Journal of Sound and Vibration 329 (2010) 1968–1980

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Development of a hand–arm mechanical analogue for evaluating chipping hammer vibration emission values

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ARTICLE INFO

Article history:
Received 11 August 2009
Received in revised form
10 October 2009
Accepted 13 October 2009
Handling Editor: H. Ouyang
Available online 16 December 2009

ABSTRACT

This paper reports on the development and validation of a mechanical system designed to simulate the hand–arm dynamic response when coupled with a chipping hammer. The design is based on a two-degree-of-freedom lumped parameters model, in which the parameters are optimized such that the apparent mass of the mechanical analogue provides a close fit with the measured apparent mass of the hand–arm mechanical system. The apparent mass of the mechanical analogue has been validated on an electrodynamic shaker, than it was used to evaluate the vibration emission values of two different chipping hammers. Preliminary results show variations of <15 percent of the vibration emission values between human subjects and the hand–arm simulator for two different types of chipping hammers, while the variability in the results is found to be considerably reduced when using the mechanical analogue. The implementation of the mechanical analogue as part of a test set-up for the determination of the vibration emission values of chipping hammers is thus seen as an attractive alternative to the use of human subjects.

1. Introduction

Current laboratory test procedures defined in the ISO 8662-2 standard for measuring the vibration emission values of percussive hand-guided tools require the use of human subjects to operate the tools under well-defined conditions in an energy dissipator. Difficulties encountered with recruiting and training the test subjects add to the complexity associated with conducting these tests, which often results in large inter-subject variability. To overcome such problems, the human subjects can be replaced with a mechanical analogue that can reasonably represent the biodynamic response of the human hand–arm system to tool vibration.

The biodynamic response of the human hand–arm system depends on the vibration exposure direction, vibration magnitude, the hand and arm posture, and the applied hand forces [1–5]. Because these factors vary with the type of tool, the mechanical analogue to be developed for testing hand-held power tools may also depend on the type of the tool and on the requirements of its standardized method for vibration emission value measurement. Only a few hand–arm simulators have been reported [6,7], and the available options are currently very limited. Further studies are required to developed more realistic simulators, especially those that can closely simulate the hand–arm postures and hand forces applied to the hand-guided power tools.

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2009.10.042

Although the biodynamic response has been extensively studied and many models of the hand–arm system have been proposed [8], the vast majority of the models are not suitable for the construction of the hand–arm simulator for hand–arm vibration tool testing [9], including those recommended in the current ISO 10068 (1998) [10]. To help the further development of hand–arm simulators for tool testing, a recent study evaluated several hand–arm models and concluded that a two degrees-of-freedom (2-DOF) model was theoretically acceptable and practically feasible for the construction of a hand–arm simulator for testing tools with a dominant vibration frequency of less than 100 Hz [11]. Such a model is theoretically better than the 1-DOF model that has been used in the reported simulator developments [7]. However, the biodynamic response under the specific postures and hand forces required in the chipping hammer test procedure defined in the ISO 8662-2 standard [12] has not been reported. As a result, the parameters of the 2-DOF model for such testing conditions have not been defined.

Therefore, the specific aims of this study are to measure the biodynamic response under the specific chipping hammer testing conditions, to optimize the 2-DOF model for such conditions, and to develop and evaluate the hand–arm simulator based on the 2-DOF model.

2. Method

To design the hand–arm simulator, the apparent mass of the hand–arm system is first measured using six male subjects gripping a cylindrical handle, while maintaining a posture compatible with the operation of a chipping hammer. This is done for different values of push force and vibration level. An optimization is then performed using a genetic algorithm to find the optimal mechanical parameters of a two-degree-of-freedom (2-DOF) mechanical analogue that can provide a best fit with the measured apparent mass data. On the basis of the model, a mechanical analogue is built, and its apparent mass response is compared with that of the subjects. Following some tuning, the mechanical analogue is fixed to a test rig and used to measure the vibration emission values of two different types of chipping hammers, whereas the results are compared with those obtained with three human operators following the procedure as prescribed in the ISO 8662-2 standard [12]. The experiments performed with human subjects were reviewed and approved by an independent ethical committee (Human Research Ethics Committee of Concordia University).

2.1. Measurement of apparent mass of six subjects

Hand–arm apparent mass measurements are performed with six male subjects gripping, with their right hand, an instrumented cylindrical handle of 40 mm diameter. The handle is made of two aluminum semi-circular sections joined by two Kistler 9212 force sensors to measure the grip force. A PCB SEN026 tri-axial accelerometer was mounted inside the handle to measure and monitor the handle acceleration while two Bruël & Kjær 8200 force transducers located between the handle and handle support were used to measure the dynamic driving force, as well as the static push force. The base of the handle support was fixed to a Unholtz–Dickie electrodynamic shaker system with 890 N force capacity. A photograph of the test set-up is shown in Fig. 1. Details of the instrumented handle are given in Marcotte et al. [3]. The main anthropometric characteristics of the six subjects are summarized in Table 1. For each test, the subjects were given sufficient time to adjust the grip and push forces to the specified values, consisting in a grip force of 30 N, and three different push forces of 80, 120 and 160 N. Displays of the grip and push force values were fed-back to the subjects such that they could maintain the forces to the required values (± 5 N). The procedure was repeated for two different levels of vibration ($a_{h,w} = 2.5\,\mathrm{m/s^2}$ and $a_{h,w} = 5.0\,\mathrm{m/s^2}$), with a constant power spectral density in the 8–1250 Hz frequency range. The posture adopted by the subjects was chosen to be compatible with the operation of a chipping hammer, and was similar to the posture shown in the ISO 8662-2 standard [12], except that the subjects were asked to grip the handle with one hand only. The posture consists in a slightly bent forearm, with the torso slightly bent forward, while gripping the handle with the palm of the hand aligned with the upper part of the handle. In addition, the subjects were standing on a platform with an adjustable elevation in order to compensate for their different heights. The three push force values were chosen to match those recommended for testing chipping hammers according to the ISO 8662-2 standard [12]. The excitation was applied with constant power spectral density in the 8–1250 Hz frequency range and was weighted following the ISO 5349-1 standard [13]. A control loop with a feedback from the handle accelerometer was used to keep constant the handle acceleration spectra. Each test was repeated until two similar patterns could be obtained to ensure data reproducibility. Each acquisition was averaged over a 16-s period with a multichannel signal analyzer (Bruël & Kjær Pulse). The apparent mass of the human hand–arm was then computed using:

