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Second edition
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Mechanical vibration and shock — Mechanical impedance of the human hand-arm system at the driving point

Vibrations et chocs mécaniques — Impédance mécanique du système main-bras au point d'entrée

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 10068 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 4, *Human exposure to mechanical vibration and shock*.

This second edition cancels and replaces the first edition (ISO 10068:1998), of which it constitutes a technical revision. The second edition includes the results of measurements of hand-arm impedance conducted since publication of the first edition, and it includes new models for apparent mass and mechanical impedance. The models now possess anatomic compatibility, and identify components for the fingers, palm, wrist and arm, and upper body. A model of the hand-arm system is provided when a glove is worn to estimate the transmissibility of vibration from a vibrating handle to the surface of the hand. The frequency dependency of the vibration power absorbed by the hand-arm system and by structures within the hand-arm system (i.e. fingers, palm and wrist, and arm) is also included. Information on methods for measuring the mechanical impedance of the hand-arm system is also provided in an annex.

Introduction

The mechanical impedance of the human hand-arm system at the driving point provides a measure of the overall biodynamic properties of the hand-arm system in specified conditions. When the hands are coupled to a vibrating tool or machine, the dynamic behaviour of the tool or machine could be affected by the biodynamic properties of the hand-arm system. Therefore, the mechanical impedance can be used to help design or develop:

a) power tools, and tool handles;

b) vibration-reducing and protective devices;

c) testing apparatus with which to measure the handle vibration of power tools.

Values of the mechanical impedance can be used to establish mechanical-equivalent models of the hand-arm system. The models can be used to analyse the vibration of tools and anti-vibration devices, and to guide the construction of testing apparatus. The models can also be used to estimate biodynamic responses such as vibration power absorption and biodynamic forces acting at the hand-tool interfaces. Such knowledge can be used to help understand the mechanisms of vibration-induced disorders and discomfort, and to help develop frequency weightings for assessing these effects. The establishment of typical values for human hand-arm impedance will foster these applications.

The response of the hand-arm system to vibration depends not only on the mechanical properties of the hand and arm, but also on the coupling between the hand and the vibrating surface. The major factors that could influence the response are as follows:

— direction of vibration with respect to the hand-arm system;

— geometry of the object grasped;

— forces exerted by the hand on the object;

— hand and arm postures;

— individual differences, such as tissue properties and anthropometric characteristics of the hand-arm system;

— vibration magnitude, because of the nonlinear properties of tissues.

The forces exerted by the hand are usually described in terms of the grip force and feed force. The latter is often called the “thrust”, “push” or “press” force.

In this International Standard, typical values for the mechanical impedance of the hand-arm system measured at the driving point of one bare hand are provided. They have been derived from the results of impedance measurements performed on groups of live male subjects by different investigators. Insufficient data are available from independent sources to specify hand-arm impedances for females.

There are large differences between the mean values of impedance reported in studies conducted independently, under nominally equivalent conditions. The variations have dictated the form in which the standardized male hand-arm impedance is presented. The most probable values of impedance modulus and phase are defined, as a function of frequency, by upper and lower envelopes, which encompass the mean values of all accepted data sets at each frequency. The envelopes have been constructed from segmental cubic spline functions, and define, at each frequency, the range of accepted values of the male hand-arm impedance. The mean of the accepted data sets, and standard deviation of the mean, are defined as a function of frequency, and represent the target values for all applications of this International Standard.

No impedance modulus or phase presented as a function of frequency in this International Standard corresponds precisely to the mean value measured in a single investigation involving human subjects, at all frequencies.

Mechanical vibration and shock — Mechanical impedance of the human hand-arm system at the driving point

1 Scope

This International Standard specifies the mechanical impedance of the human male hand-arm system at the driving point. Values of the impedance, expressed as modulus and phase, are provided for three orthogonal, translatory directions of excitation that correspond to the x_h-, y_h- and z_h-axes of the basicentric coordinate system.

NOTE 1 The basicentric coordinate system is defined in ISO 5349-1[2] and ISO 8727.[5]

The x_h-, y_h- and z_h-components of impedance are defined as a function of frequency, from 10 Hz to 500 Hz, for specified arm positions, grip and feed forces, handle diameters, and intensities of excitation. The components of impedance in the three directions are treated as being independent.

This International Standard can be used to define typical values of the mechanical impedance of the hand-arm system at the driving point, applicable to males under the circumstances specified. This International Standard can provisionally be applied to females.

Reference values of the mechanical impedance at the driving point are provided as a function of frequency for a specified grip and feed force.

NOTE 2 See Annex A.

These impedance values are intended for the determination of the transmissibility of resilient materials when loaded by the hand-arm system.

Mathematical representations of the hand-arm system that model the mean values of apparent mass or impedance are provided.

NOTE 3 See Annexes B to D.

A gloved hand-arm model is described, and the frequency dependence of vibration power absorption in the hand-arm system is also provided.

NOTE 4 See Annexes E and F.

To help conduct further measurement of the mechanical impedance, especially for circumstances that are not specified in this International Standard, information on the measurement of mechanical impedance is provided.

NOTE 5 See Annex G.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
mechanical impedance of the hand-arm system at the driving point
Z_h
complex ratio of the dynamic force F acting on the hand contact surface and the vibration velocity input v to the hand, given by the equation $Z_\mathrm{h}(\omega) = F(\omega)/v(\omega)$ [Equation (1)], where ω is the vibration frequency in radians per second

NOTE 1 The mechanical impedance can be derived from the apparent mass M_h of the hand-arm system, which is defined as the complex ratio of the dynamic force and the vibration acceleration a and is expressed by the equation $M_\mathrm{h}(\omega) = F(\omega)/a(\omega)$ [Equation (2)].

NOTE 2 The relationship between the mechanical impedance and the apparent mass can be expressed by the equation $Z_\mathrm{h}(\omega) = \mathrm{j}\omega \cdot M_\mathrm{h}(\omega)$ [Equation (3)], where

$$\mathrm{j} = \sqrt{-1}$$

NOTE 3 These biodynamic response functions are generally complex, i.e. they possess real and imaginary parts, which can be expressed as modulus and phase.

3 Mechanical impedance of the hand-arm system at the driving point

The modulus and phase of the mechanical impedance of the hand-arm system at the driving point are given in Tables 1 to 3 and (for illustration) in Figures 1 to 3 at one-third-octave band centre frequencies, for three orthogonal directions of excitation. The directions correspond to the x_h-, y_h- and z_h-axes of the basicentric coordinate system for the hand (see Figure 5). Each table and figure contains three values of modulus and phase at each frequency, for each direction of motion, to reflect the range of values measured on male hands. The upper and lower values define the range of most probable values of impedance. The third value represents an overall mean of the human data, and defines the target value for all applications. The upper and lower limiting values at each frequency encompass the mean values of all data sets selected, and are shown by bold continuous curves in Figures 1 to 3. The central value at each frequency, shown by dashed curves in Figures 1 to 3, provides an estimate of the mean of all data sets selected, and forms the target value for all applications.

Numerical values are quoted up to three significant figures for the purposes of calculation, and do not reflect the precision of knowledge of the hand-arm impedance. Linear interpolation is permitted to obtain impedance values at frequencies other than those listed in Tables 1 to 3.

Applications that generate or employ values of impedance between the upper and lower limits at any frequency satisfy the requirements of this International Standard, and represent the group mean of the male hand-arm mechanical impedance at that frequency, or frequencies.

If an application only satisfies the requirements of this International Standard at certain frequencies, then those frequencies should be stated in any description of the application.

NOTE Because each set of the selected data represents the group mean of the individuals participating in the study, the impedance for a specific individual could be beyond the limits.

Table 1 — Values of the mechanical impedance of the hand-arm system at the driving point in the x_h-direction

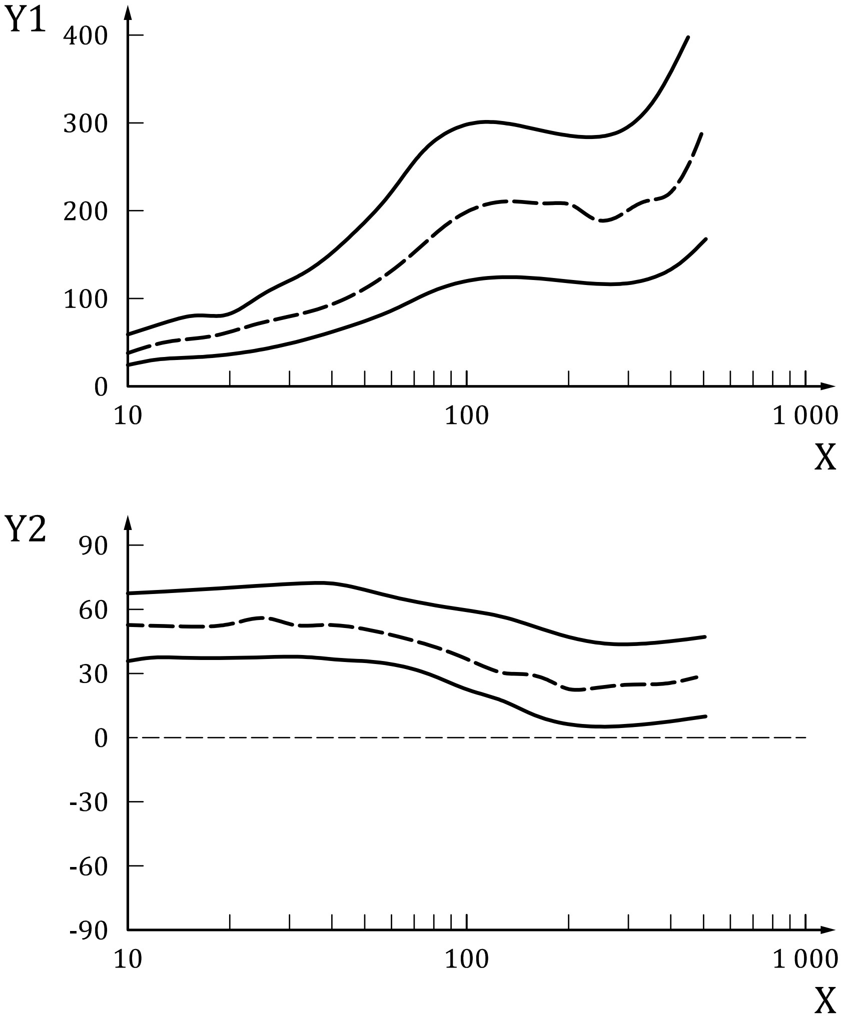
Frequency Hz	**Modulus** N·s/m			**Phase** degrees		
	Lower limit	**Mean**	**Upper limit**	**Lower limit**	**Mean**	**Upper limit**
10	24	38	59	36	53	68
12,5	30	49	71	38	53	69
16	33	54	80	38	53	70
20	36	64	84	38	54	71
25	43	72	104	38	57	72
31,5	51	80	125	38	53	73
40	62	95	154	37	53	73
50	74	112	189	36	51	70
63	90	140	233	33	47	66
80	109	172	280	29	43	63
100	120	199	300	23	37	60
125	124	211	302	18	31	57
160	123	210	294	11	29	52
200	120	208	287	7	23	48
250	119	189	287	6	24	45
315	120	207	302	6	25	44
400	134	224	360	8	26	45
500	168	292	442	10	29	47

