributes π .

For values of α greater than about two, the response curve falls off in proportion to 1/f for a single order system. If measured results indicate that the final fall is 30 dB/octave or (1/fs), then five systems are involved in the overall picture. The figure of (1/f) is independent of damping, stiffness or resonant frequency, when α becomes very large. At high frequencies the amplitude, output/input acceleration, R is proportional to $1/\alpha$ giving a slope of -6 dB/octave on a logarithmic plot.

All the previous arguments have assumed a series connection of sub-systems with little coupling, that is the secondary mass (or masses) is (or are) small compared with the mass in the first system and thus have little effect on it. But since the body is not a 'simple' series of spring systems, but rather a combination of series and parallel paths the problems of trying to define the order of the system are greatly increased. The governing equation for output/input of a simple series path has been formulated and the values of the maximum amplitudes and the frequencies at which they occur have been calculated. If we now add an unknown system as a parallel loop - the ratio of output to input across it not being measurable - then only by means of trial and error or intuition can we begin to define the sub-systems involved. Any peaks calculated or resonant frequencies found may be reflections of the superimposed parallel system's response rather than the series (and measured) network. Either way, the problems of trying to model the responses are great, and the possibility must be faced that if inspection of the response curves indicates that, either the system is not a simple series arrangement, or it is composed of multiple (>3) sub-systems, one may have to accept the response curves as applying to that situation only and abandon attempts to model the system. The relevant section (10) covering future work will recommend a mathematical exercise to model a typical curve, whilst the designer or engineer would have his basic information covering frequencies to avoid etc ready for use.

As far as the present tests are concerned, for the purposes of estimating the order of the systems involved, let us assume a 'standard' response curve. This curve has a peak at 4 Hz, of amplitude ratio 1.40, a trough at 8 Hz, of amplitude ratio 0.40, and a second peak at 13 Hz, of amplitude ratio 1.3. This is simply a theoretical curve covering head or shoulder response for all subjects and all conditions except back off condition, where the subject leaned forward off the back rest and very probably drastically altered the order of the systems involved.

Theoretically, a response transmission curve which has a resonant frequency at 4 Hz crosses the unity gain axis at a frequency of $\sqrt{2} \times 4$ Hz, or 5.6 Hz. The gradient of the curve after this ($\sqrt{2}\, f_{max}$) point is really determined by the number of systems. Assume that our curves represent a chain of systems, the first of which has a resonance at 4 Hz. The cross over point is therefore at 5.6 Hz and the curve falls off thereafter as (1/f) - at 6 dB/octave. Therefore, the frequency of the second maximum (at about 13 Hz) is about twice the cross over frequency (5.6 Hz → 13 Hz) so that the transmission ratio had fallen by a factor of 2. If it is assumed that we have a simple series-connected, two-mass system then the true value of the second peak should therefore be approximately 2 × 1.3 or 2.6. Thus we have postulated that our response curves represent a double series system with resonant frequencies and maximum amplitude ratios of 4 Hz/1.40 and 13 Hz/2.6. The higher frequency system, when treated in isolation will have an amplitude ratio of roughly 1.11 at 4 Hz, that is at the first peak. On this reasoning our first peak, in isolation, has a true amplitude ratio of 1.27, which corresponds to a fairly high damping factor of 0.72.

Continuing this reasoning but relating to the dip in the response curves which occurs at 8 Hz, then the first peak will only have fallen by about 30% and the second system will have an amplitude of about 1.50 at the same frequency. Therefore, again simply connecting in series, gives a figure greater than unity at a frequency where experimentally there is a dip below unity. In fact this series connection means that the amplitude ratio curves cannot fall below unit between 1 Hz and about 15 Hz. Therefore this cannot be the model to explain the
068 results. The only way that a dip can be generated at around 8 Hz is for the

first peak to be the result of more than one sub-system, with similar characteristics. Then the fall off would be (6 dB/octave × the number of systems involved), but the cross over point of 5.6 Hz would be the same. Thus one can calculate that for a slope equivalent to a fall off as $(1/f^2)$ the amplitude ratio following the first peak is 0.55 at 8 Hz, and for $(1/f^2)$ the figure is 0.40. However, these extreme slopes mean that the second curve now has peak amplitude ratios, when treated in isolation, of about 5.2 and 10.4 respectively, ie very lightly damped systems which in turn implies, for the second system again, amplitude ratios of around 1.55 at 8 Hz. When we now combine the circuits in series we have at 8 Hz either 0.55 times 1.55 (0.85) or 0.40 times 1.55 (0.62). It also implies that the first peak treated in isolation has a true value of only about 1.20 (0.80 damping ratio).

These figures are certainly less than unity but are a long way from the required figure of 0.40. Intuitively, this logical approach of several superimposed low frequency resonances followed by a lightly damped higher frequency resonance has advantages and disadvantages. It is well known, and has often been demonstrated by the author to visitors to his vibration facility, that the low frequency resonance of man (around 4 Hz) is brought about by, amongst other things, the resonance of major body organs contained within the rib cage and abdomen. If vibration of a sufficiently high amplitude is used, by slowly varying the frequency between about 3.5 Hz and 6 Hz, the subject can easily identify the oscillations of organs within his own body - such as stomach, lungs, etc. Thus it is extremely likely that the first peak is caused by several similar sub-systems all resonating at about the same frequency and producing one overall peak in the total response curve, and with a fall off greater than $(1/f^2)$. All these sub-systems will have a different connecting point to the major structure of the body, so simple series addition cannot be used. As far as the amplitude ratio curves are involved, in order for the argument to hold across the whole frequency range tested, we must follow the first peak with a very lightly damped second system, h about 0.05, R_{max} (maximum amplitude) about 10, with a resonance at about 13 Hz. It is doubtful whether such a lightly damped resonance exists anywhere in the body. Past literature has suggested that this second peak is due to the spine, which intuitively would be regarded as moderately damped.

Inspection of the phase response at the medium or low input levels, (the change in the shape of the phase response between the high and the other levels will be discussed in the section dealing with non-linearities) reveals that the phase lag has increased to just under 180^{o} by the time we reach the dip in the response curve. Overall the phase lag is around 540^{o} at the highest frequency tested. Again assuming that the first systems, which give a peak around 4 Hz, are moderately damped, each sub-system will give 90^{o} and it appears that we have two sub-systems. The final phase lag is 540^{o} so that the second peak needs to contribute 360^{o}. If we again assume a very lightly damped second peak, then 360^{o} can be obtained by the use of two series circuits.

8.4 Non-linearity

In the preceding section dealing with the number of sub-systems involved, the general conclusion reached was that the complexity of the situation precluded any worthwhile attempt to define the internal details of the system under test. Any discussions regarding non-linearity can be made either on the results as a whole by simply ignoring the order of the system and seeing how the curves vary with varying input level or by logical arguments based on assumptions regarding the response of simple single systems and fitting the conclusions to the experimental data. As with the preceding section both arguments will be explored and conclusions drawn in the light of the findings of both this and the preceding section.

Basically non-linearity will show itself by a variation in the response curves for the three levels tested (bearing in mind that there is a factor of 2 to 1 in the input levels). Clearly it is impossible to plot all the curves for all subjects and conditions here, therefore detailed comparisons between the responses at the three levels cannot be made. Hence in order to explore linearity, an assumption has been made that any non-linearity will affect the damping and/or stiffness of some part of the body system. In turn this will affect the values of any resonances or maxima in the response curves together with the values of the frequencies at which these maxima occur. These changes in R_{max} and α_{max} (the maximum amplitude ratio and the frequency at which it occurs) will also be reflected in changes in phase angle plots.

The values for the above maxima for all subjects and conditions are given in Tables 2 to 5. Inspection of these tables indicates a general trend for the maximum amplitudes and the frequencies at which these maxima occur, to increase as the input level decreases. The trend found for the individual results is also shown in the averaged results in Table 6 with the possible exception of condition
068 3 (slumped posture) for the head/seat results. The trend is apparent for both the head/seat and shoulder/seat results and for both the peaks. It should be

remembered throughout this discussion on non-linearity, that changes of only about 10% in peak amplitude and resonant frequency occur for a 50% reduction in input acceleration amplitude. In order to try to understand the problem of quantifying the degree of non-linearity, some of the results contained in the Table have been plotted as graphs of the frequency for maximum amplitude versus maximum amplitude in Figs 24 to 29. The curves have been annotated as being for the high (H), medium (M) and low (L) input conditions, so that the discussed trend of R_{max} and f_{max} both increasing for decreasing input level can be more easily seen. The relevant figures for the averaged results of Table 6 have also been plotted in Figs 30 and 31. Fig 32 shows a theoretical curve, for a single system, of α_{max} v. R_{max} for various values of damping ratio. By comparing this theoretical curve with the experimental results, and estimate of the degree of non-linearity can be made. The results for all the conditions have not been plotted in the above manner because of the large number of figures involved (14 graphs being needed to cover just two conditions). The conditions chosen were regarded as the most important being (a) standard (normal) position and (b) the condition which, as discussed earlier, produced the most significant result. References to Tables 2 to 5, provide a check that the other conditions behave in a similar manner.

8.4.1 Empirical approach

Summing up, as far as response of the head is concerned, for the input levels used (in both absolute and relative terms), excluding conditions where the back is off the back rest, the body behaves in a slightly non-linear manner, giving increases in the frequencies at which resonance occurs of about 20% and in the amplitudes at these resonances of about 6%, as the input level decreases. These variations must be related to the intersubject variability, at any one level, of roughly 25% in both f_{max} and R_{max}. Conditions 3 (slumped) and 8 (back-off) provide the academic type of conditions, whereas the other conditions where the subject sits back provide multiple inputs to the body. The results for the back-off conditions plotted on Figs 24 and 27 show that the first peaks for all the subjects do not follow any particular pattern, but the second peaks show an increase in f_{max} of about 30% for a very slight decrease in R_{max}.

The shoulder/seat results in general do not show to the same extent the trend that the head response shows. The graphs and tables show a much smaller increase in f_{max} (about 5%) and about 10% increase in R_{max} for the first peak as the input level decreases. It is considered that because these figures are within experimental error variations and because they are much smaller than the intersubject variability, even though there is a trend as the level decreases, this response of the body can be regarded as being linear. The second peak has a similar trend to that of the head responses, a fairly large increase in f_{max} (30%) accompanying a small (5%) increase in R_{max} for decreasing levels.

Thus from an empirical point of view, the body can be regarded as mildly non-linear for head response, and essentially linear for shoulder response. The inter-level variability in amplitude ratio for an average subject is always much less for shoulder slightly less for the head than the intersubject variability for one level.

The head/seat results for each subject under condition 1, for the first peak given in Fig 24, indicate that, in general, the subjects show the trend discussed above in 8.4. The average results give a linear relationship between f_{max} and R_{max} for decreasing input levels, a 14% increase in f_{max} relating to an 8% increase in R_{max}. This figure of 'inter-level' variability is however much less than the 'intersubject' variability for any one level. Inspection of the table for similar results for different conditions indicates that apart from conditions 3 and 8, this trend continues. Both these exceptional conditions show the increase in f_{max} but indicate a constant R_{max} (within approximately 4%). It should be borne in mind that conditions 3 and 8 are interrelated in that condition 3 is slumped posture, where the back may be just starting to leave the back rest, and condition 8 is back completely off, but maintaining an erect posture. The results for the second peak show similar trends (even to the exclusion of conditions 3 and 8 from the general trend) except that the increase in f_{max} is now 25% and the increase in R_{max}, only about 5%.

8.4.2 Theoretical approach

The basic experimental factor would appear to be that as the input level increases the amplitude at resonance and the resonant frequency both decrease. As the form of the body's response is not known, the argument will initially deal with a single system concept, as given in Appendix A. R_{max} is simply a function of damping ratio (equation (27) Appendix A) and also from the well known response curves if the value of R_{max} increases the damping ratio must decrease. Similarly α_{max} is a function of damping ratio, but α is also a function of ω_0, or $\sqrt{(k/m)}$, so that f_{max} (instead of α_{max}) is now a function of $\sqrt{k}$
068 and h. Inspection of equation (28) reveals that for f_{max} to increase

either h decreases (which is linked to the increase in R_{max}) or k increases. Hence to explain the observed effect, either the damping ratio must increase with the input level and/or the undamped remnant frequency must decrease. In physical terms we are saying that as the input level increases, the system under test becomes more heavily damped (because R_{max} decreases and possibly f_{max} decreases) and also the stiffness reduces (because f_{max} decreases). Intuitively one would expect most physical systems to have hardening characteristics, that is as the extension or relative velocity induced across the system increases the damping and stiffness increase - the ultimate being a member becoming almost infinitely stiff.

Equation (30) of Appendix A illustrated in Fig 33

$$(\alpha_{max})^4 = \left[1 - \frac{1}{R_{max}^2}\right] . \qquad (1)$$

Differentiating this equation and expressing it as change in α_{max} against change in R_{max}, we have, (equation (32) of Appendix A)

$$\left(\frac{d\alpha}{\alpha}\right) \Big/ \left(\frac{dR}{R}\right) = \frac{1}{2(R^2 - 1)} \qquad (2)$$

(to simplify matters we have omitted the suffices in (1)).

This equation states that a change in R_{max} is accompanied by a change in α_{max}, so that our original trend of R_{max} and α_{max} increasing may be due to the same factor - a decrease in damping - and variation in the stiffness factor may not be necessary to explain the experimental data. As discussed earlier, intuition suggests that physical systems have hardening characteristics, so that the earlier suggestion of increasing stiffness with reducing level was suspect, since it would tend to increase f_{max} with increase in level.

In the preceding section, values of 14% increase in f_{max} and 8% increase in R_{max} were stated. If these values are substituted into equation (2), then, solving for R we find

$$R_{max} = 1.14 . \qquad (3)$$

Thus we are saying that, assuming a first order system response, if the maximum amplitude is 1.14, then the percentage changes in f_{max} and R_{max} can be explained purely on the basis of changing damping (with constant stiffness).

The actual values found were between 1.20 and 1.60. The preceding section on order of systems involved put forward the theory that the true value of the first peak (when the effect of the second peak was removed) was reduced from 1.40 to 1.27. Examination of Fig 32 reveals that for this sort of figure for R_{max} for a multiple system situation, the experimental figures for changes in f_{max} and R_{max} can be explained as being due simply to a change in damping in the first system.

8.5 Harness effects

Sections 4.2.1 and 4.2.2 gave details of the harnesses used to measure the accelerations at the head and shoulders. The precise effect of any such harnesses under vibration is extremely difficult if not impossible to quantify. Results from tests may simply be a function of the response of the elastic harness used rather than the response of the object under test, ie the head and shoulders. It is difficult to apply a scientific test to such a system and normally the testing of such harnesses comes down to a few *ad hoc* tests which have proved in the past to provide satisfactory measurements.

First of all the harnesses must be tested as mounted on the subject. It is no use mounting the harness on a rigid block and checking it as the attachment would be completely unrepresentative. Secondly the testing must be performed at the tension which will be used in practice. This really introduces the main method used - the harness is tightened until the subject says that it is as tight as he would wish, bearing in mind that he will be wearing it for a few minutes only. The author has often been amazed at the discomfort subjects will tolerate in order to help experimenters. When the harness is thus tightened it is possible to check its response - the tendency for it to rise under vibration - by slightly lifting the accelerometer, and allowing it to fall back onto the head or shoulder. Normally the harness is assessed this way on a subjective basis, however for the experiment detailed here, the output of the accelerometer was displayed whilst the accelerometer was being lifted and released. Theoretically for this function input the system output should show a decaying sinusoid from the frequency and envelope of which an estimation of the natural frequency of the harness and its damping ratio can be made. The results of this test, which were taken from an oscilloscope display only, showed a very highly damped response - so highly damped that it was difficult to estimate the frequency of the resulting sinusoid. It was only possible to estimate it at
068 around 40 Hz, ie well above the frequency range of the tests reported.

Thus, on a subjective basis, relying on the experimenter's past experience, and on an objective basis where the response was found to give a response curve giving unity gain over the frequency of the reported tests, the harnesses were assumed to be satisfactory.

It is also worthy of note that the results indicated that all the subjects gave very similarly shaped response curves. It could be argued that if the harness was significantly contributing to the results, and as the fit was different for each subject, each subject would give a different form of response curve. The fact that they did not again bear out the assumption that within the accuracy limits of the experiment, the accelerometers were providing an accurate record of the motion of the head and shoulders.

8.6 Intersubject variability

Many of the points of discussion of intersubject variability have already been covered in sections 8.1, 8.2 and 8.3 which deal with the presentation of the basic results and the effect of the body parameters. However, in general, these sections were mainly interested in any trends due to variations in posture and limb positions, although both average and individual subject results were considered. In order to discuss intersubject variations, particular attention will be paid to the peak (and trough) amplitudes and the frequencies at which they occur as given in Tables 2 to 5 - as these are regarded as the major characteristics of the response curves. The results of Table 6 were generated by averaging the absolute value of the peak amplitudes and the frequencies at which they occur, rather than generating an average curve. After all if one curve has a peak at 3 Hz value 2.0 and another a peak at 4 Hz and a value of 3.0, to average the curves themselves will produce a curve which has two peaks, one at 3 Hz and one at 4 Hz, with peak amplitudes of about 2.5 and 3.5 respectively, this curve is completely unrepresentative of either subject's results. For this paper we have averaged the absolute values, so that our final figures would be a peak at 3.5 Hz with an amplitude of 2.5. It is felt that this presents a more representative method. Following this argument, it is not proposed to give an average response curve. It is possible of course to plot or one graph all subjects' responses for, shall we say, normal posture, head/seat results, at the high input level. The result however would be confusing and untidy and little information could be gathered regarding the behaviour of an average subject. It is better to give the average results at the peaks with the variations taken from the relevant Tables.

One way of exploring the possible reasons for the intersubject variability is to calculate each subject's averaged (as regards level) peak amplitude and frequency and to attempt to correlate these factors with body mass, age, height etc. We shall confine ourselves to considering conditions normal (1) and back-off (8) only, these representing the normal and the condition which, as shown in sections 6.2 and 6.3, gives the greatest variation from the normal. Table 7 presents these averages for the first and second peaks in the response. General inspection of this table shows the difference in responses at the peak for conditions 1 and 8. For both head and shoulders, almost all the results indicate an increase in amplitude and frequency for the first peak when the subject leans forward slightly, whilst for the second peak the dramatic attenuation of the vibration for both the head and the shoulders for this condition is very evident. The frequency at which the second peak occurs is only slightly different between the two conditions. Out of all the results shown only one subject (number 1) for one parameter (first peak response at head - difference between conditions 1 and 8) shows a different trend - and here the trend is very small, a reduction in level of 3.6%, all the other subjects showing increases in level of between 10 and 15%. Thus with respect to trends, the variation of level between conditions is extremely consistent (this point has also been covered in section 6.1, 6.2 and 6.3). As far as absolute values, per condition, are concerned, Tables 5 and 6 must be examined in conjunction with Table 1 which details the subjects body dimensions etc. The requirement is to try to correlate the results with the subject data, so that statements can be made as to whether the variation in results is due to a variation in weight, height or age or due to normal experimental, subjective scatter. In order to get the numbers involved into perspective Table 7 also contains a column of calculated means (which can be cross referenced to the relevant averages of Table 6). Inspection of these mean values with respect to the individual subject results gives the variation about the mean. The final column in the table gives the maximum percentage deviation of the individual results from the respective means. The percentages are given for the maximum amplitudes and for the frequency at which the maximum occur, for the first and second peak. Values are given for above and below the mean, eg for condition 8 head results, the mean maximum amplitude and the frequency at which it occurs for the first peak are 1.25 and 3.59 Hz, the intersubject variability gives variations of +15% and -14% for 1.25 and +12% and -14% for 3.59 Hz. Inspection of the Table generally reveals that the intersubject variability
068 (except for condition 8 second peak) is about ±15%. In terms of any experiment

involving objective measures of human responses this is an amazingly low figure! The exception quoted above concerns the amplitude ratio for condition 8, for the back off at the second peak - the variation in frequency for this condition is again extremely low, as are the results for the same condition at the first peak. No obvious explanation is apparent for this ±40% deviation, but again putting the figures into perspective, this deviation is not excessive. One possibility is that each subject had a different interpretation of 'back-off', and thus not all subjects had the same percentage of their back length in contact with the back. This is borne out to some degree in that the frequency variations between the peaks for conditions 1 and 8 are very close and the only real difference is in the amplitude ratios.

Thus having inspected the basic results, the averaged results and the percentage deviations we need to explain a swing in the results of ±15% in terms of body parameters. Table 1 gives each subjects' height, weight and age. Logically of all these parameters one would expect weight to play the major part in giving any intersubject variability - probably in terms of resonant frequency rather than peak amplitude. However in order to explore all the possibilities (of the conditions given in Table 7), a computer programme was set up to calculate the correlation coefficients between age, weight and height and the set of figures for each condition given in Table 7. The results are given in Table 8. Too much meaning should not be read into these results since with 48 calculations one would expect to find two or three significant at the 5% level and perhaps one at the 1% level for purely random figures.

Inspection of Table 8, line by line, shows that for the height variable there are no significantly high correlation coefficients - considering the experimental spread in height is only about ±4%, this is hardly surprising. As far as weight is concerned, there appears to be a slight tendency for run number 1, to give 'highish' correlation, -0.86. It was thought that there was likely to be a correlation between weight and resonant frequency but, unfortunately the results do not bear this out. The age results yield a very interesting result in that for the shoulder response, f_{max} for the first peak in the normal condition shows a high correlation coefficient, 0.90, showing that as one gets older then the frequency increases. The correlation coefficients are much reduced when the back is lifted off the seat, and are non-significat at the head.

Thus the only significant correlations found are between (a) age and the first resonant frequency at the shoulders when seated normally (Fig 34) (b) weight and the first peak amplitude at the head when seated normally (Fig 35) and (c) weight and first peak amplitude at the head when leaning forward off the back rest. Fig 35 shows a good deviation in the age factor producing a good deviation in the frequency parameter, whereas Fig 34 shows that the deviation of weight, whilst producing a high correlation against the amplitude parameters shown, is very small. In fact if we ignore the weight of subject 3, in Table 1, then the average weight is 71 kg with a deviation of only +6%/-9%. To prove any correlation between weight and frequency, a greater range of weight must be used - as great as the deviations the age.

8.7 Subjective comments

Most of the subjects were surprised that such a short test could give the required information. All agreed that the method of producing the required conditions in terms of posture and limb positions was good and that as the duration of each condition was so short they had no difficulty in maintaining these conditions. None of the subjects could detect any rotational motion of the head during the vibration.

Reactions to the vibration levels were extremely mild ranging from 'definitely aware' of the high level to just 'barely aware' of the lowest level. Clearly the fact that the tests lasted such a short time affected these comments. The only adverse comment made - by several of the subjects; concerned the head harness, which after about 15 min proved to be uncomfortable. However it was explained to the subjects that in order to measure the body's response at the head - as opposed to the response of the head harness relative to the head - the harness needed to fit very tightly. Following this explanation, the subjects were quite happy to put up with the discomfort for the sake of the tests.

The only other comments concerned the condition when the subjects leaned forward to take their backs just off the back-rest. Several of the subjects commented spontaneously that under this condition the amount of high frequency vibration - which they described as tingling, buzzing and 'making them want to scratch their faces' - was reduced appreciably. This comment bears out the objective results which show a marked reduction in the vibration measured at the head between 10 and 25 Hz for the 'back-off' condition.