$$AM(\mathrm{j}\omega) = \frac{G_{\mathrm{Fa}}(\mathrm{j}\omega)}{G_{\mathrm{aa}}(\mathrm{j}\omega)} - AM_0(\mathrm{j}\omega) \tag{1}$$

where $G_{\mathrm{Fa}}(\mathrm{j}\omega)$ is the cross-spectrum of the dynamic force and handle acceleration, both measured at the driving point, and $G_{\mathrm{aa}}(\mathrm{j}\omega)$ is the auto-spectrum of the acceleration measured at the handle. The term $AM_0(\mathrm{j}\omega)$ represents the driving-point apparent mass of the handle alone, which is subtracted from the apparent mass of the hand–handle system to account for the inertia contribution of the handle.

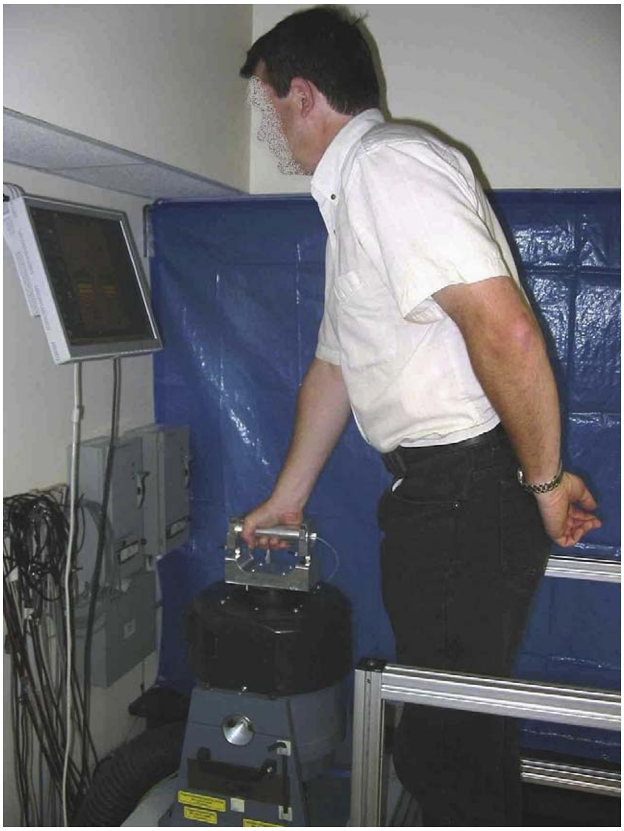

Fig. 1. Test set-up for the measurement of the hand–arm apparent mass on the electrodynamic shaker.

Table 1
Main anthropometric properties of the six subjects.

Parameter	Range	Mean	SD
Upper arm length (cm)	26–35	31.3	3.50
Forearm length (cm)	25–29	26.5	1.97
Wrist circumference (cm)	17–19	18.2	0.98
Forearm circumference (cm)	23–26	24.8	1.17
Elbow circumference (cm)	28–29	28.7	0.52
Upper arm circumference (cm)	28–33	31.2	1.94
Hand circumference (cm)	21–23	21.5	0.84
Hand length (cm)	18–21	19.5	1.22
Weight (kg)	67–86	81.0	7.35
Height (cm)	168–189	175.5	9.18

2.2. Optimization of the mechanical analogue

To guide the design of the mechanical analogue, a 2-DOF mechanical system with two masses elements was considered, its parameters being optimized through a genetic algorithm. A 2-DOF system was chosen since Dong et al. [11] have shown that a 2-DOF can be sufficient to simulate the hand–arm dynamic for up to 100 Hz, knowing that the dominant frequency of a chipping hammer is well below that value. For a 2-DOF system, as shown in Fig. 2, the driving-point apparent mass may be expressed as

$$AM(\mathrm{j}\omega) = \frac{F}{\ddot{x}_2} = \frac{-\omega^2 M_2 + \mathrm{j}\omega C_2 + k_2}{-\omega^2} + \frac{(-\omega^2 M_2 + \mathrm{j}\omega C_2 + k_2)^2}{-\omega^4 M_1 + \mathrm{j}\omega^3 (C_1 + C_2) + \omega^2 (k_1 + k_2)} \tag{2}$$

where $\mathrm{j} = \sqrt{-1}$, ω is the angular frequency, M_1 and M_2 are the masses (kg), k_1 and k_2 are the spring constants (N/m) and C_1 and C_2 are the damping coefficients (N s/m).

