Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Sound and Vibration 294 (2006) 1004–1015
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Lower limb contribution to the dynamic response of the seated man

Pierre Lemerle*, Philippe Boulanger

Modeling Laboratory for Mechanical Prevention Systems, Institut National de Recherche et de Sécurité, Avenue de Bourgogne, BP no. 27, 54501 Vandoeuvre Cedex, France

Received 12 May 2004; received in revised form 28 November 2005; accepted 19 December 2005
Available online 23 March 2006

Abstract

The aim of this study was to assess the effect of the lower limbs in transmitting vibration to the whole body of the seated man. Design of a biodynamic dummy, i.e. a mechanical system aimed at reproducing the dynamic behavior of the seated man and used to assess suspension seat efficiency, requires consideration of all parameters playing a key part in vibration transmission. To date, no study has been able to quantify the effect of considering knee- and pelvis-related movement on the dynamic response of the seat/subject system. The results of this study showed that, in the worst case, this effect plays about 15% part in this response. It was also demonstrated that lower limb effect is characterized essentially by additional damping which may be interpreted as associated with friction between subject and seat or internal damping in the joints.
© 2006 Elsevier Ltd. All rights reserved.

1. Introduction

Suspension seats are used to isolate vertical vibration in mobile machinery, especially when such vibration is severe and low frequency. To ensure optimal filtering, a suspension seat must be adapted to the vehicle on which it is installed. Moreover, this means that its natural frequency must be less than the vehicle dominant frequency.

In practice, testing standards [1,2] and a directive [3] have been drawn up for earthmoving machines, industrial trucks and agricultural tractors respectively to check, in the laboratory, whether suspension seats are adapted to the vehicle categories for which they are commercialized. Implementation of these testing codes implies resorting to the use of testing subjects. In general, running tests with human subjects is highly disadvantageous because it must meet both precise selection criteria (in particular, several weight categories are specified in the test codes) and the requirements of biomedical research-related codes of ethics (authorization request to a consultative committee, setting up of emergency aid procedures, etc.).

This is why several laboratories specialized in the vibration field [4,5] have, in recent years, invested in the design of biodynamic dummies: articulated mechanical systems supposed to reproduce the dynamic behavior of seated subjects.

*Corresponding author.
E-mail address: lemerle@inrs.fr (P. Lemerle).

0022-460X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsv.2005.12.038

In parallel, a working group was formed within the scope of European standardization, to develop current testing standards for suspension seats by offering experimenters the possibility of substituting test dummies for human subjects. However, these new testing procedures require dummy dynamic characteristics (impedance, apparent mass, etc.) to be specified to guarantee measurement representativeness and reproducibility.

Currently, all existing biodynamic dummy prototypes have been developed based on data provided by international standard ISO 5982 [6], which defines probable value ranges for characterizing biodynamic response of the seated man subjected to vertical vibration. Applicability conditions are clearly indicated in standard ISO 5982 and, in particular, it is stipulated "that the subject is supported on a rigid surface, that the feet rest on the platform, on which the rigid supporting surface is fixed and that the back is unsupported". Applicability limits correspond effectively to the measuring conditions in which data is acquired. But, these conditions are not strictly identical to laboratory conditions for testing suspension seats. The suspension system in fact introduces a degree of freedom between the subject's buttock, in contact with the seat pan, and the feet, resting on the platform, which allows relative movement of the hip and knee joints.

During interlaboratory tests, Riedel and Kinne have shown that dynamic responses of current production suspension seats measured with their self-designed biodynamic dummy, whose mechanical characteristics were optimized to reproduce the impedance curves of standard DIN45676 [7] (same measuring conditions as ISO 5982), lead to systematic differences, of around 10%, compared with tests conducted with human subjects (dynamic responses being expressed in terms of S.E.A.T.[1] factor). These differences were always noted to be in the same direction, i.e. that measurements taken with a dummy result in underestimating the S.E.A.T. factor measured with a human subject, irrespective of the subject weight and type of seat tested [8]. The same order of deviation was noted by Politis et al. [9] between subjective tests and pure mass tests carried out with low natural frequency seats. With seats of higher natural frequency (4 Hz) the deviation could reach 40%. In this case, more basic reasons were put forward: both suspension seat and human subject had close natural frequency. Moreover, the seat tested was not adapted to the input signal so that the fundamental human body mode was excited. Unlike with the articulated dummies, a pure mass was not enough to simulate this resonance effect.