8.8 Comparison with previous results

As explained in section 1, there have been very few previous reports which have dealt specifically with the effects of varying posture and limb position on the resonant frequencies and peaks produced by the body, so comparison with previous results is difficult. Also few reports have used frequencies as high as reported here and few have mentioned or measured phase lags.

As far as other papers are concerned the first major body resonance is normally reported to be in the range 4 to 6 Hz with amplification factors of around 2. The results reported here have shown peak frequencies of around 4 Hz for the head and shoulder responses with respective amplitude ratios of around 1.3 and 2.2, in general agreement with past researches. For frequencies greater than 10 Hz no comparisons are readily available. However the indications of most papers are that around 9 Hz the amplitude curves are falling, and there is little indication of any higher resonances. As far as input acceleration levels are concerned Guignard[22] has indicated that shoulder response is linear up to $\pm 5.0\ m/s^2$, and postulates a trend that increasing the level reduces the amplitude ratio for constant peak frequency. Our results show similar reductions in amplitude but include a reduction in the frequency of the peak.

Thus in general, as far as comparisons are able to be made, the results set out in this Report agree reasonably well with past work.

9 CONCLUSIONS

The overall conclusion is that body posture and limb position has a major effect on the transmission of vertical vibration to the head and shoulders of the seated man. Of the variables explored, namely, arm, leg, back position, slumped and erect posture the difference between back on and back off the seat was the most marked at both the head and shoulder, with the effects of legs straight out forward next important but for the shoulder only.

More detailed conclusions are given below.

9.1 Head/seat transmissibility

The results show two clearly defined body resonances, the first at about 4 Hz (ratio 1.3) the second at about 13 Hz (ratio 1.7). Between the peaks, at about 8 Hz, there is a dip, with an amplitude ratio of about 0.4. This pattern is maintained for the three input levels and the body conditions except 'back-off'. For this condition the 13 Hz peak is reduced to 0.8, whilst the 4 Hz peak is only slightly higher. The phase results for the high input show a fall from

0 to π with an upward trend around 8 Hz. At the other input levels the phase lag increases to nearly 3π. By moving the back just away from the seat at the higher frequency peak the vibration transmitted to the head can be reduced by a factor of between 2 and 3, whilst the same condition gives a 20% increase in the vibration transmitted at the lower frequency peak. The variations in the responses due to the leg positions were minor and much smaller than intersubject variability.

The first peak discussed is probably caused by resonance of the internal organs within the rib cage and abdomen and possibly by a shoulder girdle resonance. The second peak is probably associated with a spinal resonance. These conclusions regarding the reason for the resonant peaks have been postulated by authors of past reports[21,25,28].

9.1.1 Shoulder/seat results

The response curves again show two predominant peaks in the frequency range tested, with a sharp dip between the peaks. The frequencies at which these peaks and dips occur are all slightly higher than the values found for the head/seat tests, see Table 6. This time the amplitude ratio of the first peak is considerably higher (2.2) than for the head results (1.4 on average). On the other hand the second peak for postures other than the back off condition is considerably reduced (by between 50 and 75%) from around 1.7 to 0.70. The value of the amplitude ratio at the dip is about the same - approximately 0.40. The effect of 'back-off' is again to reduce transmission at the higher peak (0.70 to around 0.40) with little difference at the lower peak. Therefore if one wishes to minimize vibration levels at the shoulder, for high frequency the subject should lean forward off the seat back whilst at low frequency he should press firmly against it.

The effect of varying arm position was minimal although there were indications that to minimize the vibration transmitted at high frequency the hands should be in the lap and for low frequency they should be either folded or touching an external device like an oscilloscope. The leg positions had little effect at the higher frequency range but at the first peak, stretching the legs out greatly increased transmission to the shoulders, and drawing the legs right back slightly increased transmission.

In order to explain these differences, especially those for posture, it
068 should be remembered that very similar effects were found for the head/seat
results, indicating that the mechanism producing these differences is between

the seat and the top of the spine, ie 'further up' the chain. As explained in 8.1.1 it is postulated that the difference is produced by allowing or not allowing the spine to attenuate naturally the displacement imposed on its base. As suggested in the recommendations for future work, these phenomena will be more easily explained if tests aimed at measuring the response across the spine (by mounting an accelerometer on or near the seventh cervical vertebra) can be carried out. As far as the differences due to the leg positions are conerned, it is assumed that when the legs are stretched out they provide a transmission path to the head or in particular the shoulders, other than that provided when the legs are in the normal position.

9.2 Order of systems involved

It appears that from an amplitude ratio point of view, that there are about three systems contributing to the first peak followed by a very lightly damped system to give the second peak. From a phase lag point of view we have two sub-systems for the first peak, both heavily damped, followed by a further two lightly damped systems for the higher peak. This contradiction further reinforces the remarks made previously, that if it is found that the overall response is not due to simple series addition or that the system is composed of multiple (>3) sub-systems, one may have to accept the results as they are and abandon any modelling techniques. Clearly the total system is composed of parallel and series additions and many sub-systems are involved. Therefore the results are presented for what they are, a record of the frequency response of the body under numerous input conditions. The section dealing with recommended future work (9) contains a comment regarding the need to perform a computer analysis (analogue and digital) of results such as those included in this paper, in order to try to determine the nature and order of the systems involved. Only then will a reasonable model of the response of the body be found.

9.3 Linearity

In considering the linearity of the human body it must be remembered that we are dealing with only about 10% changes in maximum amplitude and resonant frequency, for a 50% reduction in input vibration amplitude. For head/seat response, this investigation suggests that the body is slightly non-linear probably due to a change in damping, on the first peak. The shoulder response can be regarded as essentially linear. Overall, the variability due to input level for the average subject is much less than the intersubject variability for any one level, so that over the range from $\pm 2\ m/s^2$ to $\pm 4\ m/s^2$ and 1 to 25 Hz non-linearity effects are of secondary importance.

9.4 Locational effects

The results indicate that rotation of the head was not a significant factor in these tests. The shape of the response curves is similar for a wide variation in input level and as it was argued that if rotation were significant its effect would increase greatly as the input level increased, this similarity supported the supposition that rotation was not a major factor. Therefore the results of this experiment must be regarded at worst as including the vertical translational components of the angular accelerations of the head and shoulders, and, at best as an accurate picture of solely vertical translational motion at these positions.

9.5 Intrasubject variability

It was found that, probably due to the care taken in controlling the experimental variables (posture, limb positions etc), as well as the short duration of the input vibration, intrasubject variability was small by an order lower than intersubject variability.

9.6 Intersubject variability

The intersubject variability in the peak and dip amplitudes and frequencies was found to be generally about ±15%, and for a few parameters, exceeded ±35%, see Table 7. No correlation was found between the results and subject age, weight or height and the variation must therefore remain unexplained. However the variations are small compared with those in previous research.

9.7 Accelerometer harness

Tests indicated that the harness used to secure the accelerometers to the head and shoulders provided an accurate measure of the motion at these positions.

9.8 Subject comments

Several subjects made unsolicited comments on the apparent reduction of vibration to the head when 'back-off' posture was assumed and all agreed that the method of adopting the required postures and limb positions was good.

9.9 Modelling

It has been shown mathematically (Appendix A) that the frequency response across a cushion is a function of the dynamic load on the cushion, that is the cushion's response refelcts the man's response. This is clearly of importance in designing seat cushions or seat suspensions to attenuate vibration.

9.10 Literature survey

Forty-nine references were found dealing with the measurement of biodynamic responses. A critical survey has been reported leading to the conclusion that the work detailed in this Report is not a duplication of previous work.

10 RECOMMENDATIONS AND FUTURE WORK

10.1 'Back-off' response

As far as practical significance is concerned, the major finding of this Report is that if a subject is not in contact with the back rest, the amount of vibration reaching his head and shoulders for a certain frequency range is considerably reduced compared with the normal 'back-on' case. Therefore, in a vehicle which exhibits appreciable vibration in such a frequency range, something could perhaps be done to the seat design to make the occupants more comfortable, or to perform their tasks more efficiently. It is therefore desirable to validate the responses found in this Report for a more normal seat, with cushions and flexible members, and possibly to design a seat back, with some form of vibration isolation, so that the subject is effectively isolated from vibration of the seat back. The author has performed some unreported tests which appear to validate the 'back-off' effect in an aircraft ejection seat, and work on designing a seat back which, in the appropriate environment could reduce vibration at the head and shoulders by possibly 50% is in hand.

10.2 Extension of input range

The present investigation has been restricted to the vertical axis only and to peak acceleration levels between $\pm 2.0\ m/s^2$ and $\pm 4.0\ m/s^2$. These conditions cover those in many vehicles, but vibration in other axes and at higher and lower levels can occur. In the literature there are many papers dealing with vertical vibration, but few cover the other axes. Therefore it is desirable that this work be extended to cover other input levels and the other axes.

10.3 Model responses and linearity

Section 8 of this Report analysed the types and order of systems which would reproduce the experimental results. The conclusions were that the results were too complex to model accurately at present. The same remarks can be applied to the question of linearity. In the end empirical approaches were used to explain the results. Future work could include mathematical modelling using analogue or digital computers, covering both parallel and series systems, in order to model the response of the body accurately.

10.4 Spinal response

To be able to investigate the response of the body at the head and shoulders in terms of modelling and linearity it would be very useful if measurements could be made at a position 'within' the body system. It is hoped to repeat the experiments detailed in this Report but measuring as an output quantity the acceleration at the top of the spine, on the seventh cervical vertebra. This point on the spine just out and provides a possible mounting platform for an accelerometer and is low enough to be unaffected by head rotation; infact it can perhaps be regarded as the main input point for head and shoulder vibration. The results of such an experiment would also be of interest and use to people concerned with injuries induced by ejection from aircraft and with setting acceleration or relative displacement limits for such systems.

10.5 Rotational components

One of the fundamental assumptions made in this investigation is that under the particular type of acceleration input used, the head exhibits linear motion only. It is well known that under steady state sinusoidal input conditions the head can have a rotational component, but the assumption has been made that for the transient input used, no rotation was present.

In order to test the assumption, it is recommended that an experiment be set up to measure the rotational accelerations induced at the head by a linear acceleration input of the type used herein.

The Institute of Aviation Medicine has investigated rotation at the head induced by rotation at the floor and there are plans for an RAE/IAM joint experiment to measure the linear and angular components at the head due to a linear input at the floor.

Appendix A

DYNAMICS OF SPRING MASS SYSTEMS

The first two sections of this Appendix will reiterate standard work on spring-mass systems, later sections will give some applications of this work to the present problems.

A.1 One degree of freedom

Let us assume that the human body can be represented by a mechanical system such as that shown schematically in Fig 36a. x represents the motion of some part of the body and is regarded as an output quantity. It can be thought of as a displacement (x) or a velocity (dx/dt or $\dot{x}$) or an acceleration (d^2x/dt^2 or $\ddot{x}$) . Similarly z is the input motion (dz/dt or d^2z/dt^2) .

Frequency response or transmission function is defined as the ratio x/z , or $\dot{x}/\dot{z}$ or $\ddot{x}/\ddot{z}$. This function, being complex, is defined (for any one frequency) by its amplitude and its phase lag.

The governing equation of the mechanical system is,

$$m\ddot{x} = C(\dot{z} - \dot{x}) + K(z - x) \tag{1}$$

where m is the mass,

c the damping ratio

and K the spring stiffness

or using the operator $D = d/dt$,

$$(x/z) = \frac{(CD + K)}{(mD^2 + CD + K)} \tag{2}$$

$$= \frac{((C/m)D + (K/m))}{(D^2 + (C/m)D + K/m)} \tag{3}$$

($\sqrt{K/m}$) is defined as the undamped circular natural frequency of the system, ω_0 . (C/m) is defined as twice the ratio of the damping to critical damping, times the undamped natural frequency, and equals $2h\omega_0$ $\left(h = \frac{C}{2\sqrt{mK}}\right)$. Thus substituting and rationalizing we have the transmissibility ratio T given by

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$$T = \left(\frac{x}{z}\right) = \left(\frac{Dx}{Dz}\right) = \left(\frac{D^2x}{D^2z}\right) = \frac{[(1 + D(2h/\omega_0)]}{[(1 + D^2/\omega_0^2) + D(2h/\omega_0)]} \tag{4}$$

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using the vector notation, letting $D = j\omega$,

$$(x/z) = \left[\frac{1 + j \, . \, 2h\alpha}{(1 - \alpha^2) + j \, . \, 2h\alpha}\right]$$

$$= \left(\frac{\dot{x}}{\dot{z}}\right) = \left(\frac{\ddot{x}}{\ddot{z}}\right) , \qquad (5)$$

where $\alpha = \omega/\omega_0$.

The amplitude ratio R is given by the modulus of the above equation and the tangent of the phase angle ϕ by the ratio of the imaginary and real parts.

Thus

$$R = \sqrt{\frac{1 + 4h^2\alpha^2}{\left(1 - \alpha^2\right)^2 + 4h^2\alpha^2}} \qquad (6)$$

and

$$\phi(\text{lag}) = \tan^{-1}\left[\frac{2h\alpha^3}{1 - \alpha^2(1 - 4h^2)}\right] . \qquad (7)$$

Sometimes it is more useful to talk in terms of the relative displacement across the system $(x - z)$ with reference to the input acceleration $(\ddot{z})$.

Manipulation of equation (1), yields

$$m(\ddot{x} - \ddot{z}) + C(\dot{x} - \dot{z}) + K(x - z) = - m\ddot{z} . \qquad (8)$$

Proceeding as before, we arrive at

$$\frac{(x - z)}{\ddot{z}} = \frac{- [1/\omega_0^2]}{[(1 - \alpha^2) + j \, . \, 2h\alpha]} \qquad (9)$$

which has modulus and phase lag given by

$$R = \frac{[1/\omega_0^2]}{\sqrt{\left[\left(1 - \alpha^2\right)^2 + 4h^2\alpha^2\right]}} \qquad (10)$$

and

$$\phi(\text{lag}) = \tan^{-1}\left(2h\alpha/(1 - \alpha^2)\right) . \qquad (11)$$

In some instances it is not possible to measure the above quantities on the body (x in particular). However there is another way of obtaining an insight into the dynamic properties of such a complicated system. A mechanical system possesses a property known as mechanical impedance, that is analogous to the impedance of an electrical circuit which consists of inductances, capacities and resistances. We define the mechanical impedance (strictly the driving point impedance) as the ratio of the applied force to the velocity, at that point where the input force is transmitted to the body.

$$Z = P/\dot{z} \quad .$$

From equation (1), it can be seen that

$$P = C(\dot{z} - \dot{x}) + K(z - x) = (CD + K)(z - x)$$

$$= m\ddot{x} \quad . \qquad (12)$$

Thus

$$Z = \frac{m\ddot{x}}{\dot{z}} = mj\omega\left(\frac{\dot{x}}{\dot{z}}\right) = \frac{(CD + K)(z - x)}{Dz} \qquad (13)$$

$$= \frac{mj\omega(1 + j\ 2h\alpha)}{\left[(1 - \alpha^2) + j\ .\ 2h\alpha\right]} \qquad (14)$$

from equation (5)

Thus for this simple circuit, the impedance = $(mj\omega)$. Multiplied by the transfer function.

Thus for a single-degree-of-freedom system, it is immaterial whether impedance or transmission is measured, the responses are the same form with a factor $(mj\omega)$ in the impedance. But the body is not a single-degree-of-freedom system. A two-degree-of-freedom system is investigated in the next section.

It is also possible to define a general quantity called acceleration driving point impedance or effective mass M (as opposed to the above, more, normal, velocity driving point impedance), where the quantity is equal to the system mass times the ratio of the motion of the centre of mass and the input motion. An advantage is that most of the measurements taken to define input motion are basically acceleration, so that the integration needed to derive the
068 velocity (in defining the usual impedance), which effectively destroys high frequency information, is eliminated.

A.2 Two-degree-of-freedom

Fig 36b shows a two-degree-of-freedom system, whose governing equations are

$$m_2\ddot{x}_2 = C_2(\dot{x}_1 - \dot{x}_2) + K_2(x_1 - x_2) \tag{15}$$

and

$$m_1\ddot{x}_1 = C_1(\dot{z} - \dot{x}_1) + K_1(z - x_1) - C_2(\dot{x}_1 - \dot{x}_2) - K_2(x_1 - x_2) \tag{16}$$

re-arranging for analogue simulation we have,

$$D^2(x_2 - x_1) = -\left[\frac{C_2}{m_2} D(x_2 - x_1) + \frac{K_2}{m_2}(x_2 - x_1)\right] - D^2(x_1 - z) - D^2 z \tag{17}$$

and

$$D^2(x_1 - z) = -\left[\frac{C_1}{m_1} D(x_1 - z) + \frac{K_1}{m_1}(x_1 - z)\right] + \frac{m_2}{m_1}\left[\frac{C_2}{m_2} D(x_2 - x_1) + \frac{K_2}{m_2}(x_2 - x)\right] - D^2 z \quad . \tag{18}$$

From (15) and (16) we can find x_1 and x_2 in terms of z, and also the impedance Z which is given by

$$Z = \left(\frac{F}{Dz}\right) = \frac{(C_1D + K_1)(z - x_1)}{Dz} \tag{19}$$

then

$$\left(\frac{x_1}{z}\right) = \frac{(m_2D^2 + C_2D + K_2)(C_1D + K)}{\left[(m_2D^2 + C_2D + K_2)(m_1D^2 + C_1D + K_1) + m_2D^2(C_2D + K_2)\right]} \tag{20}$$

$$\left(\frac{x_2}{z}\right) = \frac{(C_2D + K_2)(C_1D + K_1)}{\left[(m_2D^2 + C_2D + K_2)(m_1D^2 + C_1D + K_1) + m_2D^2(C_2D + K_2)\right]} \tag{21}$$

and

$$Z = \frac{D(C_1D + K_1)\left[m_1(m_2D^2 + C_2D + K_2) + m_2(C_2D + K_2)\right]}{\left[(m_2D^2 + C_2D + K_2)(m_1D^2 + C_1D + K_1) + m_2D^2(C_2D + K_2)\right]} \quad . \tag{22}$$

Equations (20) to (22) are clearly very complicated and general rules cannot be drawn from them. The best approach is to represent the systems on an analogue computer and then by varying the values of the damping and spring characteristics of the two systems electrically the effects of these changes can be found. This will be covered in the next section.

A.3 Simulation

The response of such a system can be reproduced on an analogue computer using a circuit of the form shown in Fig 37. Notice that this circuit allows us to monitor all the functions necessary to represent the frequency responses and the impedances. In Fig 36b let the upper system have a damping factor

$$\left(\frac{C_2}{2\sqrt{K_2m_2}}\right)$$

of 0.10 and a resonant frequency

$$\left(\sqrt{\frac{K_2}{m_2}}\right)$$

of 20 rad/s^2, the lower system a damping factor of 0.30 and a resonant frequency of 10 rad/s^2, and assume a mass ratio term (m_2/m_1) of 0.10.

Some results from the computer are given in Figs 38 and 39. Fig 38a shows the effective mass or impedance (defined as Force/Acceleration rather than the more usual Force/Velocity) and Fig 38b shows the impedances of the lower system only - the upper system being completely disconnected. Fig 39 curve (a) shows the overall frequency response function and Fig 39 curves (b) and (c) show the responses of the two systems when treated in isolation.

As far as the body is concerned it may well be that the upper system is by far the most important. This may represent the head where the vibration may produce discomfort, or it may be an internal organ such as the heart or lungs,
068 where large movements may occur resulting again in discomfort and a probable

loss in performance if a complex task has to be performed. As far as impedance measures are concerned, for the general case considered (which is reasonably realistic as far as relative resonant frequencies and damping coefficients are concerned for the body parts mentioned above) comparison of Fig 38a&b gives little indication of significant events at 20 rad/s^2 (section 3.2.2). In fact the only major differences between the curves are an increase in the frequency for maximum impedance from 1.38 Hz to 1.48 Hz and a reduction in the maximum impedance values from 2.34 to 2.00. The increase in the frequency is explainable in that the overall mass has been reduced and also the peak value will change as we have removed a relatively lightly damped system. However at 20 rad/s^2 (3.2 Hz), the impedance values are very similar. Inspection of Fig 39 however reveals that there is a peak in the frequency response curve due to the presence of the upper system, indicating that if vibration is present at about 3.2 Hz, then performance may suffer as amplification of vibration will occur. Having therefore 'discovered' that 3.2 Hz is a critical frequency, using frequency response techniques it is now possible to attempt to find where this amplification is occurring. Fig 39a&b show a breakdown of the complete system into individual sub-systems (but still coupled together and governed by equations (20) and (21) and indicate that the upper system has a lightly damped resonance at 3.1 Hz.

Thus frequency response techniques have isolated a possible problem area which impedance measures cannot yield.

This foregoing analysis assumes that the body behaves as a simple series of connected sub-systems. Fig 40 shows a possible series/parallel model of the body where m_2 is at some measurable position and m_3 may be completely unknown. Frequency response curves covering (x/z) will clearly include the effects of the unknown branch, but any attempt at analysis of (x/z) will be exceedingly difficult. Measurement of input impedance will however include all the sub-systems - so here is a special case where the impedance and the selected frequency response functions are maybe completely different. However the point still remains, the body probably senses vibration, in terms of discomfort or loss in performance, through a relatively small mass, ie the head, or an internal organ, and the measurement of input impedance, compared with a frequency or transmission response, may not show the presence of such a sub-system.

A.4 Theoretical subject/cushion relationship

The subject/cushion combination is a particular example of the general multi-degree-of-freedom system. Let us assume that man can be represented by a single-degree-of-freedom system (obviously an approximation) and that beneath this, the cushion can be represented by another different single-degree-of-freedom system, Fig 36b again.

Thus the governing equations are again as given as equations (15) and (16). But if the cushion is assumed to have zero mass, ie $m_1 = 0$, then equation (16) becomes,

$$\left[(C_1D + K_1) + (C_2D + K_2)\right]x_1 = (C_1D + K_1)z + (C_2D + K_2)x_2 \quad . \tag{23}$$

Equations (20) and (21) give us

$$\left(\frac{x_2}{x_1}\right) = \frac{(C_2D + K_2)}{(m_2D^2 + C_2D + K_2)} \tag{24}$$

which form equation (2) defines the frequency response of the man (called H).

Also the impedance of the man, from equation (12) is given by

$$Z_H = (C_2D + K_2)\frac{(x_1 - x_2)}{Dx_1} \quad . \tag{25}$$

It can be shown that this is a perfectly general equation not necessarily related to a single order system.

If we eliminate x_2 from equations (23) and (24) and include equation (25) we have

$$\left(\frac{x_1}{2}\right) = \text{frequency response of the cushion}$$

$$= \frac{1}{\left[1 + \frac{DZ_H}{(C_1D + K_1)}\right]} \quad . \tag{26}$$

The term $(C_1D + K_1)$ can be extended into a general term defining the cushion damping and stiffness - again not necessarily governed by a first order system response.

Thus in general terms we can say,

068 Frequency response across the cushion $= \dfrac{1}{\left[1 + \dfrac{D(\text{subject impedance})}{\text{cushion characteristic}}\right]}$.