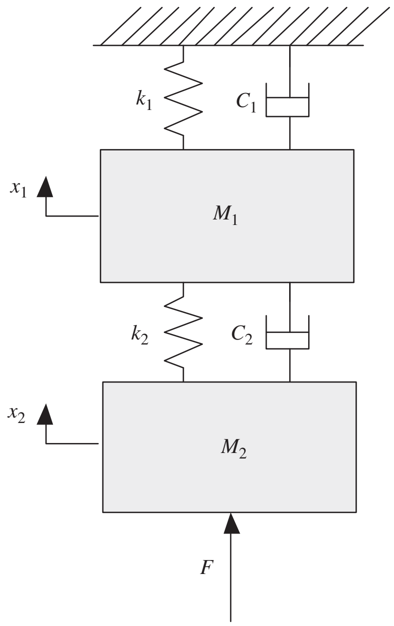

Fig. 2. Schematic of the two-degree-of-freedom mechanical analogue.

Table 2
Mechanical characteristics of the components used to build the mechanical analogue.

M_1 (kg)	M_2 (kg)	k_1 (N/m)	k_2 (N/m)	C_1 (N s/m)	C_2 (N s/m)
3.3	0.3	3200	15000	130	320

The optimization of the parameters was performed with a genetic algorithm implemented under MATLAB [14]. Six parameters were optimized simultaneously: the masses M_1 and M_2, the spring constants k_1 and k_2 as well as the damping coefficients C_1 and C_2. The cost function CF chosen for the minimization is given by

$$CF = \sum_f |AM_d(\mathrm{j}\omega) - AM_0(\mathrm{j}\omega)|^2 \tag{3}$$

where $AM_d(\mathrm{j}\omega)$ is the target apparent mass at angular frequency ω and $AM_0(\mathrm{j}\omega)$ is the apparent mass computed with the 2-DOF mechanical model. The summation was performed over the frequency range from 8 to 200 Hz, with a frequency resolution of 1 Hz, in order to avoid applying too much emphasis on the higher frequencies. In addition, the following constraints were applied on the optimized parameters:

$$0.2 \le M_1, M_2 \text{ (kg)} \le 4$$

$$2000 \le k_1, k_2 \text{ (N/m)} \le 51\,000$$

$$0 \le C_1, C_2 \text{ (N s/m)} \le 600 \tag{4}$$

The lower bound on the spring constants was to ensure reasonable maximum static deflexion of the mechanical analogue under static load (push force), the lower bound on the mass elements is to take into account the residual masses of the attachments and other components, while the upper bound on the mass elements was to be consistent with the mass of the hand–arm system. The upper bounds on the spring constants and damping coefficients were to ensure the availability and feasibility of these components. Once the six parameters were obtained from the optimization algorithm, the constituting parts for the mechanical analogue with the required characteristics were searched among commercial-of-the-shelf components. The spring components had to be chosen not only according to their spring constants, but also for their diameters and lengths, to ensure a compact system and to facilitate the overall design of the analogue. The most difficult components to obtain were the dashpots. Pneumatic dashpots of compatible dimensions were first tested on the device. However, the mechanical behavior of the dashpots was quite elastic as the excitation frequency was exceeding a few Hertz. Since it was very difficult to find hydraulic dashpots with the required characteristics and dimensions, it was decided to built these dashpots from scratch. The dashpot coefficients C were thus adjusted with the internal piston diameters as well as the oil viscosity. Table 2 gives the experimental mechanical characteristics of the six components used to build the mechanical analogue. Then, the optimal solution for the 2-DOF mechanical model that provided the best fit with the mean measured apparent mass of the six subjects was implemented using mechanical components (mass, springs and dampers) that best matched the values of the parameters provided by the optimization.

2.3. Validation of the mechanical analogue based on apparent mass

The resulting newly built mechanical analogue was then tested on an electrodynamic shaker to measure the apparent mass of the device for different values of push force applied at the top of the 2-DOF mechanical analogue. The system, shown in Fig. 3 on top of the shaker, was instrumented with a dynamic force sensor and an accelerometer to measure the driving-point apparent mass. Then, the apparent mass of the mechanical analogue was measured for two different levels of excitation ($a_{h,w} = 2.5$ and $5.0\,\mathrm{m/s^2}$) and three different push forces (80, 120 and 150 N). Since the force was applied at the top of the mechanism, the push force was defined as the sum of the weight of the mechanical analogue and of the applied force measured with a load cell located at the top of the mechanism.

Fig. 3. Testing of the 2-DOF mechanical analogue on the electrodynamic shaker.