Table 2 — Values of the mechanical impedance of the hand-arm system at the driving point in the y_h-direction

Frequency Hz	**Modulus** N·s/m			**Phase** degrees		
	Lower limit	**Mean**	**Upper limit**	**Lower limit**	**Mean**	**Upper limit**
10	21	55	80	20	39	55
12,5	23	62	90	15	35	54
16	26	70	106	11	32	52
20	30	86	119	6	31	49
25	35	96	128	1	23	44
31,5	40	88	132	−6	18	39
40	48	102	135	−12	7	30
50	55	101	130	−18	−1	22
63	61	93	117	−22	−2	16
80	64	86	106	−23	−5	10
100	63	86	106	−23	−9	7
125	60	80	106	−22	−11	6
160	54	77	107	−19	−7	7
200	49	71	108	−16	−6	9
250	45	67	110	−11	0	17
315	45	69	113	−7	8	30
400	51	71	118	−4	16	45
500	66	79	134	1	22	56

Table 3 — Values of the mechanical impedance of the hand-arm system at the driving point in the z_h-direction

Frequency Hz	**Modulus** N·s/m			**Phase** degrees		
	Lower limit	**Mean**	**Upper limit**	**Lower limit**	**Mean**	**Upper limit**
10	120	145	200	15	29	45
12,5	80	149	225	10	29	46
16	133	181	250	5	31	48
20	141	217	325	0	31	49
25	200	266	361	0	26	44
31,5	275	311	365	−2	16	27
40	240	315	358	−13	−1	6
50	220	263	321	−33	−13	3
63	140	216	285	−47	−15	1
80	95	170	240	−37	−11	−2
100	85	158	239	−12	−1	6
125	100	156	240	−5	6	20
160	108	163	247	5	16	30
200	113	184	271	10	21	34
250	150	212	320	13	21	29
315	150	235	363	5	20	30
400	190	243	365	2	21	32
500	185	254	362	7	21	30



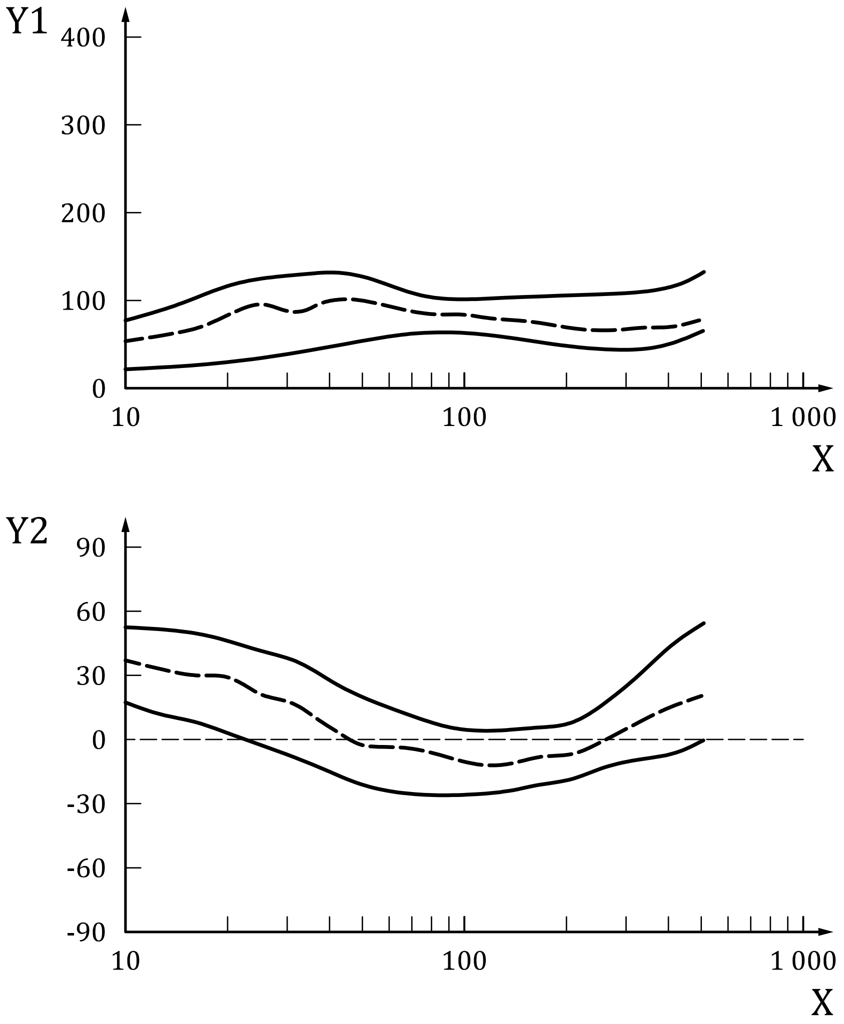
Key

X frequency (Hz)

Y1 modulus (N·s/m)

Y2 phase (degrees)

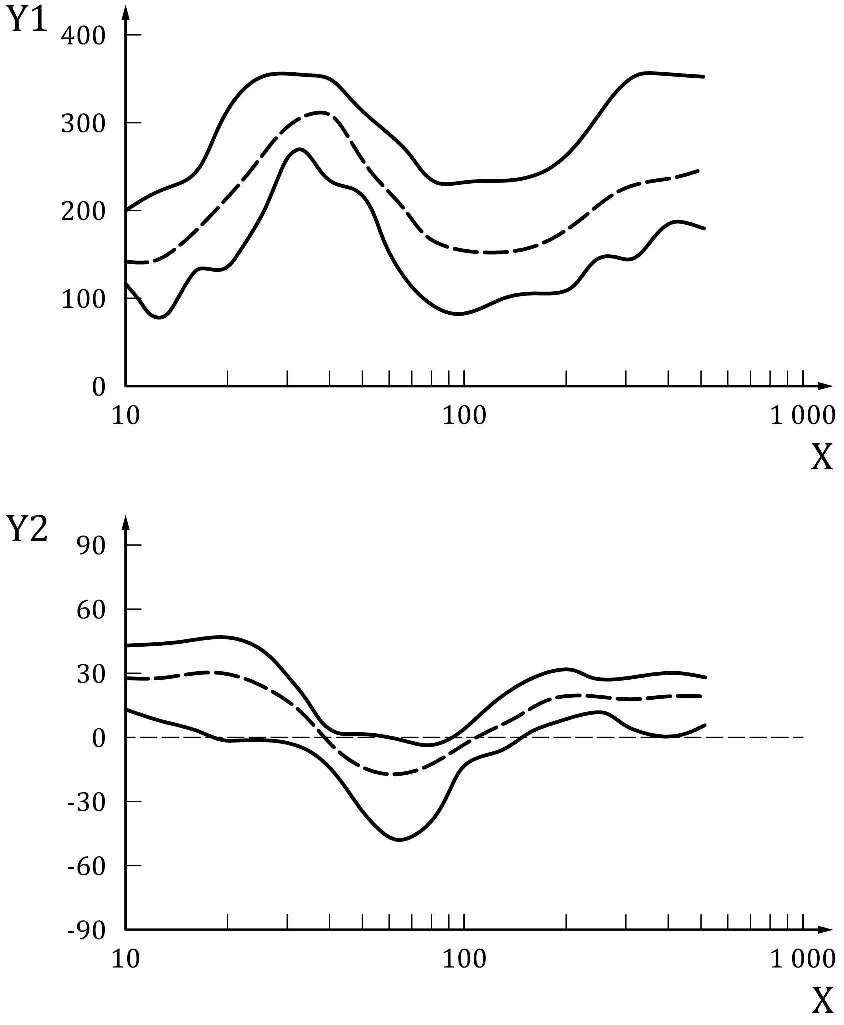
Figure 1 — Values of the mechanical impedance of the hand-arm system at the driving point in the x_h-direction (schematic)



Key

X frequency (Hz)
Y1 modulus (N·s/m)
Y2 phase (degrees)

Figure 2 — Values of the mechanical impedance of the hand-arm system at the driving point in the y_h-direction (schematic)



Key

X	frequency (Hz)
Y1	modulus (N·s/m)
Y2	phase (degrees)

Figure 3 — Values of the mechanical impedance of the hand-arm system at the driving point in the z_h-direction (schematic)

4 Applicability of values of impedance

The values of impedance are applicable to human males under the following conditions, all of which shall be met. The limits of applicability approximately correspond to the range of measurement conditions over which data were obtained.

a) The position of the arm relative to the torso falls within the ranges defined in Figure 4.

b) The wrist is in the neutral position, that is, the position involving no flexion or extension (tolerance ±15°), as shown in Figure 5.

c) One bare hand grasps a handle that is between 19 mm and 45 mm in diameter. The values of impedance are applicable to handles with non-circular cross-sections, provided that the largest and smallest cross-section dimensions are between 19 mm and 45 mm.

d) The hand grip force is between 25 N and 50 N. The feed force applied by the hand is not greater than 50 N.

NOTE 1 The impedance values are mainly based on data obtained from the right hand, and can be provisionally applied to the left hand.

NOTE 2 The impedance values can be provisionally applied to females. Research has shown the modulus of impedance for females to be up to 20 % less than the corresponding value for males.

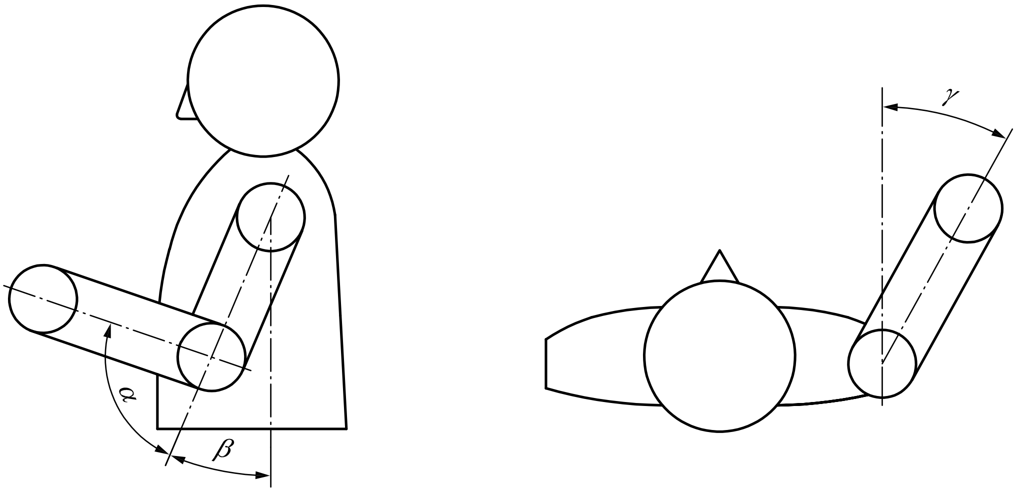
NOTE 3 An increase in grip force has been reported to result in an increase in impedance modulus, especially at frequencies in excess of about 50 Hz.