That is the response across the cushion is a function of the impedance of the subject sitting on it, as well as of its own characteristics.

A.5 Peaks of one-degree-of-freedom system

Equation (5) defines the transfer function of the system, and it can be shown that such as equation gives a peak amplitude (resonant value) at a frequency (resonant frequency) near the undamped natural frequency ω_0 .

It can be shown that, for the system shown in Fig 36a the amplitude at resonance is given by

$$R_{max} = \sqrt{\left[\frac{8h^4}{\left[8h^4 - 4h^2 - 1 + \sqrt{1 + 8h^2}\right]}\right]} \qquad (27)$$

and the relative frequency at which this occurs is given by

$$\alpha_{max} = \sqrt{\left[\frac{\sqrt{1 + 8h^2} - 1}{4h^2}\right]} \qquad (28)$$

which tends to 1 or unity as h tends to zero.

Re-arranging equation (27) yields

$$h = \frac{1}{2}\left[\sqrt{\left[\frac{R_{max}}{R_{max} - 1}\right]} - \sqrt{\left[\frac{R_{max}}{R_{max} + 1}\right]}\right] \qquad (29)$$

Also eliminating h^2 between (27) and (28), we have

$$(\alpha_{max})^4 = \left[1 - \frac{1}{R_{max}^2}\right] \qquad (30)$$

This gives a relationship (Fig 33) between the maximum amplitude on a response curve and the frequency at which it occurs.

If $R = 1$ is put into equation (16) then we find that for this condition

$$\alpha = 0 \text{ or } \sqrt{2}$$

ie for any damping coefficient all the response curves of a first order system pass through the point R O 1 , $\alpha = \sqrt{2}$.

Also the same equation indicates that for large (approximately great than 3) values of α than R is proportional to $1/\alpha$ giving a slope of -6 dB/octave.

For the phase response (equation (7)), at high values of α , $\tan \Phi$ is proportional to α thus giving a phase lag of 90^{o} or $\pi/2$.

Differentiating we have

$$\left(\frac{d\alpha_{max}}{\alpha_{max}}\right) \Big/ \left(\frac{dR_{max}}{R_{max}}\right) = \frac{1}{2}\left(R_{max}^{2} - 1\right) \qquad (31)$$

which is illustrated in Fig 32.

Appendix B

SUBJECT PRO-FORMA

Subject file - CONFIDENTIAL

Experiment Code No. ______________

Subject Code No. ________________

Form of declaration - to be filled in prior to each experiment.

The following questions regarding your health, past and present, and other personal data are intended to help us obtain useful anthropometric/physiological/medical information, and their effects on the results of any tests you may perform on the vibration rig. The medical nature of some of the questions does not imply that any experiments you participate in are dangerous (99% of the vibration levels used are less than the levels one encounters in everyday life, from walking, riding, public or private transport etc - you will be told in advance if the other 1% is to be used). People who have had recent transfusions, intestinal operations, a history of back troubles or other medical treatments could be adversely affected - by any vibration. The intention of this questionnaire is to find people in normal health who can help us in our experiments.

Finally we are looking for volunteers, nobody is press-ganging you to take part. If you do not wish to volunteer, say so - no reason will be asked. And if you want to withdraw at any time, again no-one will ask why.

Any published information will specifically exclude your name.

Part 1

(1) Surname: ________________________________ (Mr/Mrs/Miss)

(2) Christian names: ________________________________

(3) Date of birth: ________________________________

(4) Place of birth: ________________________________

(5) Address: ________________________________

____

____

(6) Height: ________________________________

(7) Weight: ________________________________

(8) Any other remarks or information:

Part 2

As a protection for you (and for the experimenters), against any possible effects of vibration, we have (with medical assistance) compiled a list of conditions which should as a rule render persons unsuitable to take part in experiments involving whole-body vibration unless lower levels than those occurring in everyday life are used, eg perception levels etc. All the questions in this part are intended simply to ensure that any subject we use is in 'normal good' health. The answers will be treated as strictly confidential and any written report will contain your code number - never your name.

(1) Do you belong to any of the following groups?

Children under 4 years of age.

People with a history of ear or eye surgery.

People with a history of coughing up, vomiting or passing blood.

People with a history of ulcers.

People with a history of haemorrhoids (piles).

People who suffer from intermittent pain, blanching or numbness of the fingers.

People who have had a back injury or bad strain, back pain or ejection experience.

Pregnancy at any stage.

YES/NO

If YES please indicate which group.

(2) Have you ever been seriously injured or suffered a serious illness, eg a long stay in hospital?

068 YES/NO

If YES please explain.

(3) Are you at present receiving any sort of medical treatment?

YES/NO

If YES please say what type of treatment.

(4) Do you suffer from any sort of disability or defect affecting your daily life, work or travelling?

YES/NO

If YES please give particulars.

(5) Would you be willing for the Senior Medical Officer at the RAE to be asked for his opinion as to your fitness to take part as a subject in vibration experiments?

YES/NO

(6) Have you during the previous month had a vaccination or inoculation or given blood for transfusion?

YES/NO

If YES please give details.

(7) Have you any objections to having accelerometers attached to you? The method of attachment will normally be via an elasticated harness.

YES/NO

(8) Do you normally wear contact lenses or spectacles?

YES/NO

(9) Any other remarks or information?

To be completed by all applicants and countersigned by the experimenter(s).

(1) I ______________________________ hereby volunteer to be an experimental subject in a vibration experiment at RAE Farnborough, Human Engineering Division, Engineering Physics Department.

(2) My replies to all the questions above are correct to the best of my knowledge and belief.

(3) I understand that the information about myself which I have given and may give in the course of the experiment will be treated as strictly confidential by the experimenter(s).

(4) Satisfactory explanations of the nature of the vibration to be used, and how I may stop the experiment, have been given to me.

(5) While agreeing to attend for the purpose of the experiment I fully understand that I may withdraw from taking part in the experiment, and that I am under no obligation to give any reason for my withdrawl, or to attend for further experiments.

(6) While in the vibration laboratory, I undertake to obey the regulations in force governing its use and safety, subject only to my right to withdraw.

Signature of applicant: ______________________________

Signature of experimenter: ______________________________

Date: ____________________

Appendix C

METHOD OF ANALYSIS

The input used for this experiment was a swept sine wave of constant acceleration amplitude lasting T seconds with frequency varying linearly from $(\omega_1/2\pi)$ to $(\omega_2/2\pi)$ Hz, so that for $0 < t < T$ the input can be defined in the form,

$$y(t) = A \sin\left\{\omega(t)t\right\} \tag{32}$$

Assume the relationship

$$y(t) = A \sin\left\{(\omega_0 + \lambda t\pi)t\right\}$$

where ω_0 is the initial frequency

then

$$\frac{dy(t)}{dt} = A(\omega_0 + 2\lambda t\pi) \cos\left\{(\omega_0 + \lambda t\pi)t\right\} \tag{33}$$

ie

$$\omega_t = (\omega_0 + 2\lambda t\pi) \quad \text{or} \quad f_t = f_0 + \lambda t \tag{34}$$

if final frequency is ω_T, and

$$\frac{df_t}{dt} = \lambda ,$$

where

$$\lambda = \frac{(\omega_T - {}_0)}{(2\pi_T)} .$$

To examine the spectral characteristics of this function, it is necessary to evaluate the Fourier transform defined as,

$$F(i\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt . \tag{35}$$

It is not proposed to demonstrate here the evaluation of this integral with its complicated Fresnel integral components, as standard mathematical papers can be quoted where the evaluation is performed.

If ω is not close to either ω_1 or ω_2, then via a series of approximations, it can be shown that the mean modulus spectrum level is

$$|F(\omega)| = A\sqrt{\frac{\pi}{4a}} \text{ where } a \text{ is a constant} \tag{36}$$

i.e. independent of frequency.

It can also be shown using the above approximation that the spectrum levels at the frequency limits ω_1 and ω_2 can be given by

$$|F(\omega_1)| = |F(\omega_2)| = \frac{A}{2}\sqrt{\frac{\pi}{4a}} \tag{37}$$

i.e. half the above value.

Thus we have mathematically defined our input function and shown that Fourier transform analysis of such an input yields a rectangular spectrum shape - the function is also deterministic so that single analysis is sufficient to completely define the input.

If one now applies such an input to the system under test, the human body, then the output from the body will again be a swept sine but this time the amplitude will not be constant as the frequency varies. The manner in which it differs will of course be the frequency response of the system under test.

Expressing this in mathematical terms, the frequency response function $H(i\omega)$ of a linear system may be derived from the response $y(t)$ to a transient input excitation $x(t)$ according to

$$H(f) = \frac{Sy(f)}{Sx(f)} \tag{38}$$

where $Sy(f)$ and $Sx(f)$ are the Fourier transforms of $y(t)$ and $x(t)$ respectively, i.e. if $x(t) = 0$ and $y(t) = 0$ for $t < 0$ then

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$$Sy(f) = \int_0^\infty y(t)e^{-i\omega t}dt \tag{39}$$

and

$$Sx(f) = \int_0^\infty x(t)e^{-i\omega t}dt \quad . \tag{40}$$

Thus by calculating the Fourier transforms of our input and output swept functions and dividing these complex quantities, we can generate the required frequency response in terms of modulus amplitude and phase angle.

In order to calculate the above transforms a Hewlett Packard type 5451A Fourier Transform Analyser was used. This analyser utilizes a digital computer to calculate the transforms of the time varying signals.

In order to implement the Fourier transform digitally, one must convert the continuous input signal into a series of discrete data samples. This is accomplished by sampling the input (or output), $x(t)$ or $y(t)$, at certain intervals of time. We will assume the samples are spaced uniformly in time, separated by an interval Δt. In order to perform the above integrals, the samples must be separated by an infinitesimal amount of time (i.e. $\Delta t \to dt$). Due to physical constraints on the analogue-to-digital converter, this is not possible. As a result we must calculate

$$\bar{S}x(f) = \Delta t \sum_{n=0}^{n=+\infty} x(n\Delta t)e^{-i\omega n\Delta t} \quad . \tag{41}$$

where $x(n\Delta t)$ are the measured values of the input function.
Equation (41) states that, even though we are dealing with a sampled version of $x(t)$, we can still calculate a valid Fourier transform. However the Fourier transform, as calculated by equation (41), no longer contains accurate magnitude and phase information at all the frequencies contained in $Sx(f)$. Rather $\bar{S}x(f)$ accurately describes the spectrum of $x(t)$ up to some maximum frequency,

F_{max} , which is dependent upon the sampling function Δt . Shannons sampling theorem states that it requires slightly more than two samples per period to uniquely define a sinusoid. In sampling a time function, this implies that we must sample slightly more than twice per period of the highest frequency we wish to resolve. Translating Shannons theorem into an equation

$$F_{max} < \frac{1}{2\Delta t} \tag{42}$$

for convenience equation (42) will be written as

$$F_{max} = \frac{1}{2\Delta t} \quad . \tag{43}$$

In order to ensure that aliasing errors do not occur, i.e. frequencies higher than F_{max} folding back to appear as frequencies lower than F_{max} , the user must make sure that the F_{max} he sets is higher than the highest frequency in the data. If this is not possible then anti-aliasing filters must be used before the data enters the analogue-to-digital converter.

In order to calculate $\bar{S}x(f)$, we must take an infinite number of samples of the input waveform (*cf*. equation (41)). As each sample must be separated by a finite time interval (Δt) , this would take an infinite time. Let us assume that the input signal is sampled from some zero time reference to time T seconds, then we have

$$T/\Delta t = N \tag{44}$$

where N is the number of samples and T is the time window.

As we no longer have an infinite number of time points, we cannot expect to calculate magnitude and phase values at an infinite number of frequencies between zero and F_{max} . Thus we have a discrete finite transform (DFT) given by,

$$\bar{S}x(m\Delta f) = \Delta t \sum_{n=0}^{n=n-1} x(n\Delta t)e^{-i2\pi m\Delta f n\Delta t} \quad . \tag{45}$$

Only periodic functions have such a 'discrete' frequency spectra, and thus equation (14) assumes that the function observed between zero and T seconds repeats itself with period T for all time. It is apparent that the DFT, is actually a sampled Fourier series.

Note: There are N prints in the time series and for our purposes the series always represents a real valued function. However to fully describe a frequency in the spectrum, two values must be calculated - the real and imaginary parts. As a result N prints in the time domain allow us to define N/2 complex quantities in the frequency domain.

Then clearly

$$F_{max}/(N/2) = \Delta f \text{ - our frequency resolution.} \tag{46}$$

If we substitute equations (43) and (44) in equation (46), then we arrive at the equation

$$\Delta f = 1/T \tag{47}$$

which in terms of basic Fourier series analysis is evident.

Thus we have established the method whereby the components of equation (38) may be calculated using the Hewlett Packard equipment; and hence by simply pressing one key on the keyboard, the calculation and print out of the required frequency response may be performed.

Table 1

SUBJECT DATA

Subject No.	Age (years)	Weight kg	Height m
1	19	72.6	1.73
2	23	72.6	1.83
3	34	89.0	1.83
4	24	70.0	1.70
5	55	75.0	1.83
6	36	64.5	1.73
Mean	32	73.9	1.78
Deviation	+72% -41%	+20% -13%	+3% -4%

Table 2

DATA FOR HEAD RESPONSE (S'S 1, 2 AND 3)

Condition and level		Subject 1 hd/st												Subject 2 hd/st												Subject 3 hd/st											
		Peak 1			Dip			Peak 2			Peak 3			Peak 1			Dip			Peak 2			Peak 3			Peak 1			Dip			Peak 2			Peak 3		
		R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ	R	f	θ
1	H	1.45	4.30	36	0.52	7.30	17	1.92	10.2	28		-		[illegible]	2.90	22	0.73	5.90	22	1.84	9.50	30		-		1.05	2.90	6	0.71	7.20	4	1.81	10.4	36		-	
	H	1.32	3.30	25	0.44	8.40	12	1.82	11.4	[illegible]		-		1.24	3.10	22	0.66	6.90	18	2.19	10.0	45		-		1.19	2.70	6	0.09	2.70	23	1.63	14.0	12		-	
	M	1.32	3.20	22	0.21	8.70	290	1.45	13.2	[illegible]		-		1.26	3.30	23	0.20	8.50	-12	2.17	12.2	57		-		1.05	3.20	13	0.50	7.40	70	1.63	14.5	419		-	
	M	1.35	3.40	43	0.20	8.60	210	1.50	14.0	437		-		1.25	3.20	19	0.40	8.30	5	2.35	12.0	56		-		1.05	3.10	14	0.18	7.40	84	1.58	13.8	416		-	
	L	1.38	3.40	32	0.61	7.75	135	1.70	14.0	348		-		1.22	3.60	25	0.27	8.10	105	2.14	14.0	69		-		1.08	3.40	18	0.53	7.20	100	1.62	14.1	362		-	
	L	1.41	3.40	26	0.40	6.90	100	1.63	13.5	336		-		1.20	3.80	24	0.23	7.70	50	2.32	14.2	40		-		1.08	3.30	18	0.52	7.00	90	1.77	13.8	332		-	
2	H	1.53	4.10	29	0.60	8.00	21	1.73	10.8	42		-		1.15	3.00	17	0.78	6.50	13	1.98	10.0	41		-		1.22	5.10	18	0.82	7.70	8	1.60	10.5	23		-	
	H	1.30	3.80	30	0.45	8.40	12	1.91	11.2	39		-		1.18	3.00	18	0.66	7.80	14	2.03	10.6	39		-		1.11	4.80	23	0.64	8.20	-17	1.55	16.4	53		-	
	M	1.30	3.20	30	0.19	8.60	82	1.66	12.5	410		-		1.22	3.10	16	0.25	7.80	25	2.06	12.5	69		-		1.04	3.00	10	0.28	7.60	80	1.75	14.6	397		-	
	M	1.25	3.20	22	0.32	8.30	115	1.34	13.7	415		-		1.14	3.10	14	0.18	8.50	280	1.96	15.0	67		-		1.03	2.80	6	0.22	7.50	85	1.76	14.0	404		-	
	L	1.39	3.10	35	0.52	7.60	120	1.53	14.5	360		-		1.24	3.70	26	0.25	8.00	100	1.92	12.0	365		-		1.00	3.20	11	0.40	7.00	71	1.73	17.0	395		-	
	L	1.35	3.40	25	0.33	7.20	85	1.74	14.4	361		-		1.28	3.90	28	0.10	8.30	85	1.80	14.3	396		-		1.03	2.90	11	0.34	7.50	122	1.65	18.0	407		-	
3	H	1.75	4.00	42	0.56	5.60	45	1.64	10.6	50		-		1.28	3.40	22	0.57	7.30	27	2.28	10.2	78		-		1.15	3.10	20	0.36	7.80	6	1.55	10.5	38		-	
	H	1.32	3.40	39	0.44	8.10	-4	1.76	11.4	44		-		1.42	3.50	26	0.57	7.30	28	2.19	10.8	76		-		1.22	3.20	20	0.06	8.10	2	1.34	11.6	67		-	
	M	1.45	3.50	50	0.15	8.70	250	1.45	12.2	420		-		1.50	3.70	42	0.19	8.40	65	1.58	10.8	48		-		1.25	3.60	30	0.19	7.40	120	1.35	12.7	427		-	
	M	1.49	3.30	36	0.26	8.40	105	1.44	12.9	414		-		1.32	3.70	31	0.16	8.60	53	1.66	11.8	56		-		1.33	3.50	30	0.24	7.40	120	1.18	12.0	413		-	
	L	1.50	3.40	40	0.42	7.10	120	1.76	14.2	360		-		1.48	3.80	39	0.81	7.20	132	2.03	12.8	410		-		1.26	3.80	37	0.47	7.50	180	1.25	13.4	374		-	
	L	1.50	3.30	36	0.26	7.80	130	1.44	13.7	407		-		1.56	4.40	48	0.62	8.90	240	1.63	12.5	404		-		1.26	3.80	38	0.52	7.20	185	1.43	14.2	400		-	
4	H	1.32	3.20	32	0.56	6.20	26	1.79	10.6	40		-		1.25	3.20	30	0.67	5.50	24	1.75	10.0	43		-		1.13	3.10	21	0.56	8.20	-1	1.45	11.0	32		-	
	H	1.33	3.00	23	0.43	9.00	33	1.48	11.6	58		-		1.33	3.20	26	0.72	6.00	19	1.78	11.0	52		-		1.07	2.80	10	0.21	8.40	-55	1.38	13.0	51		-	
	M	1.40	3.30	29	0.23	9.30	280	1.40	12.5	407		-		1.46	3.60	27	0.51	6.80	36	1.95	11.4	60		-		1.05	3.20	12	0.26	7.50	90	1.47	14.5	417		-	
	M	1.40	3.30	29	0.29	8.10	180	1.37	13.2	413		-		1.28	3.40	28	0.30	7.70	-40	1.88	12.4	51		-		1.05	3.10	13	0.24	7.20	82	1.52	15.2	419		-	
	L	1.46	3.50	37	0.54	6.60	79	1.44	13.3	343		-		1.41	3.70	38	0.29	7.70	160	2.00	13.0	397		-		1.07	3.50	19	0.51	6.70	82	1.80	15.0	387		-	
	L	1.51	3.50	34	0.25	8.40	130	1.50	13.3	387		-		1.38	3.80	37	0.39	8.00	213	2.30	12.8	386		-		1.08	3.60	21	0.54	7.30	180	1.75	14.6	378		-	
5	H	1.95	3.70	47	0.32	8.30	20	1.54	12.0	60		-		1.64	3.90	34	0.60	6.80	28	1.80	11.0	56		-		1.37	3.90	4	0.49	8.10	24	1.70	14.5	61		-	
	H	1.75	3.70	60	0.39	8.80	52	1.38	12.5	69		-		1.43	3.70	22	0.64	7.50	46	1.84	11.0	58		-		1.32	3.90	8	0.41	8.10	31	1.66	14.2	13		-	
	M	1.82	3.80	45	0.31	9.70	265	1.50	13.6	420		-		1.55	3.80	20	0.42	7.70	37	1.85	13.5	59		-		1.33	4.10	12	0.46	8.20	180	1.70	14.5	411		-	
	M	1.80	3.70	38	0.46	7.80	90	1.61	12.9	402		-		1.60	3.80	24	0.24	9.40	6	1.80	12.8	42	1.92	14.6	72	1.30	4.20	9	0.48	7.80	105	1.80	14.4	409		-	
	L	1.78	4.00	23	0.92	7.00	86	1.52	13.0	318		-		1.60	3.90	25	0.43	8.50	[illegible]	2.14	13.1	399		-		1.22	4.50	7	0.78	8.50	203	1.75	14.0	358		-	
	L	1.75	4.00	25	0.84	8.80	180	1.37	12.8	321		-		1.60	4.20	42	0.39	8.70	215	2.22	12.3	358		-		1.38	4.40	10	0.78	9.20	230	1.78	15.0	375		-	
6	H	1.30	3.40	25	0.29	8.70	-4	1.75	11.2	33		-		1.30	2.80	18	0.58	7.70	22	1.65	11.3	55		-		1.06	2.30	8	0.17	8.00	-20	1.50	12.4	53		-	
	H	1.44	3.70	30	0.44	7.50	26	1.84	10.8	55		-		1.25	2.80	18	0.56	7.20	38	1.86	12.0	74		-		1.10	3.00	11	0.06	8.10	-4	1.50	12.0	45		-	
	M	1.36	3.10	30	0.55	7.40	110	1.56	12.8	394		-		1.36	3.20	30	0.23	7.90	155	1.92	13.4	48		-		1.09	3.10	14	0.19	7.40	85	1.45	14.2	411		-	
	M	1.44	3.20	28	0.34	8.20	95	1.40	13.2	396		-		1.42	3.30	26	0.13	8.50	180	2.08	13.8	67		-		1.06	3.00	17	0.33	7.30	113	1.58	13.5	411		-	
	L	1.50	3.40	33	0.23	7.90	115	1.55	13.5	397		-		1.51	3.70	39	0.28	8.20	200	1.82	12.4	313		-		1.09	3.40	17	0.54	6.40	63	1.58	13.3	362		-	
	L	1.45	3.50	25	0.44	8.10	119	1.63	13.5	394		-		1.50	3.80	37	0.43	8.20	210	1.92	12.8	380		-		1.08	3.30	16	0.70	6.00	58	1.65	13.6	355		-	
7	H	1.26	3.00	25	0.59	8.40	33	1.10	6.20	28	1.64	11.6	52	1.13	2.90	20	0.91	4.10	24	1.87	9.80	48		-		1.05	2.60	9	0.33	8.00	-25	1.54	12.0	41		-	
	H	1.24	3.00	15	0.53	8.50	22	0.92	6.00	26	1.46	11.4	21	1.16	2.80	15	0.92	5.30	22	1.83	10.4	51		-		1.06	2.60	8	0.26	8.40	-31	1.54	13.5	52		-	
	M	1.28	3.20	27	0.28	8.20	70	1.45	14.4	426		-		1.22	3.20	12	[illegible]	7.70	11	1.77	14.6	67		-		1.01	3.00	9	0.29	7.50	180	1.82	13.3	402		-	
	M	1.33	3.30	25	0.30	8.20	105	1.40	13.0	417		-		1.22	3.40	20	0.61	7.60	10	1.93	13.3	68		-		1.02	2.50	9	0.24	7.30	-25	1.73	13.8	417		-	
	L	1.42	3.30	25	0.22	8.30	90	1.56	14.0	406		-		1.26	3.80	24	0.60	7.70	2	2.18	13.2	52		-			-		0.19	6.80	56	1.72	13.0	347		-	
	L	1.35	3.40	27	0.11	8.10	92	1.45	14.3	320		-		1.25	3.70	26	0.17	8.60	10	2.27	13.8	42		-			-		0.20	7.00	180	1.63	13.2	346		-	
8	H	1.58	4.20	55	0.37	6.20	58	0.55	10.5	22		-		1.43	3.90	33	0.39	7.40	53	0.82	10.5	22		-		1.78	4.00	[illegible]	[illegible]	8.70	78	0.78	11.0	55		-	
	H	1.15	3.50	22	0.35	9.00	68	0.61	10.4	25		-		1.36	3.70	40	0.38	7.70	72	0.85	9.80	65		-		1.25	3.80	35	0.32	8.80	[illegible]	0.75	12.6	67		-	
	M	1.35	3.60	32	0.22	6.80	62	0.58	10.5	419		-		1.20	2.60	11	0.31	7.90	103	0.79	10.6	82		-		1.27	3.90	27	0.01	10	20	0.86	12.8	418		-	
	M	1.25	3.70	34	0.17	9.80	312	0.47	12.5	416		-		1.48	3.70	37	0.34	8.50	98	0.74	12.1	101		-		1.18	4.20	31	0.17	9.70	70	[illegible]	13.0	422		-	
	L	1.28	3.80	35	0.19	8.80	225	0.58	11.4	420		-		1.68	4.00	45	0.18	9.40	128	0.69	14.0	123		-		1.38	4.10	38	0.11	9.50	290	0.70	13.2	-		-	
	L	1.30	4.00	45	0.15	9.50	280	0.50	13.4	407		-			-			-			-			-		1.33	4.10	[illegible]	[illegible]	9.30	180	0.79	13.8	403		-	