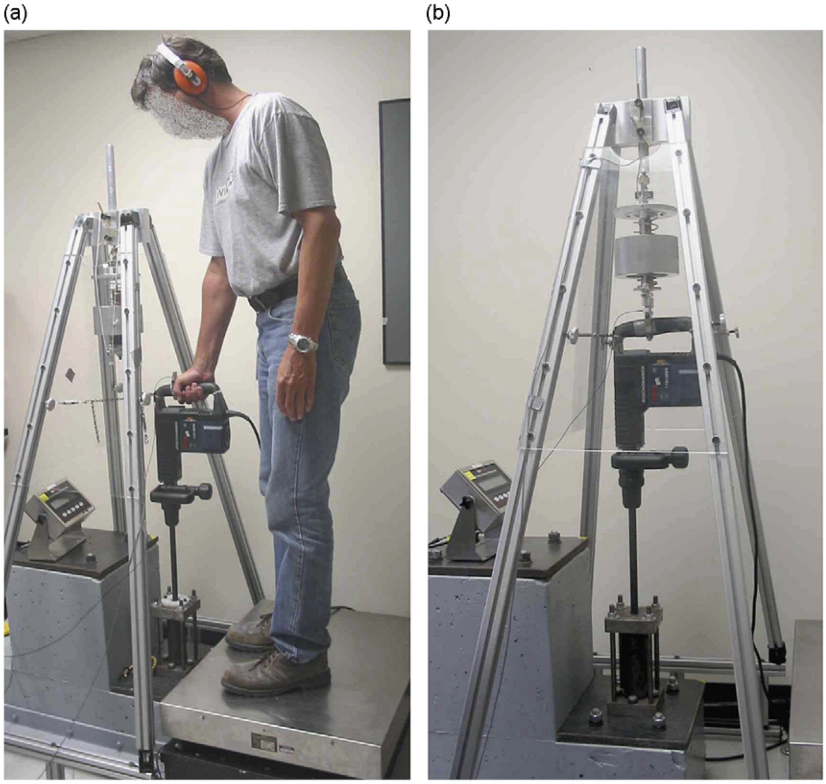

Fig. 4. Operation of the electric chipping hammer with: (a) human subject and (b) mechanical analogue.

2.4. Validation of the mechanical analogue with chipping hammers

Following the validation based on apparent mass, the mechanical analogue was used to measure the vibration emission values of two types of chipping hammers: one electric and one pneumatic. For each hammer, five measurements were performed with the mechanical analogue and repeated for three different tests. These measurements were compared with the results obtained with three subjects, each performing a set of five measurements. Between each test, the mechanical analogue was disconnected and reconnected to the chipping hammer to ensure data reproducibility. A force plate was used to help the subjects maintaining the push force at the required value. The force was maintained within ± 5 N of the required value. The vibration emission values were measured at the tool handle, in terms of frequency-weighted rms acceleration along the dominant axis (z_h-axis), with the tools operating in an energy dissipator as required in the ISO 8662-2 standard [12]. The acceleration signals were measured with a B&K 4393 accelerometer attached to a mechanical filter in order to avoid DC shift.

The mechanical analogue was first tested with an electric chipping hammer (BoshHammer 11313EVS) having a mass of 5.3 kg and a percussion frequency regulated at 40 Hz. Fig. 4 provides a representation of the test set-ups of the electric chipping hammer, for both the mechanical analogue and the human subjects. The posture adopted by the human subjects consisted in holding the tool handle with the right hand, as shown in Fig. 4, and is consistent with the posture adopted by the subjects, presented earlier, for the characterization of the hand–arm apparent mass.

The mechanical analogue was further validated with a pneumatic chipping hammer (Atlas Copco RRF31-01) having a mass of 2.5 kg and equipped with an antivibration device. The tool air pressure was regulated to 630 kPa, leading to an average percussion frequency of 44 Hz. The posture adopted by the human subjects consisted in holding the tool handle with the right hand. A push force of 100 N was applied on the chipping hammer for all the measurements done with the human subjects and the mechanical analogue. For the tests with the human subjects, the push force was applied with the right hand only and the left hand was holding the side of the tool for lateral stabilization of the tool only.

3. Results

3.1. Apparent mass of six subjects

The mean apparent mass magnitude and phase for the three levels of push force (80, 120 and 160 N) and the two excitation levels are shown in Fig. 5. It appears that the apparent mass magnitude increases slightly with the push force

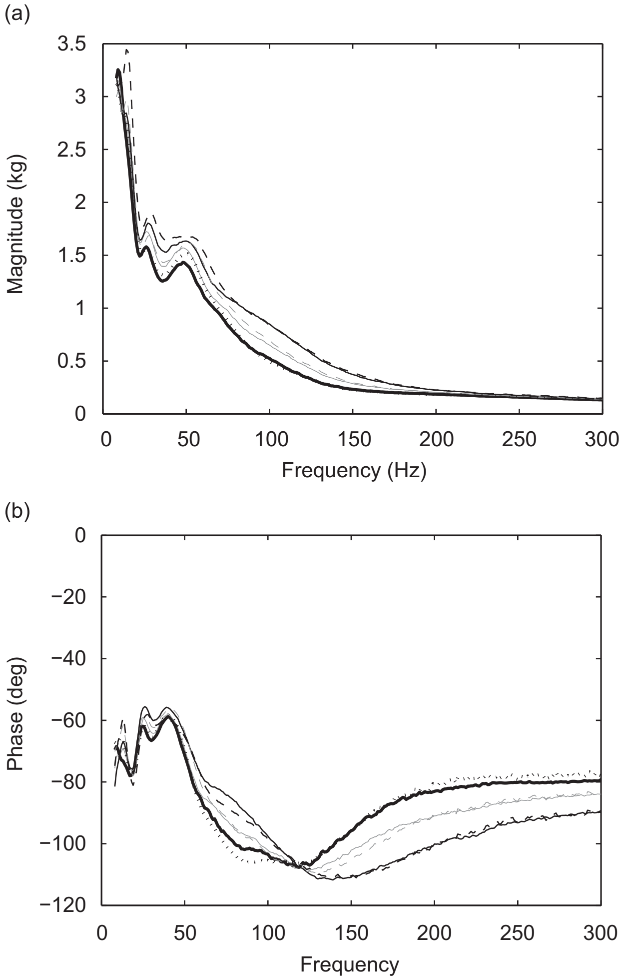

Fig. 5. Mean measured apparent mass of 6 subjects, as a function of push force and excitation level (a_{hw}) for 30 N grip force: (a) magnitude, (b) phase (——: 80 N, 5.0 m/s^2; ——: 120 N, 5.0 m/s^2; ——: 160 N, 5.0 m/s^2; ······: 80 N, 2.5 m/s^2; — — —: push 120 N, 2.5 m/s^2; and — — —: 160 N, 2.5 m/s^2).

between 20 and 200 Hz, independently of the vibration level. In addition, the magnitudes are superimposed above 200 Hz, while similar values were obtained below 20 Hz, excepted for one condition. Indeed, these results show a negligible influence of the excitation level (suggesting a linear system with respect to the excitation level) and only a slight effect of the push force on the apparent mass response, thus such influences might be neglected for the purpose of designing a mechanical analogue. In order to have a target apparent mass response for the optimization of the mechanical analogue, the measured mean apparent mass was averaged over the three push forces (80, 120 and 160 N) and the two excitation levels ($a_{h,w} = 2.5$ and $5.0\,\mathrm{m/s^2}$).

