DEVELOPMENT OF HUMAN BODY VIBRATORY MODELS THROUGH ANTHROPOMORPHIC SEGMENTS

A DISSERTATION

Submitted in partial fulfilment of the
requirements for the award of the degree
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By

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CERTIFICATE

Certified that the dissertation entitled 'DEVELOPMENT OF HUMAN BODY VIBRATORY MODELS THROUGH ANTROPOMORPHIC SEGMENTS', which is being submitted by Mr. Tikam Chand Gupta in partial fulfilment of the requirement for the award of the degree of Master of Engineering in Mechanical Engineering (Machine Design) of the University of Roorkee, Roorkee, is a record of student's own work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree.

This is to further certify that he has worked for a period of ten months from August 1987 to May 1988 for preparing this thesis.

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Tikam Chand Gupta

S Y N O P S I S

In this thesis, a generalized procedure for vibratory modeling of human body through anthropomorphic model has been presented. The assumptions underlying the modeling procedure are clearly stated. The model parameters are obtained through the mass, stiffness and damping values of the segments of the anthropomorphic model. The mass and stiffness values of the segments are obtained using the anthropometric data and elastic modulii of bones and tissues. Damping is incorporated by assigning some appropriate damping ratio values to individual segments. For the present study only the standing posture of the human body has been taken up. The validation of modeling procedure is done by first developing the model for a 50th percentile US male and comparing the response with some experimental response data of US males available in the literature. Experiments were then conducted in the laboratory to obtain frequency response of Indian males of 50th percentile group. Vibratory models of Indian males were developed using the anthropometric data collected for 50th percentile Indian males. The theoretical response of the Indian males was especially found to be in a good agreement with the corresponding experimental response.

The thesis seems to have achieved its objective with a

fair success. On the basis of this work, vibratory models of individuals can be framed which can predict the actual frequency response with reasonable accuracy. Nevertheless, the author expects that further refinements in the present modeling work would be carried out in future.

NOMENCLATURE

AR	-	amplitude ratio, head acceleration/feet acceleration
a_i, b_i, c_i	-	semiaxes of the ellipsoids Fig.2.2(a)
C_i	-	damping constants of dampers in the vibratory model
d_i	-	half length of truncated ellipsoid (Fig.2.2(b).
E	-	elastic modulus of the ellipsoidal segment
E_b	-	elastic modulus of bone
E_t	-	elastic mdoulus of tissue
f	-	natural frequency of vibratory model
i	-	subscript for ellipsoidal segments of spring elements
K_i	-	stiffness of spring element
M_i	-	mass of ellipsoidal segment and of mass element in vibratory model.
S_i	-	axial stiffness of ellipsoidal segment
X	-	generalized displacement of vibratory model
$\ddot{X}$	-	generalized acceleration of vibratory model
ζ	-	damping ratio of the ellipsoidal segment

C O N T E N T S

CHAPTER - 1

INTRODUCTION

Over the years, a great deal of research effort has been in evidence to develop a better understanding of human body response to vibratory inputs. The need for this research has arisen due to an increasing dynamic environment to which human beings are routinely subjected. These situations include sitting positions in earth moving machinery such as tractors, in aeroplanes and in helicoptors or in standing positions, such as during water skiing , riding in ground traversing machines or while operating machine tools in a factory or operating a hand held tool such as a rock drill.

The human body is. both physically and biologically a system of an extremely complex nature.When looked upon as a mechanical system it contains a number of linear as well as nonlinear elements and the mechanical properties are apt to change and are different from person to person. Measurement of some of the mechanical properties is, however, practicable since only small forces are needed for such work. But to have a clear understanding of the human body dynamics over a wide range of frequencies (due to the limits of human tolerance to mechanical forces) an approach via lumped parameters modelling and computer simulation has been found extremely effective.

The establishment of limits of human tolerance to mechanical forces, and the explanation of injuries produced when these limits are exceeded, frequently require experimentation at various degrees of potential hazard. To avoid unnecessary risks to humans, animals are used for physiological studies. However, such comparative experiments have their obvious limitations. The different structure, size and weight of most animals shift their response curves to mechanical forces into other frequency ranges and to other levels than those observed on humans. These studies on animals are worth making if care is taken into the interpretation of the data and better laws of scaling are established.

Many kinematic processes, physical loading and gross destructive anatomical effects can be studied on dummies which approximate a human being in size, form, mobility and total weight distribution in body segments. Several such dummies are commercially available. In contrast to those used for load purposes, dummies simulating basic static and dynamic properties of the human body are called 'anthropometric or anthropomorphic' dummies (Goldman and Von-Gierke,1961). The static and dynamic breaking strength of bones, ligaments and muscles and the forces producing fractures in rapid decelerations have been studied on cadavers. The anthropometric data can be used to calculate the response of human being through a mathematical model of a human body.

An appropriately designed human body model can be validated by comparing its responses to various inputs with those obtained experimentally by applying corresponding inputs directly to the human subjects.

> 'An appropriate model is one which resembles human anatomy and reproduces measured human responses including magnitude and location of resonance peaks'.

Vibrations are transmitted from feet to head in standing position and from seat to head in sitting position, progressing through various organs of the human body. As these vibratory inputs vary over a range of frequencies, different parts of the human body pass through a resonant state at various frequencies. A knowledge of these resonant frequencies can be extremely useful in a variety of ways, such as for arriving at better designs of vehicle suspension system to maximize comfort and safety, for designing orthopaedic aids (prosthesis) to replicate natural functions, or to simply provide a pleasant and protective environment for work leisure.

Extensive experiments have been performed investigating head to seat and shoulder to seat acceleration ratios, driving point impedences and subjective responses, such as pain and discomfort for human beings. Theoretical models, both continuous and lumped parameter, have been formulated with verying degrees of complexity based on anatomical/anthropometric analysis and impedance and transmission measurements. The lumped-parameter models usually have single or multidegree of freedom systems with linear and passive elements, whereas the human body is neither a passive nor a linear system. Many investigations on the vibratory modelling are indeed available in the literature.

A review of mathematical models simulating biodynamic responses to impact acceleration is given by King and Chau(1984) along with the associated experimental validation of studies that have been performed in this field.

Amongst the early works on the living human subjects are those of Goerman (1960) and Pradko et al (1966). Coerman displayed plots for the mathematical impedance of a man standing or sitting on a vertically vibrating model. Von-Gierke(1960), Goerman(1962) and Suggs (1973) proposed such models with three and seven degrees of freedom, although the details of modelling procedure and the parametric data were not provided. Goldman and Von-Gierke(1961) have discussed the determination of the structure and properties of the human body regarded as a mechanical as well as biological system. The effects of shock and vibration forces and protection required by the system under various exposure conditions with tolerance criteria for shock and vibration were also explained. The analysis attempted by Keshav(1967) for the general vibration effects on the human body reveals that if a muscle is passively stretched, certain receptors in the muscle are stimulated and the nerve impulses so generated act on the nerve to the same muscle to produce a contraction. This reflex is important for the maintenance of posture.

Amongst the important work on human body vibratory models is that of Muksian and Nash (1974). Their initial model was the same as the one proposed by Goldman and Von Gierke(1960) and Pradko et al(1966,67). They simulated the responses of the model with the experimental results. In this work, Muksian and Nash(1974) concluded the possibility of frequency dependent damping coefficient in agreement with the frequency dependent muscle forces. The possibility of frequency dependent damping coefficient was further established by Muksian and Nash(1976) in their another investigation. The model exhibited linear behaviour at low frequencies and visceral damping was found to vary parabolically at higher frequencies (10 Hz - 30 hz). Garg and Ross (1976) also developed a 16 degree of freedom vibratory model based on their experimental results for a standing human subject. Parametric values of mass distribution and joint stiffnesses were taken from the literature and damping values for various joints in human body were indirectly determined from this study. Patil et al (1978) formulated a 9-degree of freedom lumped parameter model of the occupant-tractor system and attempted to isolate vertical as well as rotational (pitching) vibrations from being transmitted to the driver of the tractor by selecting suspension parameters such that the responses of the human body parts are minimized in the frequency range of .5 - 11 Hz. This is the frequency range encountered in tractor driving and is considered to be above the socalled discomfort and unpleasant levels.

Other studies not directly concerned with the vibration problems, have also given the vibratory models and their parameters. McMahon and Green (1979) proposed a model of running in which leg is represented as a rack and pinion element in series with a damped spring. This model was used to study the effect of track compliance on step length and ground contact time, which helped in turf design. Green and McMahon (1979) analysed running over simply supported wooden planks. To substantiate the experiments, a linear 2 degree of freedom model with one degree for the standing human and the other for the plank was proposed. Mizrahi and Susak(1982) also developed a 2 degree of freedom linear dampled spring -mass model of a human body to investigate the transmission of impact force caused by single leg jumping of their subjects. Farid, M.L. (1987) presented a computer automated approach to monitor the human body vibration response in the vertical, horizontal and torsional directions. The procedure developed was based on Finite Segment Modelling (FSM) of the human body and Kane's equations as formulated by Huston and Passerello (1974) were used as governing equations of motion.

In the context of modeling of the present work, it would be worthwhile to mention some literature on anthropomorphic modeling of the human body. In an anthropomorphic model, the human is represented by a series combination of the visible segments. The segments are represented by some geometrically similar bodies like ellipsoids, right circular cylinders, frustrum of cones, spheres etc. Several papers are available in the literature on anthropomorphic modeling alone, e.g., Bartz and Gionotti(1974), Hatze (1980), Jenson(1986). The anthropomorphic models have essentially been used for the evaluation of the mass and inertial properties of the body segments and subsequent studies on rigid body kinematics and dynamics of human body during various physical activities , e.g., Aleshinsky and Zatsiorsky (1978), David and Hull (1979, 1981), Hatze(1977,1981), Onyshko and Winter(1980). Nigam and Malik(1987) applied, for the first time, the anthroporphic model to the vibratory modeling of human body.

The area of bio-mechanics is now attracting the attention of medical professionals as well. Now-a-days evluation of methods for electrical or magnetic stimulation of fracture healing has increased the demand for a non-invasive method to monitor the stiffness of a healing fracture. Vibration analysis as a technique for the determination of the bone stiffness to monitor the integrity in the bone has been a method of choice since it is non-invasive and gives no risk to the patient due to the small signals needed for investigation (Cornellission, 1986). Jurist (1974) obtained correlation between ulner resonant frequencies and degree of OSTEOPOROSIS. Thompson (1973) developed the method for the determination of invivo-elastic properties of the ulna by the measurement of mechanical impedance when ulna is subjected to sinusoidal lateral force at its mid-point. He also gave a simple lumped parameter vibratory model of the ulna in support of the experimental results. Later Orne (1974) and Orne and Mandke(1978) proposed visco-elastic beam models of the ulna which gave a better correlation with the experimental results of Thompson.

In all studies concerning vibratory models, investigators developed the models to suit the experimental conditions in which stiffness and damping characteristics were evaluated so as to match the model response with the experiments. These models indeed developed from the original idea of Goldman and Von-Gierke (1960). Although the lumping of the body into the model is derived from the obvious body segments, there have been no definitive guidelines to determine the parameters of the various elements of the model. Thus, one set of model and its parameter reported by some author could perhapse be applied to a particular experimental program and a particular class (percentile) of the subjects. Such models cannot be applied universally to various possible postures of body vibration and to all class of subjects. In order to develop a generalized approach for human body vibratory modelling, without resorting to an experimental program, Nigam and Malik (1987) proposed the use of the anthropomorphic models.

Nigam and Malik(1987) based their linear undamped lumped parameter model on the anthropomorphic model of Bartz and Gionotti (1974) in which the body segments were identified as ellipsoids. The novel feature of the model was in the determination of masses and stiffness of the various elements of the model. The calculation of the stiffness were based on the elastic modulii of bones and tissues and the geometrical size of the ellipsoidal segments. The model was conceived as 15-degree of freedom system. Interestingly, the natural frequencies of the model were found to be in the range of experimental data.

The present thesis is an extension of the work of Nigam and Malik (1987). This work was motivated by the fact that in vibratory modeling of the human body, the interest essentially lies in the body response to external excitations rather than the natural frequencies of an undamped vibratory model. The response of the model can indeed be determined by incorporating the damper elements in the model only. Nigam and Malik(1987) made use of the elastic modulii of bones and tissues in the calculation of stiffnesses of the body segments. In the available literature, no useful reliable data except for some scanty data on the damping of synovial fluid and blood, are available which could be made use of to develope a generalized approach based on anthropomorphic model for the calculation of damping constants of the segments similar to the calculation of spring constants. Neverthless, some authors, McMahan and Greene(1979), Mizrahi and Susak (1982) have given some estimate of the leg and whole body damping ratios. This provided a basis for the calculation of the damping constants. In the present work damping constants of the various segments were calculated by identifying the damping ratio of each segment on the basis of the physical structure of the body in a particular posture and using its mass and stiffness values.

Having a frequency response of a mathematical model, it becomes imperative to validate the response experimentally. Although experimental response in both standing and sitting postures are available in the literature, the information is not of much use in the context of the present modelling which requires anthropometric data of the subjects of the experiments. It was therefore planned to conduct experiments in the laboratory on an existing facility available in the department. Experiments were performed on few subjects, and their anthropometric data collected so as to develop their mathematical model as well. Thus, a comparison of the experimental and theoretical response became possible.

In this thesis, Chapter 2 presents the formulation of human body model as a linear spring-mass-dashpot system. The assumption of the modeling are clearly outlined and method of obtaining the parameters of model elements is explained. Chapter 3 presents the results of model development.

At first, some variations in the basic spring-mass model of Nigam and Malik are considered and an improved model is suggested. Damping is then included to study the frequency response of the model. The damping ratios of the body segments are estimated for the model of a 50th percentile US male on the basis of comparison of the response of the model with the available experimental response of American males. To validate the modeling procedure further, vibratory models of 50th percentile Indian male are framed and their frequency response evaluated. Experiments are conducted to determine the response of some subjects of 50th percentile group and their response is compared with the theoretical response of the vibratory model. The investigations clearly indicate that a range of damping ratios can always be set to develop a vibratory model whose response can very well predict the actual response of the human body.

The work reported in this thesis seems to have achieved the objective with fair success. Anthropomorphic model based vibratory models of individual subjects can be framed using their anthropometric data and their frequency response can be known without actually performing the experiments on the subjects. Needless to say, modeling procedure needs improvements and it is hoped that the work can be taken up in future using the guidelines provided in this thesis.

CHAPTER -2

VIBRATORY MODEL OF THE HUMAN BODY

Although a human body is a completely unified organic system, it just can not be treated as a lump of mass. When subjected to external excitations it exhibits resonances at discrete frequency levels as it should, because of its being basically an elastic system. To analyse the mechanical response of a human body, one must have the information about the constitutive mechanical properties. From a vibration stand point, a human body should be treated as a continuous system which is indeed a formidable task. The lumped parameter modeling is perhaps a relatively accessible task and has in fact been the approach used by most authors. However, unlike the vibratory models of the machine and structures, the vibratory model of a human body is at best a mathematical approximation and can never be considered to be its true representative. The reason being that human body has an inherently reflexive nature which always reacts through its nervous system to any adverse environment. This active nature is perhaps impossible to be accounted in a model which would, therefore, be always a passive model.

The vibratory model of the human body considered in the present work is a passive lumped parameter spring-mass-dashpot multidegree of freedom system. The theory underlying the development of the model follows in the succeeding sections.

2.1 DEVELOPMENT OF THE VIBRATORY MODEL

2.1.1 Assumptions for the Model Development

The modeling of the human body, like any other lumped parameter modeling, involves the following steps:

i) the segmentation of the body,

ii) the evaluation of mass, stiffness and damping values of individual segments,

iii) lumping the segments at discrete points and connecting them through massless springs and dashpots, and

iv) obtaining the stiffness and damping values of the spring and dashpot elements of the model via the corresponding values of the adjacent body segments.

A human body has physically distinct segments like head, neck, torso, limbs, etc. This has been indeed the basis of anthropomorphic modeling. The anthropomorphic segments provide a natural choice to be identified as the lumped masses of a vibratory model. As mentioned earlier, in an anthropomorphic model the body segments are represented by geometrically similar bodies like spheres, right circular cylinders, frustrum of cone, ellipsoid etc. Various anthropomorphic models are available in the literature, any of which may be suitably employed for the present modeling.

To proceed further, it is now important to outline the basic assumptions involved in the development of the model. These are as follows:

(1) The model being considered here is assumed to be linear in respect of the spring and dashpot elements. The mechanical behaviour of the bones and tissues of any living body is far from linear. However, for small displacements and velocities, the assumption would not be too unrealistic.

(2) For computing the mass and dimensional properties, the body segments are considered to be geometrical bodies of known shapes.

(3) Though a human body is in reality not a homogeneous mass, the bulk(average) densities of different body segments are nearly the same. The density of each segment is therefore taken to be the same and equal to the average density of the whole body.

(4) In the vibratory modeling of the body, only standing posture is considered. The spring and dashpot elements are considered to be axial permitting vibration in the vertical direction only. This is indeed a major assumption as joints in the human provided many degrees of freedom, However, with excitation coming from the base (feet) to a person standing in an erect state, the axial vibrations are likely to be dominant.

(5) The stiffness of a body segment is determined by

considering uniaxial loading. With regard to mechanical properties, the segments are assumed to be identical and linearly elastic homogeneous bodies. The assumption of linearity is obviously to account for the linearly of the spring and dashpot elements as given in assumption (1).