Table 3

DATA FOR HEAD RESPONSE (S'S 4, 5 AND 6)

Subject 4 hd/st

Condition and level		Peak 1 R	Peak 1 f	Peak 1 θ	Dip R	Dip f	Dip θ	Peak 2 R	Peak 2 f	Peak 2 θ	Peak 3 R	Peak 3 f	Peak 3 θ
1	H	1.14	3.60	16	0.80	6.80	17	1.78	11.6	48		-	
	H	1.18	3.40	18	0.25	7.00	20	1.83	11.2	52		-	
	M	1.23	3.30	18	0.24	6.90	180	2.07	14.2	425		-	
	M	1.32	3.50	20	0.09	7.20	180	1.92	13.0	417		-	
	L	1.35	3.90	29	0.40	7.70	200	2.25	13.5	409		-	
	L	1.30	3.70	23	0.37	7.70	180	2.05	13.3	395		-	
2	H	1.20	4.20	20	0.82	6.70	25	1.62	13.6	53		-	
	H	1.15	3.00	14	0.37	7.10	14	1.42	16.0	64		-	
	M	1.18	3.50	21	0.13	7.60	250	1.50	14.9	421		-	
	M	1.20	3.40	14	0.03	7.50	180	1.38	14.8	423		-	
	L	1.23	3.90	21	0.19	7.60	180	1.48	16.0	413		-	
	L	1.20	3.90	21	0.12	8.00	260	1.57	16.8	420		-	
3	H	1.83	3.10	20	0.39	6.90	40	1.80	4.30	43	1.54	8.60	36
	H	2.18	3.50	30	0.34	7.60	35	1.48	12.0	78		-	
	M	1.45	3.30	25	0.26	8.00	240	1.08	12.7	427		-	
	M	1.85	3.40	16	0.35	8.00	230	1.18	13.0	425		-	
	L	1.45	4.00	36	0.36	8.00	215	1.30	13.5	417		-	
	L	1.40	4.00	30	0.36	8.20	235	1.54	13.5	395		-	
4	H	1.20	4.20	21	0.39	6.60	25	1.76	14.3	73		-	
	H	1.22	3.10	20	0.17	7.50	180	1.80	15.1	74		-	
	M	1.25	3.50	27	0.25	7.50	180	1.85	14.0	422		-	
	M	1.28	3.40	22	0.35	7.50	180	1.91	13.5	408		-	
	L	1.35	3.90	28	0.55	7.90	225	2.07	15.3	412		-	
	L	1.33	3.70	23	0.37	8.00	235	2.00	16.3	438		-	
5	H	2.17	3.50	43	0.53	7.30	48	1.50	10.5	67		-	
	H	2.32	3.80	48	0.65	7.40	46	1.50	10.0	67		-	
	M	1.96	3.80	42	0.12	9.00	180	1.35	12.5	70		-	
	M	1.62	4.00	40	0.26	10.0	260	1.28	13.2	436		-	
	L	1.64	4.30	33	0.05	9.00	180	1.53	15.0	422		-	
	L	1.75	4.30	32	0.05	9.50	180	1.72	14.2	412		-	
6	H	1.35	3.70	27	0.15	7.50	180	1.60	12.0	397		-	
	H	1.28	4.00	24	0.28	7.10	58	1.75	12.5	82		-	
	M	1.34	3.60	33	0.52	7.40	180	1.52	14.2	442		-	
	M	1.46	3.70	37	0.56	8.00	180	1.57	13.8	423		-	
	L	1.42	3.80	36	0.50	8.50	220	1.72	14.5	408		-	
	L	1.56	4.00	40	0.45	9.00	260	1.65	14.0	410		-	
7	H	1.23	3.50	17	0.58	6.30	20	1.81	10.0	39	1.66	12.5	64
	H	1.48	4.10	23	0.45	6.60	21	1.70	9.50	36	1.77	11.5	62
	M	1.22	3.30	17	0.47	6.40	25	1.58	14.5	429		-	
	M	1.22	3.50	17	0.14	7.70	180	1.58	13.3	415		-	
	L	1.32	3.90	37	0.28	7.70	220	1.55	14.5	420		-	
	L	1.34	3.90	26	0.07	8.20	180	1.62	14.6	420		-	
8	H	1.33	4.00	24	0.27	8.00	77	1.00	11.5	66		-	
	H	1.41	4.2	24	0.60	7.40	56	1.05	9.00	57		-	
	M	1.58	4.50	41	0.28	8.50	62	0.82	10.6	76		-	
	M	1.42	3.30	28	0.15	8.70	90	0.72	12.0	94		-	
	L	1.27	4.30	33	0.20	9.00	85	0.70	13.0	80		-	
	L	1.30	4.40	30	0.25	8.70	98	0.72	14.0	85		-	

Subject 5 hd/st

Condition and level		Peak 1 R	Peak 1 f	Peak 1 θ	Dip R	Dip f	Dip θ	Peak 2 R	Peak 2 f	Peak 2 θ	Peak 3 R	Peak 3 f	Peak 3 θ
1	H	1.15	3.70	13	0.15	8.50	180	2.14	10.8	52		-	
	H	1.10	3.30	12	0.03	8.40	5	2.12	10.9	57		-	
	M	1.16	4.20	22	0.16	8.40	180	2.10	12.9	408		-	
	M	1.23	4.00	22	0.56	7.90	180	2.14	13.6	409		-	
	L	1.35	4.50	28	0.38	8.50	225	2.13	13.3	370		-	
	L	1.26	4.30	21	0.36	8.10	180	2.15	13.6	403		-	
2	H	1.06	3.70	8	0.15	8.30	180	2.10	11.5	50		-	
	H	1.17	4.20	12	0.47	6.70	14	1.83	11.3	40		-	
	M	1.24	4.60	27	0.18	8.00	180	2.01	10.6	37	2.00	12.6	423
	M	1.22	4.40	15	0.17	8.10	180	2.04	11.5	395		-	
	L	1.32	4.20	13	0.21	8.40	180	1.82	14.4	411		-	
	L	1.25	4.70	19	0.19	8.50	180	1.90	15.0	418		-	
3	H	1.25	3.90	21	0.50	8.40	25	1.62	10.7	70		-	
	H	1.16	4.20	23	0.33	8.70	35	1.50	11.0	60		-	
	M	1.23	4.10	30	0.28	8.00	180	1.66	11.8	419		-	
	M	1.32	4.30	28	0.47	8.00	170	1.77	13.0	430		-	
	L	1.54	4.90	39	0.49	7.60	220	1.55	13.5	401		-	
	L	1.45	4.80	42	0.36	8.10	210	2.00	14.4	402		-	
4	H	1.20	3.70	12	0.45	8.40	32	1.81	12.5	74		-	
	H	1.19	3.80	12	0.48	8.60	30	1.46	11.6	59		-	
	M	1.35	3.80	12	0.27	7.70	80	2.08	12.0	417		-	
	M	1.30	3.80	18	0.23	8.10	180	1.92	14.4	420		-	
	L	1.42	4.20	17	0.27	8.20	180	1.95	15.0	422		-	
	L	1.40	4.30	20	0.19	8.50	180	2.04	14.6	398		-	
5	H	1.43	4.10	21	1.04	8.20	43	1.67	13.5	80		-	
	H	1.54	4.20	24	1.07	8.20	43	1.60	12.5	70		-	
	M	1.55	5.50	22	0.68	9.40	40	1.88	13.2	417		-	
	M	1.52	4.60	11	0.65	9.40	75	1.58	13.6	424		-	
	L	1.60	4.60	15	0.32	11.0	50	1.49	14.6	56		-	
	L	1.55	4.80	9	0.12	10.5	13	1.95	16.5	67		-	
6	H	1.12	3.70	10	0.44	8.00	45	1.83	10.0	36	1.81	12.0	80
	H	1.14	3.60	13	0.31	9.00	25	1.70	12.5	74		-	
	M	1.30	3.80	14	0.28	8.00	180	1.90	13.1	421		-	
	M	1.28	3.80	17	0.23	8.10	95	1.75	13.9	440		-	
	L	1.38	4.50	30	0.41	8.00	180	1.86	12.8	385		-	
	L	1.41	4.50	28	0.12	8.60	280	1.88	13.8	399		-	
7	H	1.07	3.30	13	0.69	8.20	23	1.98	10.1	40		-	
	H		-			-						-	
	M	1.23	3.60	15	0.29	8.10	180	1.67	11.4	360		-	
	M											-	
	L	1.20	4.20	15	0.23	7.30	125	1.96	14.6	398		-	
	L	1.25	4.30	18	0.35	8.20	10	1.66	14.5	65		-	
8	H	1.15	4.60	21	0.56	8.30	70	0.96	10.3	90		-	
	H	1.23	4.80	31	0.63	8.70	80	1.01	10.8	95		-	
	M	1.45	4.30	33	0.31	9.20	235	0.95	12.6	465		-	
	M	1.56	4.40	35	0.32	8.50	245	1.20	12.6	442		-	
	L	1.42	3.70	17	0.33	8.20	210	1.29	13.6	412		-	
	L	1.50	4.60	33	0.08	8.80	335	0.86	13.0	421		-	

Subject 6 hd/st

Condition and level		Peak 1 R	Peak 1 f	Peak 1 θ	Dip R	Dip f	Dip θ	Peak 2 R	Peak 2 f	Peak 2 θ	Peak 3 R	Peak 3 f	Peak 3 θ
1	H	1.32	3.60	26	0.63	7.70	32	1.63	10.8	59	1.73	12.2	74
	H		-			-			-			-	
	M	1.40	4.00	27	0.20	8.60	80	1.45	12.9	410	1.59	15.0	432
	M	1.35	3.80	26	0.41	8.00	110	1.56	13.3	413		-	
	L	1.60	4.30	28	0.47	8.00	151	1.70	15.0	385		-	
	L	1.50	4.40	28	0.40	8.00	160	1.57	13.8	360	1.52	16.5	423
2	H	1.42	4.30	25	0.71	8.10	26	1.96	12.0	65		-	
	H		-			-			-			-	
	M	1.36	4.20	23	0.19	8.60	100	1.95	13.9	418		-	
	M	1.28	4.10	17	0.29	8.70	30	1.96	13.4	62		-	
	L	1.25	4.40	21	0.09	8.70	250	2.47	16.8	417		-	
	L	1.50	4.30	25	0.24	8.30	150	2.30	15.0	404		-	
3	H	1.25	3.50	24	0.60	8.30	27	1.65	11.2	50	1.55	14.3	70
	H		-			-			-			-	
	M	1.36	3.70	20	0.32	8.20	120	1.67	12.3	396	1.61	15.2	432
	M	1.35	3.50	27	0.45	8.20	220	1.47	13.0	381	1.68	15.4	431
	L	1.50	4.30	28	0.21	8.50	180	2.05	15.2	378		-	
	L	1.40	4.10	26	0.51	8.00	145	1.90	15.0	388		-	
4	H	1.35	3.80	32	0.42	8.70	27	1.40	12.0	55	1.46	15.2	70
	H		-			-			-			-	
	M	1.46	3.90	30	0.75	7.80	105	1.29	16.7	432		-	
	M	1.45	3.90	27	0.26	8.10	100	1.45	15.2	428		-	
	L	1.60	4.30	40	0.52	8.50	180	1.56	15.0	380	1.50	17.2	423
	L	1.56	4.20	27	0.60	7.90	155	1.80	15.0	389	1.78	17.0	429
5	H	1.70	4.30	18	0.75	8.00	64	1.61	13.0	71		-	
	H		-			-			-			-	
	M	1.70	4.90	20	0.42	10.6	270	1.44	16.2	430		-	
	M	1.72	4.80	22	0.77	9.20	113	1.46	15.2	413		-	
	L	1.75	5.20	25	0.36	10.0	143	1.85	14.4	375		-	
	L	1.60	5.00	35	0.80	8.90	245	1.82	15.5	392		-	
6	H	1.32	3.90	29	0.53	8.60	88	1.37	11.7	51	1.36	14.6	67
	H		-			-			-			-	
	M	1.33	4.00	27	0.45	8.00	180	1.22	13.4	380	1.30	19.2	420
	M	1.42	4.10	25	0.27	8.00	180	1.12	12.4	380	1.24	15.7	422
	L	1.50	4.40	33	0.59	8.50	210	1.84	13.9	402	1.66	16.6	434
	L	1.50	4.30	40	0.65	9.20	223	1.50	16.6	414		-	
7	H	1.28	3.20	14	0.98	8.50	29	1.53	11.8	57		-	
	H		-			-			-			-	
	M	1.25	3.80	15	0.26	8.50	180	1.63	12.6	393	1.60	15.6	422
	M	1.25	3.70	13	0.16	7.60	80	1.65	12.4	374	1.56	15.6	417
	L	1.35	4.30	20	0.20	9.00	10	1.82	15.8	45		-	
	L	1.35	3.90	27	0.38	8.40	150	1.80	15.2	401		-	
8	H	1.53	4.40	27	0.63	7.30	46	1.12	11.8	70		-	
	H		-			-			-			-	
	M	1.60	4.40	26	0.65	9.30	61	1.05	13.3	78		-	
	M	1.57	4.30	30	0.37	9.10	61	1.16	14.4	84		-	
	L	1.63	4.70	34	0.31	9.00	58	1.26	15.8	77		-	
	L	1.78	4.70	37	0.36	9.00	50	1.29	13.2	69		-	

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Fig 4

Table 4

DATA FOR SHOULDER RESPONSE (S'S 1, 2 AND 3)

Subject 1 sh/st

Condition and level		Peak 1 R	Peak 1 f	Peak 1 θ	Dip R	Dip f	Dip θ	Peak 2 R	Peak 2 f	Peak 2 θ	Peak 3 R	Peak 3 f	Peak 3 θ
1	H	2.12	4.70	70	0.16	8.30	95	0.61	10.9	112		-	
	H	2.13	3.50	44	0.11	9.00	95	0.69	11.3	108		-	
	M	2.18	3.60	52	0.15	9.50	360	0.70	12.8	119		-	
	M	2.00	3.40	45	0.19	9.80	295	0.75	13.6	118		-	
	L	2.16	3.70	40	0.38	10.2	273	0.75	14.6	415		-	
	L	2.12	3.90	45	0.37	12.3	364	0.75	13.8	392		-	
2	H	2.34	4.90	70	0.20	8.20	120	0.52	11.2	106		-	
	H	2.12	4.20	61	0.14	9.00	85	0.79	11.4	102		-	
	M	1.93	3.40	45	0.13	9.50	320	0.73	12.4	116		-	
	M	1.88	3.60	40	0.25	10.3	315	0.72	13.4	110		-	
	L	1.98	3.40	34	0.35	10.5	277	0.63	13.6	390		-	
	L	2.07	3.60	37	0.42	11.0	336	0.63	13.4	452		-	
3	H	2.85	4.20	60	0.22	8.70	76	0.63	10.7	110		-	
	H	2.40	3.70	52	0.12	9.00	108	0.60	11.4	107		-	
	M	2.37	3.60	65	0.10	9.70	260	0.60	12.5	117		-	
	M	2.15	3.50	52	0.25	9.60	315	0.56	12.7	105		-	
	L	2.08	3.50	32	0.26	9.70	280	0.71	14.2	426		-	
	L	2.27	3.60	40	0.35	9.50	290	0.70	13.8	452		-	
4	H	1.70	3.40	48	0.39	7.80	78	0.86	10.9	107		-	
	H	1.80	3.20	43	0.34	8.60	75	0.77	11.2	83		-	
	M	2.05	3.30	40	0.28	9.00	215	0.77	12.4	107		-	
	M	2.08	3.50	47	0.21	8.60	255	0.75	12.2	80		-	
	L	2.43	3.80	55	0.45	8.70	230	0.80	13.0	390		-	
	L	2.45	3.70	45	0.38	8.30	210	0.90	13.2	456		-	
5	H	3.12	4.00	85	0.14	8.60	98	0.69	11.9	116		-	
	H	3.03	3.80	72	0.29	9.00	112	0.65	12.4	117		-	
	M	3.15	3.90	60	0.20	9.80	205	0.73	13.0	103		-	
	M	3.05	3.90	53	0.24	10.8	380	0.72	12.8	93		-	
	L	3.20	4.10	55	0.58	12.5	330	0.63	14.2	395		-	
	L	3.20	4.20	48	0.43	12.9	355	0.53	15.0	435		-	
6	H	2.25	3.60	65	0.18	8.70	119	0.70	11.2	97		-	
	H	2.36	3.80	60	0.26	8.40	85	0.78	10.8	111		-	
	M	2.30	3.60	50	0.24	10.0	302	0.68	12.5	64		-	
	M	2.14	3.50	50	0.30	10.2	335	0.69	13.2	78		-	
	L	2.27	3.90	55	0.35	9.20	265	0.70	13.2	90		-	
	L	2.45	3.90	45	0.45	11.3	370	0.80	13.6	101		-	
7	H	1.91	3.60	65	0.49	8.90	63	1.07	11.5	80		-	
	H	1.72	3.30	47	0.48	8.70	87	1.04	11.6	114		-	
	M	1.66	4.40	54	0.37	10.3	360	1.00	12.6	101		-	
	M	2.14	4.70	76	0.27	10.0	260	1.10	13.0	116		-	
	L	1.97	3.50	28	0.20	10.0	310	1.01	13.0	458		-	
	L	1.79	3.40	29	0.29	10.1	295	0.91	12.7	468		-	
8	H	2.48	4.40	56	0.10	9.00	63	0.43	11.0	93		-	
	H	2.20	4.10	60	0.12	9.10	115	0.40	10.6	110		-	
	M	2.23	4.30	75	0.19	9.60	95	0.35	11.3	104		-	
	M	2.40	4.50	65	0.09	10.8	370	0.30	12.6	445		-	
	L	2.25	4.40	55	0.14	10.2	360	0.37	12.3	400		-	
	L	2.38	4.80	70	0.18	11.2	325	0.31	16.0	573		-	

Subject 2 sh/st

Condition and level		Peak 1 R	Peak 1 f	Peak 1 θ	Dip R	Dip f	Dip θ	Peak 2 R	Peak 2 f	Peak 2 θ	Peak 3 R	Peak 3 f	Peak 3 θ
1	H	1.70	4.20	70		-			-			-	
	H	1.77	3.90	52	0.40	8.30	118	0.51	12.0	120	0.45	16.0	128
	M	1.91	2.80	50	0.32	9.40	102	0.69	14.6	113		-	
	M	1.74	4.10	50	0.34	9.20	00	0.73	12.8	110		-	
	L	1.96	4.10	45	0.07	9.80	65	0.76	13.8	72		-	
	L	1.87	3.90	35	0.19	9.10	55	0.82	15.2	95		-	
2	H	1.78	4.10	62	0.45	10.0	118	0.47	11.2	122		-	
	H	1.68	3.40	40	0.38	8.00	122	0.47	10.3	107	0.49	13.0	118
	M	2.04	4.10	45	0.46	9.20	89	0.65	13.3	108		-	
	M	1.85	4.10	55	0.28	8.80	116	0.56	13.9	87		-	
	L	1.87	4.30	34	0.20	10.0	60	0.69	13.8	85		-	
	L	1.85	4.20	42	0.20	10.6	50	0.63	13.0	61		-	
3	H	2.18	3.70	60	0.51	9.30	142	0.54	10.8	134	0.31	16.8	156
	H	2.06	3.70	57	0.40	8.80	140	0.59	10.8	124	0.50	14.5	192
	M	2.23	3.90	63	0.52	9.70	115	0.60	13.9	144		-	
	M	2.05	4.10	60	0.45	9.50	117	0.65	12.0	96		-	
	L	2.14	4.00	46	0.46	11.0	84	0.80	13.2	95		-	
	L	2.15	4.40	67	0.15	9.60	73	0.65	12.5	68		-	
4	H	1.70	3.20	41	0.58	7.70	97	0.89	10.0	104		-	
	H	1.88	3.30	48	0.57	8.20	90	0.96	10.4	90		-	
	M	2.14	3.70	50	0.64	8.40	70	1.01	11.3	90		-	
	M	1.86	3.50	40	0.26	8.50	60	1.01	11.3	73		-	
	L	1.93	3.80	37	0.12	8.60	180	1.10	13.4	427		-	
	L	1.92	3.90	44	0.19	8.60	180	1.20	12.4	405		-	
5	H	2.33	4.00	51	0.39	8.50	108	0.47	10.3	105	0.40	15.0	122
	H	2.44	3.80	54	0.30	8.50	126	0.55	12.6	116		-	
	M	2.80	4.00	56	0.40	10.0	88	0.60	13.2	95		-	
	M	2.72	3.90	60	0.23	9.40	98	0.60	13.0	85	0.72	15.2	107
	L	2.78	4.30	60	0.37	10.0	330	0.77	13.5	437		-	
	L	2.89	4.30	45	0.45	9.30	292	0.97	12.8	401		-	
6	H	1.74	3.70	57	0.31	13.5	120	0.45	10.3	118		-	
	H	1.72	3.70	65	0.38	9.20	117	0.50	11.3	116		-	
	M	1.99	3.90	55	0.23	8.30	115	0.63	12.2	80	0.61	15.7	108
	M	2.02	3.60	67	0.36	10.1	85	0.67	13.5	103		-	
	L	2.20	4.00	52	0.12	9.50	310	0.69	12.5	447		-	
	L	2.25	4.00	51	0.34	8.70	280	0.83	12.7	318		-	
7	H	1.40	3.10	24	1.21	9.10	37	1.40	6.00	72		-	
	H	1.42	3.10	27	1.23	9.00	41	1.30	5.50	62		-	
	M	1.50	3.50	34	0.73	8.00	30	1.30	5.90	40	1.17	14.2	96
	M	1.60	3.50	35	0.74	7.30	35	1.38	12.2	92		-	
	L	1.60	3.90	31	0.24	8.30	15	1.25	12.5	52		-	
	L	1.52	3.60	29	0.35	8.40	49	1.10	14.1	72		-	
8	H	2.20	4.00	60	0.20	13.5	108	0.25	11.1	119		-	
	H	1.98	3.90	65	0.22	10.2	120		-			-	
	M	2.14	4.30	70	0.28	10.1	140		-			-	
	M	2.41	3.90	56	0.28	10.4	145	0.25	14.3	126	0.26	17.5	135
	L	2.52	4.20	55	0.18	12.0	131		-			-	
	L		-			-			-			-	