3.2. Validation of the mechanical analogue

The measured apparent masses for the different conditions are shown in Fig. 6. It is suggested that the vibration level has a slight influence on the mechanism apparent mass, which is attributed to dry friction in the dampers and linear bearings, where friction is more important for small displacements. In contrast to the apparent mass measured with human subjects, the push force has a negligible influence on the mechanism apparent mass. The peak that appears around 210 Hz in the mechanism apparent mass has been attributed to an internal resonance of the spring k_2. However, it has been verified that this peak has a negligible effect upon the analogue base acceleration in the corresponding 200 Hz one-third octave band, when operated with chipping hammers.

Fig. 7 presents a comparison of the measured apparent mass of the mechanical analogue with the optimal apparent mass obtained with the 2-DOF mechanical model, and with the mean apparent mass of the six subjects for the condition involving a 120 N push force and a vibration level of $a_{h,w} = 5.0\,\mathrm{m/s^2}$. These results suggest that the optimal 2-DOF model of

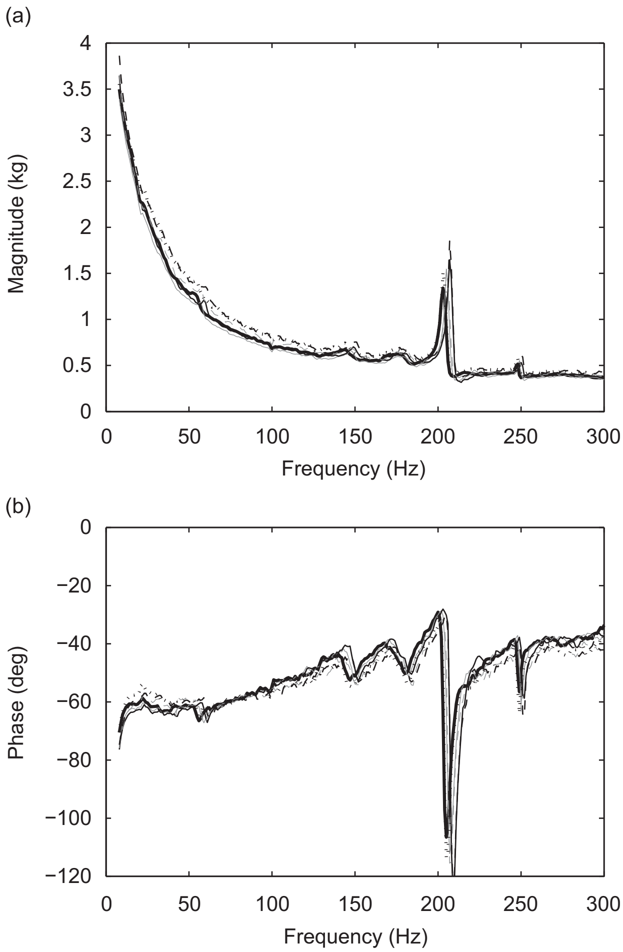

Fig. 6. Measured apparent mass of mechanism, as a function of push force and excitation level (a_{hw}): (a) magnitude, (b) phase (——: 80 N, 5.0 m/s^2; ——: 120 N, 5.0 m/s^2; ——: 150 N, 5.0 m/s^2; ······: 80 N, 2.5 m/s^2; — — —: push 120 N, 2.5 m/s^2; and — — —: 150 N, 2.5 m/s^2).

the mechanical analogue provides a good approximation of the magnitude of the mean subject apparent mass up to 300 Hz. The apparent mass magnitude provided by the mechanical analogue is slightly larger above 100 Hz, and a phase shift of 40° appears at higher frequencies. However, since chipping hammers dominant frequency is usually situated below 50 Hz, it was considered that the phase shift as well as the resonance occurring at 210 Hz would not affect the response of the mechanical analogue in a significant manner. In addition, it is shown that around 40 Hz, which is the typical dominant frequency of chipping hammers, both the magnitude and phase are very similar between the mechanical analogue and the human subjects, increasing the potential agreement between the vibration emission values obtained with the human subjects and the mechanical analogue.

3.3. Electric chipping hammer

The resulting one-third octave frequency band spectra of the vibration measured on the handle of the electric chipping hammer are shown in Fig. 8 for both the mechanical analogue (a) and the human subjects (b). These represent the mean spectra of a series of five measurements with the mechanical analogue and five measurements with the human subjects, for a total of 15 measurement for both the mechanical analogue and the human subjects. A push force of 150 N was applied on the chipping hammer for all the measurements carried out with the human subjects and the mechanical analogue. It is shown, in Fig. 8, that both the mechanical analogue and the human subjects provide similar trends in the emission spectra, although the mechanical analogue provides a better reproducibility. The mechanism reproductibility at the 40 Hz one-third octave band (percussion frequency) is much better than the human one, giving a good example of the kind of problems that are encountered when using human subjects for determining the vibration emission values of power tools. The human subjects and mechanical analogue emission spectra are further compared in Fig. 9, where the emission spectra are averaged over the three subjects and the three tests, for, respectively, the human subjects and the mechanical analogue.