NOTE 4 The impedance modulus and phase do not appear to be substantially influenced by feed force at frequencies above 100 Hz. An increase in impedance modulus with increased feed force has been reported at lower frequencies. The values can be expected to change by less than 10 % for feed forces of up to 100 N.

NOTE 5 The impedance can be marginally influenced by the magnitude of the acceleration of the handle, especially when the dominant components of the vibration are at frequencies less than 100 Hz. The values in this International Standard are believed to be applicable to unweighted r.m.s. accelerations of up to 50 m/s^2 in the frequency range 10 Hz to 500 Hz.

NOTE 6 It is anticipated that clothing marginally increases the low frequency impedance (<25 Hz). The impedance values were measured in various laboratories at room temperature when the subjects wore normal working clothes.

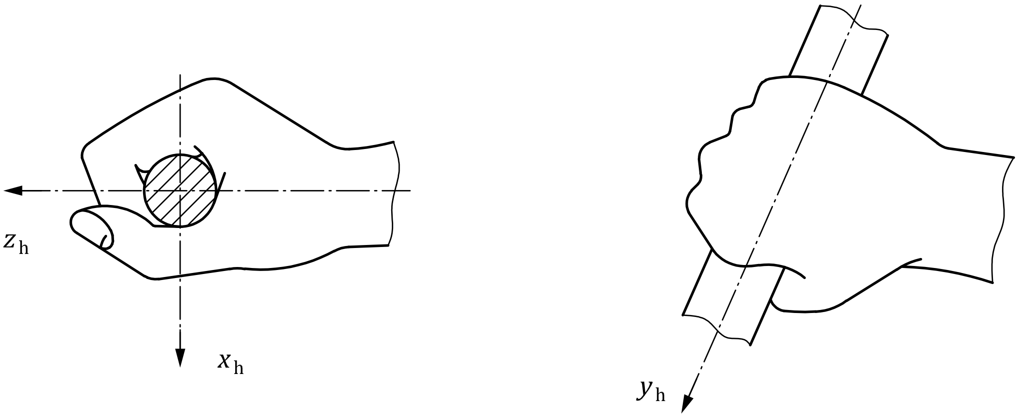
NOTE 7 Wearing a glove generally increases the impedance or apparent mass at low frequencies (<25 Hz), but could reduce the impedance at higher frequencies.



$15° < \alpha < 120°$; $-15° < \beta < 75°$; $-15° < \gamma < 15°$; $\alpha + \beta < 120°$

NOTE Angles are positive in sign when measured in a clockwise direction.

Figure 4 — Ranges of allowable arm positions



NOTE 1 **Origin:** The centre or midpoint of the axis of the instrumented handle used for measuring biodynamic response functions of the hand-arm system.

NOTE 2 **Orientation:** The z_{h}-axis approximates the principal functional axis of the instrumented handle; it passes through the origin of the handle and is parallel to, or aligned with, the forearm centreline when the wrist is in the neutral position; the y_{h}-axis is along the centreline of the handle, and the x_{h}-axis passes through the origin and is mutually perpendicular to y_{h}- and z_{h}-axes.

Figure 5 — Basicentric coordinate system for the measurement of biodynamic response functions of the hand-arm system

5 Applications

5.1 General

The mechanical impedance of the entire hand-arm system at the driving point is the vector summation of the distributed impedance at the hand-object interface. In the design and analysis of many tools and anti-vibration handles, the total impedance is likely to be of concern, and the impedance values listed in Tables 1 to 3 can be directly applied. A doubled value of the impedance at each frequency can be used if both hands are coupled on the vibrating object with similar hand-arm postures and interacting conditions.

In some cases, such as estimates of the vibration transmissibility of an anti-vibration glove at the palm and the vibration power input to the palm, only a portion of the distributed impedance is involved in the interaction or response. Only the impedance distributed at the location effectively involved in the response of concern shall be used in applications.

5.2 Evaluation of the transmissibility of resilient materials when loaded by the hand-arm system

Reference values for the z_{h}-component of the mechanical impedance of the hand-arm system at the driving point and its distribution at the palm and the fingers are given in Annex A as a function of frequency for a grip force of 30 N, a feed force of 50 N, and an elbow angle of 90°. The impedance values are provided for evaluating the transmissibility of resilient materials, when loaded by the hand-arm system (details are given in ISO 13753[7]). To compare the predicted transmissibility with that measured with the method defined in ISO 10819,[6] the impedance distributed at the palm shall be used.

When the equivalent stiffness, damping, and mass of a resilient material are measured or estimated, the vibration transmissibility of the material at the fingers and palm may also be estimated using the modelling method described in Annex E.

5.3 Models of the hand-arm system

Models of the hand-arm system that comply with the provisions of this International Standard are provided in Annexes B to D. The models possess varying degrees of complexity for different applications. Annexes B to D are provided to facilitate mathematical modelling, and the construction of mechanical analogues of the hand-arm system for use in testing apparatus.

NOTE 1 The selection of the biodynamic function (mechanical impedance or apparent mass) for the model development depends primarily on the application. Because the dynamic force is directly associated with the apparent mass, it is more suitable to use the apparent mass when the interacting dynamic force is of primary concern. Because the apparent mass generally decreases with an increase in frequency, a mechanical equivalent model based on the apparent mass emphasizes the low frequency response. Therefore, apparent mass-based models are more suitable for the design, analysis, and testing of tools and anti-vibration devices. On the other hand, impedance-based models are more suitable for estimating the vibration power absorption because the impedance is directly associated with the vibration power absorption.

NOTE 2 The biodynamic models can provisionally be used to predict hand-arm impedance up to 1 kHz.

5.4 Estimation of power absorbed in the hand-arm system and its frequency dependence

The mechanical power P_h absorbed in the hand-arm system at each frequency ω can be estimated from the real part of the mechanical impedance Re Z_h and the vibration acceleration input a to the hand as:

$$P_\mathrm{h}(\omega) = \operatorname{Re} Z_\mathrm{h}(\omega) \left[\frac{a(\omega)}{\omega}\right]^2 \tag{4}$$

The frequency dependence w_P of the vibration power absorption in one-third octave bands is expressed as follows:

$$w_P(\omega) = 0{,}958 \frac{\sqrt{\operatorname{Re} Z_\mathrm{h}(\omega)}\Big/\omega}{\sqrt{\operatorname{Re} Z_\mathrm{h}(\omega_\mathrm{Ref})}\Big/\omega_\mathrm{Ref}} \tag{5}$$

where ω_Ref is the reference frequency for normalization and 0,958 is the maximum weighting in the one-third octave band centre frequencies in ISO 5349-1.[2]

NOTE The hand-arm system is assumed to be a linear system in these estimations, but the system is actually nonlinear. Therefore, this assumption could introduce errors. The estimated frequency dependence can only be used for identifying the basic trend of the power absorption as a function of frequency.

The power absorbed in a substructure P_s can be estimated from a model for a given vibration spectrum. The frequency dependence of the substructure-specific power absorption w_{P_s} can be estimated from

$$w_{P_\mathrm{s}}(\omega) = 0{,}958 \frac{\sqrt{P_\mathrm{s}(\omega)}\Big/a(\omega)}{\sqrt{P_\mathrm{s}(\omega_\mathrm{Ref})}\Big/a(\omega_\mathrm{Ref})} \tag{6}$$

Examples of the frequency dependency are given in Annex F.

Annex A
(normative)

Reference values for the z_h-component of the mechanical impedance of the hand-arm system

Reference values for the z_h-component of the mechanical impedance are given in Table A.1 as a function of frequency, from 10 Hz to 500 Hz. The values have been derived from impedance measurements conducted on human male subjects and are intended for the evaluation of the transmissibility of resilient materials when loaded by the hand-arm system (details are given in ISO 13753[7]). Linear interpolation is permitted to obtain impedance values at frequencies other than those listed in Table A.1.

The reference values of the impedance are applicable to human males under the following measurement conditions, all of which shall be met:

a) The elbow angle is 90° (tolerance ±15°), so that the position of the arm relative to the torso falls within the ranges defined in Figure 4, under conditions b), c) and d).

b) The wrist is in the neutral position (tolerance ±15°), as shown in Figure 5.

c) The hand grasps a handle, which is between 19 mm and 45 mm in diameter. The reference values are applicable to handles with non-circular cross-sections, provided the largest and smallest cross-sections are between 19 mm and 45 mm.

d) The grip force is (30 ± 5) N and the feed force is (50 ± 8) N.

NOTE These measurement conditions are comparable with those required for the anti-vibration glove test defined in ISO 10819.[6]

Table A.1 — Reference values of the mechanical impedance of the hand-arm system at the driving point in the z_h-direction and at the palm and fingers

Frequency Hz	**Hand**		**Palm**		**Fingers**	
	Modulus N·s/m	**Phase** degrees	**Modulus** N·s/m	**Phase** degrees	**Modulus** N·s/m	**Phase** degrees
10	145	29	112	25	32	37
12,5	149	29	123	26	35	40
16	181	31	141	28	42	43
20	217	31	166	27	51	44
25	266	26	201	23	63	41
31,5	311	16	238	11	76	32
40	315	−1	241	−7	78	18
50	263	−13	206	−20	69	12
63	216	−15	165	−26	61	15
80	170	−11	134	−26	59	24
100	158	−1	115	−22	64	34
125	156	6	103	−16	76	40
160	163	16	94	−9	96	42
200	184	21	90	−2	116	39
250	212	21	89	5	134	33
315	235	20	89	14	142	25
400	243	21	93	22	141	20
500	254	21	99	31	137	19

Annex B
(informative)

Model 1

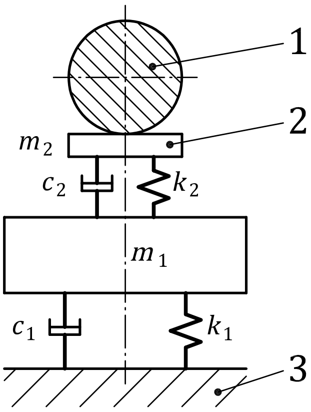
Figure B.1 shows a two-degrees-of-freedom (2-DOF) mechanical-equivalent model. The same general configuration is employed for each of the three directions. Because of its simplicity, this model is suitable for the design and construction of a tool-testing apparatus when the reaction dynamic force of the entire hand-arm system is of primary concern. Because the dynamic force is directly related to the apparent mass of the hand-arm system, the model parameters are determined from the apparent mass values derived from the mean values of the impedance listed in Tables 1 to 3 using Equation (3) (see Note 2 to definition 2.1). Different values of model parameters, listed in Table B.1, are used for each direction to obtain the values of impedance shown in Figures B.2 to B.4.