(6) Disregarding the effect of all other constituents, the axial deformation in the segments is assumed to be contributed by bones and tissues. Further, the axial elastic modulus of the segments is approximated as a geometric mean of the elastic modulii of bones and tissues. The rationale in this approximation is that the two modulii differ by an order of magnitude of 10^6 and a geometric mean would seemingly give a more realistic value of the segment elastic modulus rather than the one defined by series or parallel combination of bones and tissues. This however, remains a questionable matter as how the mechanical properties of the constituents could be combined to give a more realistic elastic modulus of body segments.

(7) The damping constants of the individual segments are established through its mass, stiffness and a damping ratio. The damping ratio of any segment depends primarily on its structure (bone/tissue proportion) and the posture. In selecting the damping ratio, the general guidelines are as follows:

(i) In a standing posture, the legs and the lower torso offer the maximum damping.

(ii) The central torso offers minimum amount of damping. This is on the basis that central torso is mostly a tissue structure with considerable amount of voids inside of it.

(iii) The hands if resisting against a fixed body over the arms, would offer as much damping as the legs. However, in standing posture, the hands are assumed to be free and hence their contribution towards damping is also taken to be small.

2.1.2 Mass of the Segments:

In view of assumption (3), the mass of an ith segment may be expressed as

$$M_i = MV_i \Big/ \sum_{j=1}^{n} V_j \qquad \ldots (2.1)$$

where, V_i is the volume of an ith segment, n is the total number of segments and M is the total body mass.

Expressions for volumes of the segments with different geometrical shapes are given in Table 2.1.

2.1.3 Spring Stiffness of a Segment

Consider a body segment in uniaxial loading as shown in Fig.2.1. The change in axial length is given by

$$\delta\ell = \int_{-c_i}^{+c_i} \frac{F}{E\,A(z)}\,dz$$

The axial stiffness of the segment then becomes:

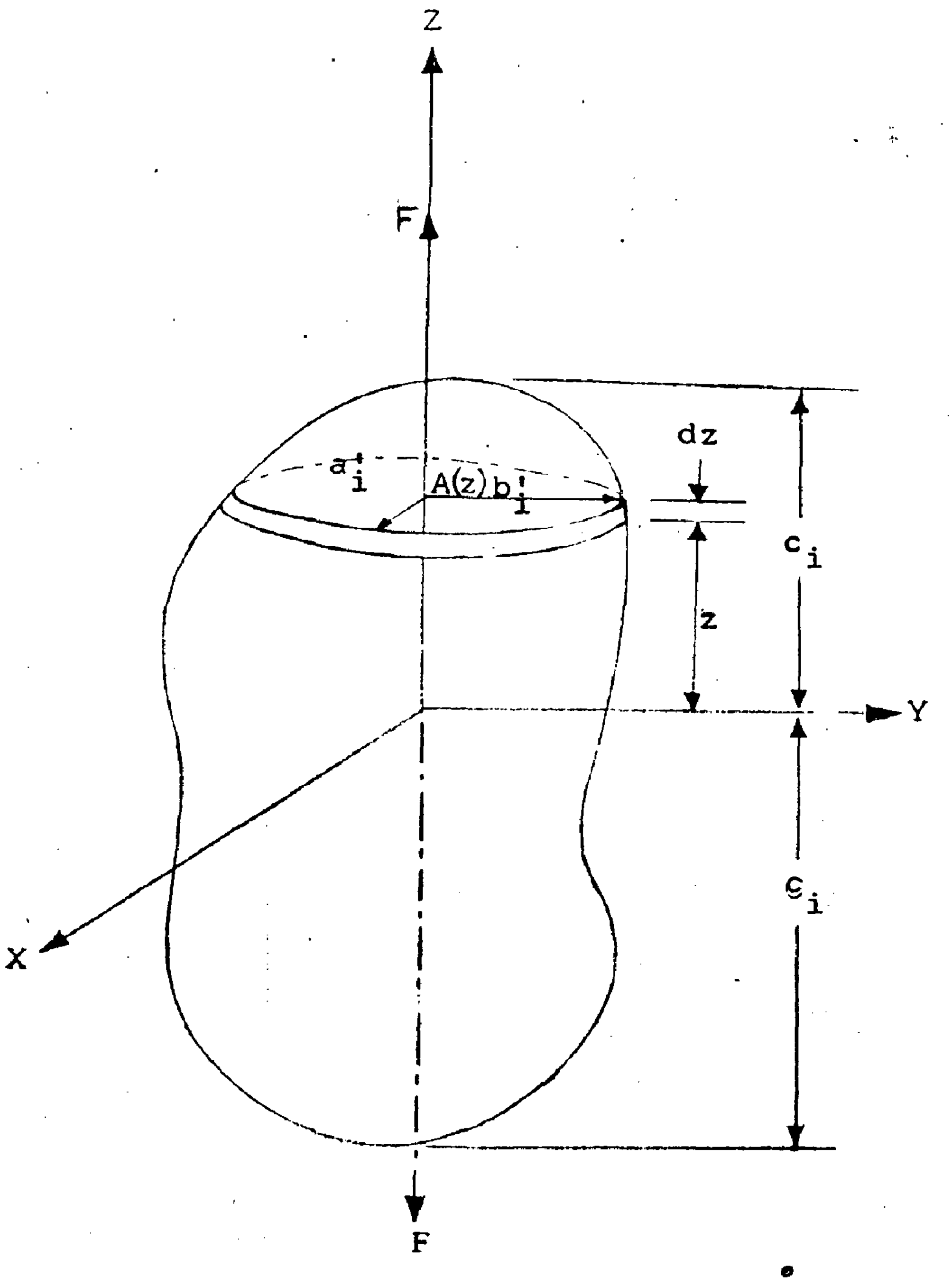
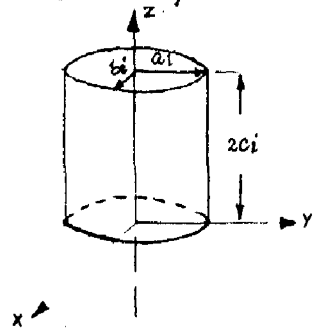
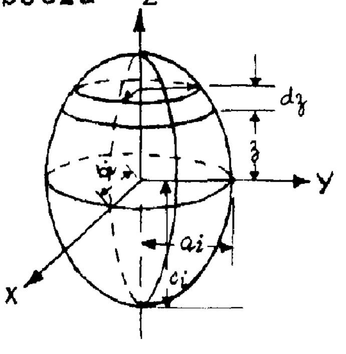
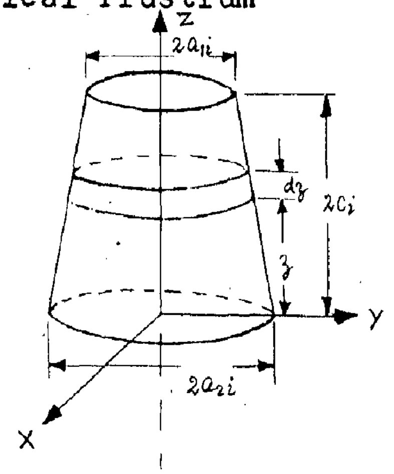


Fig.2.1- A body segment in uniaxial loading

Table 2.1- Formulae to determine volume and stiffness for different shapes of segments.

Shape	Volume (V_i)	Stiffness (S_i)
A prizmatic cylinder 	$2\pi a_i b_i c_i$	$\frac{\pi a_i b_i E}{2c_i}$
Ellipsoid 	$a_i b_i c_i$	$\frac{\pi E a_i b_i}{c_i I_i}$ where $I_i=\log((c_i+d_i)/(c_i-d_i))$
Conical frustrum 	$\pi a_{1i}^2 h+ \frac{1}{3}\pi(a_{2i}-a_{1i})^2 h$	$\frac{\pi E a_{1i} a_{2i}}{2c_i}$

$$S_i = \frac{F}{\delta l} = \frac{1}{\int_{-c_i}^{+c_i} \frac{1}{EA(z)} dz}$$

$$= \frac{E}{I}$$

where,

$$I = \int_{-c_i}^{+c_i} \frac{1}{A(z)} dz$$

In the above equations, E is the axial elastic modulus of the segment and as per assumption (6), is given by

$$E = \sqrt{E_b \cdot E_t}$$

where E_b and E_t are the elastic modulii of bone and tissue, respectively.

The expressions of the stiffness for various segment shapes are given as follows:

(i) A prismatic cylinder (Fig.2.2(a))

$$I = \int_{-c_i}^{+c_i} \frac{1}{A_i(z)} dz$$

$$= \frac{2c_i}{A_i} \qquad (A(z)=A_i)$$

$$I = \frac{2c_i}{\pi\ a_i b_i}$$

Thus, $S_i = \frac{E}{I}$

$$S_i = \frac{\pi E a_i b_i}{2c_i} \qquad \ldots (2.2)$$

For a right circular cylindr $a_i = b_i$.

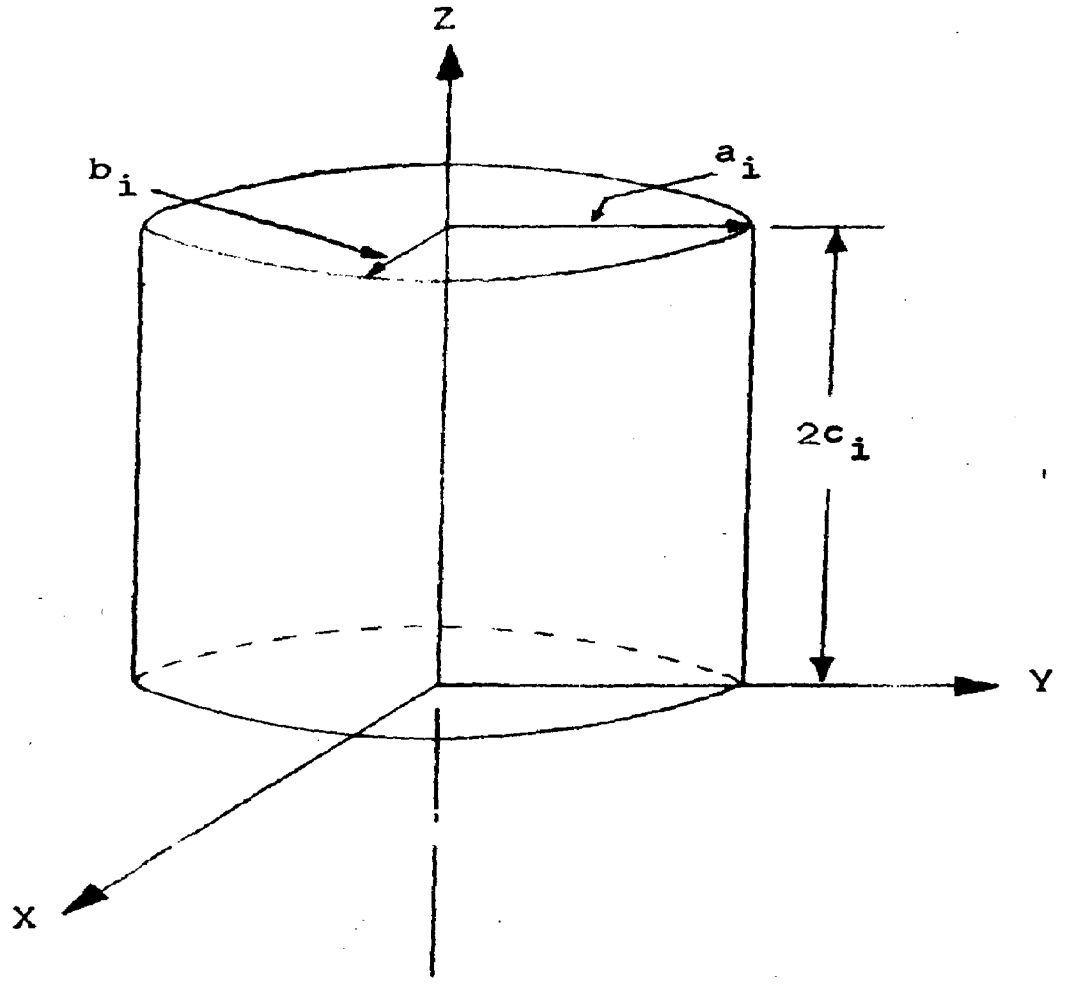


Fig.2.2(a)- A prismatic cylinder

(ii) Ellipsoid

The equation of ellipsoid is given as follows:

$$\frac{X^2}{a_i^2} + \frac{Y^2}{b_i^2} + \frac{Z^2}{c_i^2} = 1$$

where a_i, b_i and c_i are the semi-axes of the ellipsoid. If a_i', b_i' are the semi-axes at any transverse section of the ellipsoid (Fig.2.2(b)), then $A(z) = \pi a_i' b_i'$. Also,

$$\frac{b_i'^2}{b^2} = 1 - \frac{z^2}{c_i^2}$$

$$b_i' = b_i \sqrt{1 - \frac{z^2}{c_i^2}}$$

Similarly,

$$a_i' = a_i \sqrt{1 - \frac{z^2}{c_i^2}}$$

Hence,

$$A(z) = \frac{\pi a_i b_i}{c_i^2}(c_i^2 - z^2)$$

$$\text{Thus, } I_i = \int_{-c_i}^{c_i} \frac{c_i^2}{\pi a_i b_i (c_i^2 - z^2)}\, dz$$

$$= \frac{c_i^2}{\pi a_i b_i} \int_{-c_i}^{c_i} \frac{dz}{(c_i^2 - z^2)}$$

$$= \frac{c_i}{2\pi a_i b_i} \log \frac{c_i + z}{c_i - z} \Bigg|_{-c_i}^{c_i}$$

The above integral is obviously undefined at the lower and upper limits of integration i.e. at $z = \pm c_i$. However,

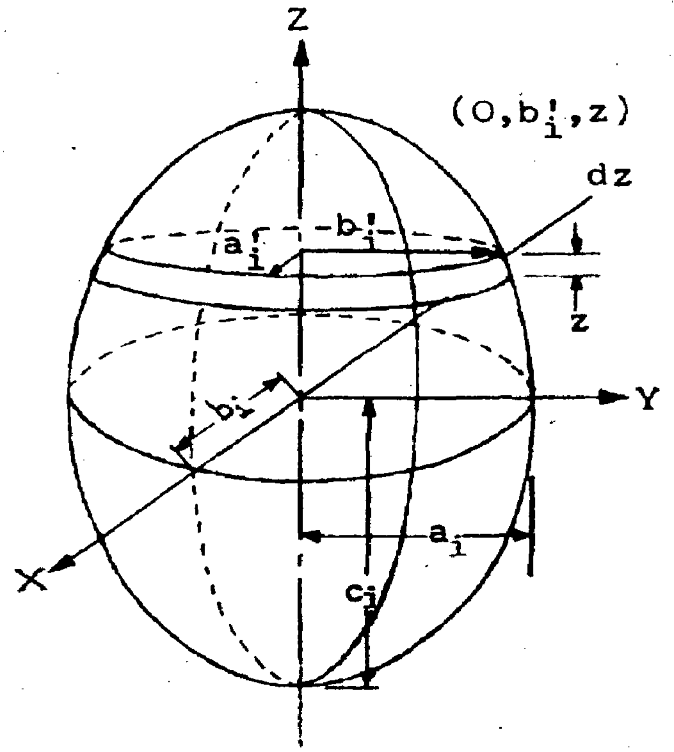


Fig. 2.2(b)-i An ellipsoidal segment

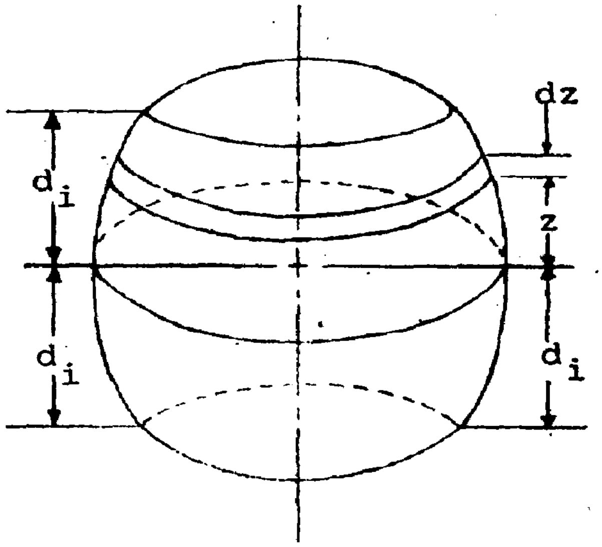


Fig. 2.2(b)-ii Truncated ellipsoid

the integral may be evaluated if the ellipsoids are assumed to be truncated at the two ends. Although this assumption arises as a mathematical requirement, it complies with the physical state also. In an anthropomorphic model with the segments represented by ellipsoids, the contact between adjacent segments cannot be a point contact. In fact such a model would be fragile and in a real model the contact between adjacent segments should be an area contact. This purpose is served by taking the ellipsoids to be truncated.

Taking the truncated length of the ellipsoid to be $2d_i (d_i < c_i)$, (Fig.2.2(b)), the integral becomes

$$I = \frac{c_i}{\pi a_i b_i} \log \frac{c_i + d_i}{c_i - d_i}$$

Thus, $S_i = \frac{E}{I}$

$$= \frac{\pi E a_i b_i}{c_i \log((c_i + d_i)/(c_i - d_i))} \qquad \ldots (2.3)$$

Nigam and Malik(1987) have used ellipsoidal segments in their vibratory model and have used a truncation of 5% at both the ends i.e. $d_i = 0.95\ c_i$.