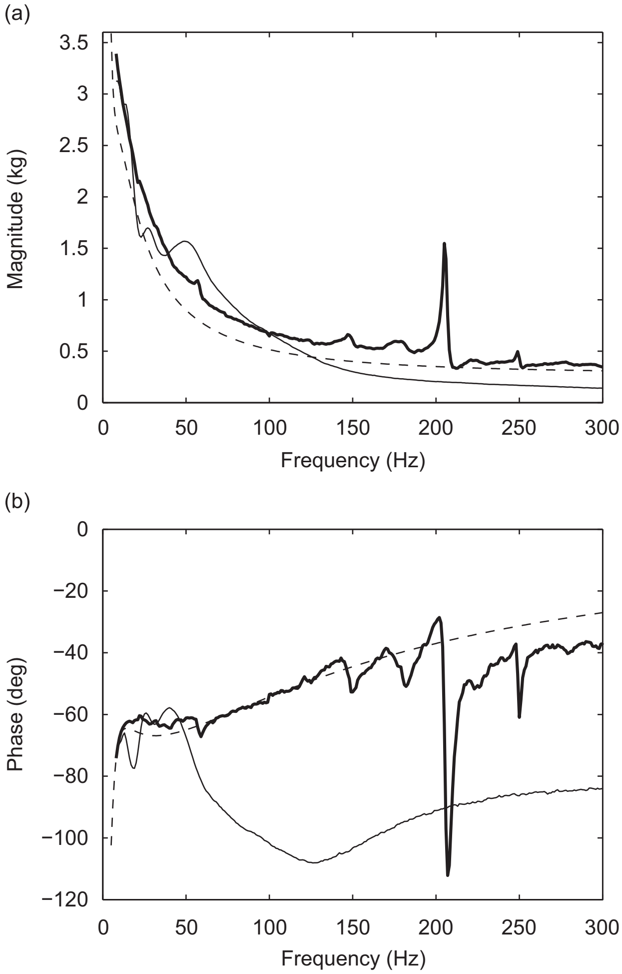

Fig. 7. Validation of the mechanical analogue based on apparent mass: (a) magnitude, (b) phase (————: mean of 6 subjects; — — —: optimal 2-DOF model; and ━━━━: mechanical analogue, 120 N, 5.0 m/s^2).

It can be seen that the mean vibration spectra obtained with the mechanical analogue closely follows that of the human subjects, excepted for the one-third octave frequency bands between 80 and 160 Hz, where the vibration levels are more elevated for the human subjects.

The vibration emission values corresponding to these spectra for each of the measurements are shown in Table 3. It shows that the coefficients of variation (COV) for the mechanical analogue (1–2 percent) are much lower than those measured with the human subjects (6–8 percent). In addition, the vibration emission value is on average 6.2 percent lower with the mechanical analogue. The ISO 8662-2 standard [12] requires a COV <15 percent between the different measurements for the data to be valid. This condition is seen to be met by both the subjects and the mechanical analogue methods, although the latter leads to considerably less variation.

3.4. Pneumatic chipping hammer

The resulting one-third octave band frequency spectra of the vibration measured at the handle of the pneumatic chipping hammer are shown in Fig. 10 for both the mechanical analogue (a) and human subjects (b). Both the mechanical analogue and the human subjects are shown to provide similar trends in the vibration emission spectra. It can be observed that the energy of vibration at the percussion frequency (44 Hz) is distributed in the two adjacent one-third frequency bands of 40 and 50 Hz. This distribution varies in time due to some fluctuations in the percussion frequency. In addition, one of the subject had a much more elevated acceleration amplitude at the one-third frequency band of 25 Hz. The human subjects and mechanical analogue emission spectra are further compared in Fig. 11, where the emission spectra are averaged over the three subjects and the three tests, for, respectively, the human subjects and the mechanical analogue. It is shown that the mean vibration spectra obtained with the mechanical analogue closely follows that of the human