Subject 3 sh/st

Condition and level		Peak 1 R	Peak 1 f	Peak 1 θ	Dip R	Dip f	Dip θ	Peak 2 R	Peak 2 f	Peak 2 θ	Peak 3 R	Peak 3 f	Peak 3 θ
1	H	1.85	4.60	58	0.57	8.20	94	0.67	9.70	93		-	
	H	1.85	4.50	62	0.31	8.70	112	0.45	10.8	109		-	
	M	1.90	4.60	51	0.20	8.70	255	0.47	12.5	457		-	
	M	1.90	4.60	37	0.28	9.80	340	0.50	11.8	453		-	
	L	1.85	5.10	56	0.36	8.80	260	0.72	13.7	418		-	
	L	1.84	5.10	55	0.36	8.20	230	0.83	13.7	417		-	
2	H	1.72	4.80	35		-			-			-	
	H	1.86	4.60	50	0.22	8.50	125	0.45	9.80	73		-	
	M	1.56	3.90	35	0.27	9.70	360	0.43	12.2	443		-	
	M	1.58	3.90	27	0.32	10.0	385	0.45	12.5	285		-	
	L	1.82	5.00	54	0.40	8.50	222	0.73	13.5	410		-	
	L	1.78	5.00	55	0.42	8.50	240	0.65	14.1	423		-	
3	H	2.04	4.10	65	0.45	8.40	90	0.64	10.4	90		-	
	H	1.96	4.10	55	0.24	8.50	10	0.63	10.6	100		-	
	M	1.90	3.80	40	0.27	8.90	330	0.73	11.8	460		-	
	M	1.83	3.70	38	0.34	9.00	345	0.78	11.2	459		-	
	L	1.77	3.90	33	0.13	8.40	300	0.75	12.5	397		-	
	L	1.74	3.70	40	0.16	8.20	180	0.65	13.2	425		-	
4	H	1.42	3.50	23	0.34	8.40	75	0.80	10.5	72		-	
	H	1.78	4.70	50	0.25	8.60	85	0.79	11.2	75		-	
	M	1.56	3.70	27	0.27	6.50	270	0.75	12.8	430		-	
	M	1.50	3.70	25	0.39	9.40	306	0.72	12.2	425		-	
	L	1.63	3.80	27	0.28	8.00	330	1.10	13.6	401		-	
	L	1.55	3.90	30	0.29	8.10	235	1.16	13.5	400		-	
5	H	2.25	4.00	45	0.35	8.80	90	0.52	10.4	92		-	
	H	2.50	4.10	49	0.35	8.80	105	0.56	11.6	104		-	
	M	2.43	4.20	50	0.28	9.50	254	0.55	12.8	453		-	
	M	2.54	4.60	60	0.28	9.30	290	0.60	12.5	442		-	
	L	2.60	4.70	47	0.70	11.4	355	0.83	13.5	410		-	
	L	2.82	4.80	37	0.70	11.5	365	0.86	13.8	420		-	
6	H	1.74	4.50	60	0.19	8.30	133	0.55	10.2	93		-	
	H	1.75	4.40	58	0.11	8.60	60	0.80	11.0	92		-	
	M	1.83	4.30	51	0.61	8.00	235	0.63	9.30	330		-	
	M	1.77	4.50	57	0.65	7.80	235	0.59	9.80	345		-	
	L	1.75	4.40	45	0.65	9.80	327	0.80	13.0	414		-	
	L	1.86	4.70	50	0.83	11.2	358	0.88	13.6	416		-	
7	H	1.28	2.80	16	0.29	8.10	71	1.00	12.0	86		-	
	H	1.30	2.80	12	0.26	8.60	68	1.12	12.0	76		-	
	M	1.38	3.20	18	0.24	8.00	140	1.10	12.4	430		-	
	M	1.33	3.20	17	0.34	7.70	125	1.00	12.7	432		-	
	L	1.47	3.40	21	0.25	7.20	130	1.20	14.2	400		-	
	L	1.50	3.80	26	0.25	7.50	220	1.23	13.8	390		-	
8	H	2.00	4.40	55	0.15	14.0	96		-			-	
	H	2.22	4.20	45		-			-			-	
	M	2.31	4.40	70	0.25	10.0	108	0.34	12.5	100		-	
	M	2.22	4.70	50	0.25	10.0	127	0.35	12.0	102		-	
	L	2.20	4.80	50	0.20	9.80	45	0.45	13.5	88		-	
	L	2.32	5.70	70	0.23	9.50	97	0.47	13.6	70		-	

Table 5

DATA FOR SHOULDER RESPONSE (S'S 4, 5 AND 6)

Subject 4 sh/st

Condition and level		Peak 1 R	Peak 1 S	Peak 1 θ	Dip R	Dip S	Dip θ	Peak 2 R	Peak 2 S	Peak 2 θ	Peak 3 R	Peak 3 S	Peak 3 θ
1	H	1.66	4.10	42	0.47	9.80	79	0.58	16.6	106		-	
	H	1.58	4.50	48	0.59	7.40	99	0.77	11.8	101		-	
	M	1.86	3.80	42	0.19	7.10	60	0.86	14.0	95		-	
	M	1.90	3.70	40	0.19	8.00	65		-			-	
	L	2.07	4.20	45	0.22	7.90	230	0.88	13.2	77		-	
	L	1.94	4.20	34	0.10	8.20	240	0.85	15.5	460		-	
2	H	1.78	4.30	35	0.48	15.2	151	0.54	13.6	141	0.55	17.2	161
	H	1.53	5.00	58	0.55	8.70	86	0.56	9.90	91		-	
	M	1.55	4.20	35	0.20	8.10	84	0.63	11.0	82		-	
	M	1.57	3.50	24	0.34	8.40	89	0.70	11.0	90		-	
	L	1.96	4.80	50	0.31	7.80	101	0.74	12.0	75		-	
	L	1.80	5.00	49	0.22	8.30	87	0.85	11.8	70		-	
3	H	2.34	4.40	48	0.61	7.20	73	0.98	10.0	82		-	
	H	2.04	3.80	37	0.45	7.70	98	0.79	11.5	100		-	
	M	1.88	3.80	40	0.25	7.70	285	0.70	12.4	85		-	
	M	1.95	4.00	39	0.31	7.90	260	0.70	12.5	85		-	
	L	2.27	4.60	55	0.36	7.80	270	1.00	14.0	448		-	
	L	2.27	4.60	55	0.48	7.70	245	1.00	13.0	417		-	
4	H	1.50	4.00	35	0.71	6.60	61	1.24	12.2	82			
	H	1.50	3.30	35	0.15	8.00	320	1.05	12.5	445			
	M	1.60	3.60	35	0.12	8.10	260	1.09	12.5	82		-	
	M	1.62	3.50	32	0.27	8.20	250	1.16	13.0	82		-	
	L	1.78	4.00	41	0.34	8.10	240	1.28	14.2	440		-	
	L	1.74	3.60	27	0.15	8.20	290	1.15	15.5	458		-	
5	H	2.64	3.60	55	0.45	7.80	130	0.54	9.50	120		-	
	H	2.94	3.90	50	0.47	8.00	126	0.56	9.50	112		-	
	M	2.98	3.80	95	0.05	9.00	360	0.50	13.0	472		-	
	M	2.78	4.20	62	0.12	9.80	305	0.55	12.5	463		-	
	L	2.76	4.50	50	0.09	9.40	172	0.68	12.5	81		-	
	L	2.88	4.50	43	0.15	9.40	125	0.68	14.0	96		-	
6	H	1.82	3.80	47	0.17	7.60	130	0.58	10.8	94		-	
	H	1.85	4.70	58	0.50	7.30	120	0.63	9.40	98		-	
	M	1.94	3.70	43	0.25	9.10	355	0.60	11.4	425		-	
	M	2.36	3.80	50	0.31	8.80	325	0.58	13.2	470		-	
	L	2.21	4.40	56	0.35	8.20	260	0.77	13.0	440		-	
	L	2.55	4.20	50	0.34	9.30	350	0.71	11.0	418	0.75	14.0	452
7	H	1.83	5.20	74	0.72	7.20	43	1.32	9.40	90		-	
	H	1.75	6.20	45	0.65	7.00	72	1.28	9.40	87		-	
	M	1.83	3.60	30	0.59	7.20	70	1.28	10.8	83		-	
	M	2.00	4.50	58	0.17	7.90	70	1.18	10.8	80		-	
	L	1.83	3.90	30	0.11	7.70	260	1.16	12.5	440		-	
	L	2.38	4.10	52	0.10	8.10	260	1.21	11.8	437		-	
8	H	2.01	4.30	48	0.33	8.70	140	0.55	13.0	107		-	
	H	2.16	4.50	62	0.51	7.90	115	0.58	9.00	96		-	
	M	2.35	4.50	57	0.25	9.50	140	0.36	10.7	121		-	
	M	2.13	4.40	57	0.20	10.2	124		-			-	
	L	2.17	5.20	65	0.15	11.0	75	0.40	15.7	120		-	
	L	2.40	5.20	76	0.12	10.4	115	0.45	17.0	126		-	

Subject 5 sh/st

Condition and level		Peak 1 R	Peak 1 S	Peak 1 θ	Dip R	Dip S	Dip θ	Peak 2 R	Peak 2 S	Peak 2 θ	Peak 3 R	Peak 3 S	Peak 3 θ
1	H	2.04	5.00	68	0.07	8.70	126	0.86	10.6	102		-	
	H	1.81	4.80	64	0.21	9.00	100	0.93	10.8	108		-	
	M	1.90	4.50	45	0.24	8.50	230	0.80	10.0	425		-	
	M	2.05	4.80	50	0.37	8.80	285	0.86	14.2	445		-	
	L	2.13	5.30	58	0.11	8.90	305	0.95	13.2	425		-	
	L	2.06	5.30	64	0.23	8.60	210	0.96	13.7	437		-	
2	H	1.74	5.10	65	0.16	9.80	430	0.65	11.2	105		-	
	H	1.76	4.80	53	0.37	8.90	130	0.66	10.8	104		-	
	M	2.10	5.40	60	0.18	9.20	290	0.77	10.6	450		-	
	M	2.00	5.00	58	0.13	9.30	288	0.86	11.4	437		-	
	L	2.40	5.50	63	0.14	9.40	365	0.69	13.4	435		-	
	L	2.22	5.50	64	0.11	9.10	355	0.56	12.8	425		-	
3	H	2.26	6.60	60	0.41	8.80	105	0.83	10.6	116		-	
	H	2.35	6.80	70	0.32	9.10	116	0.69	11.3	118		-	
	M	2.22	4.80	60	0.25	9.70	380	0.79	11.4	456		-	
	M	2.18	4.60	47	0.45	8.50	255	0.89	12.9	458		-	
	L	2.49	5.30	60	0.36	9.20	312	0.75	14.0	458		-	
	L	2.44	5.20	64	0.18	9.30	345	1.10	14.6	430		-	
4	H	1.74	5.10	54	0.51	8.80	78	1.00	10.6	88		-	
	H	1.56	4.50	41	0.55	8.70	87	0.97	11.0	92		-	
	M	1.65	4.50	42	0.35	8.60	270	1.08	11.8	458		-	
	M	1.48	4.00	33	0.16	8.00	340	0.92	14.1	449		-	
	L	1.76	4.30	26	0.22	9.10	336	0.88	14.6	456		-	
	L	1.75	4.30	37	0.11	9.00	30	1.06	13.6	78		-	
5	H	2.24	4.20	53	0.63	9.00	107	0.66	10.0	102		-	
	H	2.47	4.40	55	0.57	9.10	87	0.64	10.2	97		-	
	M	2.26	5.10	55	0.30	9.50	125	0.58	12.8	96		-	
	M	2.27	5.10	62	0.37	11.2	108	0.50	14.2	147		-	
	L	2.96	5.70	72	0.07	11.0	253	0.70	14.6	445		-	
	L	2.70	5.60	62	0.18	10.6	290	0.73	14.2	430		-	
6	H	1.77	4.50	55	0.48	8.80	95	0.81	10.4	105		-	
	H	1.75	4.50	54	0.26	9.20	105	0.69	11.3	95		-	
	M	1.89	4.30	45	0.19	9.20	317	0.69	12.8	104		-	
	M	1.89	4.50	45	0.10	8.90	280	0.58	11.4	427		-	
	L	2.35	4.80	51	0.20	9.00	325	0.85	12.7	427	0.76	14.7	106
	L	2.34	5.20	64	0.24	9.80	53	0.80	13.7	84	0.75	15.6	94
7	H	1.63	5.00	52	0.48	8.40	55	1.51	10.0	73		-	
	H	1.88	5.10	57	0.47	9.70	113	0.63	12.4	137		-	
	M	1.68	4.60	47	0.55	8.20	210	0.80	11.2	365		-	
	M	1.71	4.90	42	0.29	9.00	290	0.87	10.8	310		-	
	L	1.85	5.10	56	0.52	8.10	240	1.00	12.9	415		-	
	L	1.89	5.00	93	0.14	8.60	180	0.80	12.0	425	0.80	14.5	458
8	H	2.31	4.70	61	0.41	9.30	127	0.46	10.5	124		-	
	H	2.38	4.80	70	0.44	9.50	128	0.50	10.5	131		-	
	M	2.94	4.70	60	0.09	8.80	320	0.65	12.8	118		-	
	M	2.78	4.70	58	0.24	8.80	335	0.67	12.5	100		-	
	L	2.43	5.10	70	0.20	8.70	260	0.77	7.40	451		-	
	L	2.50	5.00	62	0.32	9.70	103	0.43	8.10	102		-	

Subject 6 sh/st

Condition and level		Peak 1 R	Peak 1 S	Peak 1 θ	Dip R	Dip S	Dip θ	Peak 2 R	Peak 2 S	Peak 2 θ	Peak 3 R	Peak 3 S	Peak 3 θ
1	H	2.06	3.80	47	0.80	9.56	141	0.84	10.7	145		-	
	H	2.06	3.80	28	?.50	9.20	125	0.75	11.5	130		-	
	M	2.26	4.30	50	0.29	10.2	310	0.75	14.8	482		-	
	M	2.10	4.40	47	0.37	10.1	343	0.75	13.2	463		-	
	L	2.53	4.60	60	0.32	10.4	334	1.00	15.0	460		-	
	L	2.10	4.70	53	0.35	10.2	300	0.86	15.4	460		-	
2	H	1.94	4.70	60	0.40	9.70	114	0.55	11.2	98	0.58	13.0	122
	H		-			-			-			-	
	M	2.56	4.80	55	0.14	9.80	345	0.70	13.6	471		-	
	M	2.33	5.10	65	0.30	9.20	105	0.68	12.6	117		-	
	L	2.00	4.50	44	0.13	10.7	75	1.08	15.1	85		-	
	L	2.27	4.70	58	0.07	10.0	330	1.05	15.3	470		-	
3	H	2.06	3.90	41	0.44	9.10	121	0.75	10.7	124	0.74	12.1	140
	H		-			-			-			-	
	M	2.35	4.00	50	0.23	10.4	360	0.70	15.2	497		-	
	M	2.29	4.20	52	0.27	8.50	262	0.77	15.3	483		-	
	L	2.28	4.50	55	0.09	10.5	-30	1.10	15.0	68		-	
	L	2.15	4.50	52	0.50	10.0	340	1.14	15.0	44		-	
4	H	1.85	3.80	30	0.45	9.20	125	1.05	10.8	118		-	
	H		-			-			-			-	
	M	2.00	3.80	43	0.24	9.40	285	0.86	12.7	463		-	
	M	2.27	4.00	52	0.25	9.60	315	0.80	12.3	470		-	
	L	2.41	4.30	60	0.30	9.20	220	1.28	15.0	439		-	
	L	2.30	4.20	40	0.43	9.50	307	1.36	15.2	445		-	
5	H	3.48	4.60	77	0.56	9.00	135	0.83	11.6	127		-	
	H		-			-			-			-	
	M	3.32	4.90	70	0.32	10.6	340	0.75	16.0	500		-	
	M	3.25	5.10	66	0.25	9.50	455	0.75	15.2	478		-	
	L	3.06	5.20	68	0.41	11.1	340	0.96	14.8	440		-	
	L	2.95	5.60	75	0.61	11.8	335	1.07	15.6	452		-	
6	H	2.16	4.50	60	0.33	9.10	125	0.65	11.8	128		-	
	H		-			-			-			-	
	M	2.55	4.60	65	0.50	9.90	337	0.69	14.0	465		-	
	M	2.40	4.50	63	0.35	9.50	385	0.74	15.2	488		-	
	L	2.44	4.70	63	0.50	10.5	320	1.04	14.6	440		-	
	L	2.25	4.60	57	0.41	11.0	332	0.82	16.2	472		-	
7	H	1.60	4.50	50	0.28	9.40	138	0.85	13.2	125		-	
	H		-			-			-			-	
	M	1.76	3.70	33	0.32	9.00	240	0.80	12.9	458	0.81	15.6	482
	M	1.74	4.00	40	0.53	10.5	355	0.75	12.2	444	0.75	14.0	457
	L	1.96	4.70	47	0.38	9.50	230	0.93	16.1	468		-	
	L	1.87	4.20	32	0.53	7.10	240	0.78	15.2	452		-	
8	H	2.44	4.50	55	0.39	10.1	101	0.45	14.0	106		-	
	H		-			-			-			-	
	M	2.65	4.80	60	0.29	10.5	117	0.42	14.2	105		-	
	M	2.68	4.60	65	0.22	10.2	125	0.52	14.0	97		-	
	L	2.35	5.10	60	0.15	11.6	110	0.52	16.0	109		-	
	L	2.52	5.00	51	0.06	11.5	100	0.58	16.4	105		-	

Table 6

SUBJECT AVERAGE (OVER SIX SUBJECTS) RESPONSE - VARIATION WITH INPUT AND POSTURE

Condition and level		Average hd/st								
		Peak 1			Dip			Peak 2		
		R	f	θ	R	f	θ	R	f	θ
1	H	1.21	3.35	18	0.46	6.98	17	1.88	10.9	44
	M	1.25	3.54	23	0.28	7.99	151	1.83	13.3	419
	L	1.31	3.83	25	0.41	7.30	140	1.92	13.8	337
2	H	1.12	3.92	19	0.58	7.77	17	1.80	12.2	47
	M	1.21	3.55	18	0.20	8.07	115	1.80	13.5	407
	L	1.25	3.80	21	0.23	7.93	137	1.82	15.4	397
3	H	1.43	3.52	26	0.43	7.51	25	1.70	11.0	60
	M	1.38	3.63	30	0.28	8.19	156	1.46	12.4	416
	L	1.44	4.05	36	0.45	7.84	191	1.66	13.8	395
4	H	1.23	3.37	22	0.45	7.59	27	1.63	12.2	57
	M	1.37	3.23	23	0.29	7.78	136	1.67	13.8	418
	L	1.38	3.85	28	0.46	7.81	167	1.85	14.4	393
5	H	1.54	3.88	28	0.53	7.88	41	1.62	12.2	59
	M	1.62	4.27	25	0.60	9.10	134	1.60	13.8	417
	L	1.61	4.10	23	0.49	9.13	185	1.68	14.2	402
6	H	1.24	3.34	19	0.38	7.95	32	1.67	11.7	57
	M	1.32	3.49	25	0.35	7.85	144	1.67	13.5	409
	L	1.40	3.89	31	0.44	8.05	176	1.70	13.7	382
7	H	1.19	3.10	16	0.63	7.23	24	1.61	9.35	42
	M	1.20	3.32	14	0.32	7.71	128	1.65	13.3	405
	L	1.37	3.87	22	0.25	7.94	137	1.77	14.2	386
8	H	1.34	4.10	31	0.50	7.96	66	0.88	10.6	59
	M	1.40	3.91	30	0.28	8.85	92	0.87	12.4	436
	L	1.44	4.22	35	0.20	9.04	147	0.85	13.5	410

Condition and level		Average sh/st								
		Peak 1			Dip			Peak 2		
		R	f	θ	R	f	θ	R	f	θ
1	H	1.89	4.28	54	0.41	8.72	107	0.69	11.5	112
	M	1.98	4.14	47	0.26	9.09	268	0.72	13.1	454
	L	2.05	4.47	49	0.28	9.38	275	0.79	14.2	429
2	H	1.84	4.56	54	0.34	9.01	117	0.57	11.1	105
	M	1.91	4.25	45	0.25	9.30	303	0.69	12.5	95
	L	2.00	4.63	49	0.26	9.53	238	0.74	13.5	431
3	H	2.12	4.53	55	0.38	8.59	107	0.72	10.8	109
	M	2.12	4.00	51	0.31	9.09	287	0.71	12.8	473
	L	2.18	4.32	50	0.31	9.35	284	0.87	13.8	435
4	H	1.67	3.85	41	0.44	8.21	86	0.96	11.1	92
	M	1.82	3.74	39	0.29	8.74	274	1.12	12.4	449
	L	1.93	3.97	39	0.27	8.62	253	1.11	13.9	429
5	H	2.52	3.99	59	0.37	8.64	113	0.64	10.8	110
	M	2.80	4.40	62	0.29	9.87	289	0.63	13.4	468
	L	2.92	4.79	55	0.44	10.9	286	0.81	14.0	429
6	H	1.90	4.08	58	0.29	8.25	109	0.63	10.8	104
	M	2.02	4.07	52	0.37	9.15	322	0.66	12.4	421
	L	2.24	4.40	58	0.40	9.79	310	0.81	13.3	418
7	H	1.62	4.16	44	0.59	8.53	74	1.19	11.3	96
	M	1.69	3.99	40	0.43	8.59	236	1.11	12.2	413
	L	1.89	4.05	40	0.28	8.38	237	1.21	13.4	433
8	H	2.22	4.35	58	0.29	10.1	111	0.48	11.2	110
	M	2.27	4.49	62	0.23	9.92	158	0.43	12.7	105
	L	2.36	4.89	62	0.18	10.5	156	0.48	15.1	95

Table 7

INTER SUBJECT AVERAGE DATA

Peak		Condition	Subject S1	S2	S3	S4	S5	S6	Mean	Maximum % deviations
1st	Head	Normal	1.37/3.50	1.22/3.32	1.08/3.10	1.25/3.57	1.20/4.00	1.43/4.02	1.25/3.59	14-15/14-12
		Back off	1.32/3.80	1.43/3.58	1.28/4.02	1.39/4.12	1.38/4.40	1.62/4.50	1.40/4.07	9-16/12-11
2nd		Normal	1.67/12.7	2.17/12.0	1.67/13.4	1.98/12.8	2.13/12.5	1.58/13.2	1.87/12.8	16-16/ 6-5
		Back off	0.55/11.5	0.79/11.4	0.77/12.7	0.85/11.7	1.05/12.2	1.18/13.7	0.86/12.2	36-37/ 7-12
1st	Shoulders	Normal	2.12/3.80	1.83/4.00	1.86/4.75	1.85/4.08	2.00/4.95	2.19/4.27	1.97/4.31	7-11/12-15
		Back off	2.32/4.42	2.25/4.06	2.21/4.61	2.20/4.68	2.56/4.83	2.53/4.80	2.35/4.57	6-9/11-6
2nd		Normal	0.71/12.8	0.70/13.7	0.61/12.0	0.79/14.2	0.89/12.1	0.83/13.4	0.76/13.0	20-17/ 7-9
		Back off	0.36/12.3	0.25/12.7	0.40/12.9	0.47/13.1	0.58/10.3	0.50/14.9	0.43/12.7	42-35/19-18

The figures given are values of R_{max}/f_{max} for the two major peaks for subjects 1 to 6 and normal posture and back off posture. The % deviations give the maximum variation of the data about the mean (for the lowest and highest values).