(iii) Conical Frustrum: (Fig.2.2(c))

$$I = \int_0^{2c_i} \frac{1}{A(z)} dz_o$$

$$= \int_0^{2c_i} \frac{1}{\pi (a_{zi})^2} dz_o$$

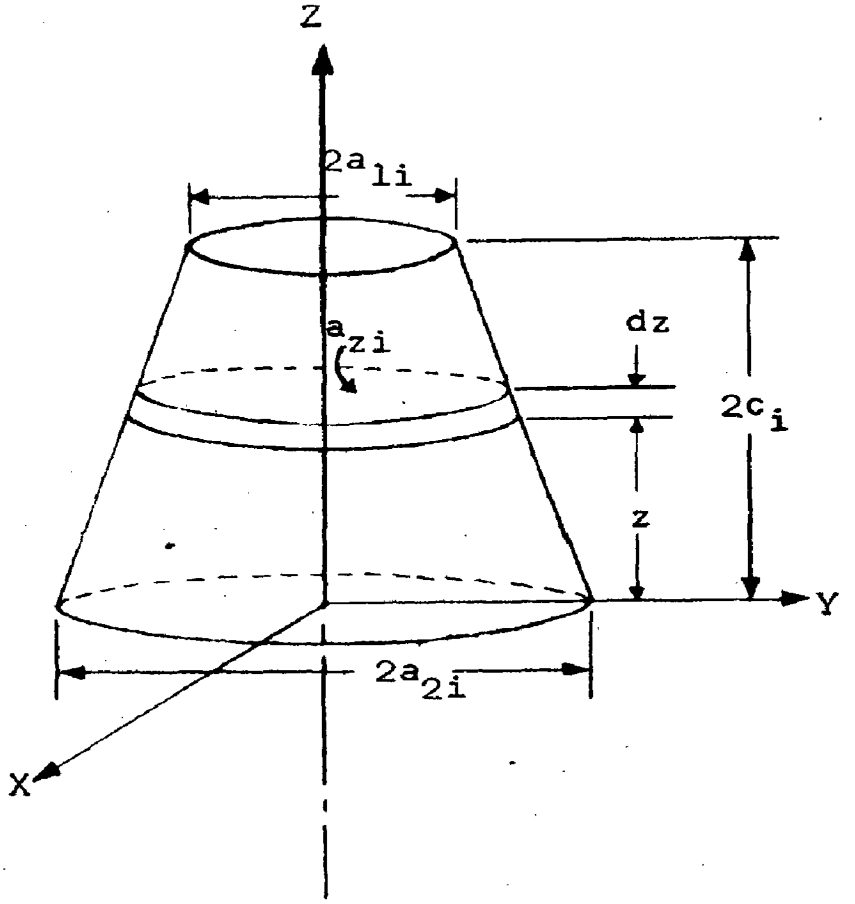


Fig.2.2(c)- Conical Frustrum

$$= \int \frac{1}{\pi(a_{2i}-Kz)^2}\, dz$$

where,

$$K = \left(\frac{a_{2i}-a_{1i}}{2c_i}\right)$$

$$I = \frac{2c_i}{\pi a_{1i} a_{2i}}$$

Thus,

$$S_i = \frac{E}{I}$$

$$= \frac{\pi E a_{1i} a_{2i}}{2c_i} \qquad \ldots (2.4)$$

2.1.4 Damping Constant of a Segment

Assuming the ith segment to be having a damping ratio, ζ_i, the damping constant of the segment is given by

$$B_i = 2\zeta_i \sqrt{S_i\ M_i} \qquad \ldots (2.5)$$

2.2 VIBRATORY MODEL:

The number of mass elements in the vibratory model equals the number of segments in the anthropomorphic model. The anthropomorphic models formulated by various authors differ in the geometrical shape of the segments as well as in the identification of the segments.

In the present work identification scheme of Bartz and Gionotti(1974) is being adopted in which human body is considered to comprise of 15 distinct segments. The various segments as identified by Bartz and Gionotii are shown in Fig.2.3.

Having identified the distinct segments of the body, the vibrating model may now be framed by replacing the segments with rigid masses and connecting them through linear mass less spring and dashpot elements. Such a vibratory model in standing position is shown in Fig.2.4. The stiffness and damping of spring and dashpot elements in the model are obtained by suitable combination of the stiffness and damping of the adjacent segments. It may be noted that the various segments in the body are connected in a series fashion and hence the stiffness and damping of the adjacent segments form series combination. On this basis formulas for the stiffness and damping of the various spring and dashpot elements of the vibratory model may be derived in terms of the stiffness and damping of body segments. These formulae are given in Table 2.2.

2.3 VIBRATION ANALYSIS OF THE HUMAN BODY MODEL

Of interest in formulating the vibratory model of the human body, is the vibration analysis. At first, considering the case of undamped free vibration the natural frequency of the model may be obtained. Although damping is inherently present in the human body, the undamped natural frequencies signify the locations of the resonance peaks of the actual model as well. Thus, the evaluation of natural frequencies would always be helpful in the modelling by comparing the

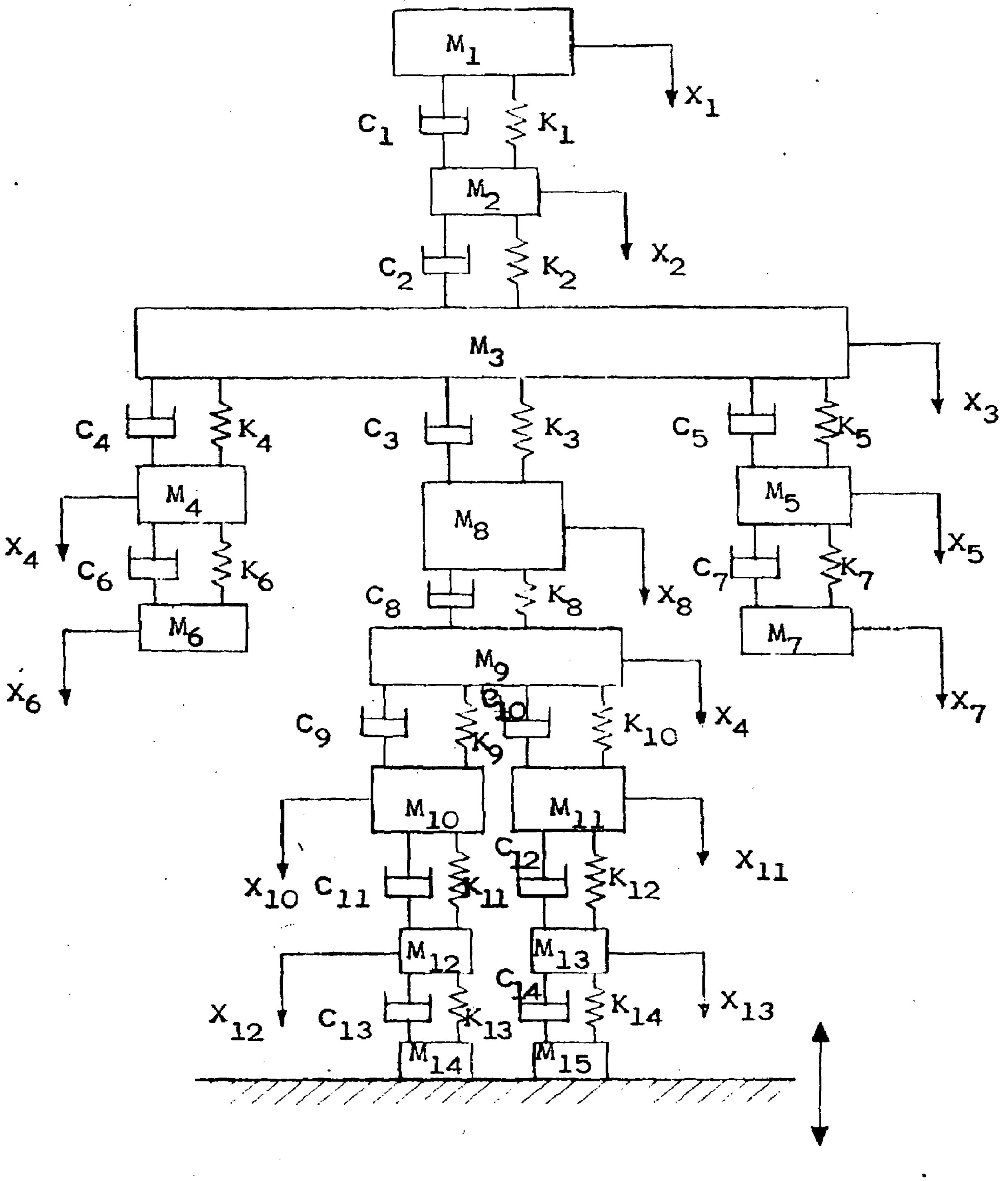


Fig.2.4- Vibratory model of human body

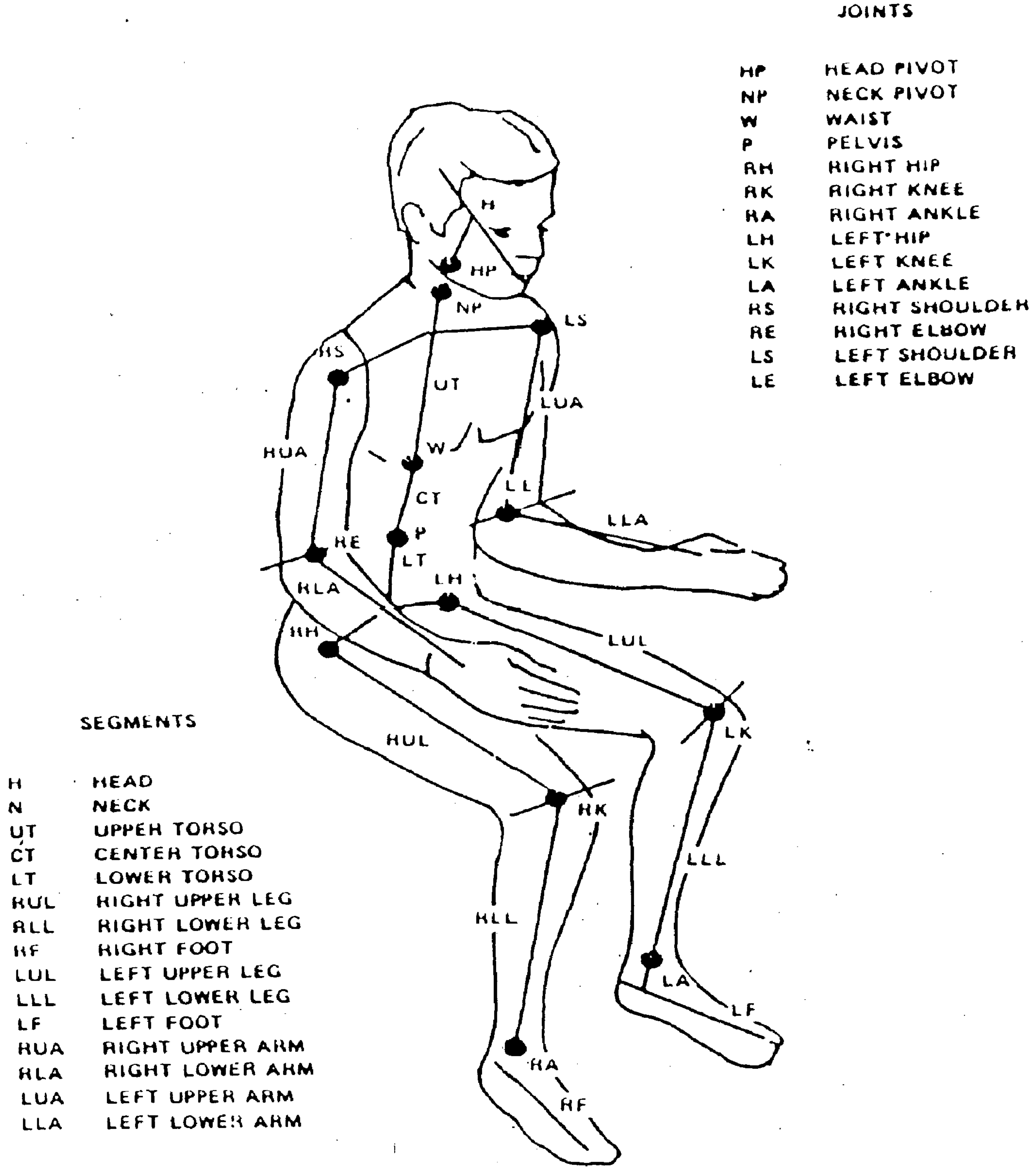


Fig.2.3- 15-Segment man model

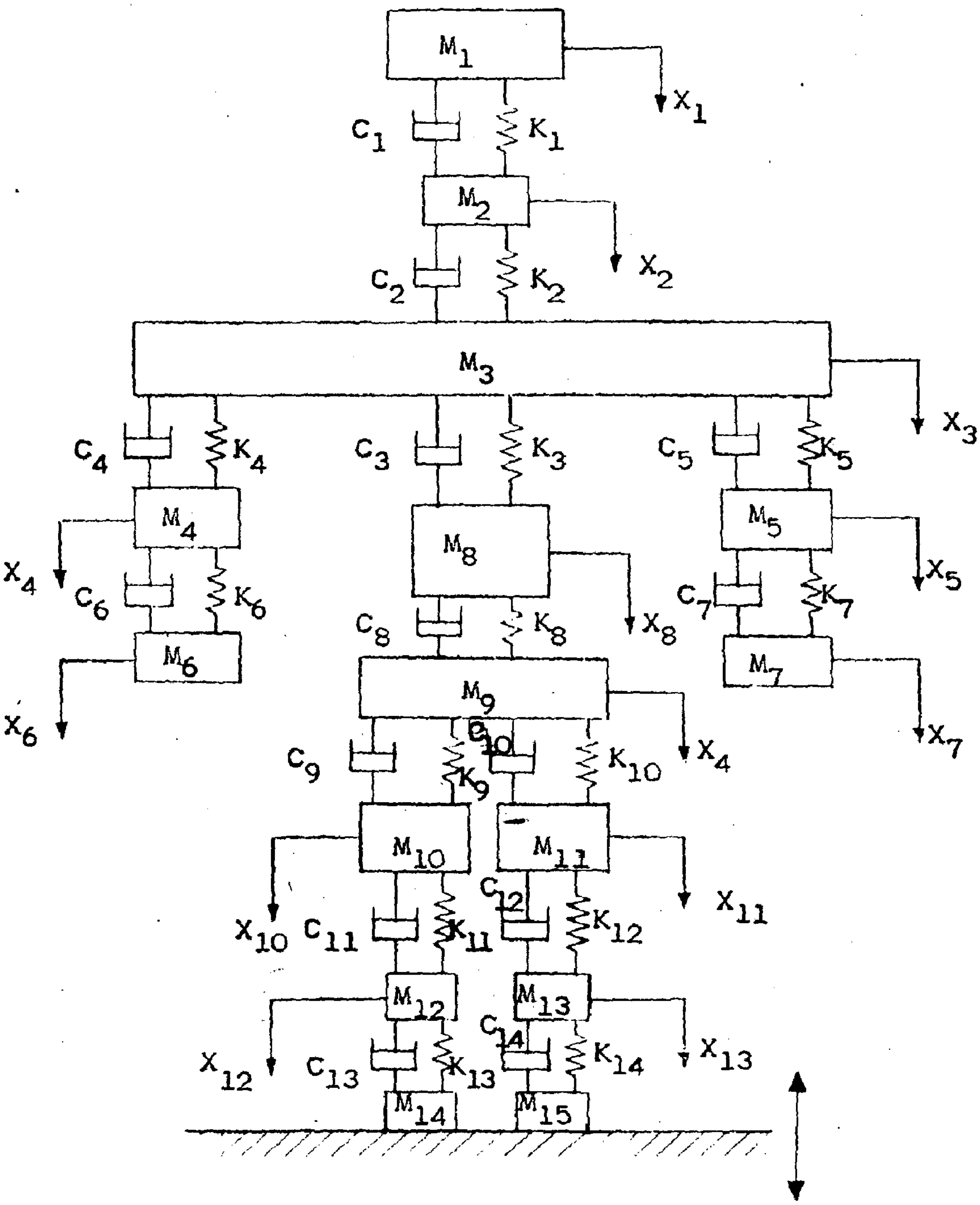


Fig.2.4- Vibratory model of human body

Table 2.2 Stiffness of the spring elements in vibratory model

Spring element designation (Fig.2.4)	Series combination of the ellipsoid elements forming the spring	Spring stiffness, K_i
K_1	H	S_1
K_2	N,UT	$S_2S_3/(S_2+S_3)$
K_3	UT,CT	$S_3S_4/(S_3+S_4)$
K_4	UT,RUA	$S_3S_4/(S_3+S_4)$
K_5	UT,LUA	$S_3S_5/(S_3+S_5)$
K_6	RLA	S_6
K_7	LLA	S_7
K_8	CT,LT	$S_8S_9/(S_8+S_9)$
K_9	LT,RUL	$S_9S_{10}/(S_9+S_{10})$
K_{10}	LT,LUL	$S_9S_{11}/(S_9+S_{11})$
K_{11}	RUL,RLL	$S_{10}S_{12}/(S_{10}+S_{12})$
K_{12}	LUL,LLL	$S_{11}S_{13}/(S_{11}+S_{13})$
K_{13}	RF	S_{14}
K_{14}	LF	S_{15}

* Symbols H,N,UT etc. are as defined in Fig.3.1

Note: The formulae for damping constants (C_i) of the dashpots are similar to the spring stiffness formulae with S_i replaced by B_i.

undamped natural frequencies with the values of frequencies of the resonant peaks available from the experimental results.