In this two-degrees-of-freedom (2-DOF) model, the masses, springs and dampers do not correspond to physiological structures within the hand-arm system.

Table B.1 — Values for model 1 parameters

Parameter	Unit	Direction of vibration		
		x_h	y_h	z_h
m_1	kg	0,547 9	0,537 4	1,245 8
m_2	kg	0,039 1	0,010 0	0,074 2
k_1	N/m	400	400	1 000
k_2	N/m	0	17 648	50 000
c_1	N·s/m	22,5	38,3	108,1
c_2	N·s/m	202,6	75,5	142,4

NOTE While the model can be easily applied to any modelling analysis, it is difficult to build a testing apparatus that meets the requirements of all the parameters in the three directions. However, it is feasible to build a testing apparatus based on the model in the z_h-direction, which is the most important for tests of many tools. The small mass component m_2 and large stiffness k_2 and damping c_2 components represent the dynamic properties of tissues of the hand (palm and fingers), which may be physically simulated using a piece of rubber or resilient material, or their combination.

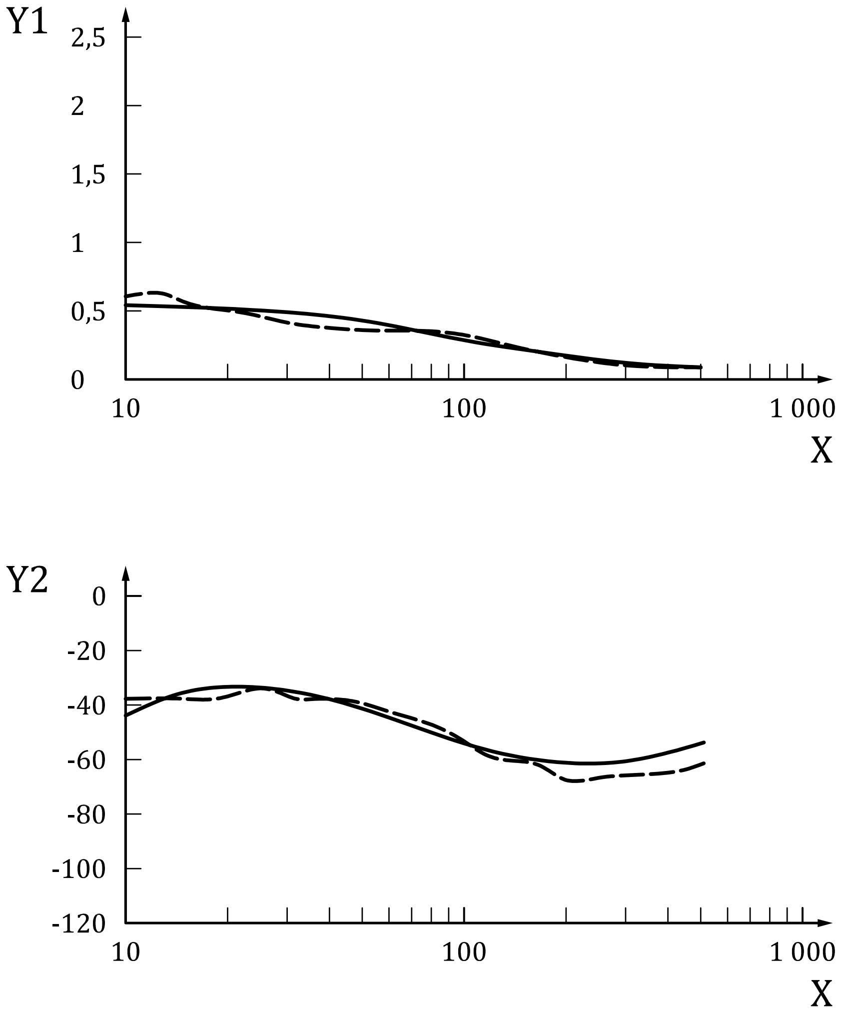


Key

1 handle
2 contact skin
3 upper body

NOTE In this two-degrees-of-freedom (2-DOF) model, the masses, springs and dampers do not correspond to physiological structures within the hand-arm system.

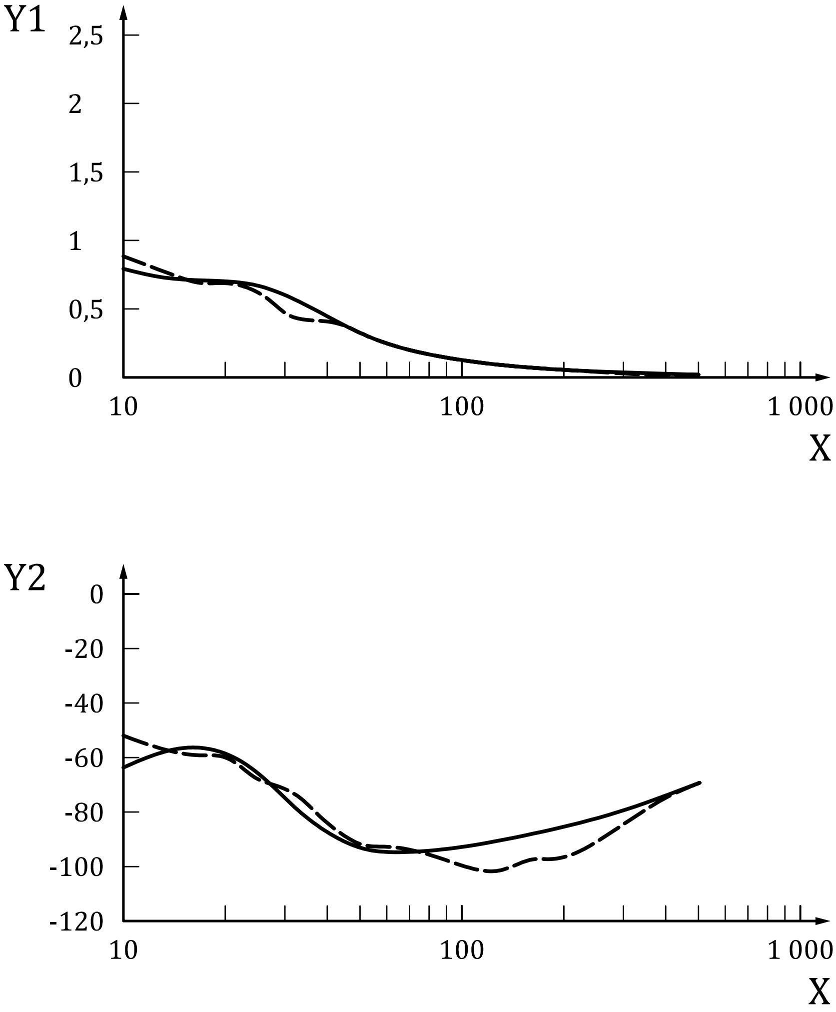
Figure B.1 — A 2-DOF mechanical-equivalent model of the hand-arm system



Key

X frequency (Hz)
Y1 apparent mass (kg)
Y2 phase (degrees)

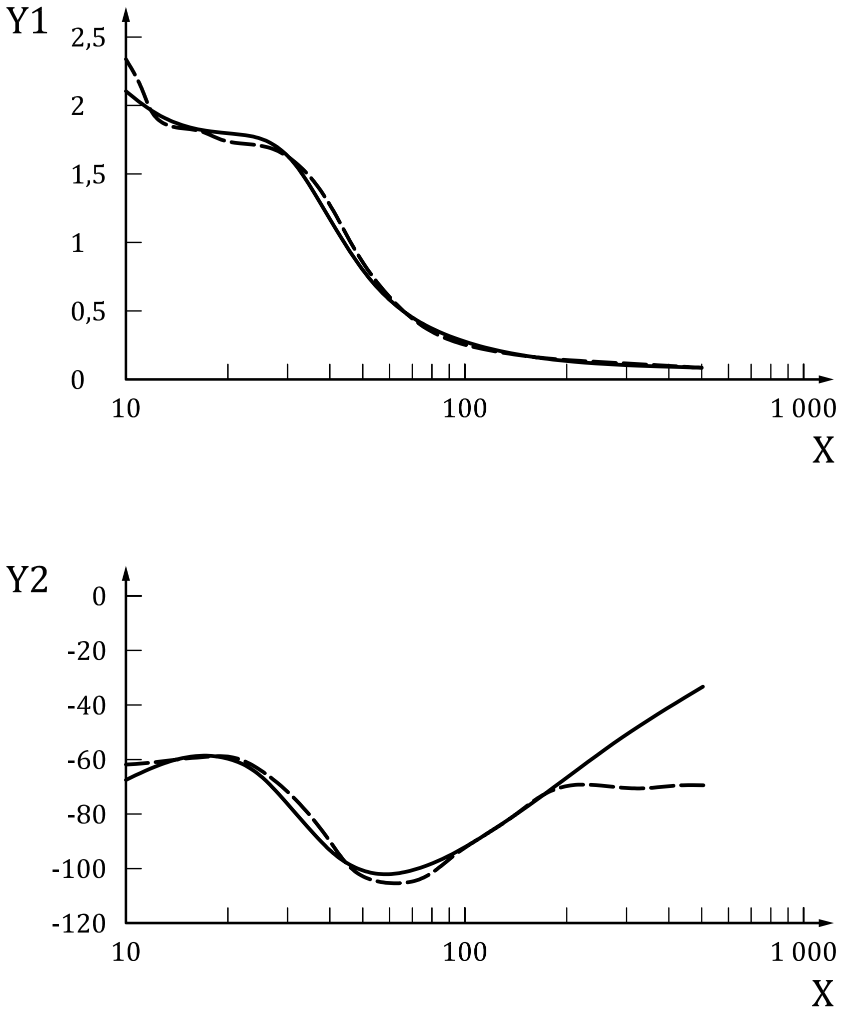
Figure B.2 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the apparent mass of the human hand-arm system in the x_h-direction



Key

X	frequency (Hz)
Y1	apparent mass (kg)
Y2	phase (degrees)

Figure B.3 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the apparent mass of the human hand-arm system in the y_h-direction



Key

X	frequency (Hz)
Y1	apparent mass (kg)
Y2	phase (degrees)

Figure B.4 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the apparent mass of the human hand-arm system in the z_h-direction

Annex C
(informative)

Model 2

This mechanical-equivalent model is an extension of model 1 obtained by considering the fingers as one separate part (Figure C.1). The same general configuration is employed for each of the three directions. This model makes it possible to examine the interactions at the fingers and the palm. The model parameters are determined from the impedance values listed in Tables 1 to 3. Different values of model parameters, listed in Table C.1, are used for each direction to obtain the values of impedance shown in Figures C.2 to C.4.