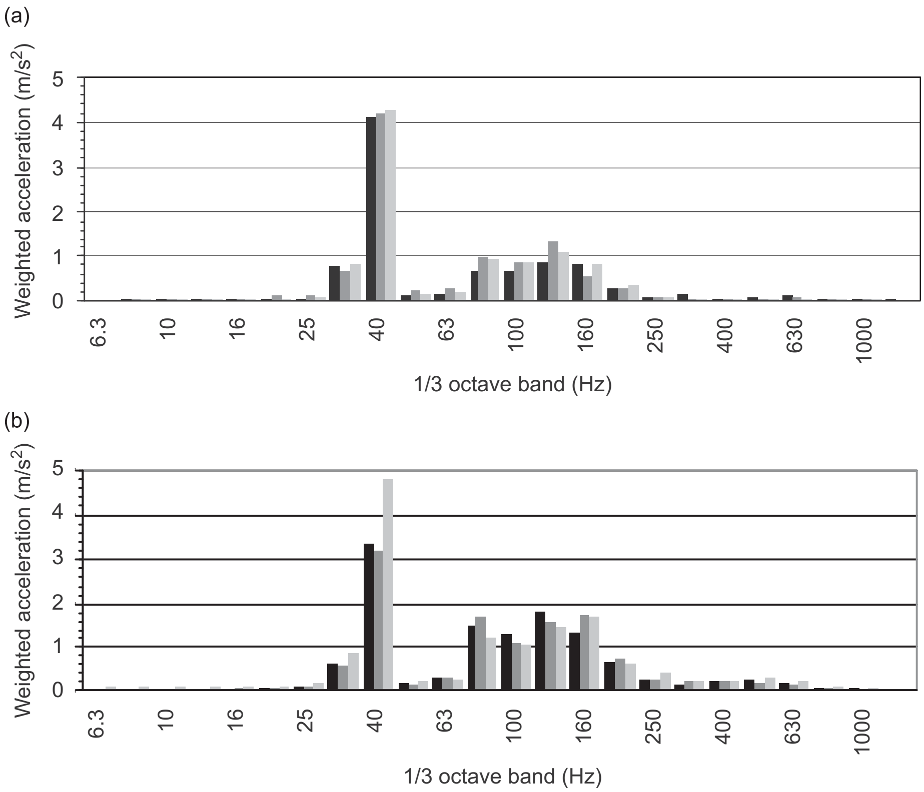

Fig. 8. Vibration emission spectra of the electric chipping hammer measured with: (a) mechanical analogue (3 tests) and (b) human subjects (3 subjects).

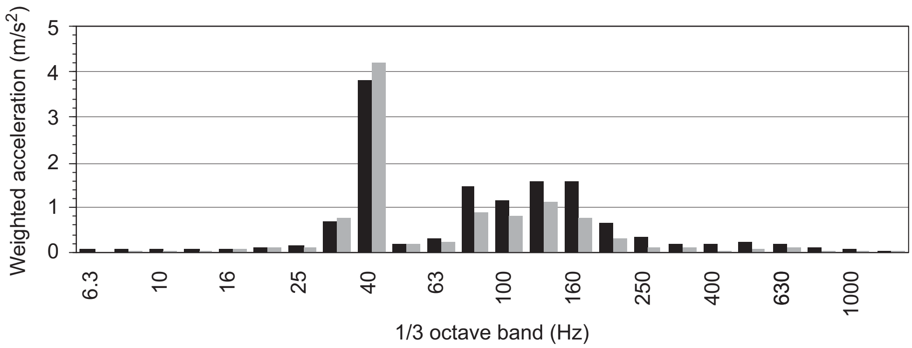

Fig. 9. Mean vibration emission spectra of the electric chipping hammer: human subjects compared to mechanical analogue (■: mean of 3 subjects; and ■: mean of 3 tests with analogue).

subjects, except for the 25 Hz band, where the larger difference is attributed to a less stable gripping of the tool by one of the subjects.

The vibration emission values corresponding to those spectra are further compared in Table 4. It can be seen that the coefficients of variation (COV) are much lower for the mechanical analogue (1–2 percent) than for the human subjects (6–15 percent). In addition, the vibration emission value is 10.6 percent lower with the mechanical analogue. Furthermore, it can be seen that the benefits of using a mechanical analogue are more important in this particular case because of the considerably larger variations recorded with the human subjects.

4. Discussion

Fig. 7 shows some differences in the apparent mass magnitude and phase between the mean of 6 subjects and the mechanical analogue. Above 50 Hz, a phase shift of about 40° appears between the human apparent mass and mechanical

Table 3
Vibration emission values for the electric chipping hammer.

Measurement	$a_{h,w}$ (m/s^2), z_h direction						Variation (%)
	Subject			Test (analogue)			
	1	2	3	1	2	3	
1	5.12	4.63	5.80	4.43	4.51	4.75	
2	4.59	4.59	5.70	4.51	4.62	4.77	
3	4.16	4.75	5.95	4.34	4.78	4.76	
4	4.64	4.69	5.13	4.49	4.64	4.65	
5	4.21	4.15	5.38	4.34	4.64	4.68	
Mean value	4.54	4.56	5.59	4.42	4.64	4.72	
COV (%)	8.5	5.2	6.0	1.8	2.0	1.1	
Mean emission value		4.90			4.60		−6.2