The equation of motion of the undamped free vibration of the model are

$$[M]\{\ddot{X}\} + [K]\{X\} = 0 \quad \ldots (2.6)$$

where $[M]$ and $[K]$ are respectively, the mass and stiffness matrices of order 15x15. The matrix $[M]$ is a diagonal matrix of 15 mass segments. The stiffness matrix may be easily constructed by the usual methods of vibration analysis.

Once the mass and stiffness matrices are known, the frequencies may be computed by using any of the available standard eigen value softwares (e.g. Bathe and Wilson, 1976).

From a practical stand point, the frequency response of the model, is of interest. The equations of motion of the vibratory model with excitation coming from the feet are

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F\} \quad \ldots (2.7)$$

where in the $\{F\}$ vector the forcing function appears only at the mass location where excitation is being given. The frequency response from Eq.(2.7) has been obtained by Impedence method.

CHAPTER-3

RESULTS AND DISCUSSION

Similar to the vibratory modeling of any machine structure, the vibratory model of a human body has to be initially framed as a basic spring-mass system. Having decided upon the modeling procedure, the model development was, therefore, taken up by deriving the models from anthropomorphic models of the human body. The comparison of such models was made on the basis of available resonant frequencies data of a human body. Further development in the vibratory models was then made by incorporating damping. For this purpose it was necessary to identify the damping ratio of body segments. The relative magnitude of damping ratios of the various body segments are taken on physical grounds and applied to study the response of a 50th percentile US male. A comparison of this response with the experimental response of US males gives a fairly good idea of the damping ratio of the various body segments. Experiments were then performed on seven- young Indian subjects of 50th percentile group in standing posture to determine their in-vivo response at various frequency levels. The vibratory models of the experimental subjects were then framed on the basis of their anthropometric data and the theoretical response compared with the corresponding experimental response.

The results of the aforementioned studies are described in the following sections.

3.1 DEVELOPMENT OF VIBRATORY MODEL AS A BASIC SPRING-MASS SYSTEM

The prerequisites for developing the modeling scheme are the anthropometric data and the mechanical properties of the constitutive elements of the human body.

As mentioned earlier the axial deformation in the segments is assumed to be contributed by bones and tissues. The elastic modulii of these two constituents as given by Goldman and Von-Gierke(1961) are

bone : $E_b = 22.6\ GN/m^2$

tissue: $E_t = 7.5\ KN/m^2$

Thus the elastic modulus of the segment is taken as

$$E = \sqrt{E_b \cdot E_t}$$
$$= 13.02\ MN/m^2$$

where E may be referred as the global elastic modulus of the body.

Amongst a large number of research papers available on anthropomorphic modeling, the authors have generally evaluated the inertial properties of the body segments without giving any details of the size dimensions of the body. Of interest in the present modeling, is the anthropometric data itself. In all the available literature on anthropomorphic modeling, only Bartz and Gionotti (1975) provide such information for 50th percentile US males. Their data has indeed been the basis of modeling by Nigam and Malik (1987) and same is being used in the present work for the development of the basic model. The anthropometric data of 50th percentile US male as given in Bartz and Gionotti are reproduced in Table 3.1.

Bartz and Gionotti approximated the body segments by ellipsoids (Fig.3.1) and the same were used by Nigam and Malik for mass and stiffness calculation. However, the vibratory modeling of the later work is questionable on two accounts. In stiffness calculations, Nigam and Malik have used same value of the elastic modulus for all the segments. Although, the assumption seems to be plausible for the bony parts of the body like legs, limbs, and upper and lower torsos, the central torso is basically a tissue structure with considerable amount of voids. Secondly, the vibratory model of Nigam and Malik as derived on the basis of anthropomorphic model differs from the vibratory model of the other authors in which the backbone is represented as a separate spring and dashpot combination. Lastly, all the mass segments of a body do not look like ellipsoids. In contrast, the anthropomorphic models suggested by other authors (e.g. Hustun and Psarrello, 1971, Fig.3.2) appear to have a better general resemblance with human body.

Incidentally, Nigam and Malik reported the natural frequencies of their model to be well within the range of

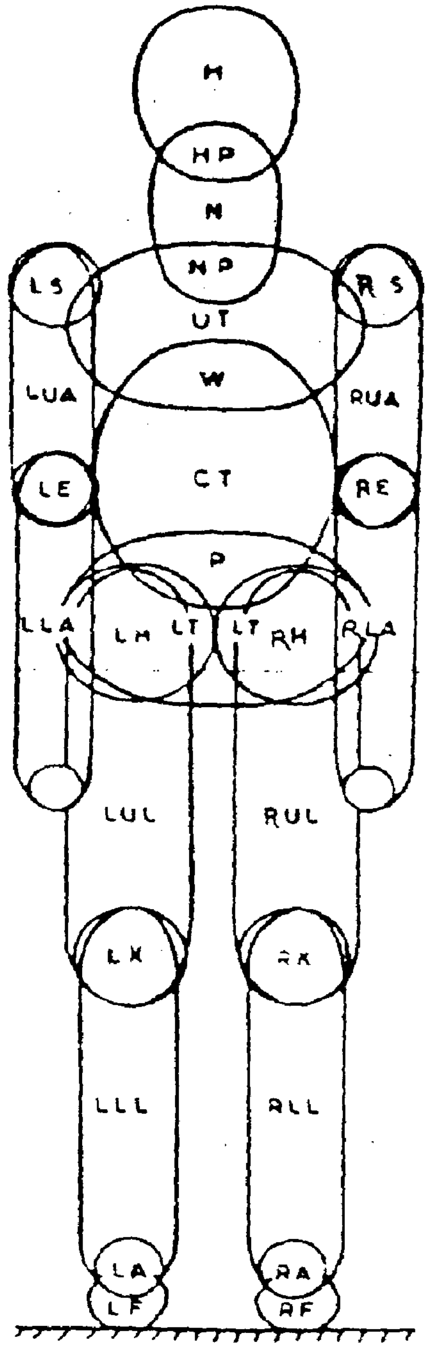
Table 3.1 Anthropometric measurements of 50th percentile US male

Body mass, M = 74.9 Kg

Dimensional data	Measurement (cm)
L_1 Standing height	168.67
L_2 Shoulder height	146.33
L_3 Armpit height	136.02
L_4 Waist height	108.38
L_5 Seated height	92.96
L_6 Head length	19.86
L_7 Head breadth	15.57
L_8 Head to chin height	23.24
L_9 Neck circumference	37.95
L_{10} Shoulder breadth	46.20
L_{11} Chest depth	23.32
L_{12} Chest breadth	32.89
L_{13} Waist depth	21.51
L_{14} Waist breadth	28.22
L_{15} Buttock depth	23.19
L_{16} Hip breadth (standing)	35.43
L_{17} Shoulder to elbow length	37.54
L_{18} Forearm hand length	48.69
L_{19} Biceps circumference	32.92
L_{20} Elbow circumference	31.42
L_{21} Forearm circumference	29.08
L_{22} Wrist circumference	17.86
L_{23} Knee height (seated)	53.14
L_{24} Thigh circumference	50.52
L_{25} Upper leg circumference	37.24
L_{26} Knee circumference	36.20
L_{27} Calf circumference	33.32
L_{28} Ankle circumference	21.06
L_{29} Ankle height (outside)	6.91
L_{30} Foot breadth	9.35
L_{31} Foot length	25.40

Joints

HP	Head pivot
NP	Neck pivot
W	Waist
P	Pelvis
RH	Right hip
RK	Right knee
RA	Right ankle
LH	Left hip
LK	Left knee
LA	Left ankle
RS	Right shoulder
RE	Right elbow
LS	Left shoulder
LE	Left elbow



Segments

H	Head
N	Neck
UT	Upper torso
CT	Center torso
LT	Lower torso
RUL	Right upper leg
RLL	Right lower leg
RF	Right foot
LUL	Left upper leg
LLL	Left lower leg
LF	Left foot
RUA	Right upper arm
RLA	Right lower arm
LUA	Left upper arm
LLA	Left lower arm

Fig.3.1- Anthropomorphic model of a human body
(with ellipsoidal shapes of body segments)

Segment No.	Segment Designation
1	H
2	N
3	UT
4,5	RUA, LUA
6,7	RLA, LLA
8	CT
9	LT
10,11	RUL, LUL
12,13	RLL, LLL
14,15	RF, LF

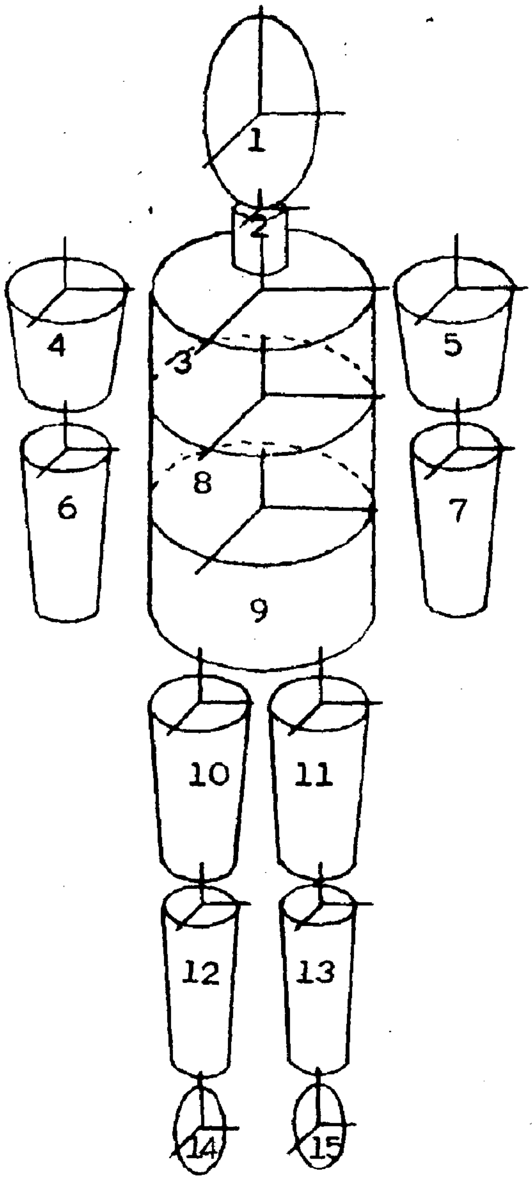


Fig.3.2- Anthropomorphic model of a human body (with mixed shapes of body segments)

available experimental values. Inasmuch as the present modeling was aimed towards the response studies, it was thought appropriate to try out some other variations in the basic model and check out as to which model would represent more closely the actual vibratory response of human body. Taking the model of Nigam and Malik as Model1, the other three variations based on the aforediscussed considerations are as follows:

Model 2: In the first model, the assumption of a uniform value of elastic modulus for all the segments does not seem to be appropriate in respect of the central torso. So, in the second model, the stiffness of central torso is taken on the basis of tissue elastic modulus only.

Model 3: In this model the effect of the back bone is represented by taking the stiffness of the central torso as the sum of the stiffness of the complete torso as one ellipsoidal segment on the basis of $E = 13.02$ MN/m^2 value and the stiffness of central torso on the basis of $E_t = 7.5$ kN/m^2 value. This calculation is taken on two grounds. The central torso gets its support mainly from the backbone and the two elements make a parallel combination of the springs. Secondly, the back bone is a bony part and its stiffness may be calculated on the basis of global elastic modulus.

Model 4: This model is derived from the anthropomorphic model of Huston and Psarrello (Fig.3.2). In this vibratory model, the body segments are represented by geometric bodies of more closely resembling geometrical shapes.

It may be seen that the first three models are based on the ellipsoidal segments only. Table 3.2 and 3.3 give the formulae for the geometrical properties of the various segments of anthropomorphic models of Bartz and Gionotti (1975) and Huston and Psarello(1971) respectively. Using the anthropometric data of Table 3.1, the formulae from Table 3.2 and 3.3 and Eqs.(2.1) to (2.4), the mass and stiffness values of various segments are calculated from the anthropomorphic models of Bartz and Gionotti(1975) and Huston and Psarrello(1971) in Tables 3.4 and 3.5 respectively.

The stiffness of the spring elements of the vibratory model are obtained from the formulae of Table 2.2. The stiffness of the spring elements of four vibratory models as described earlier are given in Table 3.6.

The natural frequencies of the four models were computed for standing posture with feet strapped to a base. The values are given in Table 3.7. The table includes, for the purpose of comparison, the values of experimental resonant frequencies (Negi and Siegler ,1987).

While comparing the natural frequencies of the models with the availa-ble experimental resonance

Table 3.2 Formulae for statistical dimensions of the ellipsoids representing body segments

Body segment (Fig.2.3)	Mass elements (Fig.2.4)	Formulae		
		a_i	b_i	c_i
Head	M_1	$L_7/2$	$L_7/2$	$L_6/2$
Neck	M_2	$L_9/2\pi$	$L_9/2\pi$	$(L_1-L_2-L_6)/2$
Upper torso	M_3	$L_{12}/2$	$L_{11}/2$	$L_{17}/2$
Central torso	M_8	$L_{14}/2$	$L_{13}/2$	$(L_{17}+L_{18})/4$
Lower torso	M_9	$L_{16}/2$	$L_{15}/2$	$L_{18}/4$
Upper arms	M_4, M_5	$L_{19}/2\pi$	$L_{19}/2\pi$	$L_{17}/2$
Lower arms	M_6, M_7	$L_{21}/2\pi$	$L_{21}/2\pi$	$L_{18}/2$
Upper legs	M_{10}, M_{11}	$L_{25}/2\pi$	$L_{25}/2\pi$	$(L_2-L_{17}-L_{23})/2$
Lower legs	M_{12}, M_{13}	$L_{27}/2\pi$	$L_{27}/2\pi$	$(L_{23}-L_{29})/2$
Feet	M_{14}, M_{15}	$L_{10}/2$	$L_{31}/2$	$L_{29}/2$

Table 3.3 - Formulae for statistical dimensions of geometrical bodies representing body segments of Fig.3.2

Body Segments (Fig.2.3)	Shape of the segment taken (Fig.3.2)	Mass Elements (Fig.2.4)	Formulae		
			a_i	b_i	c_i
Head	Ellipsoidal	M_1	$L_7/2$	$L_7/2$	$L_6/2$
Neck	Right circular cylinder	M_2	$L_9/2\pi$	$L_9/2\pi$	$(L_1-L_2-L_6)/2$
Upper torso	Elliptical cylinder	M_3	$L_{12}/2$	$L_{11}/2$	$L_{17}/2$
Upper arms	Right circular cylinder	M_4, M_5	$L_{19}/2\pi$	$L_{19}/2\pi$	$L_{17}/2$
Lower arms	conical frustrum	M_6, M_7	$L_{22}/2\pi$	$L_{21}/2\pi$	$L_{18}/2$
Central torso	Elliptical cylinder	M_8	$L_{14}/2$	$L_{13}/2$	$(L_{17}+L_{18})/4$
Lower torso	Elliptical cylinder	M_9	$L_{16}/2$	$L_{15}/2$	$L_{18}/4$
Upper leg	Conical frustrum	M_{10}, M_{11}	$L_{25}/2\pi$	$L_{24}/2\pi$	$(L_2-L_{17}-L_{23})/4$
Lower leg	Conical frustrum	M_{12}, M_{13}	$L_{28}/2\pi$	$L_{26}/2\pi$	$(L_{23}-L_{29})/2$
Foot	Ellipsoid	M_{14}, M_{15}	$L_{20}/2$	$L_{31}/2$	$L_{29}/2$

Table 3.4- Mass and stiffness values of the ellipsoidal segments (Fig.3.1) (50th percentile US Male)

Truncation factor, $t_r = 0.05$
Segment elastic modulus, $E = (E_b E_t)^{1/2} = 13.0$ MN/m^2
($E_b = 22.6$ GN/m^2, $E_t = 7.5$ kN/m^2)

Segment No.	Segment designation (Fig.3.1)	Semi-axes of ellipsoids as computed from Table 3.1 and 3.2 (cm)			M_i(kg) (eq.2.1)	S_i(kN/m) (eq.2.1a)
		a_i	b_i	c_i		
1	H	7.785	7.785	9.931	3.044	680.5
2	N	6.02	6.02	1.13	0.207	3576.0
3	UT	16.43	11.66	9.385	9.105	2279.0
4,5	RUA,LUA	5.239	5.239	18.77	2.322	163.0
6,7	RLA,LLA	4.629	4.629	24.33	1.91	98.1
8	CT	14.11	10.76	21.33	16.33	783.3
9	LT	17.72	11.6	12.11	12.59	1893.0
10,11	RUL,LUL	3.926	3.926	27.93	7.827	140.2
12,13	RLL,LLL	3.304	5.304	23.11	3.443	135.7
14,15	RF,LF	4.674	12.7	6.909	1.198	938.0

Table 3.5 Mass and stiffness values of the body segments of Fig.3.2 (50th percentile US male)

Segment No.	Segment Designation (Fig.3.2)	Dimensions of body segments of Fig.3.2 as computed from Table 3.1 and 3.3			Mass of Segment M_i(kg)	Stiff-ness of segments S_i(kN/m)
		a_i	b_i	c_i		
1	H	7.785	7.785	9.931	2.219	681.05
2	N	6.02	6.02	1.13	0.249	6007.66
3	UT	16.45	11.66	9.385	19.82	2086.0
4,5	RUA,LUA	5.239	5.239	18.77	2.83	298.64
6,7	RLA,LLA	2.84	4.629	24.33	1.76	110.34
8	CT	14.11	10.77	21.55	9.01	1437.0
9	LT	17.72	11.6	12.11	13.77	3445.84
10,11	RUL,LUL	5.926	8.04	27.93	7.29	349.73
12,13	RLL,LLL	3.35	5.72	23.11	2.26	157.02
14,15	RF,LF	4.674	12.7	6.909	0.753	958.0