The hypothesis proposed to justify the slight differences observed by Riedel and Kinne is the effect of the lower limbs in transmitting vertical vibration through the human body in a seated position: relative movement of the lower limbs, made possible by introducing a suspension system and not considered in experiments conducted for standard ISO 5982 definition, is assumed to have a significant effect on the overall dynamic response of the subject.

Fairley [10] provided the first elements of an answer. He measured the lower limb apparent mass of 8 subjects and used these experimental data to estimate, by a simplified impedance connection calculation, the apparent mass of the seated man with and without relative movement of the lower limbs (i.e. seated on a suspension seat and on a rigid seat, respectively). His calculations showed that lower limb movement results in attenuation of the subject's apparent mass, especially below his resonance frequency.

The purpose of this study is to check this hypothesis using a direct experimental approach and, more generally, to understand how the lower limbs contribute to transmitting vibration within the human body in a seated position.

2. Experimental procedure

The principle of the experiment involves comparing the apparent mass of a subject sitting on a seat fitted with a suspension system, whose mechanical characteristics compare with those of current production suspension seats, and the apparent mass of the same subject sitting on the same seat, whose suspension has been previously blocked such that the testing conditions are strictly identical to those stipulated in standard ISO 5982.

Let us consider a subject sitting on a suspension seat. With respect to the seat, his apparent mass M_s is defined as the ratio between the contact force F_s and the seat pan acceleration γ_s (cf. Fig. 1):

$$M_s = \frac{F_s}{\gamma_s} - m, \tag{1}$$

[1]Ratio between rms values of frequency-weighted acceleration measured at the seat pan section and at the platform.

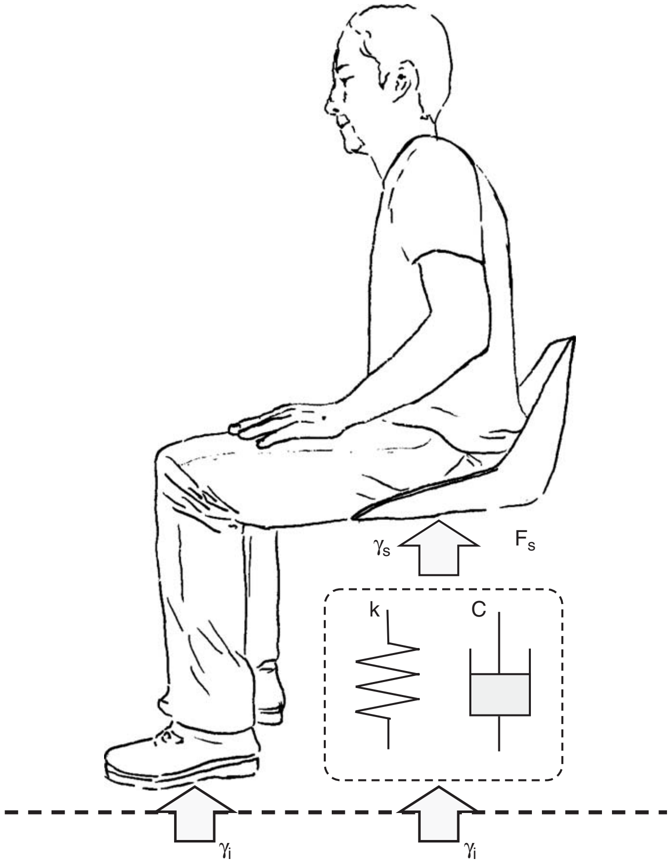

Fig. 1. Principle of experiment.

where m is the mass of the mobile part of the suspension seat located between the force sensor and the subject. This part is composed of the seat pan, a thick steel plate and steel struts which can obviously be considered as pure rigid bodies in the frequency range of the study [0–10 Hz] (cf. Fig. 2).

M_s is to be compared with M, the apparent mass measured in the same way with the same subject, but with the suspension system blocked.

Preliminary experiments were realized with 12 subjects (in good health, 10 male subjects, 2 female subjects, aged 20–60) to measure their apparent mass with the same vertical input acceleration signal (at the seat base) in both configurations, with the suspension blocked and with the suspension free. All the subjects were asked to seat hands in lap without any support from the backrest. The acceleration input γ_i delivered by the vibrating platform was chosen as a limited bandwidth random signal ranging from 1 to 10 Hz.