R_{max} = peak transmissibility

f_{max} = frequency in Hz at which R_{max} occurs

Table 8

CORRELATION COEFFICIENTS OF VIBRATION RESPONSE V SUBJECT CHARACTERISTICS

	Head/seat								Shoulder/seat							
	1st peak				2nd peak				1st peak				2nd peak			
	1		8		1		8		1		8		1		8	
	R_{max}	f_{max}	R_{max}	f_{max}	R_{max}	f_{max}	R_{max}	f_{max}	R_{max}	f_{max}	R_{max}	f_{max}	R_{max}	f_{max}	R_{max}	f_{max}
Age	-0.25	0.58	0.13	0.73	0.20	0.13	0.70	0.47	0.16	0.90**	0.73	0.67	0.59	-0.59	0.77*	-0.45
Weight	-0.86*	-0.70	-0.78*	-0.26	-0.05	0.30	-0.40	-0.08	-0.51	0.52	-0.43	-0.08	-0.67	-0.69	-0.17	-0.35
Height	-0.72	-0.30	-0.33	-0.21	0.44	-0.27	0.33	-0.07	-0.44	0.62	0.04	-0.26	-0.24	-0.60	-0.17	-0.52

Each block contains the linear correlation coefficient averaged over all the subjects' R_{max} and f_{max} values against the subject characteristics in the first column. Thus the first block gives a coefficient of -0.25 for age against the R_{max} values for the first peak at the head and a coefficient of 0.58 against the f_{max} value for the same first peak.

* = 5% significance

** = 1% significance

REFERENCES

No.	Author	Title, etc
1	C. Ashley B.K.N. Rao	Equal sensation study of differential vibration between seat and feet. Birmingham University, report in preparation
2	J.S. Bendat A.G. Piersol	Random data: analysis and measurement procedures. Pub: J. Wiley and Sons Inc. (1971)
3	British Standards Institute	Draft for development. Guide to the safety aspects of human vibration experiments. DD23 (1973)
4	British Standards Institute	Draft for development. Guide to the evaluation of human exposure to whole body vibration. DD32 (1974)
5	B. Caiger	Some effects of vertical vibration on a pilot's head motion and his instrument reading ability. NRC, Ottowa (1966) Aero Rep. LR-463
6	P.C. Calcaterra D.W. Schubert	Active isolation of human subjects from severe dynamic environments. ASME 69-VIBR-65
7	R.E. Chaney	Whole body vibration of standing subjects. Mil. Aero Division, Boeing D3-6779 (1965)
8	W.S. Clark K.O. Lange R.R. Coermann	Deformation of the human body due to unidirectional forced sinusoidal motion. Human Factors, 4(5), pp.255-274 (1962)
9	R.R. Coermann	The mechanical impedance of the human body in sitting and standing position at low frequencies. Human Factors, 4(5), pp.227-253 (1962)
10	R.R. Coermann	The passive dynamic mechanical properties of the human thorax-abdomen system and of the whole body system. Aerosp. Med. 31, pp.443-455 (1960)
11	D.A. Dieckmann	A study of the influence of vibration on man. Ergonomics, 1(4), pp.347-355 (1958)

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REFERENCES (continued)

No.	Author	Title, etc
12	F.P. DiMasi *et al.*	Effect of vertical active vibration isolation on tracking performance and on ride qualities. NASA-CR-2146
13	R.G. Edwards K.O. Lange	A mechanical impedance investigation of human response to vibration. AMRL-TR-64-91
14	K.V. Frolov	Dependence on position of the dynamic characteristics of a human operator subjected to vibration. ASME Conf. Proc. "Dynamic Response of Biomechanical Systems" (1972)
15	H. von Gierke	Dynamic characteristics of the human body. AMRL unpublished communication
16	D.E. Goldman	Biological effects of vibration, National Research Council, Washington DC, Report NONR 2300(05)
17	J.A. Gillies (Ed.)	Textbook of Aviation Physiology. Pergamon Press
18	M. Griffin	Whole body vibration and human vision. ISVR Southamption University Ph.D Thesis
19	M. Griffin	Transmission of tri-axial vibration to pilots in the Scout helicopter. ISVR Southampton University Report 58
20	J.C. Guignard P.F. King	Aeromedical aspects of vibration and noise. AGARDograph 151
21	J.C. Guignard A. Irving	Effects of low frequency vibration on man. Engineering, pp.364-367 (1960)
22	J.C. Guignard	Physiological effects of mechanical vibration, a selected bibliography Part I, body resonance phenomena. RAF/IAM Report 12 (1959)
23	J.C. Guignard	Physilolgical effects of mechanical vibration. *Proc. Roy. Soc. of Medicine*, 53, pp.92-96 (1960)

REFERENCES (continued)

No.	Author	Title, etc
24	G.N. Hoover	Biology of whole body mechanical vibration - annotated bibliography. Ohio State University Report 862 (1962)
25	R.J. Hornick N.M. Le Fritz	A study and review of human response to prolonged random vibration. Human Factors, 8(6), pp.481-492 (1966)
26	R.J. Hornick	Vibration isolation in the human leg. Human Factors, 4(5), pp.301-303 (1962)
27	R.J. Hornick C.A. Boettcher A.K. Simons	The effect of low frequency high amplitude whole body longitudinal and transverse vibration upon human performance. Report DA-11-022-509-ORD-3300, Bostram Research Labs, Mitwaukee (1961)
28	H.E. Krause K.O. Lange	Non-linear behaviour of biomechanical systems. ASME 63-WA-279
29	R.A. Lee F. Pradko	Analytical analysis of human vibration. SAE/AE Congress, Detroit, 1968, 680091
30	E.J. Lovesey	Transport vehicles vibration environment. Unpublished RAE Communication (1973)
31	J. Matthews	Ride comfort for tractor operators. J. of Agr. Eng. Res. Vol.9, No. 1 (1964)
32	J.F. Parker V.R. West	Bio-astronautics data book NASA SP-3006 (1973)
33	P.R. Payne	Dynamics of human restraint systems. Nat. Acad. of Scis. NRC/Publ. 1961, pp.195-258
34	B.A. Potemkin K.V. Frolov	Representation by models of the biomechanical system man-operator under the action of random vibrations. RAE Library Translation 1651 (Translated 1974)
35	F. Pradko R.A. Lee	Human vibration response theory. Biomechanics Monograph, ASME (1967)

REFERENCES (continued)

No.	Author	Title, etc
36	F. Pradko R.A. Lee V. Kaluza	Theory of human vibration response. ASME-1966, 66-WA/BHF-15
37	G.F. Rowlands	Transmission of harmonically distorted low frequency vibration to the head of the seated man. RAE Technical Report 72080 (1972)
38	G.F. Rowlands	Transmission of vertical vibration to the shoulder of the seated man. RAE Technical Memorandum EP540 (1975)
39	G.F. Rowlands	The RAE two-axis man carrying vibrator. RAE Technical Memorandum (1977)
40	I. Schmid	The seat as an element connecting the motor vehicle and man. Automob. Zeit, 74, p.4 (1972)
41	M.A. Schmitz A.K. Simons C.A. Boettcher	The effect of low frequency, high amplitude, whole body vertical vibration on human performance Report DA-49-007-MD-797, Bostrom Research Labs., Mitwaukee (1960)
42	C. Shurmer	Review of the effects of low frequency vibration on man and on his tracking performance. BAC (OP) Ltd., Hum. Fact. Study Note, Series 4, No.7
43	E.L. Stech P.R. Payne	Dynamic models of the human body. AMRL-TDR-WPAFB
44	C.W. Suggs C.F. Abrams L.F. Stikeleather	Application of a damped sprung-mass human vibration simulator in vibration testing of vehicle seats. Ergonomics, 12(1), pp.79-90 (1969)
45	E.B. Weiss W.S. Clarke H. von Gierke	Mechanical impedance as a tool in biomechanics. USAF, AMRL-TR-66-84
46	R.G. White	Evaluation of the dynamic characteristics of structures by transient testing. J. Sound Vib. 15(2), 147-161 (1971)

REFERENCES (concluded)

No.	Author	Title, etc
47	T.J. Whittman N.S. Phillips	Human body non-linearity and mechanical impedance analysis. AMRL-TR-66-126 (1966)
48	A.G. Woods	Human response to low frequency sinusoidal and random vibration. Aircraft Engineering, Aug 6-14 (1967)
49	R.J. Zember	Bibliography of research reports and publications issued by the Biodynamics and Bionics Division. AMRL covering 1963-1970, published by AMRL WPAFB, Ohio.

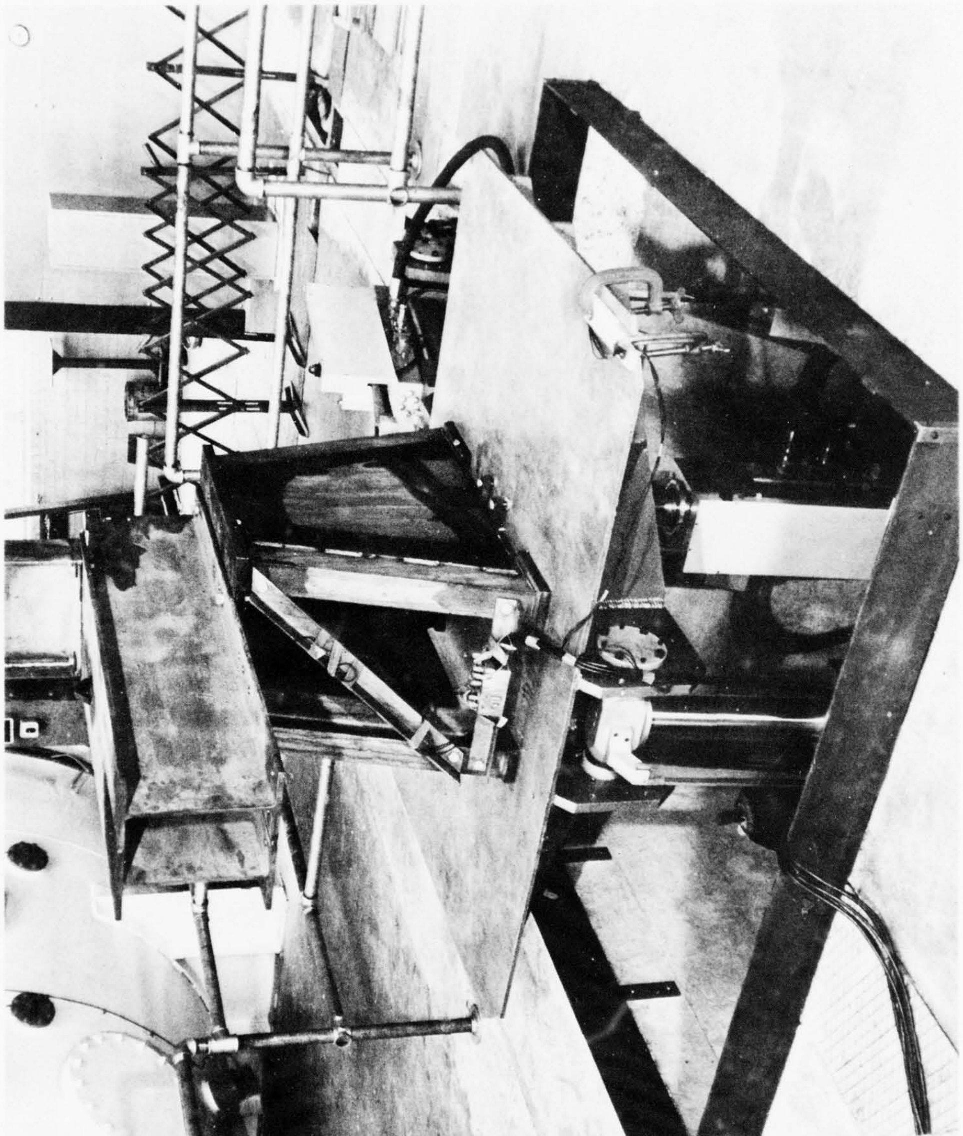

Fig 1 Vibration rig with 'test' load mounted

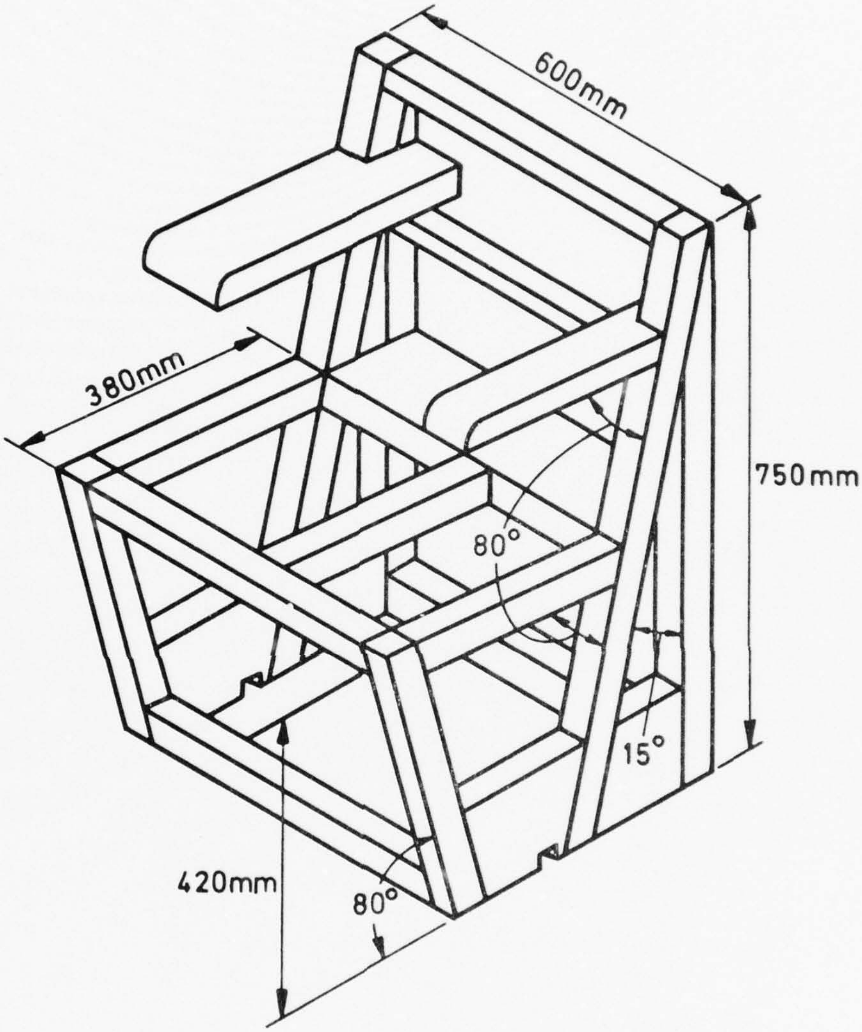

Fig 2 Schematic diagram of seat frame

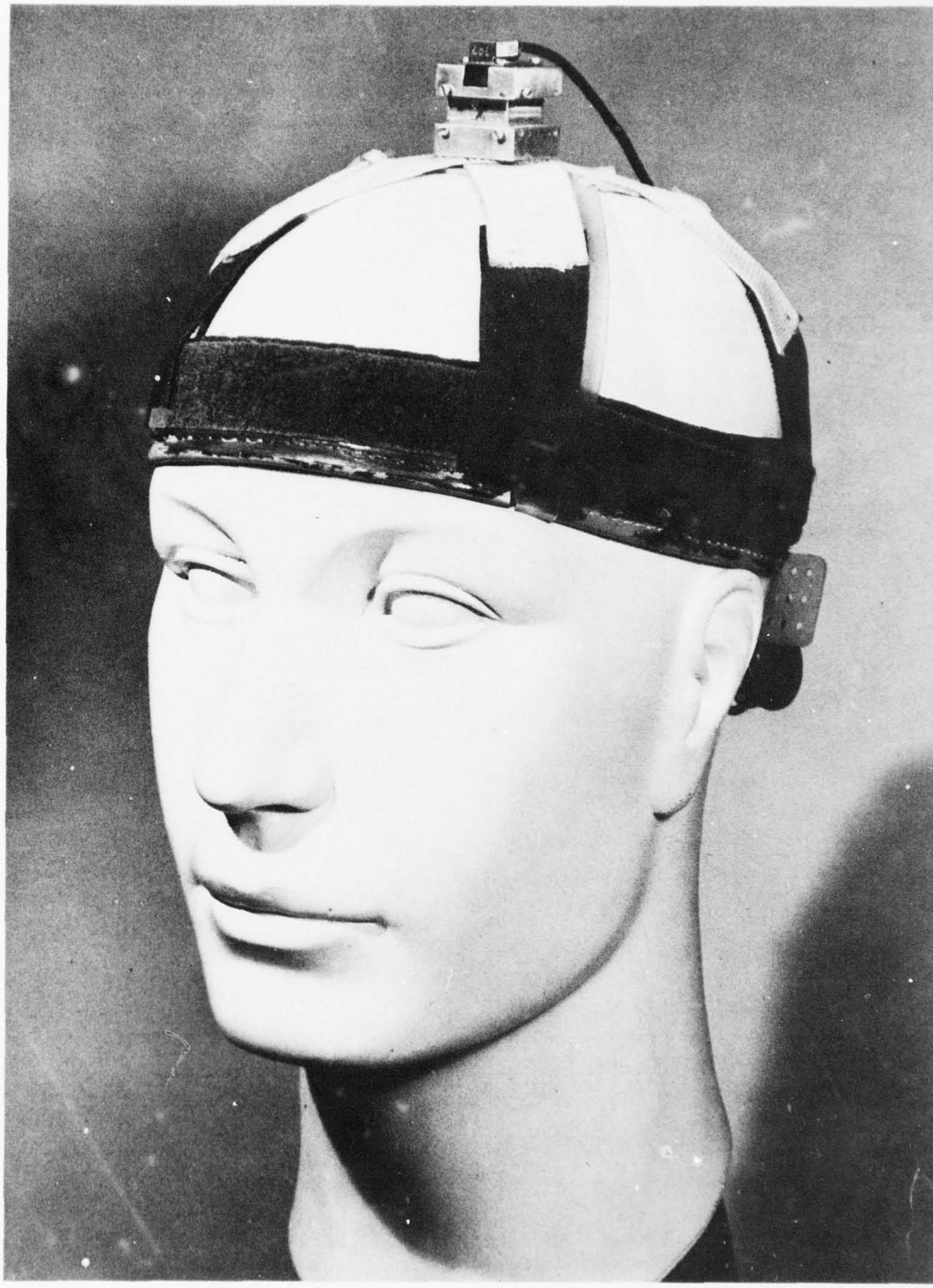

Fig 3 Head harness mounted on dummy head

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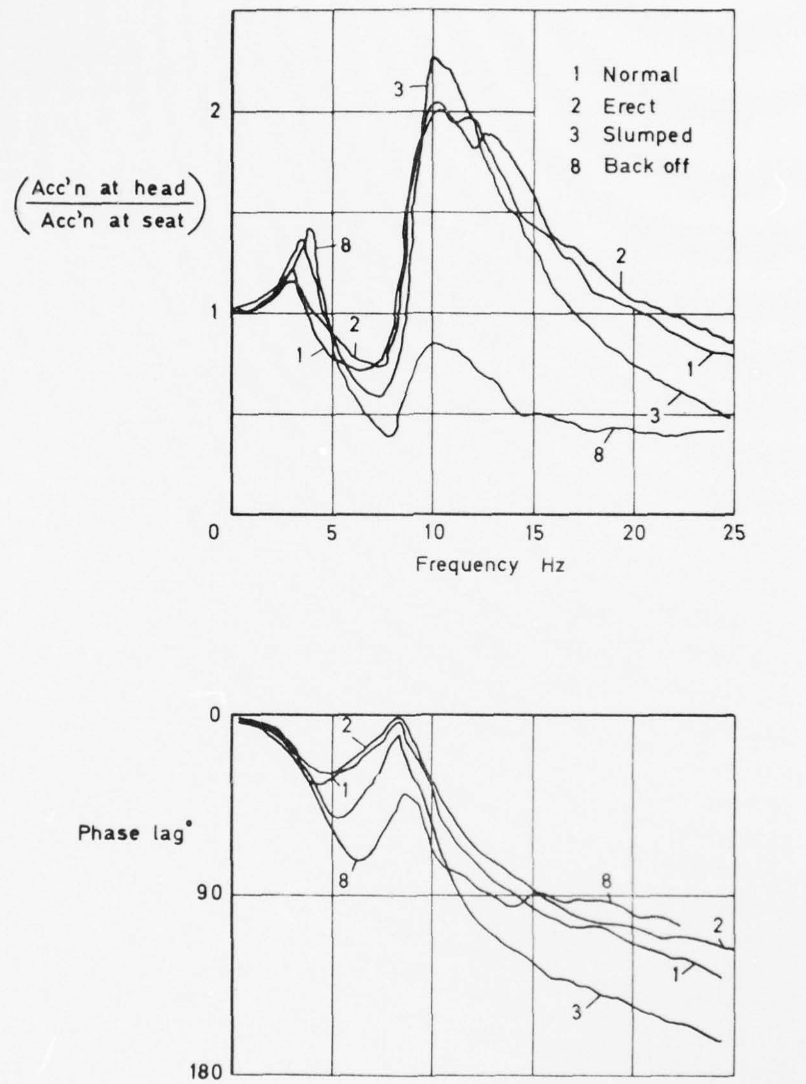

Fig 4 Frequency response of the head, high acceleration level – effect of posture (subject 2)