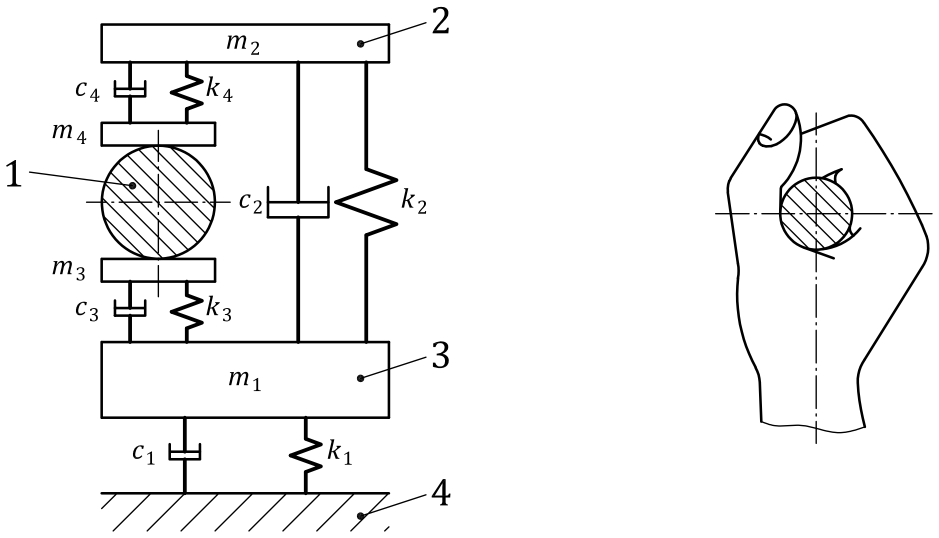
In this four-degrees-of-freedom (4-DOF) model, masses, springs and dampers do not correspond exactly to physiological structures within the hand-arm system.

Table C.1 — Values for model 2 parameters

Parameter	**Unit**	**Direction of vibration**		
		x_h	y_h	z_h
m_1	kg	0,412 9	0,760 0	1,125 2
m_2	kg	0,0736	0,052 1	0,076 9
m_3	kg	0,016 3	0,006 0	0,020 0
m_4	kg	0,010 0	0,002 8	0,010 0
k_1	N/m	400	500	1 000
k_2	N/m	200	100	12 000
k_3	N/m	4 000	4 907	43 635
k_4	N/m	8 000	17 943	174 542
c_1	N·s/m	20,0	28,1	111,5
c_2	N·s/m	100	39,7	39,3
c_3	N·s/m	144,6	50,7	86,8
c_4	N·s/m	79,9	14,3	121,0

NOTE 1 While the model can be easily applied to any modelling analysis, it is difficult to build a testing apparatus that meets the requirements for all the parameters in the three directions. However, it can be feasible to build a testing apparatus based on the model in the z_h-direction, which is the most important for the tests of many tools. The small mass components, m_3 and m_4, and large stiffness, k_3 and k_4, and damping, c_3 and c_4, components represent the dynamic properties of the tissues of the hand (palm and fingers), which can be physically simulated using two pieces of rubber or resilient material, or their combination.

NOTE 2 This model is provisionally applicable up to 1 000 Hz.

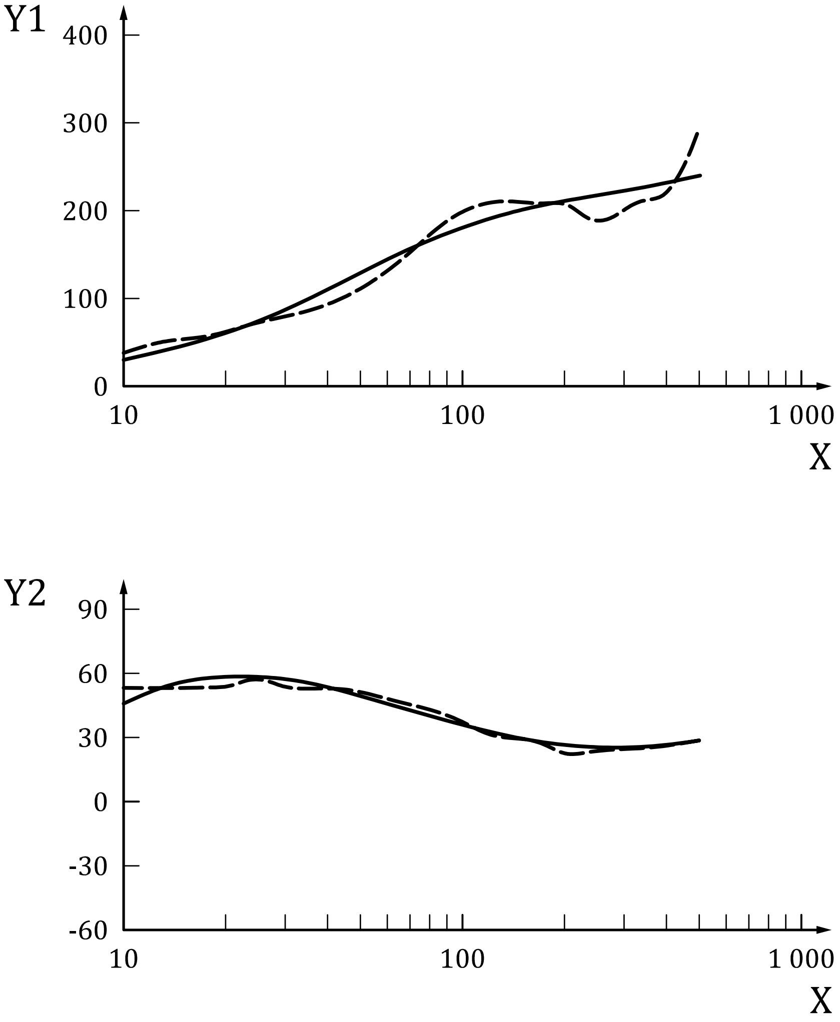


Key

1 handle
2 fingers
3 palm, wrist and arm
4 upper body

NOTE In this four-degrees-of-freedom (4-DOF) model, masses, springs and dampers do not correspond exactly to physiological structures within the hand-arm system.

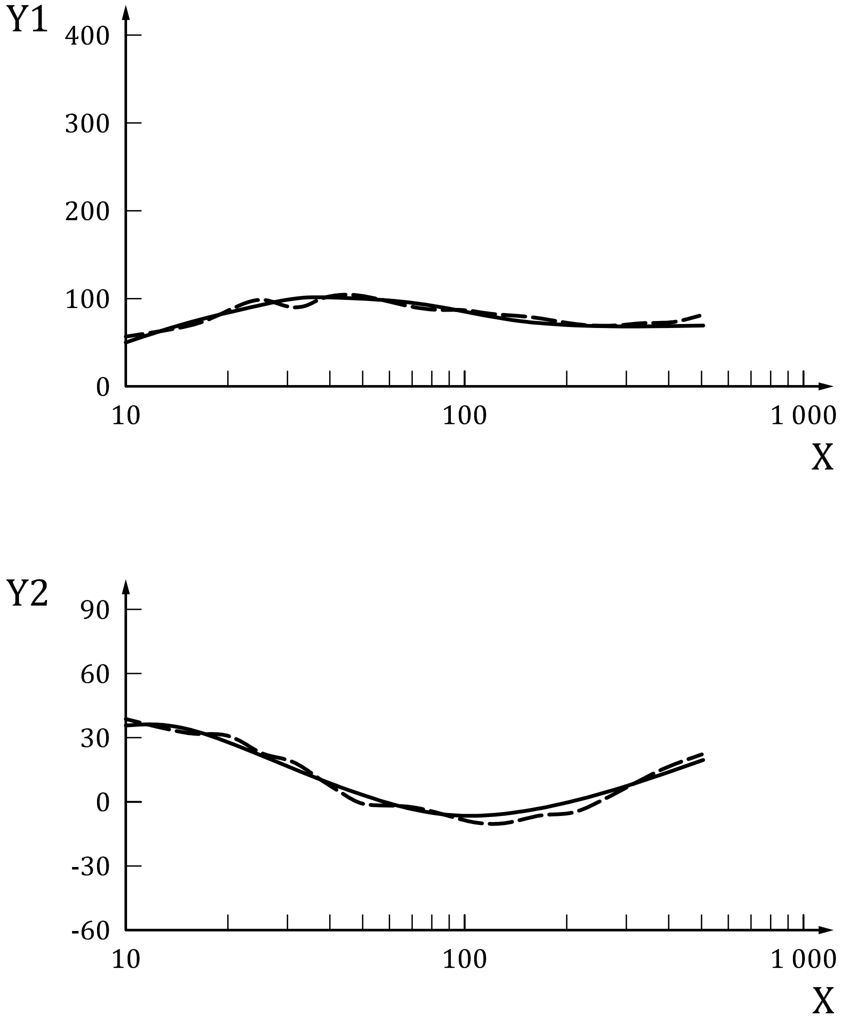
Figure C.1 — A 4-DOF mechanical-equivalent model of the hand-arm system



Key

X frequency (Hz)
Y1 modulus (N·s/m)
Y2 phase (degrees)

Figure C.2 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the mechanical impedance of the human hand-arm system in the x_h-direction