Because the suspension amplified the acceleration input around its natural frequency, the acceleration signals γ_s at the seat pan were not identical in both cases and because the dynamic behavior of the human body is highly nonlinear and thus any "best fit" linear frequency response function generated will be dependent on the input level, the apparent masses measured in both configurations were not strictly comparable. That is the reason why the test procedure was improved to ensure that acceleration γ_s was exactly the same whether or not the suspension was active: Firstly, input acceleration γ_i imposed at the test platform using a electro-hydraulic shaker was a limited bandwidth [1–10 Hz] random signal and the apparent mass of the subject was measured. Suspension output acceleration γ_s was recorded throughout the test with the suspension system in action.

The recorded time history (further named narrow band excitation signal) was then reproduced by the electro-hydraulic shaker during the test conducted with the suspension system blocked. Thus, the movement imposed at the seat pan was identical to the movement occurring during the test with the suspension system in action (cf. Fig. 3). The recorded signal depended on the coupled dynamic behavior of the subject and of the

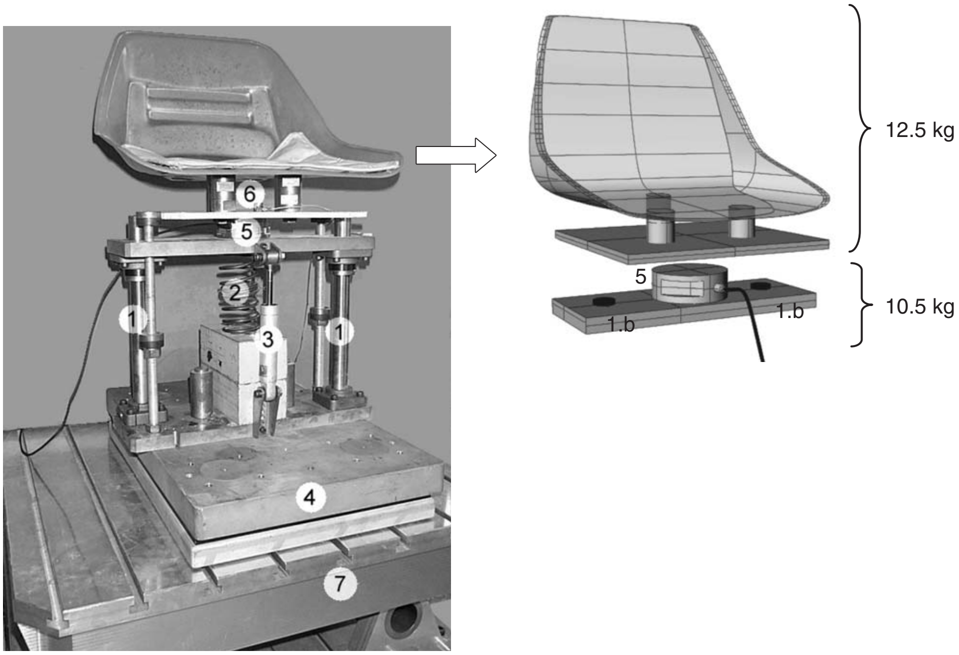

Fig. 2. Test apparatus (1) guiding axle; (1.b) ball bearing guide; (2) spring; (3) damper; (4) piezoelectric force plate, 6 dof; (5) force sensor, 6 dof, strain gage technology; (6) accelerometer, capacitive technology; (7) testing platform actuated by electro-hydraulic shaker.

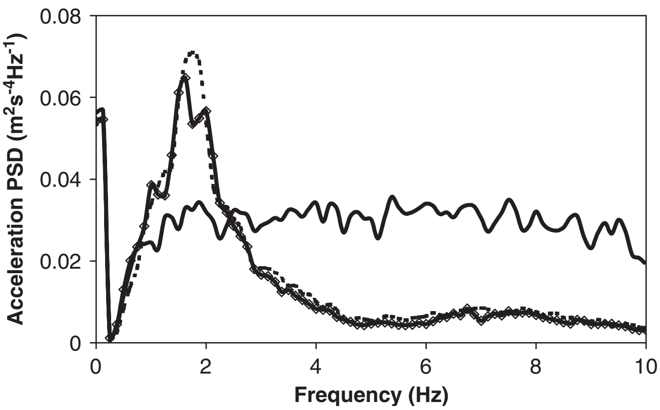

Fig. 3. Input acceleration frequency spectra: (—) limited bandwidth acceleration measured on platform during test with suspension free, (◇) narrow band acceleration measured on seat pan during test with suspension free, (- -) narrow band acceleration measured on seat pan (= platform) during test with suspension blocked.