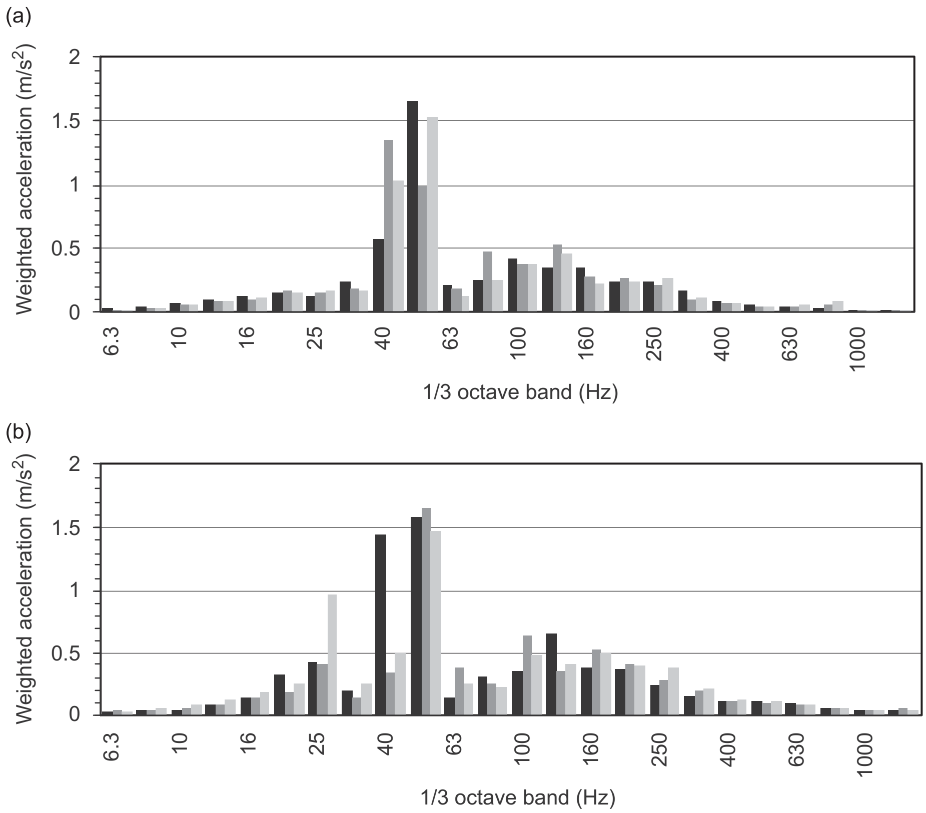

Fig. 10. Vibration emission spectra of the pneumatic chipping hammer measured with: (a) mechanical analogue (3 tests) and (b) human subjects (3 subjects).

analogue. Such a different would be translated by decrease amount of damping of the mechanical analogue compared to the human subject. This phenomena, coupled with the overestimation of the apparent mass magnitude by the mechanical analogue above 150 Hz, could explain that the vibration spectra shown in Figs. 9 and 11 are underestimated by the mechanical analogue at 100 Hz and above for both chipping hammers. However, for percussive tools where the dominant frequency is generally below 50 Hz, these differences at higher frequencies have only a marginal effect on the overall vibration emission value of the tools.

The hand–arm simulator reported in this study allows for the application of a controlled push force at the top of the simulator. Such a mechanism is important for chipping hammers, since some of these tools would not even operate if a push force is not applied on them. In addition, the ISO 8662-2 [12] requires to test the chipping hammer for several applied

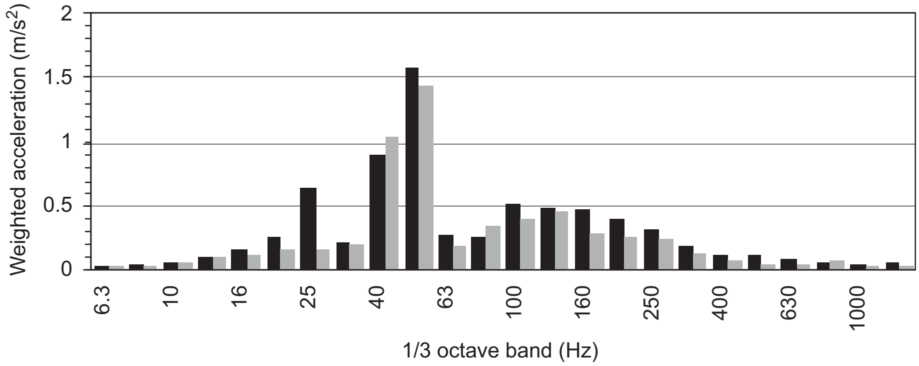

Fig. 11. Mean vibration emission spectra of the pneumatic chipping hammer: human subjects compared to mechanical analogue (■: mean of 3 subjects; and ■: mean of 3 tests with analogue).

Table 4
Vibration emission values for the pneumatic chipping hammer.

Measurement	$a_{h,w}$ (m/s^2), z_h direction						Variation (%)
	Subject			Test (analogue)			
	1	2	3	1	2	3	
1	2.67	1.99	1.80	1.95	1.95	1.97	
2	2.30	2.18	2.53	1.95	1.94	2.01	
3	2.61	2.08	2.20	1.98	1.93	2.07	
4	2.42	1.93	2.28	1.92	1.96	2.05	
5	2.10	2.26	1.84	1.98	1.96	2.03	
Mean value	2.42	2.09	2.13	1.96	1.95	2.03	
COV (%)	9.6	6.4	14.5	1.3	0.7	1.8	
Mean emission value		2.21			1.98		−10.6

push forces. Such a mechanism for the application of the push force has not been reported in the previous studies [6,7]. In addition, in those studies, elastomeric materials have been used for the elastic components of the hand–arm simulator. While such materials can be used when relatively small deformations occur in the simulator, these might not be sufficient for tools with large displacements like chipping hammers. For these reasons, the hand–arm simulator presented in this study was based on linear bearings, solid springs and dashpots rather than elastomeric materials.

Based on the apparent mass response, the hand–arm simulator presented in this paper has the potential to be applied to other percussive tools, as long as the tool dominant frequency is not greater than 50 Hz. The simulator could be also adapted to allow displacements in the lateral directions, allowing also for the tool testing in the x_h and y_h axes.

5. Conclusion

A two-degree-of-freedom (2-DOF) mechanical analogue model, for the determination of the vibration emission values of chipping hammers, has been optimized in order to simulate the apparent mass response of the human hand–arm system while operating a chipping hammer. This model was used as a basis for designing a mechanical analogue of the hand–arm system. When used in conjunction with two different types of chipping hammers, the mechanical analogue was found to provide vibration emission values and spectral characteristics of the tools in good agreement with those measured with human subjects, although providing values which were 6–11 percent lower. Furthermore, the coefficient of variation associated with the mechanical analogue was found to be 4–8 times lower than that measured with the human subjects. In view of the good agreement obtained in these preliminary results, it is suggested that the mechanical analogue could provide a good alternative to using human subjects for evaluating the vibration emission values of chipping hammers.

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