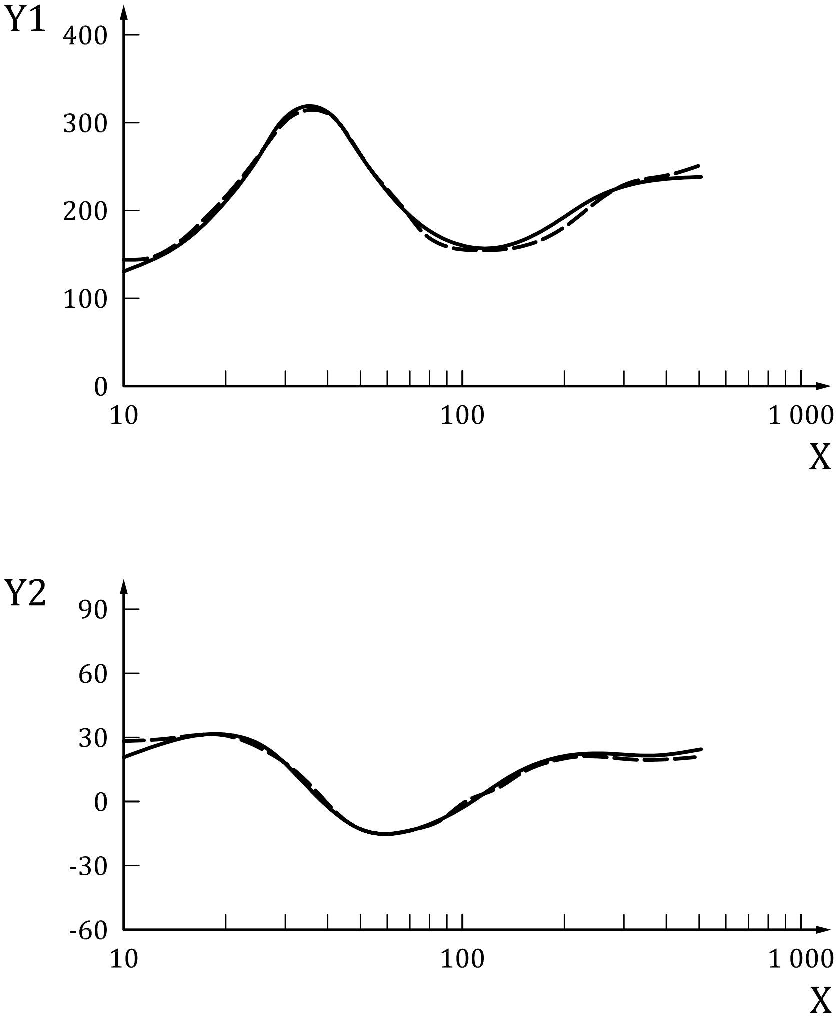
Key

X frequency (Hz)

Y1 modulus (N·s/m)

Y2 phase (degrees)

Figure C.3 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the mechanical impedance of the human hand-arm system in the y_h-direction



Key

X frequency (Hz)
Y1 modulus (N·s/m)
Y2 phase (degrees)

Figure C.4 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the mechanical impedance of the human hand-arm system in the z_h-direction

Annex D
(informative)

Model 3

This mechanical-equivalent model is an extension of model 2 obtained by considering the upper-arm-shoulder substructures as one separate part (Figure D.1). The same general configuration is employed for each of the three directions. The model parameters are determined from the impedance values listed in Tables 1 to 3. Different values of model parameters, listed in Table D.1, are used for each direction to obtain the values of impedance shown in Figures D.2 to D.4.

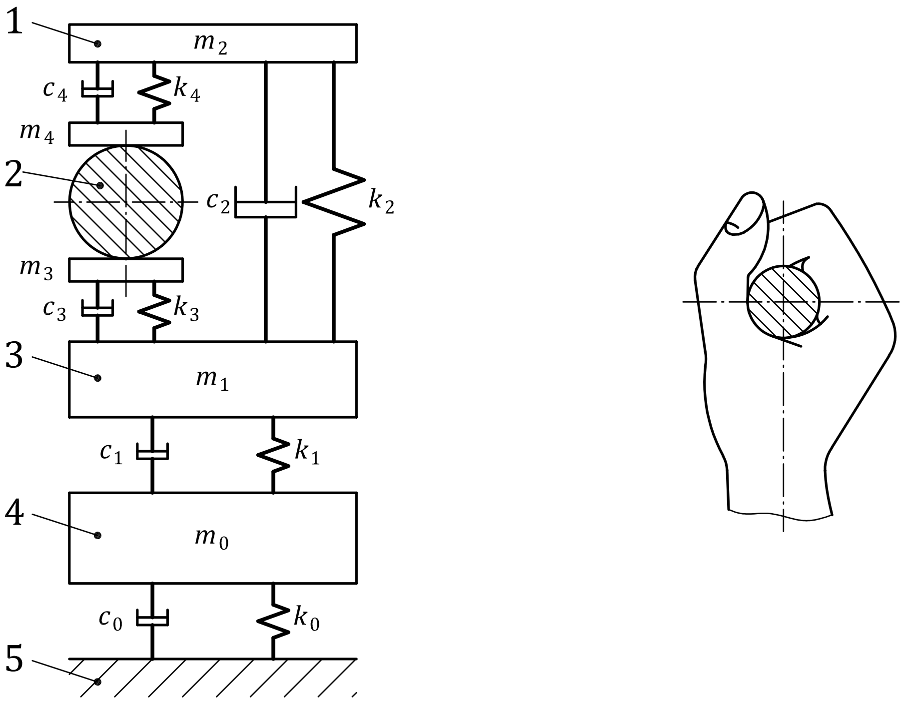
In this five-degrees-of-freedom (5-DOF) model, masses, springs and dampers do not correspond exactly to the physiological structures within the hand-arm system, but it can provide a crude approximation of the major substructures (fingers, palm-wrist-forearm, upper-arm-shoulder) of the hand-arm system.

Table D.1 — Values for model 3 parameters

Parameter	**Unit**	**Direction of vibration**		
		x_h	y_h	z_h
m_0	kg	0,236 0	0,360 5	7,500 0
m_1	kg	0,399 8	0,551 5	1,072 1
m_2	kg	0,057 6	0,072 5	0,076 0
m_3	kg	0,020 5	0,005 0	0,020 0
m_4	kg	0,010 0	0,003 0	0,010 0
k_0	N/m	1 000	1 000	8 059
k_1	N/m	6 972	1 000	1 891
k_2	N/m	100	100	12 000
k_3	N/m	4 000	5 443	44 220
k_4	N/m	65 844	15 170	176 880
c_0	N·s/m	21,8	40,5	93,1
c_1	N·s/m	22,1	95,7	112,1
c_2	N·s/m	69,8	37,6	39,7
c_3	N·s/m	128,6	51,5	83,9
c_4	N·s/m	81,5	11,4	116,7

NOTE 1 It is possible that this model is only suitable for modelling analysis because it is very difficult to build a testing apparatus based on such a model. However, because this model provides more detailed information on the fingers and palm-wrist substructures, it can be used to estimate the vibration transmission and power absorption in these substructures, especially those in the z_h-direction.

NOTE 2 This model is provisionally applicable up to 1 000 Hz.

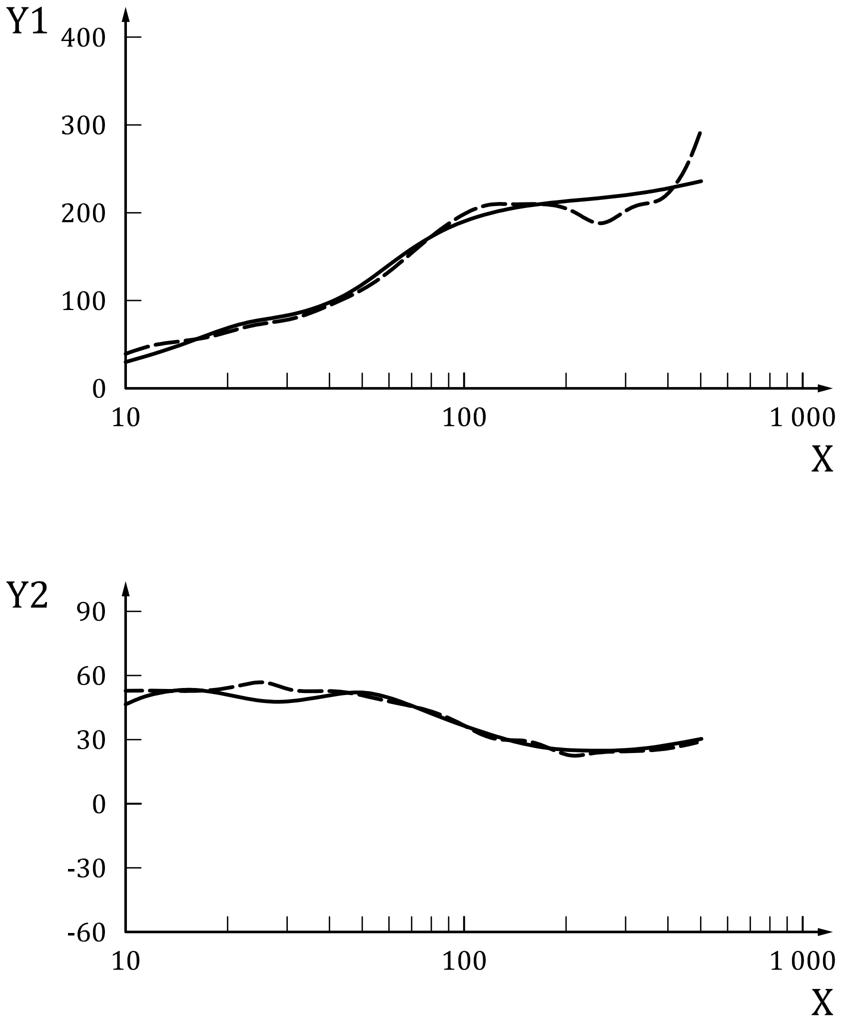


Key

1 fingers
2 handle
3 palm, wrist and forearm
4 upper arm and shoulder
5 upper body

NOTE In this five-degrees-of-freedom (5-DOF) model, masses, springs and dampers do not correspond exactly to the physiological structures within the hand-arm system, but it can provide a crude approximation of the major substructures (fingers, palm-wrist-forearm, upper-arm-shoulder) of the hand-arm system.