Table 3.6 - Stiffness of the vibratory model elements (Fig.2.4)

Model No. / Element No.	K_1	K_2	K_3	K_4, K_5	K_6, K_7	K_8	K_9, K_{10}	K_{11}, K_{12}	K_{13}, K_{14}
Model 1	680.5	1392.0	584.2	152.1	98.1	555.1	130.5	68.9	958.0
Model 2	680.5	1392.0	0.454	152.1	98.1	0.454	130.5	68.9	958.0
Model 3	680.5	1392.0	295.02	152.1	98.1	287.44	130.5	68.9	958.0
Model 4	681.0	1548.36	850.86	260.75	110.34	1014.09	317.5	108:36	958.0

Table 3.7- Computed natural frequencies
(50th percentile US Male)

Serial No.	Model 1	Model 2	Model 3	Model 4	Reported frequency range (Francis)	Corresponding part of the body (Fig.3.3)
f_1	7.5	0.414	6.7	11.8	2-20	Knees
f_2	22.68	1.3	19.6	29.83	4-5	Shoulder girdle
f_3	25.20	11.8	25.2	37.9	10-20	Upper arm
f_4	28.78	25.21	28.04	40.4	10-20	Spinal column
f_5	29.66	26.8	28.78	41.5	16-20	Lower arm
f_6	40.42	31.1	35.87	52.4	30-80	Eye ball
f_7	53.33	33.5	41.84	70.5	50-200	Hand
f_8	58.16	58.2	58.16	70.6	60	Chest
f_9	58.8	58.86	58.75	75.3		
f_{10}	79.79	74.2	76.54	83.05		
f_{11}	86.95	86.9	86.95	122.6		
f_{12}	86.95	86.9	86.95	122.6		
f_{13}	508.03	508.1	508.02	461.9		

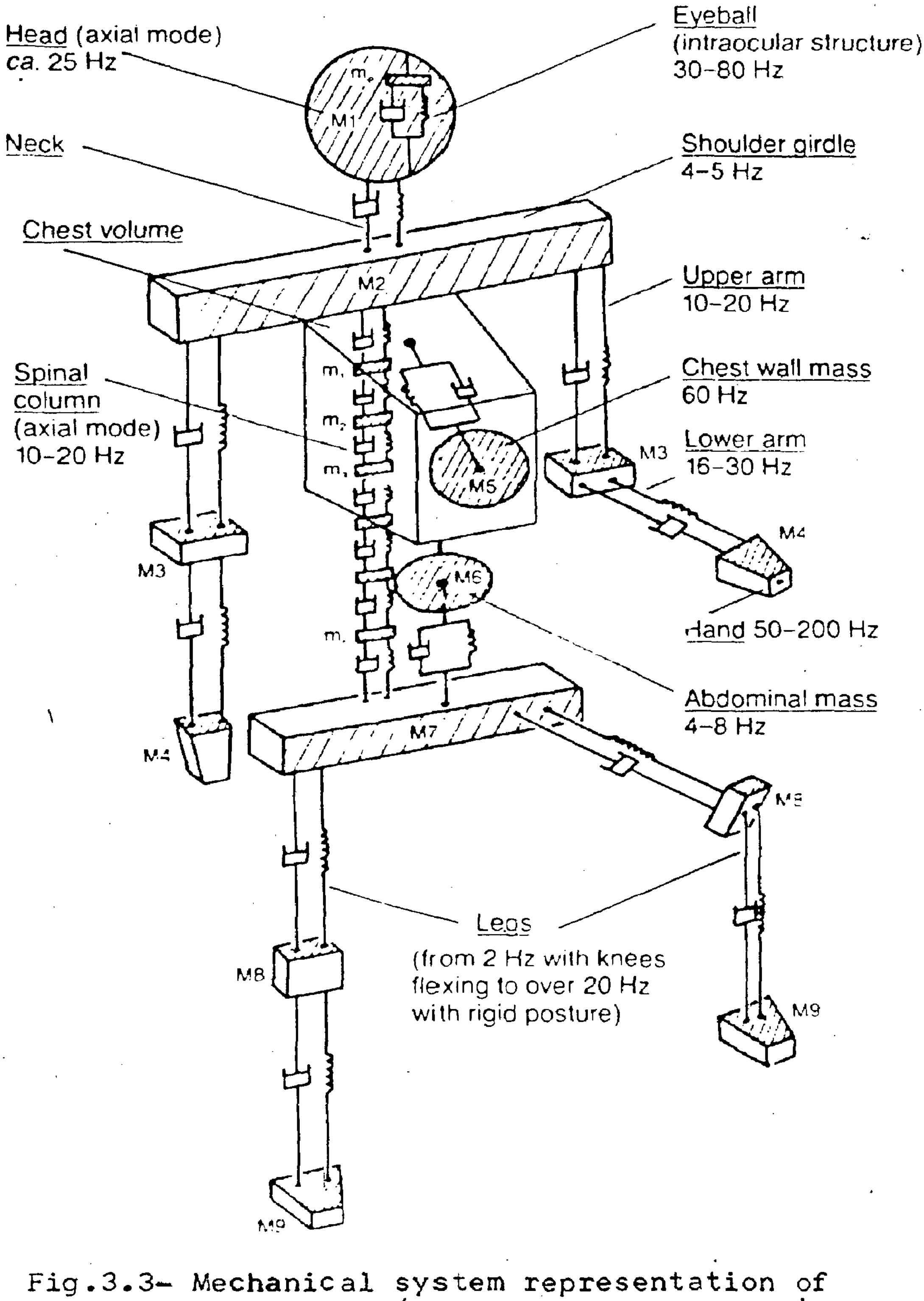


Fig.3.3- Mechanical system representation of human body (Nagy and Siegler,1987)

peak frequency values, it should be noted that the frequencies of the undamped vibratory models would always be higher than the experimental values. Looking into Table 3.7 the higher order frequencies of the first three models are nearly the same. In fact all the values of the three models fall within the frequencies ranges of the experimental as given in the Table 3.7. However, comparing the first two lower range frequencies of the three models with the corresponding experimental ranges, Model 3 seems to be more appropriate. Model 4, though based on a seemingly better anthropomorphic model, gives the lower range frequencies (below 50 Hz) which do not match with the experimental ranges. In fact, physically, neither of the two anthropomorphic model give an exact representation of the body. However, it seems that the anthropomorphic model with all segments represented by ellipsoids only gives better averaged approximation of the body thus leading to a better vibratory model.

Model 3 appears to be an improvement on the original model of Nigam and Malik. The improvement is indeed a result of the changes incorporated in the central torso of the body and accounting of the back bone stiffness.

The models may also be compared on the basis of some experimental stiffness data reported by Greene and McMahon (1979) and Mizrahi and Susak(1982). Greene and McMahon conducted experiments on bounding motion of the subjects standing on simply supported wooden planks. The vibratory model of the human body and the plank was considered to be a two degree of freedom system. On the basis of experiments on a large number of subjects, Greene and McMohan have given average value of leg stiffness as 37.6 kN/m in the bounding mode. In a subsequent work the same authors (1979) gave the values of leg stiffness in running in the range of 73 to 100 kN/m. The experiments of Mizrahi and Susak (1982) were on the single leg jumping and the vibratory model was represented by two degrees of freedom system with one degree each associated with leg and remaining part of the body. Experiments were conducted by allowing the subject to jump on a single leg and measuring the transient acceleration at the level of greater trochantor. The stiffness of the leg and remaining part of the body were then estimated from the equations of motion and the experimental results. For the two subjects of the experiment, these stiffnesses are reported as

Subject	leg stiffness (kN/m)	Stiffness of remaining part of the body (kN/m)
A	8.45	45.2
B	5.32	42.3

It may be noted that there is considerable difference in the leg stiffness value of McMahon and Greene(1979) and Mizrahi and Susak (1982). However, the Greene and McMahon (1979) performed experiments on five subjects with leg stiffness varying in the range of 19.7 to 55.3 and average value of 37.6. As such data of this work seems to be more reliable.

For the present vibratory models, the leg stiffness may be estimated taking the springs K_9, K_{11}, K_{13} (Fig.2.4) in series. Similarly for the upper part of the body the stiffness may be estimated taking K_1, K_2, K_3 and K_8 (Fig. 2.4) in series. Thus the values of stiffness of the leg and the remaining part of the body for the four models are calculated as

Stiffness of	Model 1	Model 2	Model 3	Model 4
Leg (kN/m)	43.06	43.06	43.06	74.5
Trunk (kN/m)	175.4	0.2258	110.41	233.88

where it may be noted that leg stiffnesses of the first three models are the same.

The leg stiffness of the vibratory models with ellipsoidal segments (Models 1 to 3) are quite comparable to the value of average leg stiffness reported by McMahon and Greene(1979).

Considering the difference in the leg stiffnesses of McMahon and Greene(1979) and Mizrahi and Susak, the stiffness of the trunk of the body as estimated in the later work also seems to be on a lower side. As seen from above Table, Models 2 and 4 underestimate and overestimate the trunk stiffness. Both Models 1 and 3 perhaps give better estimates of the stiffnesses.

The foregoing analysis clearly shows that out of the four models considered, only models 1 and 3 are adequate. These two models will now be assessed on the basis of frequency response.

3.2 DEVELOPMENT OF DAMPED VIBRATORY MODEL OF HUMAN BODY

The response of the vibratory model of the human body can be evaluated by including damping in the basic model described in Section 3.1. For evaluating the damping constants of the dashpots in the model as explained in Section 2.1.4, it is first necessary to identify the damping ratios of individual body segments. The damping ratios, whatever identified, have to be assessed on the basis of the frequency response of model against the experimental response. The basic model has been developed for a 50th percentile US male. As such in the experimental response data available in the literature, the anthropometric data or the percentile group of the subjects are not reported. Garg and Ross (1976) report to have conducted the experiments on young males of 20-25 age group. Assuming that the subject of their work belong

50th percentile group, a comparison of the response of vibratory model of 50th percentile US male with the experimental response of Garg and Ross may then provide a basis for adjusting the damping ratios of the segments in the model.

Garg and Ross performed experiments on eight subjects and gave the response plots of the two extreme cases and an average plot of all the subjects. The experimental frequency response plots of this work are reproduced in Fig.3.4. This would indeed be more meaningful to assess the response of the present model on the basis of the response of two extreme cases of Fig.3.4 rather than the average response.

Looking at the structure of human body and its vibratory response in standing posture, it is apparent that most significant body parts are in the order feet, legs, central torso, lower torso and upper torso. In a freely standing posture, the presence of hands, while not resting against any support, can not be expected to change the response of the body any significantly. In a similar manner, the head, though with stout skull, being free is also not as effective as the aforesaid body parts. Keeping this physical structure in mind, response of the vibratory model (Model 3) were obtained by changing the damping ratios of the various body segments. The results of some of these trial computations applied to Model 3 are shown in Table 3.8 in which the peak values of the amplitude ratio and

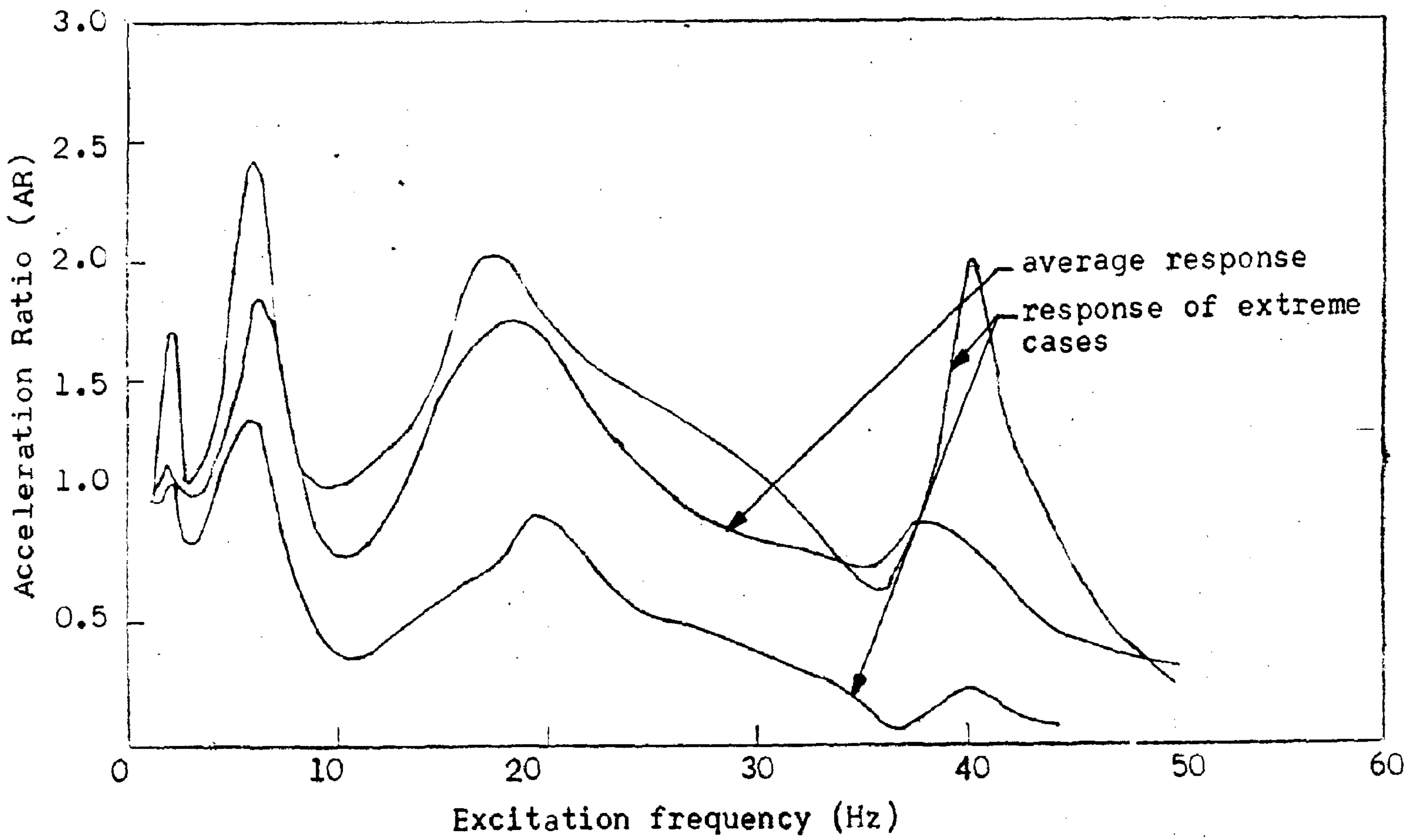


Fig.3.4- Experimental response of US males (Garg and Ross, 1976)

Table 3.8 Effect of damping 'ζ' of particular segment on the resonant peaks of model response (Model 3)

Body Segment	H	N	UT	UA/LA	CT	LT	UL/LL	F	I f(Hz)	I AR	II f(Hz)	II AR	III f(Hz)	III AR	IV f(Hz)	IV AR
ζ	0.004	0.015	0.002	0.040	0.20	0.50	0.60	0.70	6	4.70	21	0.450	-	-	42	0.36
	0.004	0.015	0.002	0.040	0.20	0.50	1.00	1.25	6	3.11	20	0.47	-	-	38	0.49
	0.004	0.015	0.002	0.040	0.20	0.80	1.00	1.25	6	3.03	20	0.47	-	-	38	0.49
	0.004	0.015	0.002	0.010	0.20	0.80	1.00	1.25	6	3.03	21	0.47	-	-	40	0.49
	0.004	0.015	0.008	0.010	0.20	0.80	1.00	1.25	6	3.03	20	0.47	-	-	38	0.51
	0.004	0.015	0.002	0.040	0.20	0.50	1.25	1.50	6	2.65	21	0.49	-	-	38	0.57
	0.004	0.015	0.002	0.040	0.20	0.80	1.25	1.50	6	2.57	20	0.50	-	-	38	0.57
	0.004	0.015	0.002	0.040	0.20	1.00	1.25	1.50	6	2.54	20	0.50	-	-	40	0.57
	0.004	0.015	0.002	0.010	0.20	1.00	1.25	1.50	6	2.54	20	0.50	-	-	40	0.61
	0.004	0.015	0.020	0.010	0.20	1.00	1.25	1.50	6	2.54	Suppressed		-	-	40	0.61
	0.004	0.015	0.040	0.010	0.20	1.00	1.25	1.50	6	2.56	21	0.58	-	-	34	0.95
	0.004	0.015	0.002	0.010	0.40	0.80	1.25	1.50	6	2.08	21	0.58	-	-	38	0.86
	0.004	0.015	0.015	0.060	0.40	0.80	1.25	1.50	6	2.77	21	0.58	-	-	36	0.44
	0.004	0.015	0.002	0.001	0.01	1.00	1.50	1.50	6	2.63	17	0.918	30	0.96	38	2.29
	0.004	0.015	0.002	0.001	0.01	1.00	2.00	2.00	6	2.24	17	1.03	30	0.96	38	2.74
	0.004	0.015	0.002	0.001	0.01	1.50	1.50	1.50	6	2.59	17	0.92	30	0.97	38	2.34
	0.004	0.015	0.002	0.001	0.01	0.75	1.50	1.50	6	2.67	17	0.90	30	0.94	38	2.23
	0.004	0.015	0.002	0.001	0.05	1.00	1.50	1.50	6	2.62	17	0.86	30	0.664	38	1.43
	0.004	0.015	0.002	0.001	0.10	1.00	1.50	1.50	6	2.59	16	0.814	30	0.664	38	1.01
	0.004	0.01	0.002	0.001	0.10	1.00	1.50	1.50	6	2.59	16	0.814	30	0.664	38	1.01
	0.004	0.05	0.002	0.001	0.10	1.00	1.50	1.50	6	2.59	16	0.814	30	0.664	38	1.01
	0.004	0.001	0.002	0.001	0.10	1.00	1.50	1.50	6	2.59	16	0.814	30	0.664	38	1.01
	0.700	0.700	0.700	0.700	0.70	0.70	0.70	0.70	6	4.49	- continuously suppressed response					

corresponding frequencies are given for each set of the damping ratios. The aim was to achieve a response which could be enveloped by the response of two extreme cases of Fig.3.4. These trials did in fact lead to a set of damping ratios as would be discussed later which give a reasonable response in relation to the response of Fig.3.4.