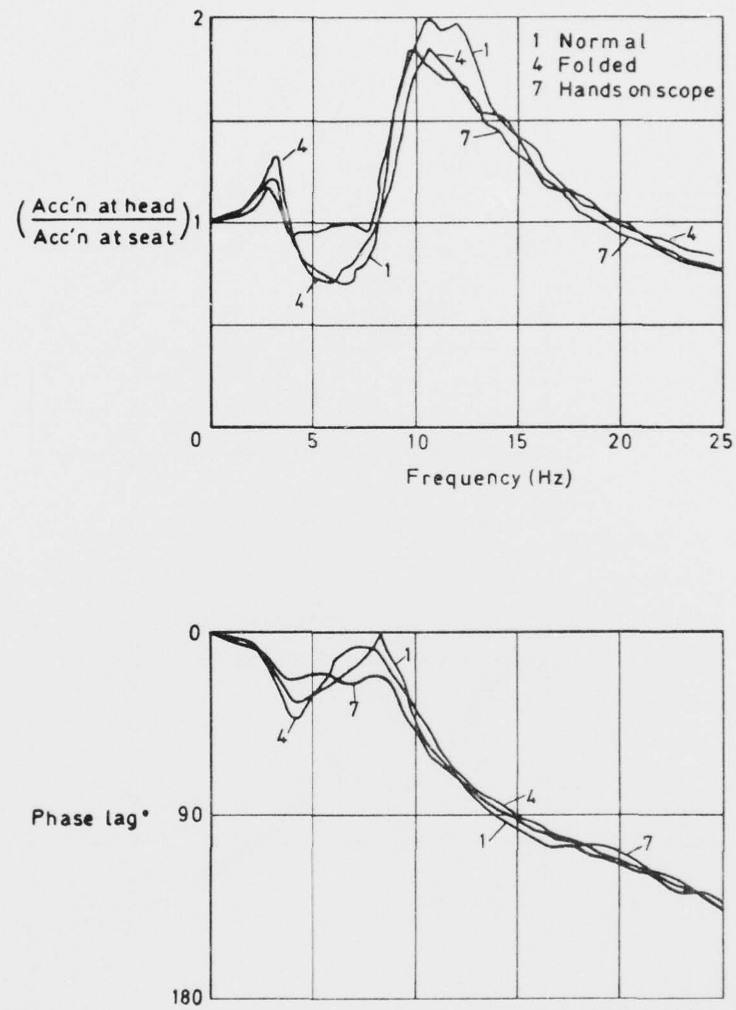

Fig 5 Frequency response of the head, high acceleration level – effect of arm position (subject 2)

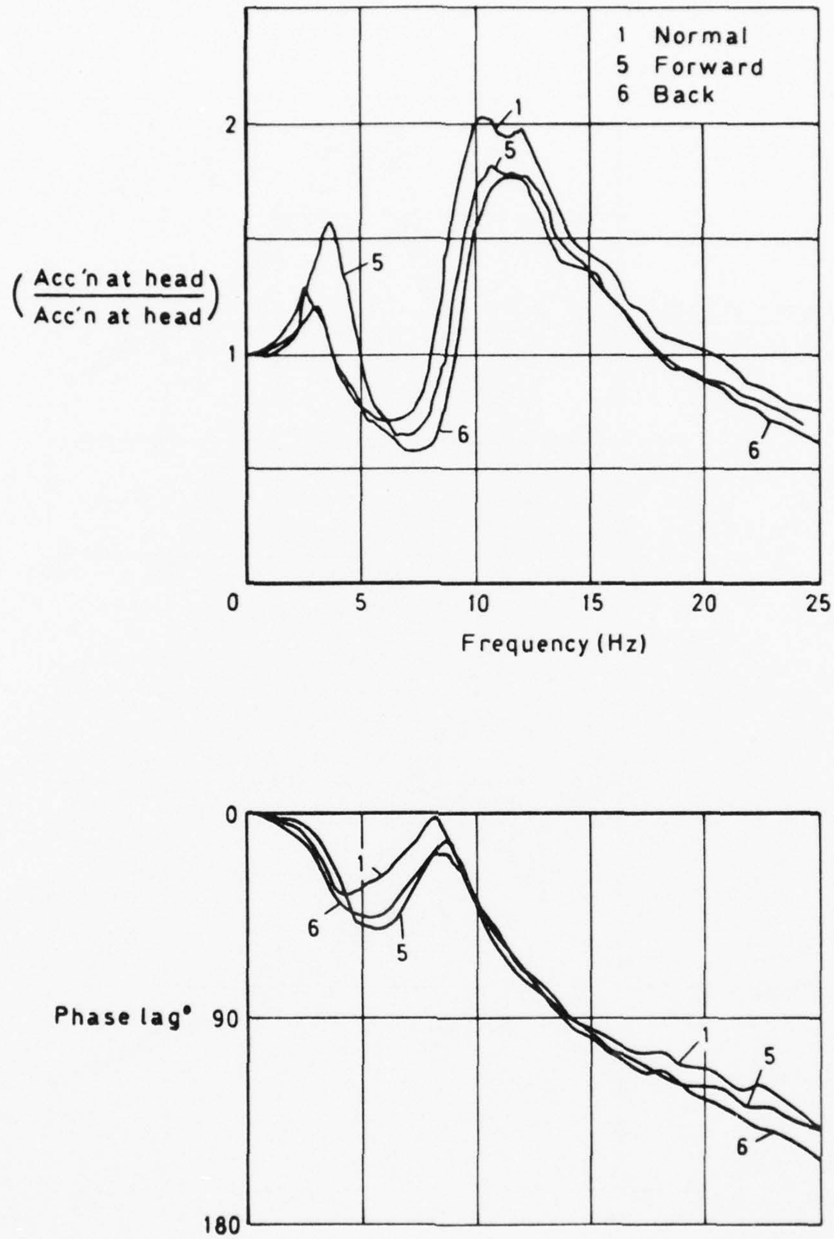

Fig 6 Frequency response of the head, high acceleration level – effect of leg position (subject 2)

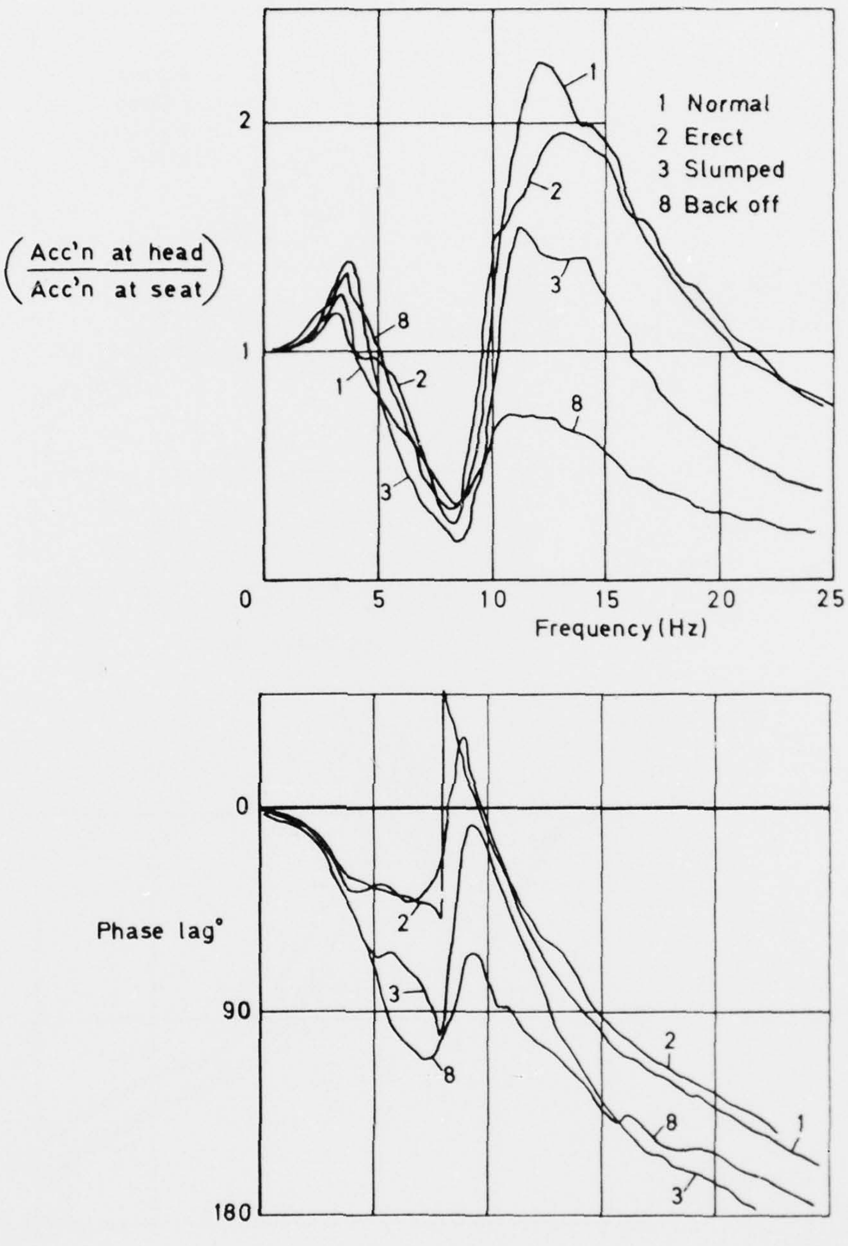

Fig 7 Frequency response of the head, medium acceleration level – effect of posture (subject 2)

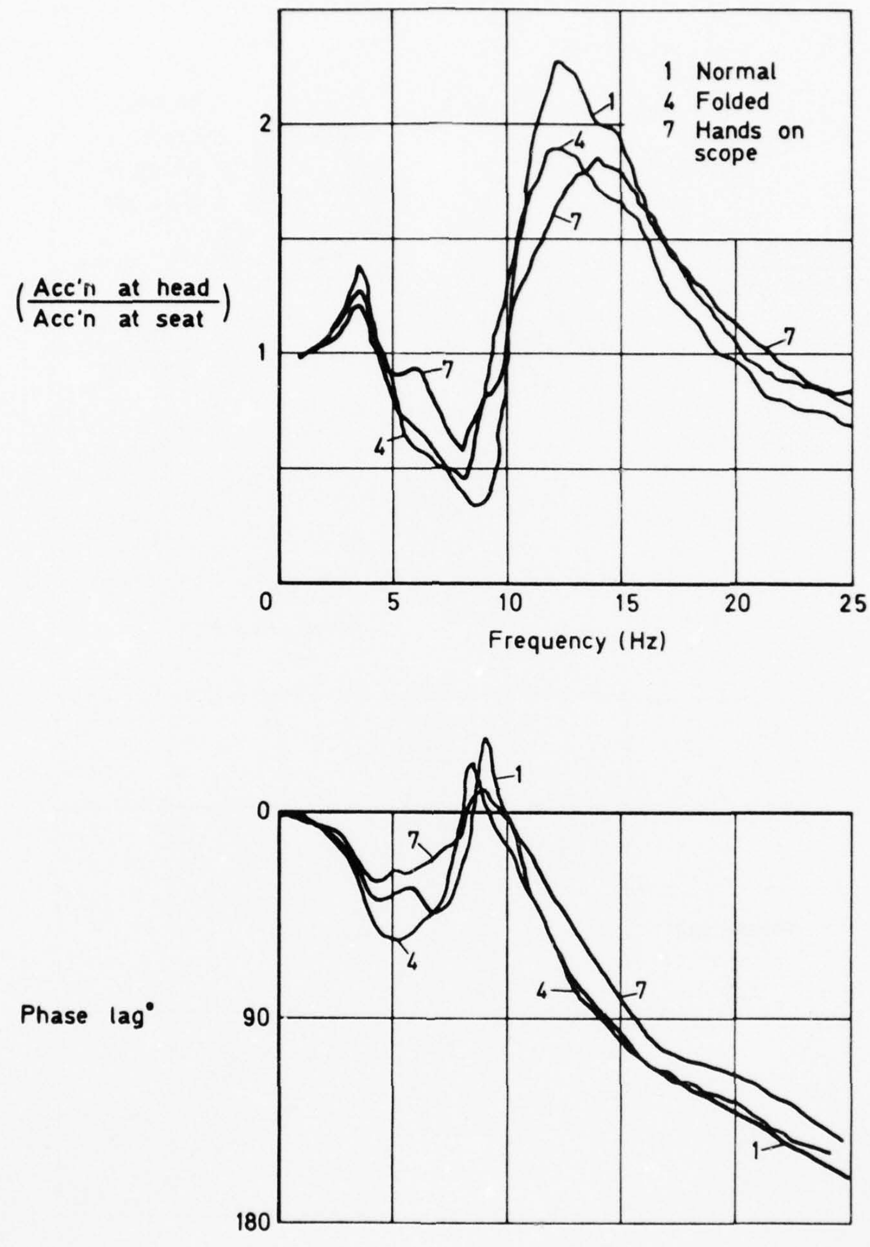

Fig 8 Frequency response of the head, medium acceleration level – effect of arm position (subject 2)

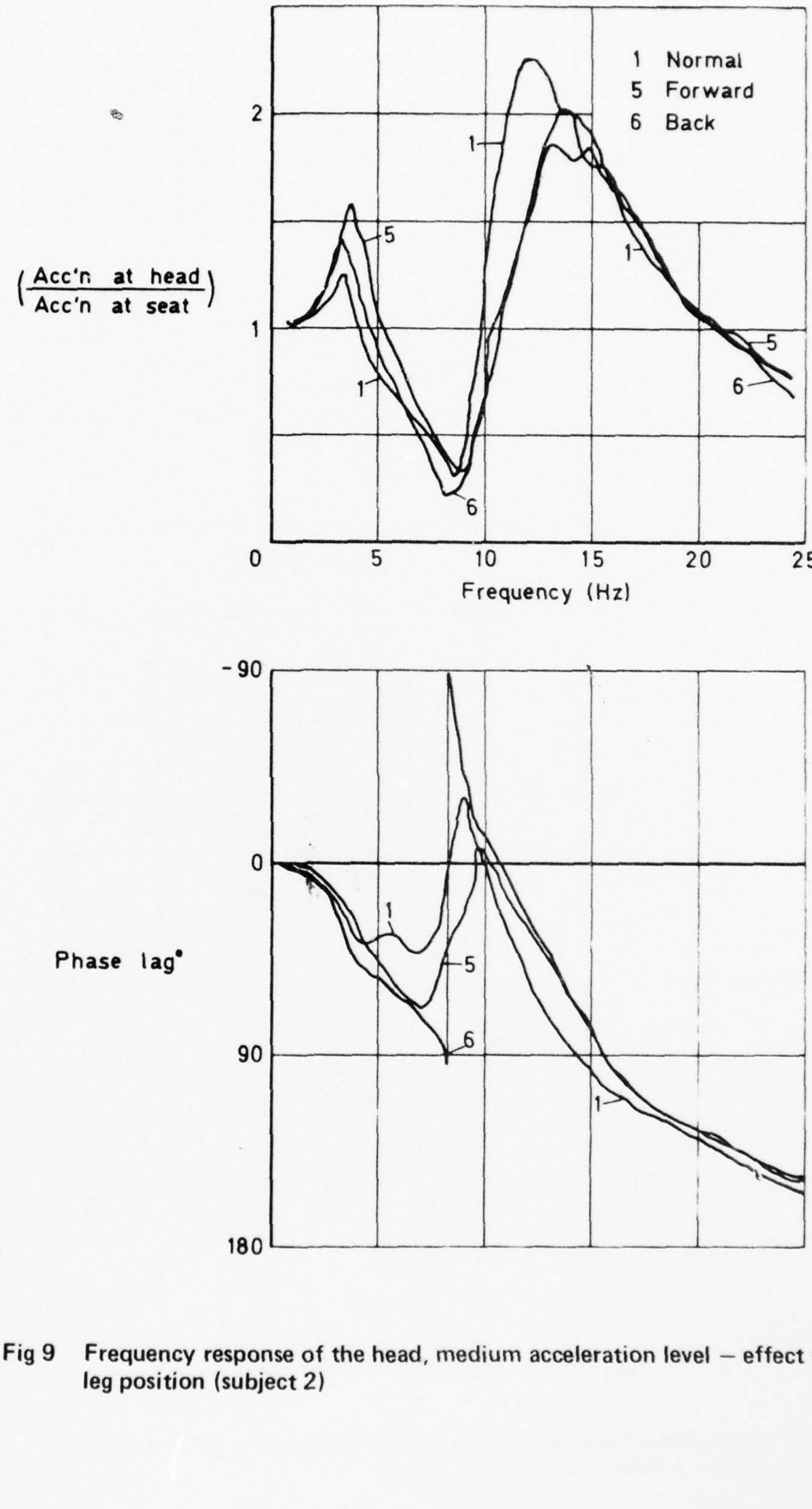

Fig 9 Frequency response of the head, medium acceleration level – effect of leg position (subject 2)

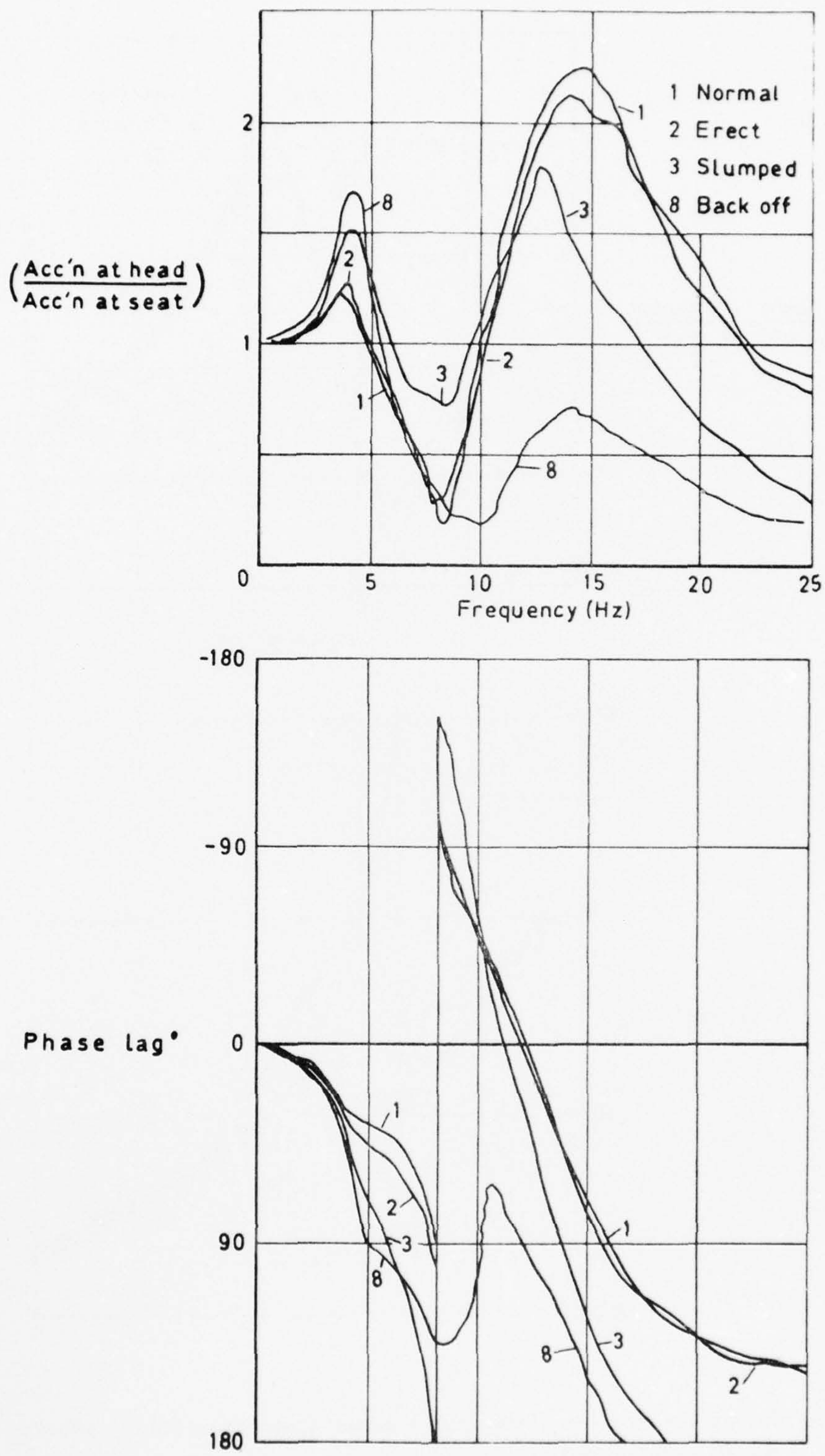

Fig 10 Frequency response of the head, low acceleration level – effect of posture (subject 2)

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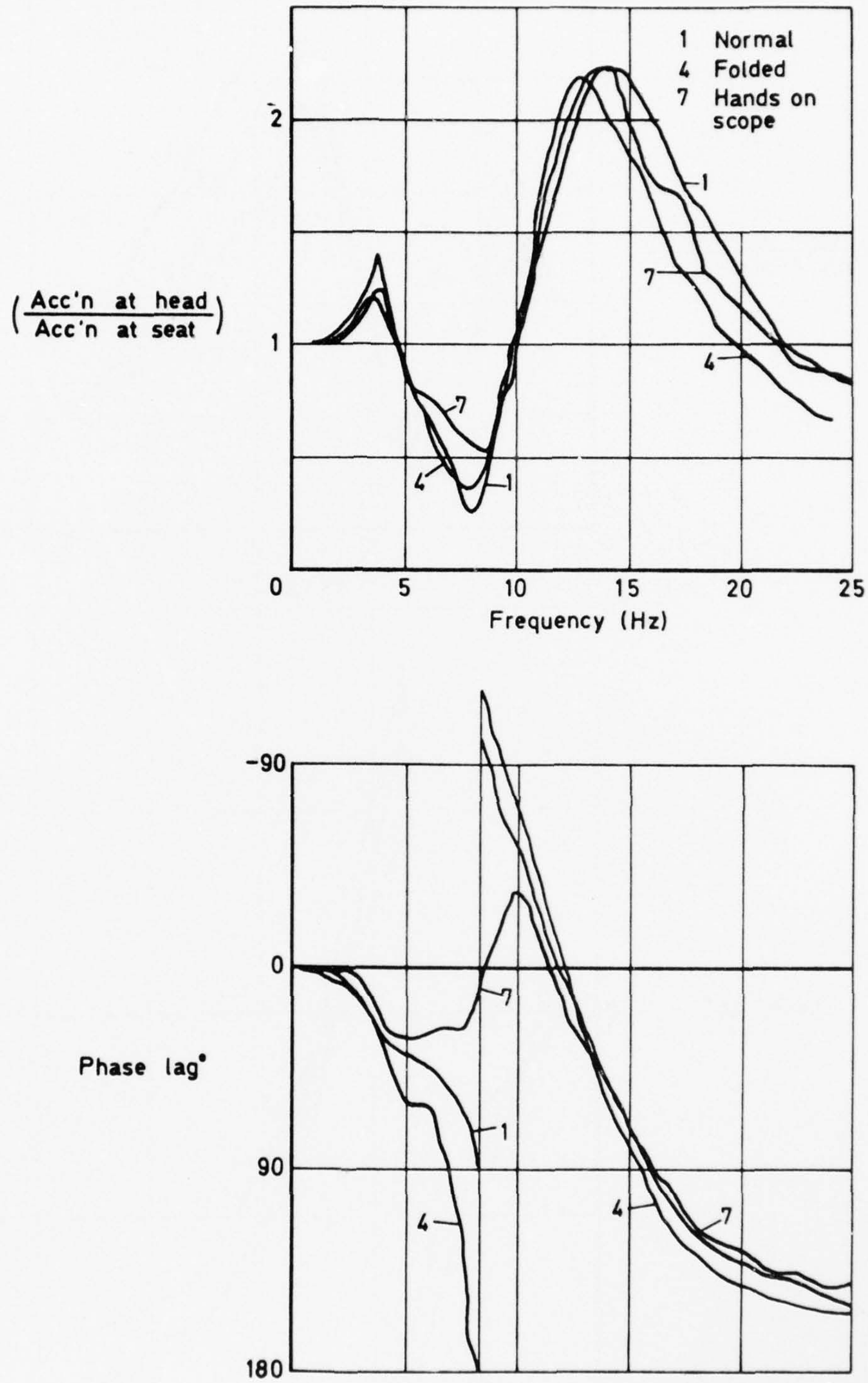