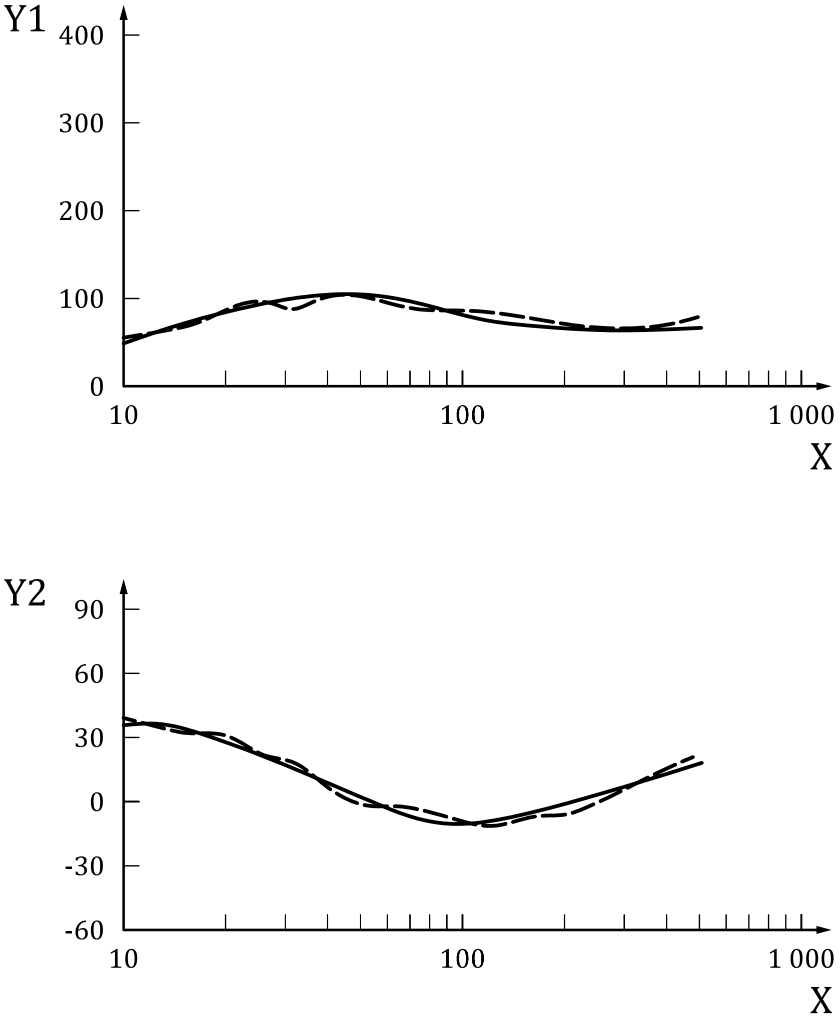
Figure D.1 — A 5-DOF mechanical-equivalent model of the hand-arm system



Key

X	frequency (Hz)
Y1	modulus (N·s/m)
Y2	phase (degrees)

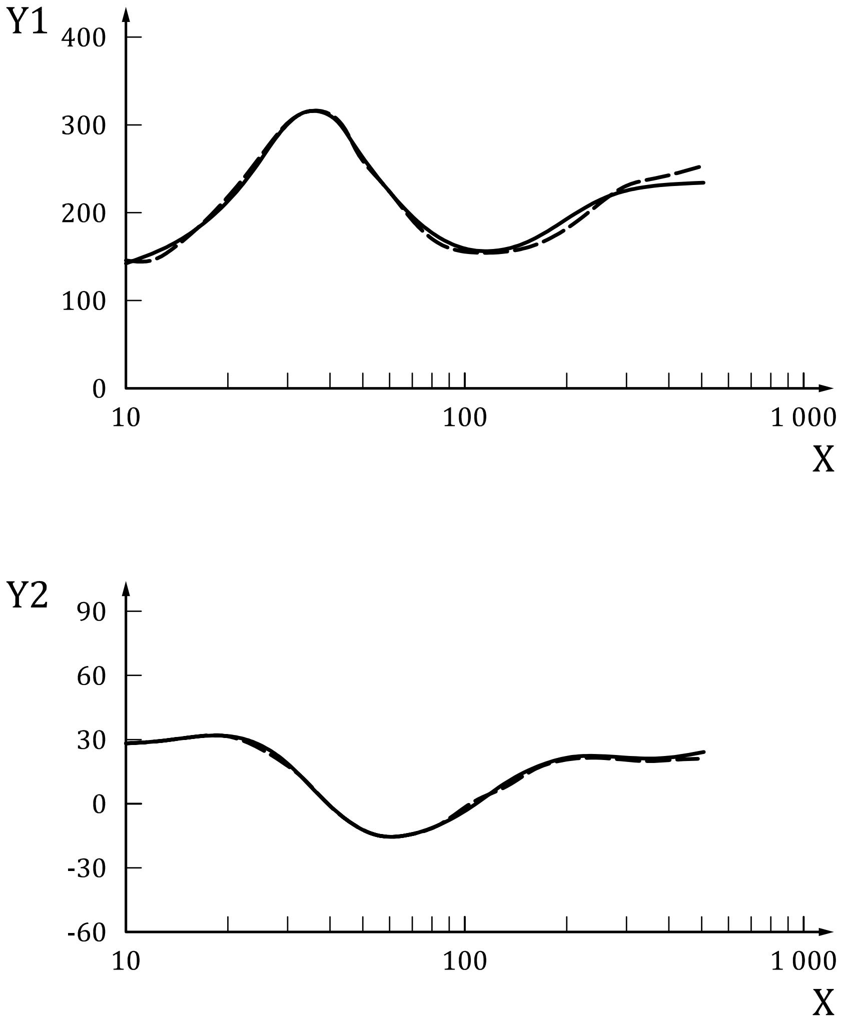
Figure D.2 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the mechanical impedance of the human hand-arm system in the x_h-direction



Key

X frequency (Hz)
Y1 modulus (N·s/m)
Y2 phase (degrees)

Figure D.3 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the mechanical impedance of the human hand-arm system in the y_h-direction



Key

X	frequency (Hz)
Y1	modulus (N·s/m)
Y2	phase (degrees)

Figure D.4 — Comparison between modelled values (solid line) and mean of the synthesized values (dashed line) of the mechanical impedance of the human hand-arm system in the z_h-direction

Annex E
(informative)

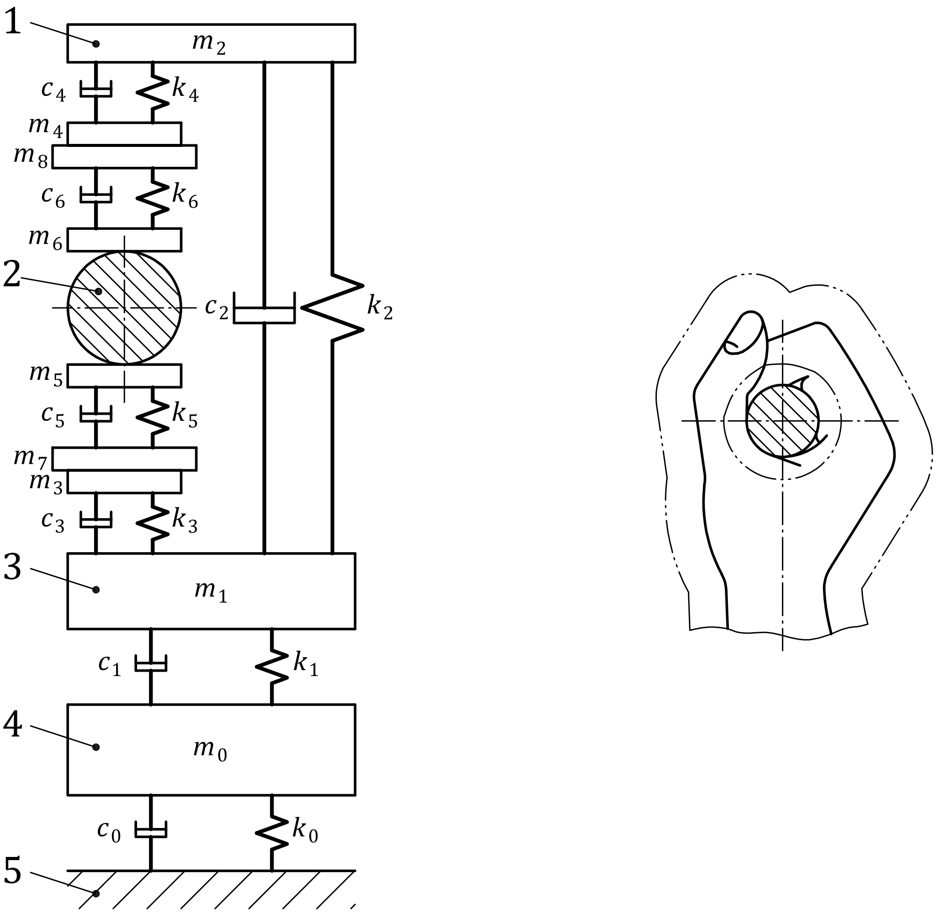
Model of the gloved hand-arm system

Similar to the hand-arm system, a glove can also be approximately simulated using an equivalent mass-spring-damper system. The effective mass, spring stiffness and damping values of the glove model can be measured or estimated from material experiments. They may also be estimated from the mechanical impedances measured with and without wearing the glove. Combining the glove model with a model of the hand-arm system, a model of a gloved hand-arm system can be formed.

Figure E.1 shows an example of such a model. The parameters of the glove model in the z_h-direction are listed in Table E.1. With the parameters of the hand-arm system model for the z_h-direction in Annex D, the vibration transmissibility functions of the glove at the fingers and the palm of the hand are calculated, and the results are presented in Figure E.2. The basic trend of the estimated transmissibility T is consistent with that measured with the method defined in ISO 10819.[6]

Table E.1 — Example of the parameters in z_h-direction for a glove model

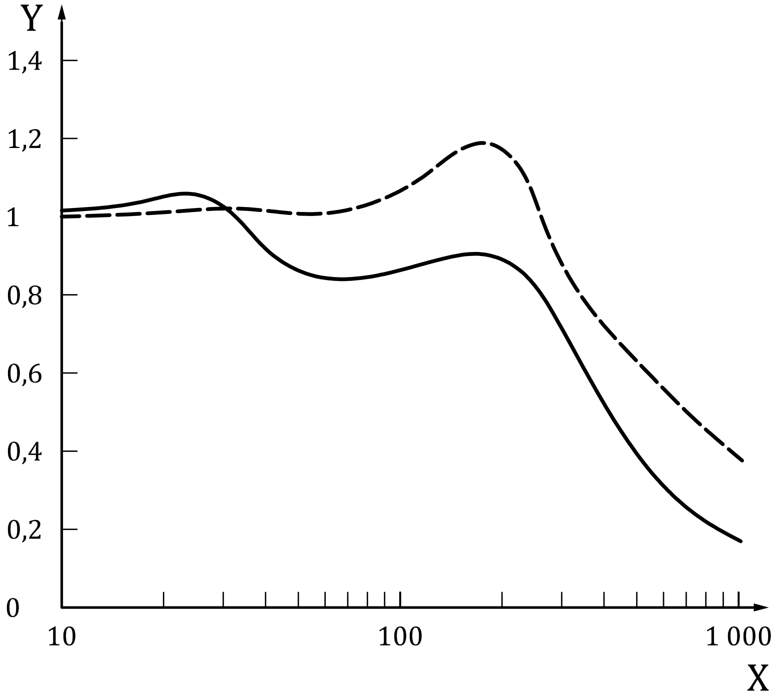
Parameter	Unit	Value
m_5	kg	0,002 0
m_6	kg	0,001 0
m_7	kg	0,067 3
m_8	kg	0,020 0
k_5	N/m	17,738 5
k_6	N/m	32,730 1
c_5	N·s/m	88,8
c_6	N·s/m	75,2



Key

1 fingers
2 handle
3 palm, wrist and forearm
4 upper arm and shoulder
5 upper body

Figure E.1 — A 7-DOF mechanical-equivalent model of the gloved hand-arm system



Key

X frequency (Hz)

Y transmissibility

Figure E.2 — Predicted vibration transmissibility of a glove at the fingers (solid line) and palm (dashed line) of the hand in the z_h-direction

Annex F
(informative)

Examples of frequency dependence derived from vibration power absorption

The three frequency dependencies of the vibration power absorption derived using Equation (5) from the means of the synthesized values of the mechanical impedance in the x_h-, y_h- and z_h-directions listed in Tables 1 to 3 are shown in Figure F.1, together with the frequency weighting defined in ISO 5349-1.[2] Values for the frequency dependency factors are listed in Table F.1.