Table 3.8 brings out clearly the effect of damping ratios of the various segments. The peaks at 6 Hz and around 40 Hz are essentially governed by the damping of the feet and the legs; the larger the damping the smaller would be the 6 Hz peak. Also with equal damping of the feet and legs, the peak around 40 Hz is spontaneously raised and a mild peak at 30 Hz also appears. The damping ratio of lower torso also effects the two peaks although not as significantly as the feet and leg. The damping of central torso has a quite significant effect on the peak value around 40 Hz; increase in central torso damping suppresses the peak. The damping of upper torso effects the response around 20 Hz. It is also to be seen that the damping ratio of arms, head and neck have no significant effect on the peak values. With equal damping ratio of all the body segments, the response shows only a single peak at 6 Hz with a continually decaying amplitude ratio with increasing frequencies.

Based on the computation summarised in Table 3.8, the following set of damping ratios was found to be most appropriate.

Body Segment	H	N	UT	ARMS	CT	LT	LEGS	F
ζ	-.004	.015	.002	.001	.05	1.0	1.5	1.5

The theoretical response obtained with above set of damping ratios is plotted in Fig.3.5 and Fig.3.6. In most of the frequency range, the response of the present vibratory model for 50th percentile US male is within the experimental response envelope of Garg and Ross. The difference lies mainly in the frequency range of nearly 18 to 28 Hz. The theoretical response shows a valley at 25 Hz while the experimental response shows a clear peak at 20 Hz. Though the theoretical response shows a mild peak at nearly 17 Hz., the response in 18 to 28 Hz. region could not be brought within the envelope by any combination of the damping ratios. Also the peak at 1.6 Hz observed in the experimental response could not be obtained from the theoretical model. Although in the most region, the theoretical response looks to be quite satisfactory, the response in 18 to 28 Hz region possibly needs some modification in the basic model itself.

In Section 3.1, the stiffnesses of leg and remaining part of the body were evaluated and compared with the reported values. A similar comparison may also be made for the damping ratio as well. Considering a single leg, its damping constant can be evaluated taking series combination of the dashpots C_9, C_{11} and C_{13}. The damping ratio of the leg is then given by

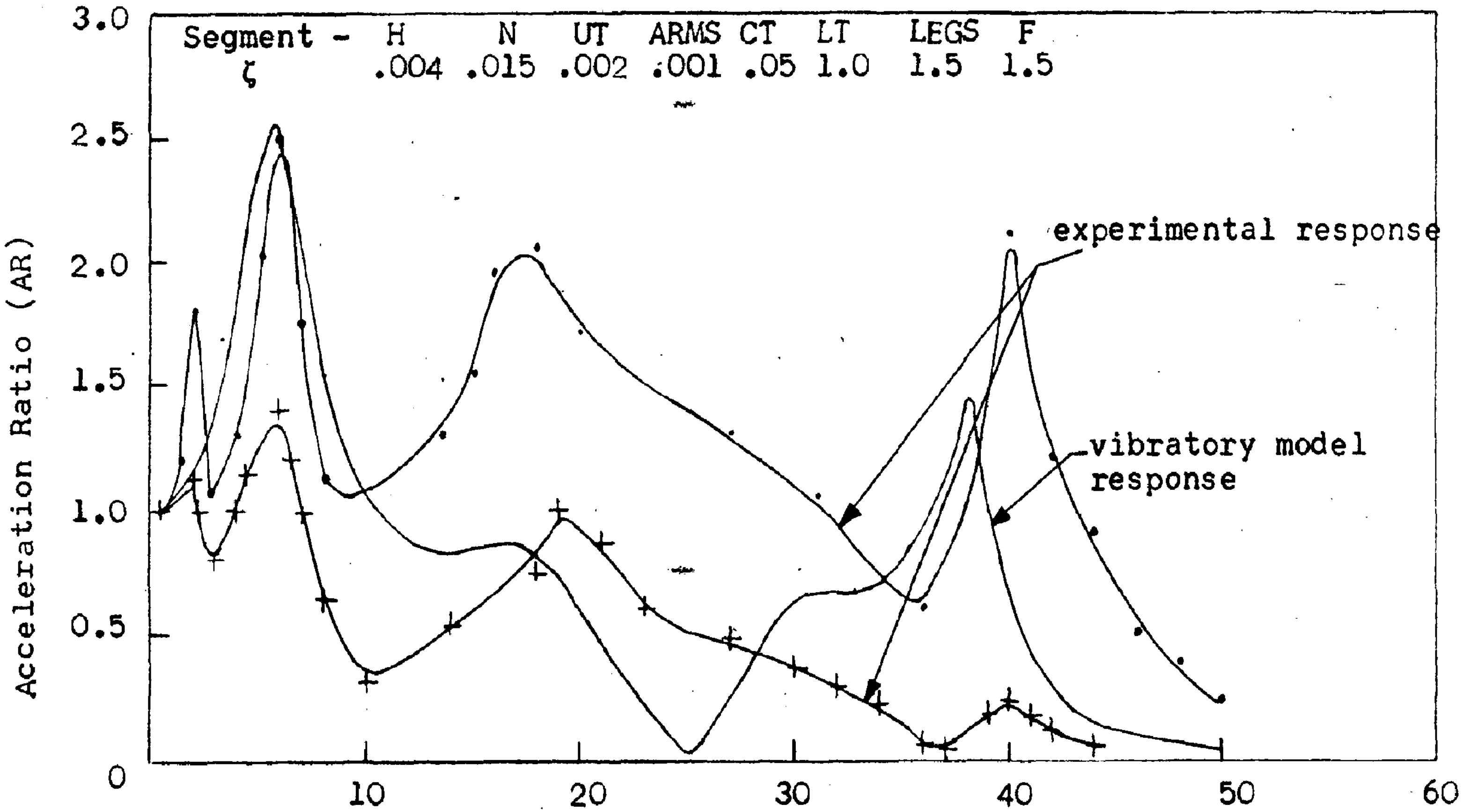


Fig.3.5 Comparison of vibratory model response (50th percentile US male) with experimental response of two extreme cases (Garg and Ross,1976).

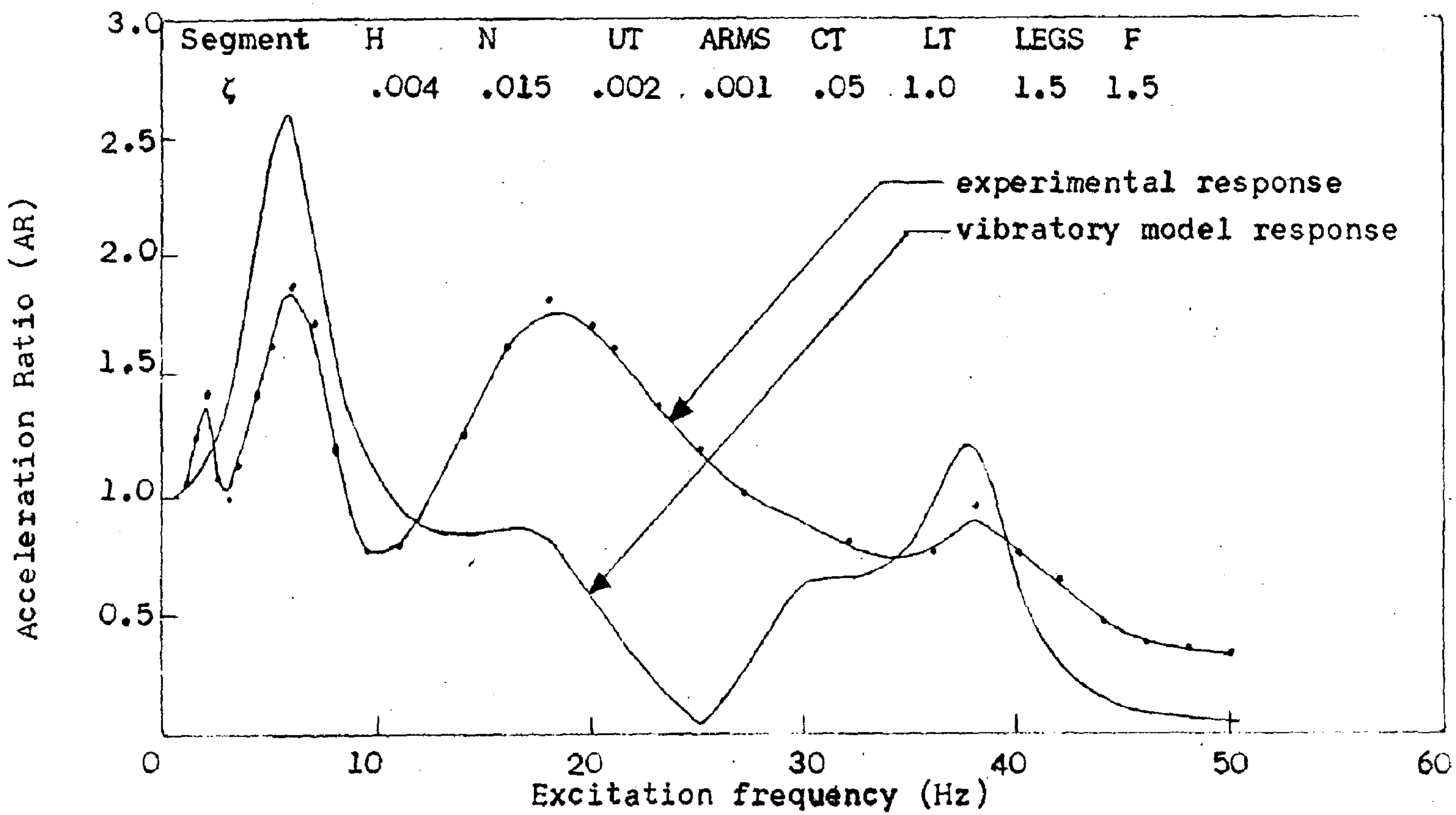


Fig.3.6- Comparison of vibratory model response (50th percentile US male) with average experimental response (Garg and Ross,1976)

$$\zeta_{leg} = \frac{C_{leg}}{2\sqrt{K_{leg}\, m_{leg}}}$$

For the damping ratio data of the theoretical response of Fig.3.5, the leg damping ratio comes out to be 0.443. The value is comparable to the corresponding damping ratio of 0.55 reported by Greene and McMahon(1979) and, 0.52 and 0.67 reported by Mizrahi and Susak(1982). The damping ratio for the model seems to be on a lower side. However, in the above two works, experiments were on bounding and jumping modes when the body takes the support on the toes rather than whole feet. In the present model, if the damping ratio are computed considering the feet and lower leg only or the upper and lower leg only, the damping ratio values are obtained as under

Lower leg and feet combination: ζ = 0.82
Upper and lower legs combination ζ = 0.57

The three values (0.443, 0.57 and 0.84) of the damping ratio of the present model bracket the leg damping ratio data of the aforesaid experimental works.

The response studies presented in this section have been based on Model 3 only. The objective was to gain the idea of damping ratios of the various body segments. The experimental response taken up for the comparison do not really represent the actual response of the 50th percentile US male used for vibratory model development. Therefore, only one model was considered to be sufficient to achieve the desired objective. However, the investigations of this section do give a fairly good idea of damping ratios of the various body segments. The information may now be used to develop vibratory models of the Indian subjects and make a more meaningful comparison with their actual vibratory response. For the Indian subjects both Model 1 and Model 3 would be considered. However, before presenting these results, a human body vibration experimental set up used in the present work is being first described in the following section.

3.3 EXPERIMENTS ON HUMAN BODY RESPONSE

An accurate simulation of the environmental condition to which a man is subjected, is frequently not feasible or even desirable, because of a need for more systematic investigation under somewhat simplified conditions. Thus most investigations are limited to the study in which human subject is vibrated in only one direction. It is the same situation here, which is an oversimplification and it may require important changes in future.

The response of an individual to vibration depends on a complex combination of intrinsic and extrinsic variables (factors). During experiments, there is control over the extrinsic variables only.

The schematic of the human vibration response measuring set up is shown in Fig.3.7. Figure 3.8 shows the photograph

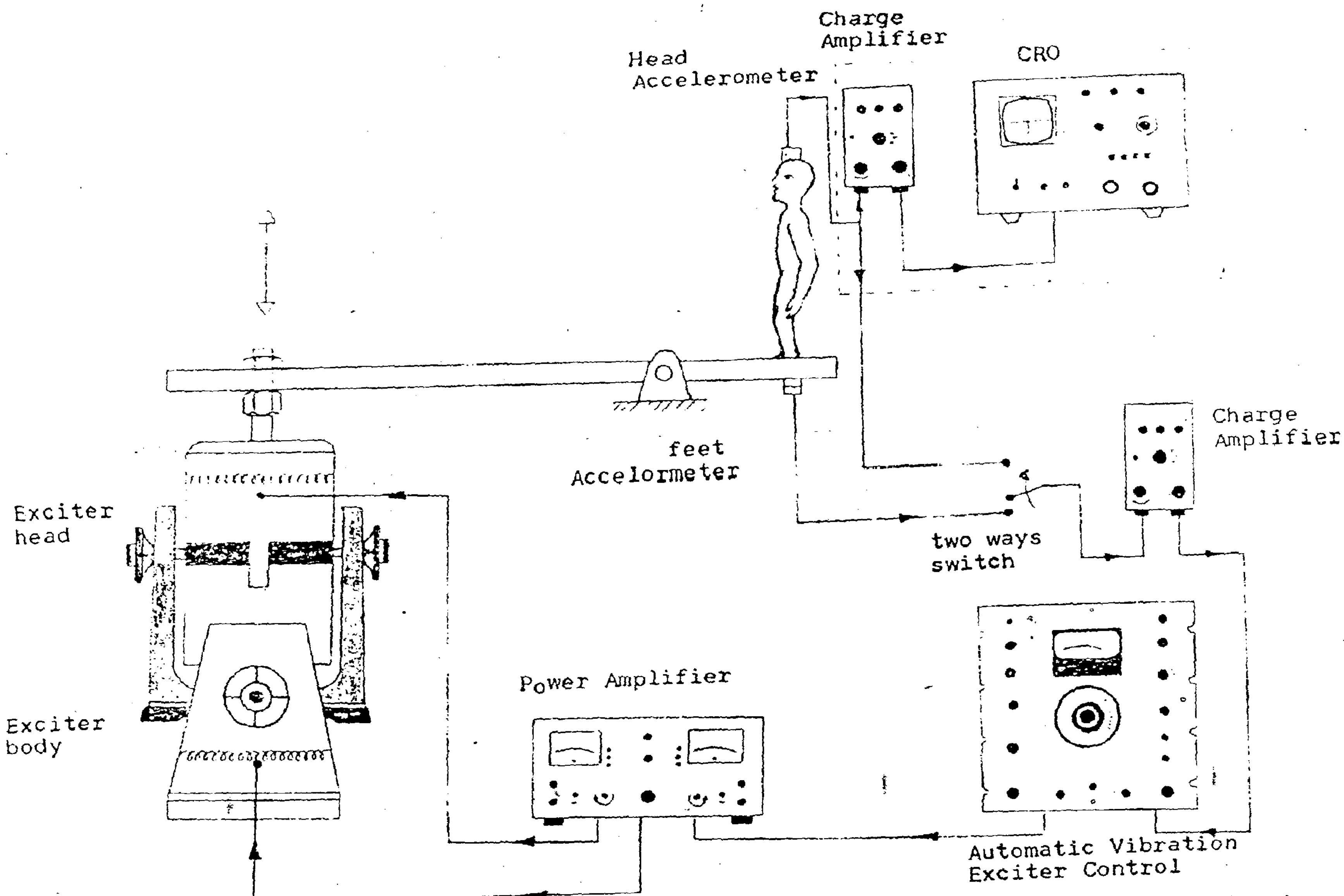


Fig. 3.7- Schematic representation of set-up for frequency response experiment

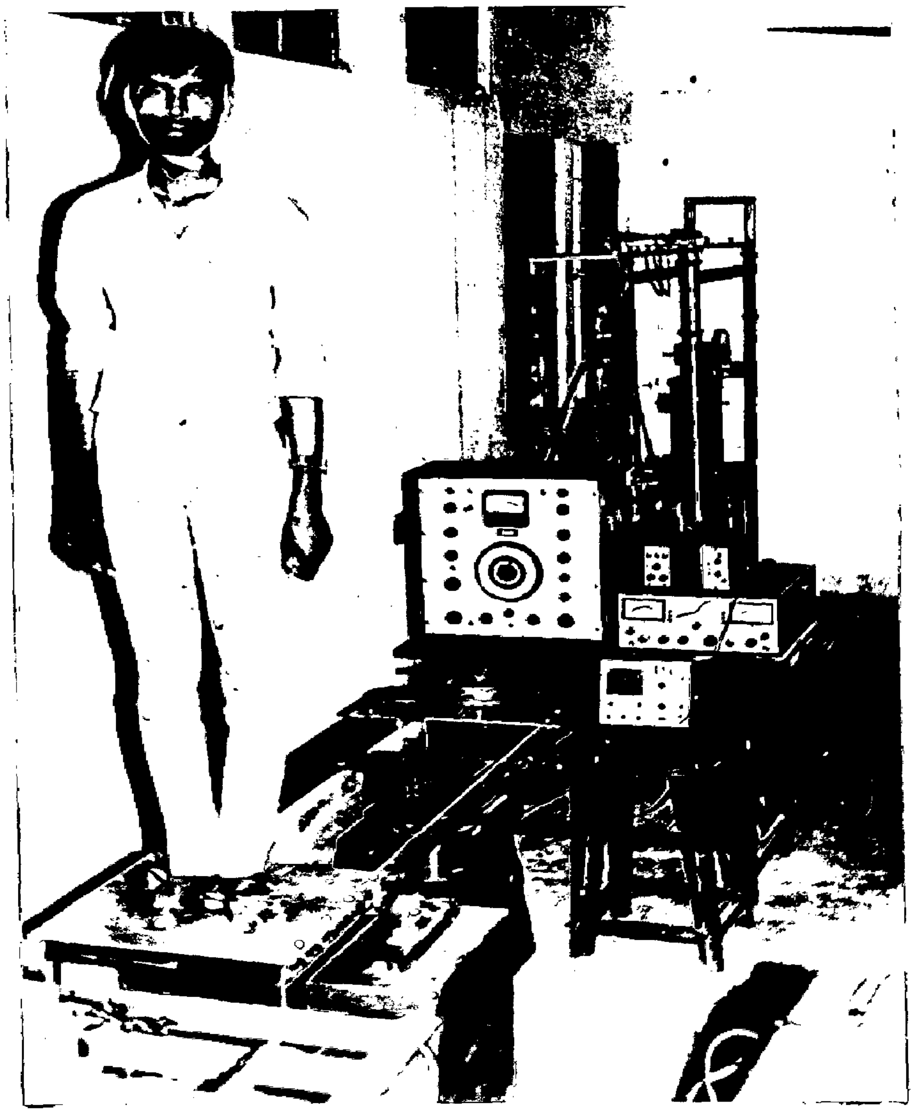


Fig.3.8- Typical experiment subject mounted on test table and restrained from shifting his feet by guides and strapes.

of the actual set up. The test table in this set up is vibrated by an electrodynamic shaker. A four to one lever arm ratio has been used for the plateform on which the test subject rests, to increase the mass supporting capacity of the plateform though at the cost of amplitude.