Fig 11 Frequency response of the head, low acceleration level, effect of arm position (subject 2)

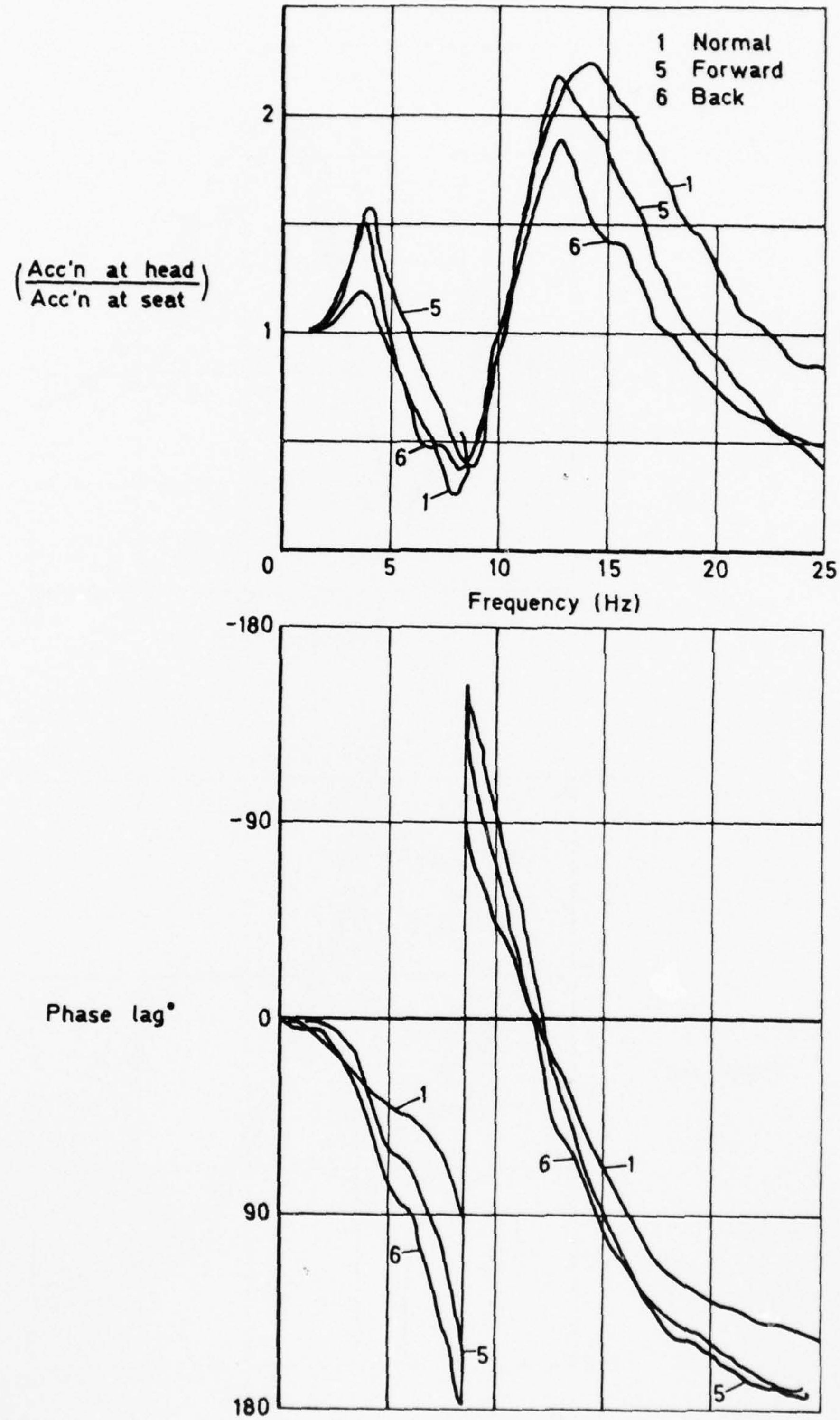

Fig 12 Frequency response of the head, low acceleration level – effect of leg position (subject 2)

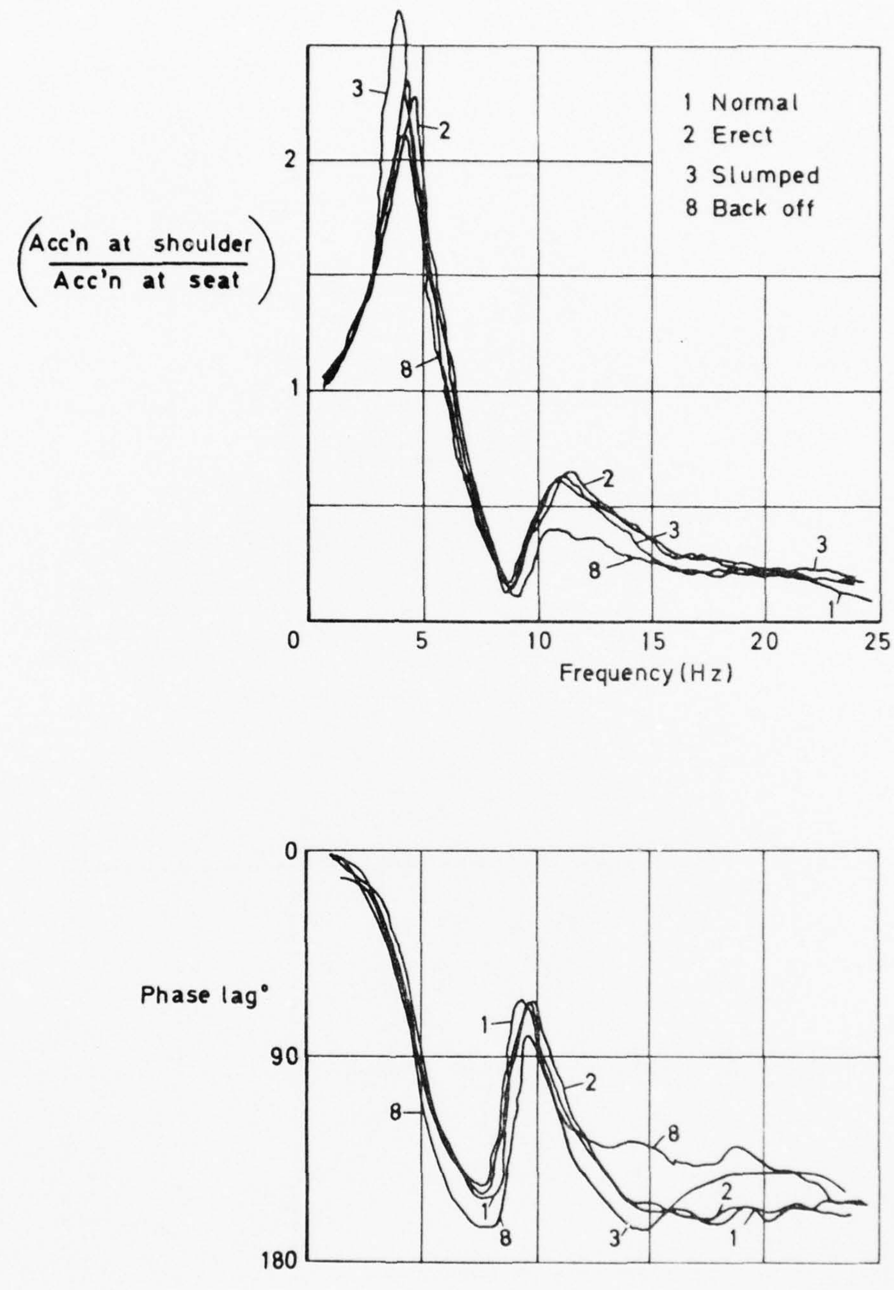

Fig 13 Frequency response of the shoulder, high acceleration level – effect of posture (subject 1)

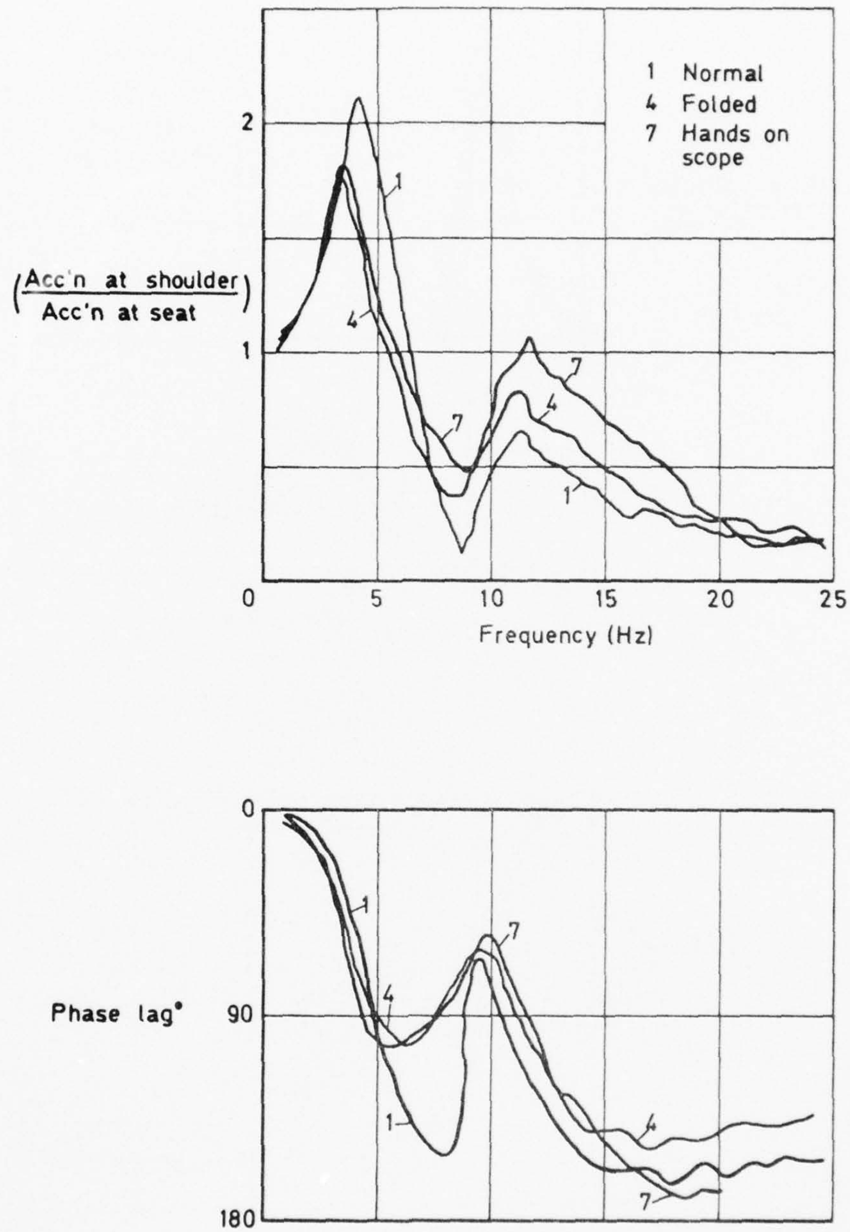

Fig 14 Frequency response of the shoulder, high acceleration level – effect of arm position (subject 1)

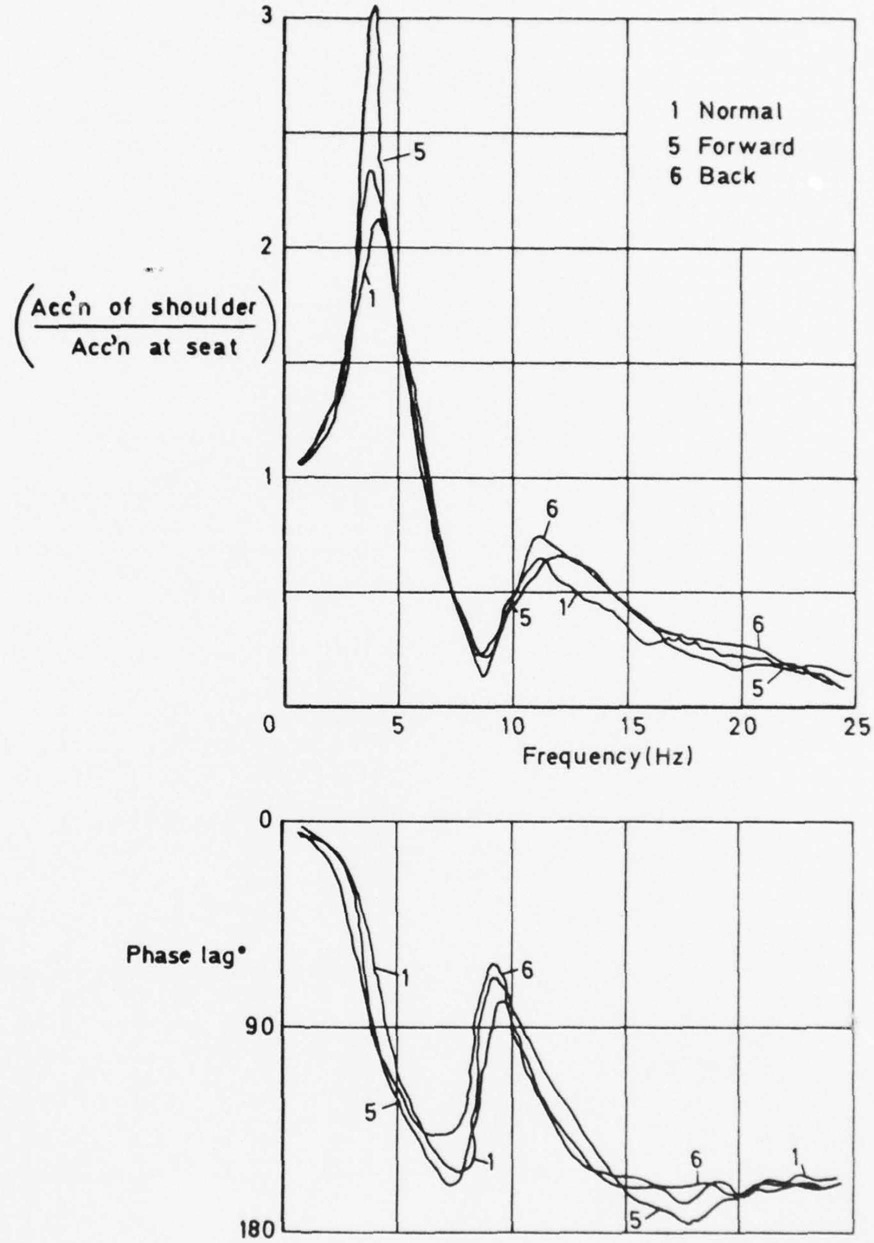

Fig 15 Frequency response of the shoulder, high acceleration level – effect of leg position (subject 1)

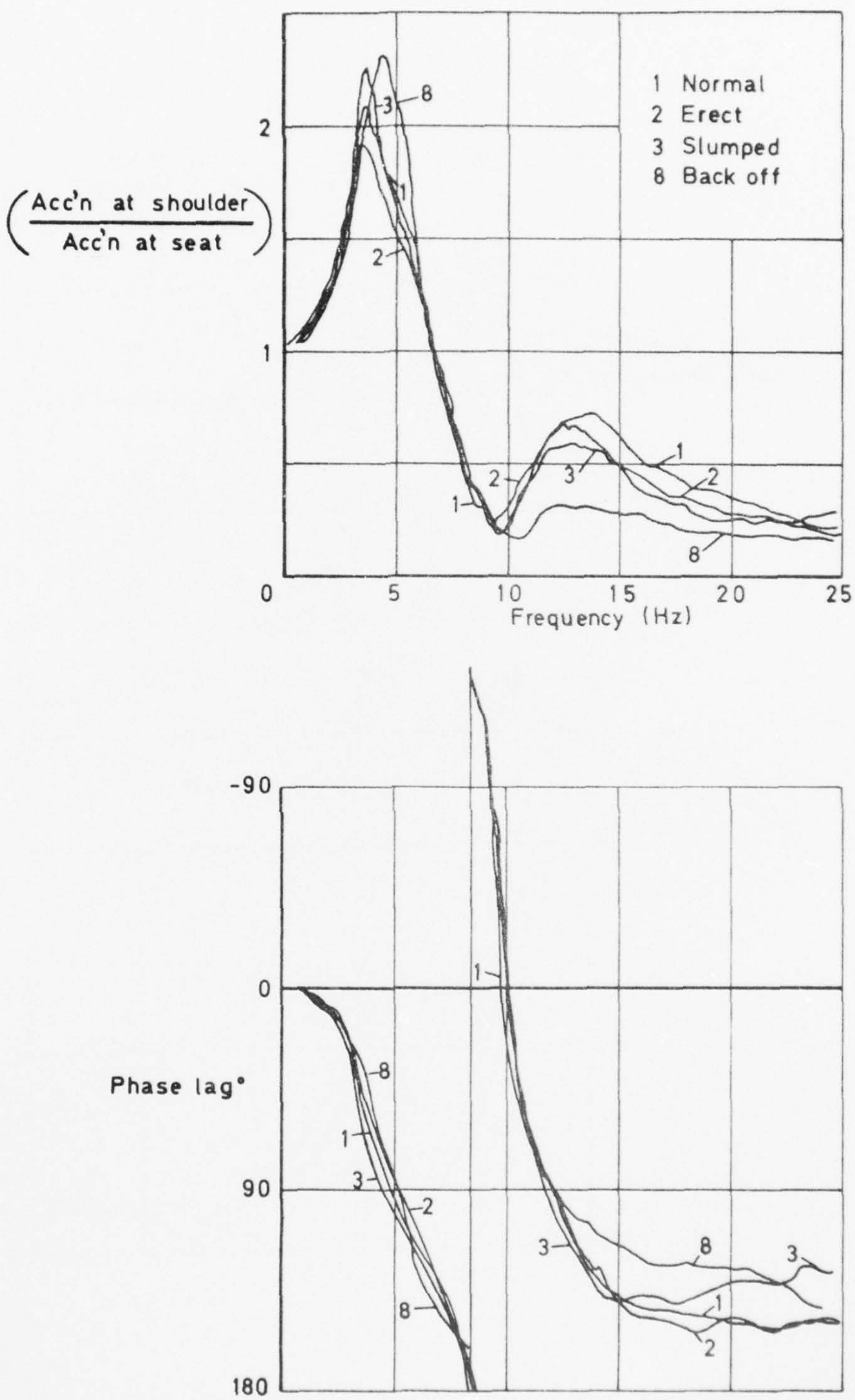

Fig 16 Frequency response of the shoulder, medium acceleration level – effect of posture (subject 1)

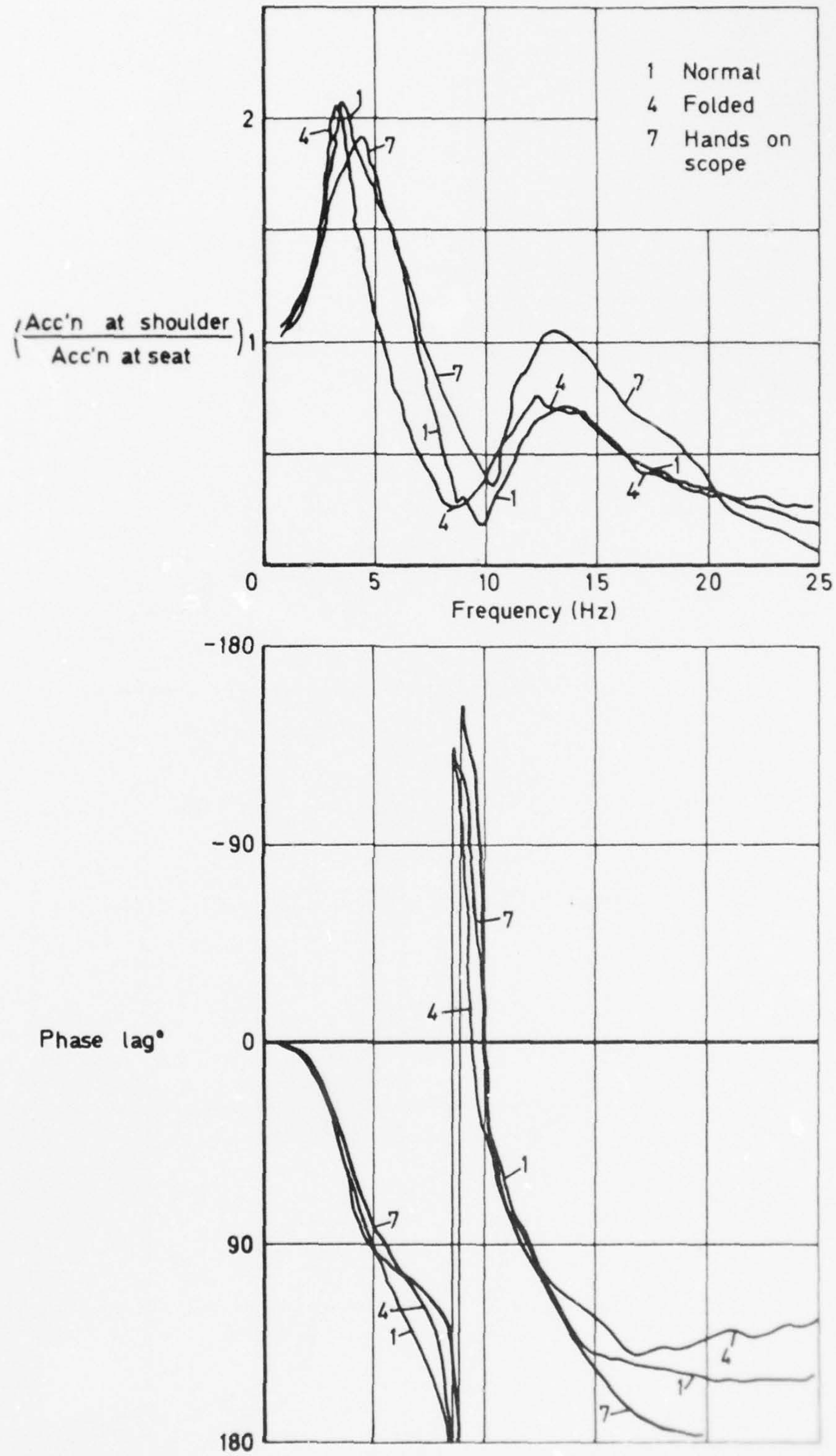

Fig 17 Frequency response of the shoulder, medium acceleration level – effect of arm position (subject 1)