Table F.1 — Frequency dependency factors for the entire hand-arm system

Frequency	Direction of vibration		
Hz	x_h	y_h	z_h
10	1,055	1,099	1,186
12,5	0,958	0,958	0,958
16	0,786	0,809	0,818
20	0,676	0,721	0,716
25	0,552	0,632	0,651
31,5	0,486	0,488	0,577
40	0,417	0,423	0,466
50	0,370	0,338	0,337
63	0,342	0,257	0,241
80	0,309	0,194	0,170
100	0,278	0,155	0,132
125	0,237	0,119	0,105
160	0,187	0,092	0,082
200	0,153	0,071	0,069
250	0,116	0,055	0,059
315	0,096	0,044	0,050
400	0,078	0,035	0,040
500	0,070	0,029	0,032

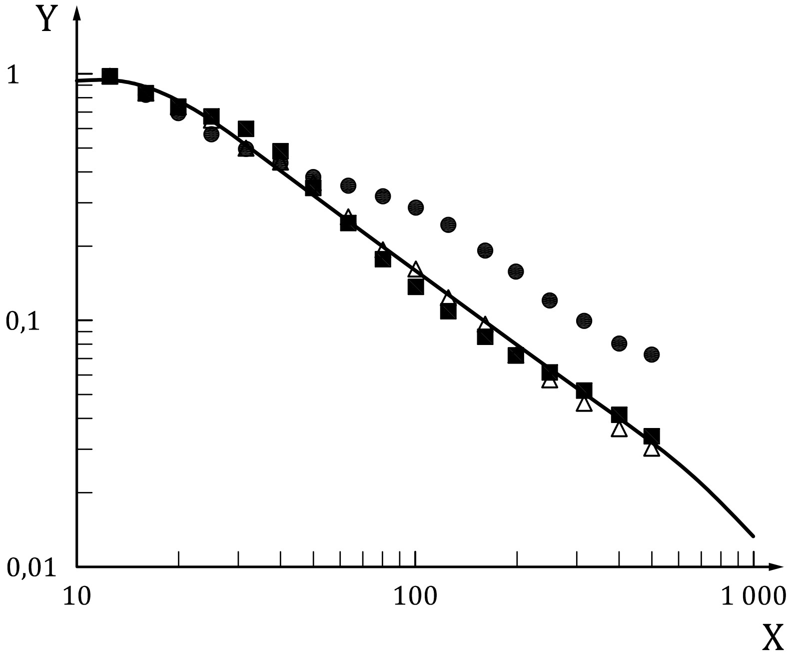
NOTE 1 The basic trends of the frequency dependence derived from the vibration power absorption are consistent with those of the frequency weighting defined in ISO 5349-1.[2]

Examples of the frequency dependence of the vibration power absorption for the major substructures of the hand-arm system (fingers, wrist-forearm, upper arm and shoulder) estimated using Equation (6) are shown in Figure F.2, together with the frequency weighting defined in ISO 5349-1.[2] They are derived from the power absorption estimated with model 3 (see Annex D) in the z_h-direction. Values for the frequency dependency factors are listed in Table F.2.

Table F.2 — Frequency dependency factors for the fingers, palm-wrist-forearm, and upper-arm-shoulder in the z_h-direction

Frequency	**Substructure-specific frequency dependency factors**		
Hz	**Fingers**	**Palm-wrist-forearm**	**Upper-arm-shoulder**
10	0,294	0,476	0,958
12,5	0,338	0,525	0,815
16	0,409	0,603	0,678
20	0,506	0,707	0,578
25	0,640	0,843	0,491
31,5	0,781	0,958	0,388
40	0,816	0,909	0,251
50	0,743	0,730	0,142
63	0,671	0,548	0,075
80	0,648	0,407	0,040
100	0,677	0,313	0,023
125	0,747	0,244	0,014
160	0,853	0,187	0,008
200	0,938	0,148	0,005
250	0,958	0,118	0,003
315	0,884	0,093	0,002
400	0,744	0,072	0,001
500	0,607	0,058	0,001
633	0,484	0,046	0,000
800	0,380	0,036	0,000
1 000	0,303	0,029	0,000

NOTE 2 The frequency dependence for the arm indicates that the vibration power at low frequencies (<25 Hz) can be effectively transmitted to and absorbed in these substructures. Therefore, low frequency tools can cause larger discomfort in these substructures, which is consistent with both laboratory and field observations. The frequency dependence for the palm-wrist substructure reflects the global resonance of the entire hand-arm system in the z_h-direction (at about 31,5 Hz for this case), which primarily depends on the palm contact stiffness and the effective mass of the palm-wrist-forearm subsystem. The frequency dependence for the fingers is influenced by both the global resonance and the major local resonance of the fingers (about 250 Hz in this case). The large differences among the location-specific frequency dependences suggest that the frequency dependence of the potential disorders or injuries are also likely to be location- or substructure-specific.



Key

X frequency (Hz)

Y normalized frequency dependency

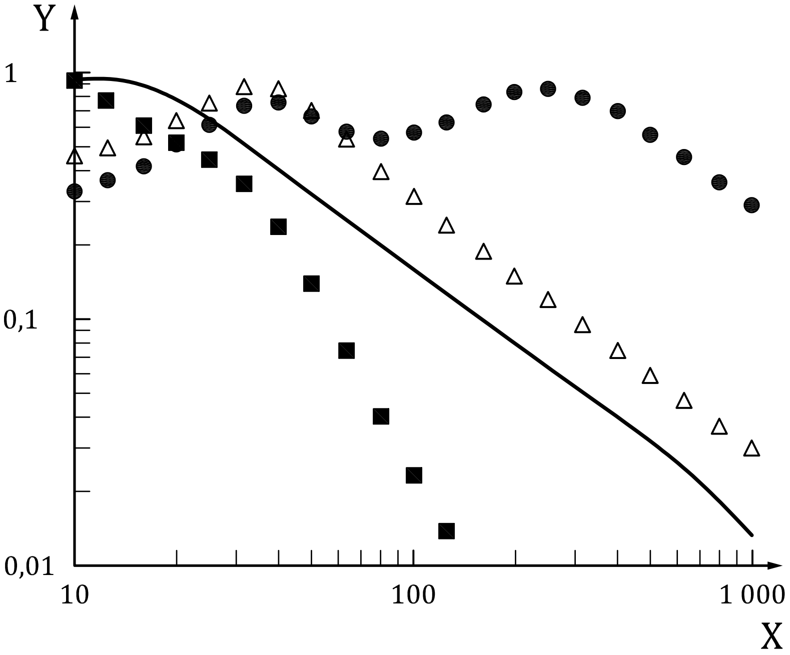
● x_h-direction

Δ y_h-direction

■ z_h-direction

NOTE The reference frequency for the normalization is 12,5 Hz.

Figure F.1 — Comparison of the frequency weighting (solid line) defined in ISO 5349-1[2] and the frequency dependencies derived from the vibration power absorption of the entire hand-arm system in the x_h-, y_h- and z_h-directions



Key

X	frequency (Hz)
Y	normalized frequency dependency
●	fingers
Δ	palm-wrist
■	arm

NOTE The frequency for the maximum power absorption for each substructure is used as the reference frequency for the normalization.

Figure F.2 — Comparison of the frequency weighting (solid line) defined in ISO 5349-1[2] and the frequency dependencies derived from the vibration power absorption in the fingers, the palm-wrist and the arm in the z_h-direction

Annex G
(informative)

Measurement of the mechanical impedance of the hand-arm system

According to the definitions of the biodynamic response functions, it is necessary to measure the dynamic force and the vibration to evaluate the mechanical impedance. The dynamic force and vibration are usually measured using an instrumented handle equipped with force sensors and accelerometers. The vibration velocity required to evaluate the impedance is usually derived from the measured acceleration. Alternatively, the impedance can be derived from the apparent mass using Equation (3) (see Note 2 to definition 2.1), which avoids the derivation of the velocity from the acceleration.

A significant amount of handle mass is usually involved in the measurement of the dynamic force. It is thus necessary to cancel the handle mass induced impedance or apparent mass, which can be measured without the hand coupled to the handle.

NOTE 1 The effective handle mass is also a complex function of frequency. The potential phase difference between the force and motion sensors can result in a significant artificial phase angle of the impedance at frequencies less than 40 Hz. The impedance can be overestimated or underestimated at higher frequencies because the effective mass of the hand is usually small compared with the handle mass. Such potential errors can be largely avoided if a frequency domain method is used to cancel these effects after the impedance or apparent mass of the entire handle-hand-arm system is measured.

It is highly recommended to use at least three small metal weights with different masses [e.g. (5 ± 1) g, (15 ± 2) g, (30 ± 5) g] to calibrate or verify the performance of the measurement system. Each mass should be firmly attached to the instrumented handle. The percentage errors of the magnitude should be less than 5 %, and phase errors shall be within ±10° for the entire frequency range of interest.

To ensure stability, the calibration weights should have a curved contact surface. Such a weight can be fastened to the handle using one or more rubber bands. The mass of the rubber bands positioned on the handle should also be considered as part of the calibration mass.

The applied hand forces should be controlled in the measurement of the impedance or apparent mass. The measurement is based on the definitions recommended in ISO 15230.[8] Specifically, the grip force is the quasi-static component of the force applied by the fingers, and it can be measured using the same force sensors in the instrumented handle provided for the measurement of the dynamic force. The applied feed force is also a quasi-static force applied by the palm (in a push action). It can be measured using separate sensors that could also be installed in the instrumented handle or by having the test subject stand on a force plate during the measurement.

NOTE 2 The hand and arm are usually treated as a system in which translational vibrations in the three mutually perpendicular directions are independent. In reality, some coupling effects can be involved in the response. Investigation of the coupled responses requires that the measurement be conducted on a multi-axis test system.

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