The Automatic Vibration Exciter control feeds the shaker table via a power amplifier and the frequency of excitation is altered by means of a built in drive. The signals measuring the motion of the shaker table is fed back to the Automatic Vibration Exciter Control via conditioning amplifier (accelerometer preamplifier). However, owing to uneven frequency response of the test subject, the power required to vibrate the test subject at a given level is dependent on frequency. To keep the vibration level constant, the power output to the exciter head is regulated manually by changing the voltage output of the Automatic Vibration Exciter control. Either an accelerometer or a velocity pick-up may be used as transducer. The vibration derivation section of the exciter control contains all the integrator and differentiator networks necessary for deriving acceleration, velocity or displacement from either input. It is possible to keep any of these dynamic properties constant on the shaker table.

The experimental set up can be used for two postures namely standing and sitting. In the present work only the standing posture is being considered. For this posture, the test subject is allowed to stand on the table in his normal stance and feet are strapped at the position of his choice of feet placement. With this arrangement the subject remain comfortable but is restrained from changing the position of his feet during the experiment. The head accelerometer already bolted to a plexiglass frame is strapped to the subject head.

The subject is given vibrations at a particular frequency for a time which is sufficient for the decay of the transients but is not so large as to cause any fatigue in the subject. Thus the sequence of experiments is to be followed with due regard for the time which is necessary for the subject's rest.

At each frequency, the acceleration amplitudes at the feet and the head are measured with the help of Automatic Vibration Exciter Control by connecting output signals from feet and head one by one at each frequency. This is rather awkward way of the measurements in which the accuracy can not be guaranteed. This limitation was due to the unavailability of the equipments in the laboratory. It is actually desirable to use another circuit consisting of conditioning preamplifier and transducer amplifier with level recorder to measure the output signals from head accelerometer. During the experiments, the acceleration at the feet of the subject is maintained at a constant level for complete frequency sweep.

3.4 VIBRATORY MODEL OF INDIAN MALE

The comparison of the 50th percentile US male vibratory model with the experimental response of Garg and Ross (1976) and response on US males, provides a guideline for prescribing the damping ratios to various body segments and development of the complte vibratory model. However, this comparison was on the anticipation that the subjects of Garg and Ross belonged to 50th percentile group. In order to have a more meaningful comparison, it was therefore decided to develop the vibratory model of Indian subjects and perform experiment on the same. For a response study program and development of generalized models, it is indeed useful to categorise the subject population into percentile or some other groups. In the present work, it was decided to collect the anthropometric data of the young University students of 18-24 years age group. Such data were collected for 100 subjects. From these data, the anthropometric measurements of 50th percentile were evaluated. These are given in Table 3.9.

Having the 50th percentile Indian male data, vibratory models (Model 1 and 3) were developed and their theoretical response computed. Experiments were then conducted on seven subjects of the 50th percentile group to obtain the frequency response. The theoretical response of the two models are compared with the response of two extreme cases in Fig.3.9 and 3.10. In Figs.3.11 and 3.12, the theoretical response are compared with an average response of the seven subjects. In

Table 3.9 Anthropometric measurements of 50th Percentile Indian Male

Body mass, M = 57.5

Dimensional data	Measurements (cm)
L_1 Standing height	170.28
L_2 Shoulder height	146.75
L_3 Armpit height	133.75
L_4 Waist height	103.75
L_5 Seated height	89.178
L_6 Head length	19.85
L_7 Head breadth	16.95
L_8 Head to chin height	24.41
L_9 Neck circumference	34.43
L_{10} Shoulder breadth	42.6
L_{11} Chest depth	20.03
L_{12} Chest breadth	30.64
L_{13} Waiste depth	18.0
L_{14} Waist breadth	28.93
L_{15} Buttock depth	20.92
L_{16} Hip breadth (standing)	34.09
L_{17} Shoulder to elbow length	35.75
L_{18} Forearm hand length	48.93
L_{19} Biceps circumference	25.0
L_{20} Elbow circumference	24.27
L_{21} Forearm circumference	24.39
L_{22} Wrist circumference	16.65
L_{23} Knee height (seated)	53.69
L_{24} Thigh circumference	47.4
L_{25} Upper leg circumference	37.9
L_{26} Knee circumference	35.92
L_{27} Calf circumference	31.87
L_{28} Ankle circumference	22.09
L_{29} Ankle height (outside)	10.01
L_{30} Foot breadth	10.7
L_{31} Foot length	25.95

Table 3.10 - Mass and stiffness values of the ellipsoidal segments (50th percentile Indian male)

Truncation factor, $t_r = 0.05$

Segment elastic modulus $E = \sqrt{E_b E_t} = 13.0\ MN/m^2$

$E_b = 22.0\ MN/m^2$, $E_t = 7.5\ kN/m$

Segment No.	Segment Designation (Fig.2.3)	Semi axes of ellipsoids as computed from Tables 3.1 and 3.9			Mass of Segment M_i (Kg)	Stiffness of Segment S_i (kN/m)
		a_i	b_i	c_i		
1	H	8.475	8.475	9.925	2.543	807.94
2	N	5.48	5.48	1.84	0.917	1822.1
3	UT	15.32	15.02	17.87	14.67	1437.18
4,5	RUA,LUA	3.98	3.98	17.87	1.01	98.94
6,7	RUA,LLA	3.88	3.88	24.46	1.32	68.69
8	CT	14.46	9.0	21.47	9.83	686.55/447.75*
9	LT	17.05	15.46	12.23	11.49	2406.23
10,11	RUL, LUL	6.03	6.03	28.65	3.72	141.665
12,13	RLL, LLL	5.07	5.07	21.84	2.0	131.39
14,15	RF, LF	5.35	13.97	5.005	1.33	1667.75

* For Model-3

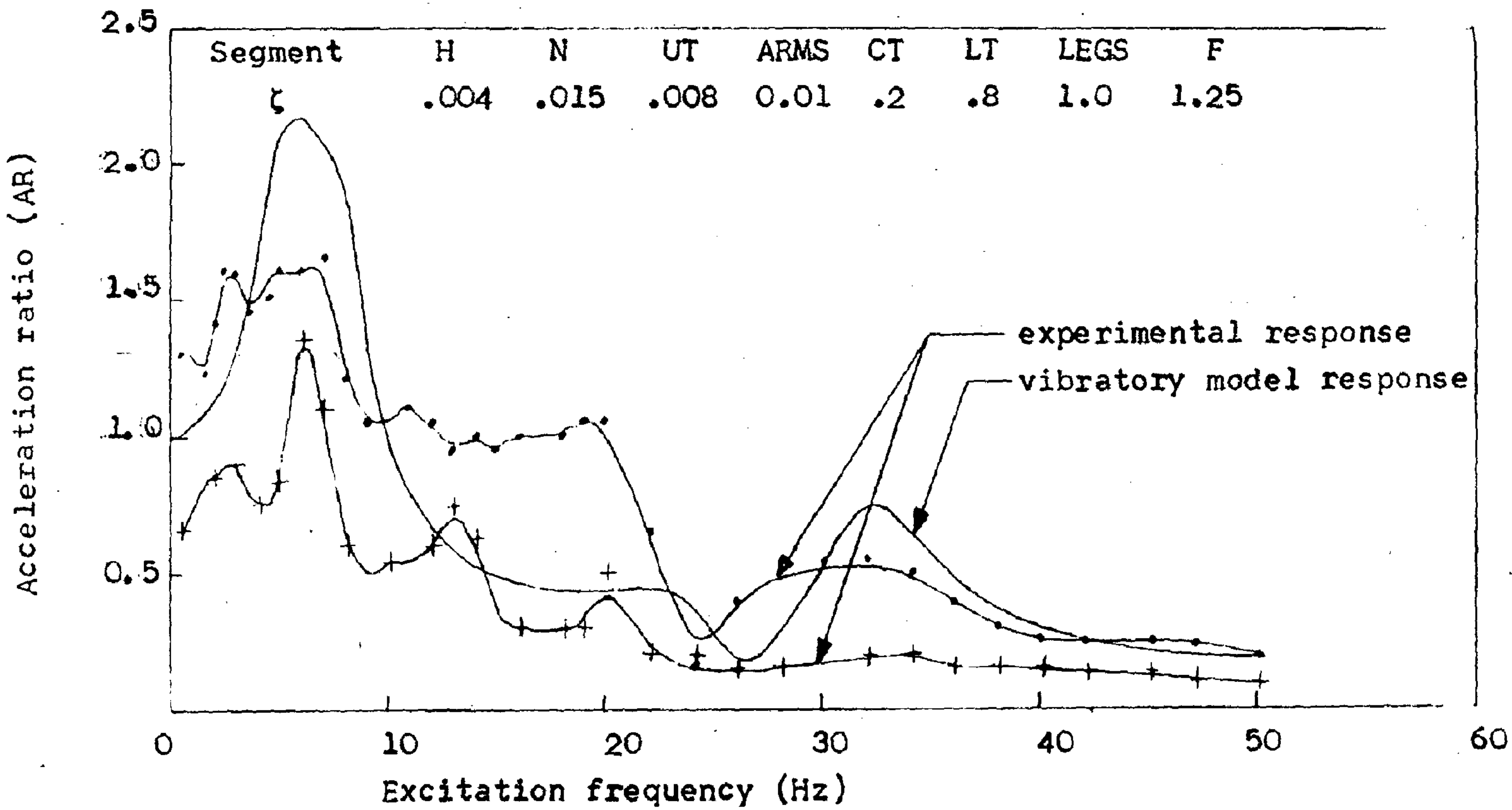


Fig.3.9- Comparison of vibratory model (Model 1) response (50th percentile Indian male) with experimental response of two extreme cases.

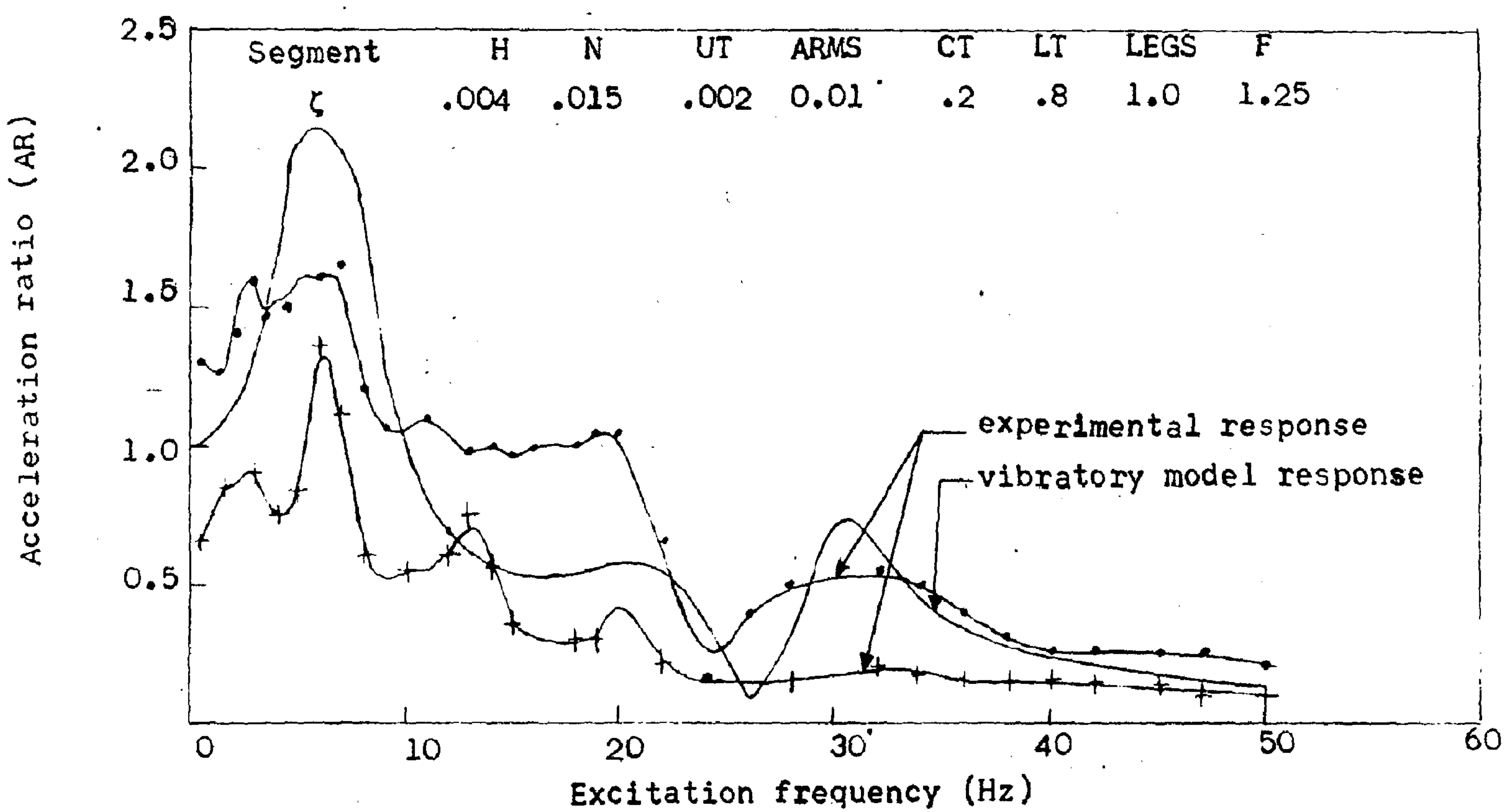


Fig.3.10— Comparison of vibratory model ($M_o$del 3) response (50th percentile Indian male) with experimental response of two extreme cases.

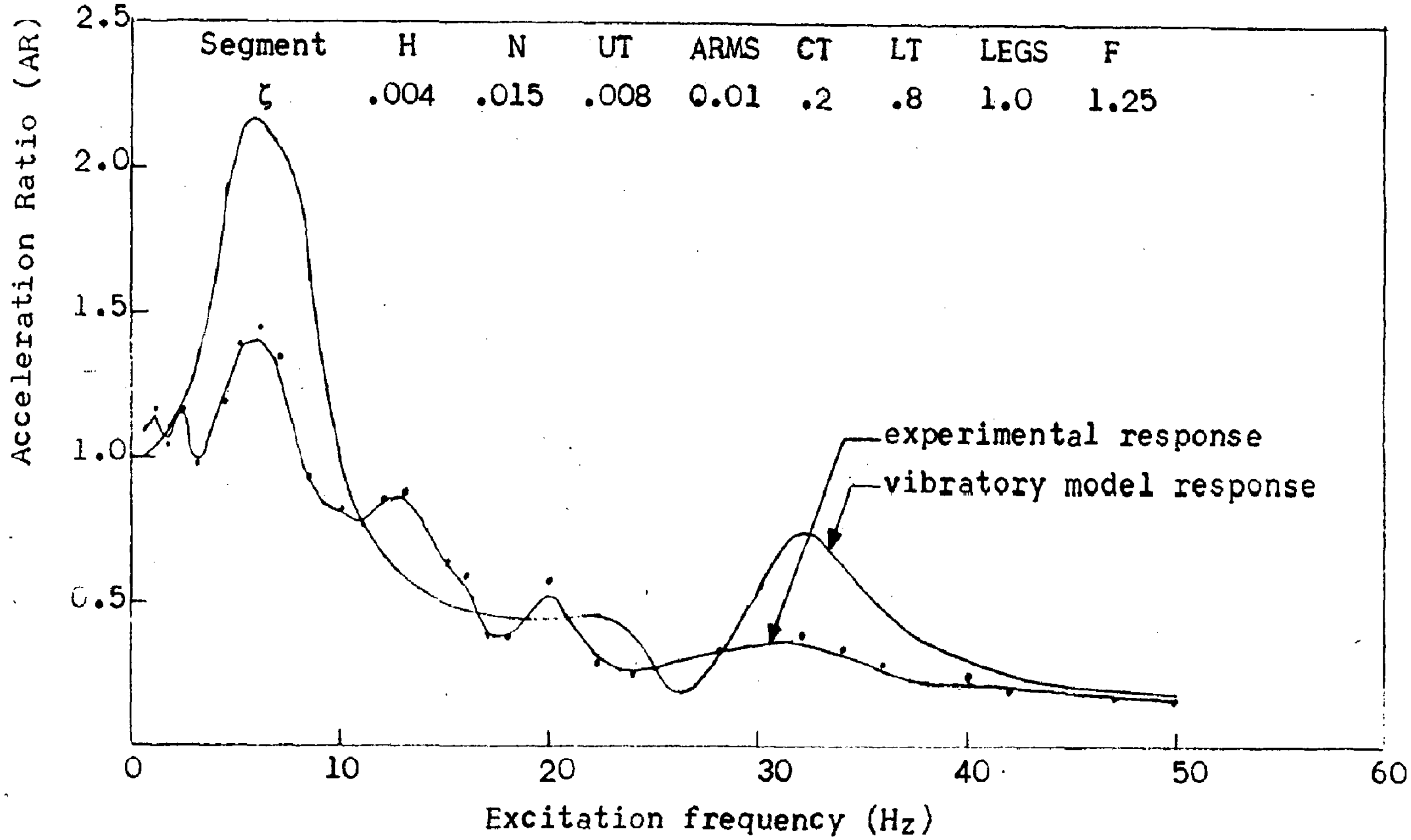


Fig.3.11 Comparison of vibratory model (Model 1) response (50th percentile Indian male) with average experimental response

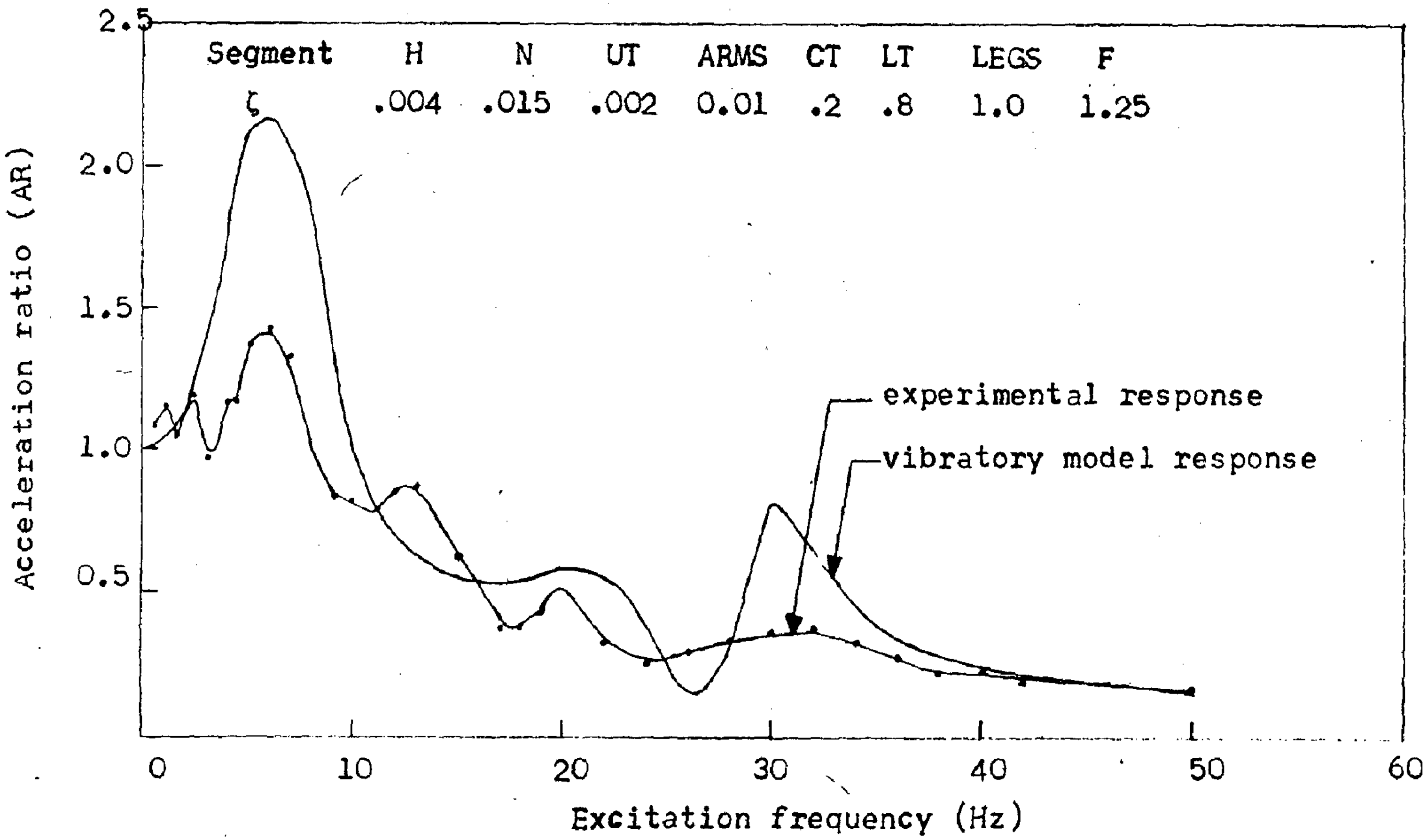


Fig.3.12 Comparison of vibratory model (Model 3) response (50th percentile Indian male) with average experimental response.

the development of the vibratory model of 50th percentile Indian male some adjustments were required in the values of damping ratio used for the 50th percentile US male as described in Section 3.2. The damping ratio values used for the model are given in the Figs.3.9 to 3.12 and it may be seen that these values are in the same range as used for the 50th percentile US male.

Looking at Figs.3.9 to 3.12, it is interesting to note that the agreement between the theoretical and experimental response of Indian males is better than that for the US males given in Figs.3.7 and 3.8. Also the response of Model 3 (Figs.3.10 and 3.12) appear to be closer to the experimental response. In fact except for two peak values at 6.0 Hz and 18.0 Hz. the theoretical response matches very well with the experimental results. The theoretical values of the Acceleration Ratio at 6.0 Hz and 18.0 Hz. are higher than the experimental values. The difference may possibly be reduced by further adjustment of the damping ratio of the body segments, However, effort was not thought to be worthwhile as the experimental peak values could not possibly be measured with sufficient accuracy.During the experiments acceleration level at input to the feet was constant throughout the frequency range. The exciter can provide a maximum constant acceleration level of 0.3 g at the feet for complete frequency sweep. Even this maximum acceleration level (0.3 g) at the input seems to be insufficient especially at the higher frequency side as the signals at the head become weaker with increasing frequencies. In fact, inherent damping of the plateform itself decreases the displacement amplitude at the point where the subject is standing. The lower value of acceleration ratio of the first two peaks in experimental response seems to be the result of limited magnitude of displacement allowed by the exciter head. However, with all these limitations all possible care was taken to ascertain the reproducibility of the experimental results.

In Fig.3.13, the experimental response of an individual subject (MJ) is compared with the theoretical response of the vibratory model developed on the basis of anthropometric data (Table 3.11) of the subject (MJ) itself. Except for some peak values, the theoretical response for the subject compares very well with its experimental response.

3.5 CONCLUDING REMARKS

Compared to the experimental response of the US males, the response of the present model show a better agreement with the experimental response of Indian males in the entire frequency range. While discussing the model response against the experimental response of US males, it was pointed that some refinements in the basic model might be necessary. In context of the Indian males, however, this conclusion needs reconsideration.

Table 3.11 Anthropometric measurements of Manoj Jain

Body Mass, M = 54.0 Kg

Dimensional data	Measurements (cm)
L_1 Standing height	169.5
L_2 Shoulder height	144.0
L_3 Armpit height	120.5
L_4 Waiste height	98.5
L_5 Seated height	89.0
L_6 Head length	21.0
L_7 Head breadth	18.0
L_8 Head to chin height	21.0
L_9 Neck circumference	33.5
L_{10} Shoulder breadth	42.0
L_{11} Chest depth	22.0
L_{12} Chest breadth	30.5
L_{13} Waist depth	21.0
L_{14} Waist breadth	28.0
L_{15} Buttock depth	22.5
L_{16} Hip breadth (standing)	32.0
L_{17} Shoulder to elbow length	31.5
L_{18} Forearm hand length	47.5
L_{19} Biceps circumference	23.5
L_{20} Elbow circumference	23.5
L_{21} Forearm circumference	23.0
L_{22} Wrist circumference	16.0
L_{23} Knee height (seated)	47.0
L_{24} Thigh circumference	48.0
L_{25} Upper leg circumference	36.5
L_{26} Knee circumference	34.0
L_{27} Calf circumference	32.0
L_{28} Ankle circumference	23.5
L_{29} Ankle height (outside)	9.7
L_{30} Foot breadth	10.5
L_{31} Foot length	26.0

Table 3.12 Mass and stiffness values of the ellipsoidal segments (Manoj Jain)

Truncation factor = 0.05
Segment elastic modulus = $(E_b E_t)^{1/2} = 13.0$ MN/m^2
$E_b = 22.0$ MN/m^2, $T_t = 7.5$ kN/m^2

Segment No.	Segment Designation (Fig.2.2)	Semi axes of ellipsoids as computed from tables 3.1 and 3.11			Mass of Segment M_i(Kg)	Stiffness of Segment S_i (KN/m)
		a_i	b_i	c_i		
1	H	9.0	9.0	10.5	3.41	861.25
2	N	5.3	5.3	2.25	0.25	1393.09
3	UT	15.25	11.0	15.75	10.58	1189.08
4,5	RUA,LUA	3.74	3.74	15.75	0.88	99.15
6,7	RLA,LLA	3.66	3.66	23.75	1.274	62.97
8	CT	14.0	10.5	19.75	11.63	830.96/388.25*
9	LT	16.0	11.25	11.87	8.56	1692.2
10,11	RUL,LUL	5.88	5.31	32.75	4.43	115.07
12,13	RLL,LLL	5.09	5.09	19.0	1.97	152.23
14,15	RF,LF	5.25	13.0	4.5	1.23	1693.25

* For Model-3

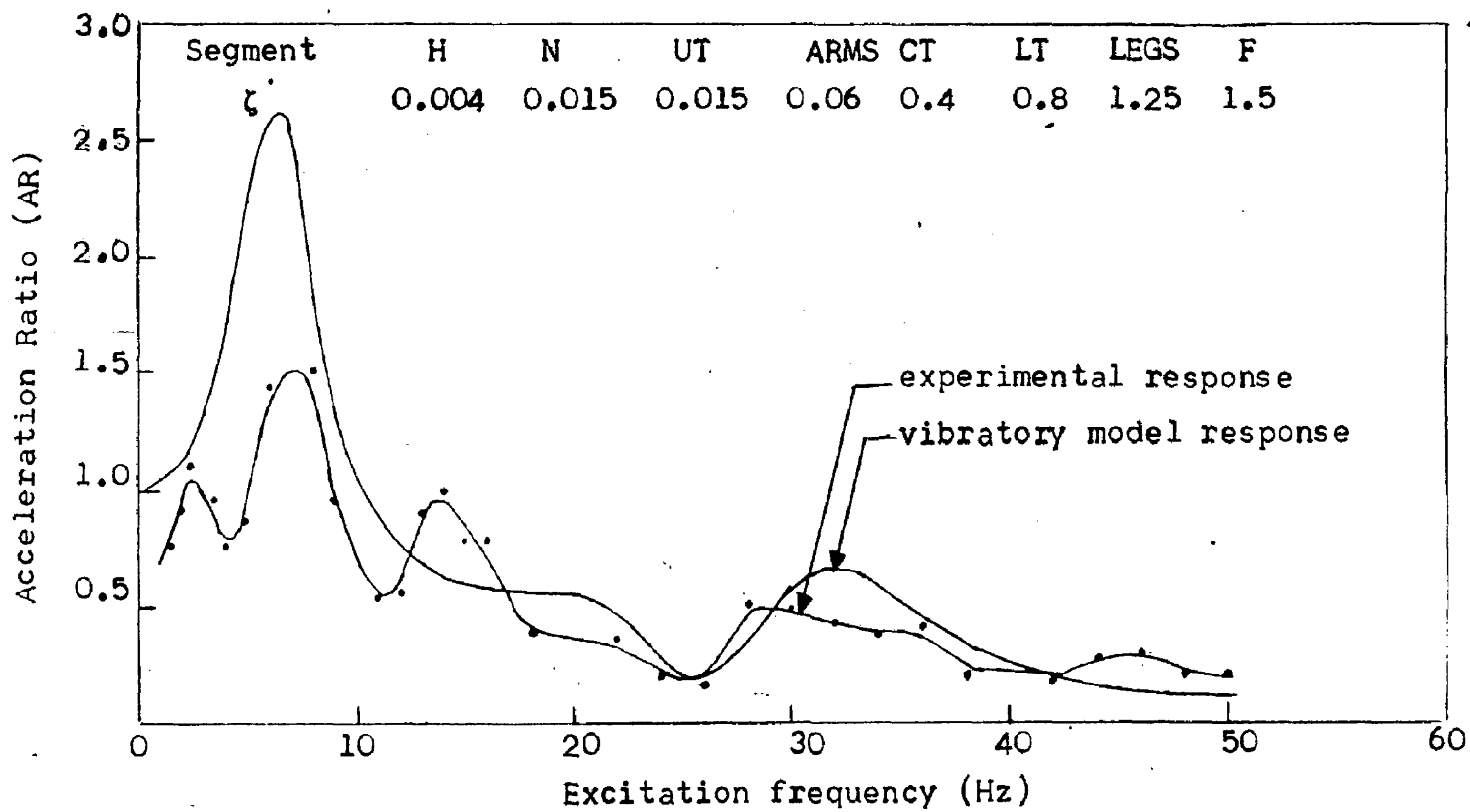


Fig.3.13- Comparison of vibratory model response (Manoj Jain) with experimental response (Model 3)

Refinements in the basic model if at all necessary, have to be supported by more experimental data with better facilities and some improvement in the experimental set up existing in the laboratory.

CHAPTER -4

C L O S U R E

Modeling of the human body as a vibratory system has been the subject matter of many investigations. The approach in modeling has essentially been of computer simulation of the experimental frequency response data of the human body. The experimental results based on modeling results are applicable to the subjects of the experiments and as such do not provide any generalized guideline for the modeling of the human body in general.

The object of the present work was to develop a generalized approach towards human body vibratory modeling by which the model of any subject could be framed whose response would predict the actual vibratory response of the subject. The background available to this work was the approach of Nigam and Malik(1987) who proposed that an undamped spring-mass vibratory model of the human body can be framed through the anthropomorphic model and using the anthropometric data and some elastic properties of the bones and tissues. The problem was then to introduce damping in the basic spring-mass model. This has been done first by calculating the damping constants of the various segments of the anthropomorphic model and then using the combination of these constants to calculate the damping constants of dampers in the vibratory model. The damping constants of the segments are obtained through their mass, stiffness and damping ratio values.

The methodology in the development of complete vibratory model of a human body may be summarized as under:

1. Identification of segments and their geometrical shapes through anthropomorphic model,
2. Calculation of the mass of the segments,
3. Calculation of the stiffness of segments using the elastic modulii values of bones and tissues,
4. Calculation of damping constants using stiffness, mass and damping ratio values and
5. Framing the model by taking (i) segments as rigid masses (ii) calculating the stiffness and damping constants of the connecting springs and dashpots through suitable combination of corresponding values of the segments.

In general, the elastic modulus of the segments is taken as geometric mean of elastic modulii of bones and tissues. The damping ratios are identified on physical grounds.

Before developing the damped vibratory models, some variations in basic model of Nigam and Malik were considered and an improved model by including the effect of back bone was worked out. For the response studies, damped vibratory models derived from the model of Nigam and Malik and the improved model have been considered. The response of the developed models have been supported by experimental response of US males from an earlier work and an extensive response data collected on Indian subjects in the laboratory. On the basis of these investigations certain ranges of damping ratio of the various segments have been identified. These are as follows:

	ζ
Foot and legs	= 1-1.5
Lower torso	= 0.5-1.0
Central torso	= 0.01-0.2
Upper torso	= 0.002-0.015
Hands	= 0.001-0.01
Neck	= 0.015
Head	= 0.004

The human body vibratory models in this work has been developed for standing posture. only, However, the posture is not a restriction for modeling procedure.

The objective of the thesis seems to have been achieved with a reasonable success. However, the theoretical response of model shows some deviations from the actual response and hence further refinements in the model are certainly needed. It should however be emphasized that theoretical model is developed to predict the response of an actual system with a certain level of confidence and really not to duplicate the actual response of that system.

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Appendix -1

LIST OF TABLES

APPENDIX 2

LIST OF FIGURES