suspension seat. So this test procedure was relevant for a given subject as a comparative study, in order to assess the lower limb contribution to the transmission of vibration. Unlike for preliminary experiments, computing mean values of apparent masses was meaningless because input acceleration was not identical for each subject tested.

This experiment was made possible by implementing a force sensor used in robotics for remote handling experiments, which offers the advantage of being able to measure 6 components of the connecting force between two substructures, without requiring additional guides. Only the force along the vertical axis was analyzed in practice and used in this study. Torque measurement indications were used in real time to monitor the subject posture and check his or her position on the seat pan.

The testing apparatus featuring an instrumented suspension seat is illustrated in Fig. 2. Seat mechanical characteristics are as follows:

$$K = 9000\,\mathrm{N/m},$$
$$C = 500\,\mathrm{N/m/s},$$
$$m = 12.5\,\mathrm{kg}.$$

The whole mobile part (seat, force sensor and suspension components) weighs 23 kg. Ball bearing axles with low friction were used as linear guides. Friction was low enough to be neglected in comparison with damping forces. The natural frequency of the seat weighted with an inert mass of 60 kg is 1.65 Hz.

These mechanical characteristics implies that this suspension seat meets the performance criteria specified in standard EN 13490 [2] for the two excitation spectrum classes IT1 and IT2. These two classes correspond to covered platform lift-trucks, driver-controlled lift-trucks, etc., with an average wheel diameter of less than 200 mm and retractable mast or fork lift-trucks, etc., with an average wheel diameter of less than 450 mm.

3. Results

3.1. Limited bandwidth random input

Fig. 4 illustrates the apparent masses of 12 seated subjects measured in both configurations: with the suspension free or with the suspension blocked. Each test was performed with a limited bandwidth [1–10 Hz] random acceleration signal imposed by the hydraulic shaker at the seat base.

The acceleration and force were acquired at 20 Hz max frequency (resolution of 0.05 Hz and sampling frequency of 50 Hz) during 200 s. A total of 10 blocks were acquired sequentially (with no overlap) with a Hanning windowing.

The estimated apparent masses for all subjects exhibited the same trends, i.e., the effect of the suspension was to shift the peak in the frequency response towards higher frequencies and to lower the amplitude of the resonance peak; this trend can also be observed in the mean apparent mass plot.

3.2. Narrow band random input

The testing procedure was improved to ensure that the acceleration at the seat pan was always the same whether or not the suspension was acting. In that way, as explained above, nonlinear effects of the human body would not interfere with the effect of the lower limbs on the transmission of vibration.

The first series of tests (cf. Fig. 5, curve (—)) was conducted according to the strict conditions of standard ISO 5982, i.e. with the suspension system blocked. Limited bandwidth random acceleration with an RMS value of 1.5 $\mathrm{m/s^2}$ was imposed on the testing platform (cf. Fig. 3, curve (—)). Curve ($\diamond$) in Fig. 5 represents the magnitude of the apparent mass measured with the same input acceleration, but with the suspension system acting. During this test, vertical acceleration was measured on the seat pan. Similarly, the time history of this acceleration was reproduced at the testing platform in the third series of tests (cf. Fig. 5, curve (- -)).

Apparent mass measuring conditions are therefore comparable for these latter two series of tests because the acceleration imposed on the subject's buttock is identical in both cases. Only the acceleration imposed on the feet changes.

The acceleration recorded during the first step of the testing procedure resulted from the coupled response of the seat and the seated subject. Then, unlike for the preliminary tests, it was not possible to input exactly the same acceleration signal for every subjects tested and it was meaningless to process mean responses. That is the reason why the results of the comparative study presented in this paper were obtained with only one subject.

For the three series of tests, the acceleration and force were acquired at 50 Hz max frequency (resolution of 0.125 Hz and sampling frequency of 125 Hz) during 1000 s. A total of 20 blocks were acquired sequentially (with no overlap) with a Hanning windowing.

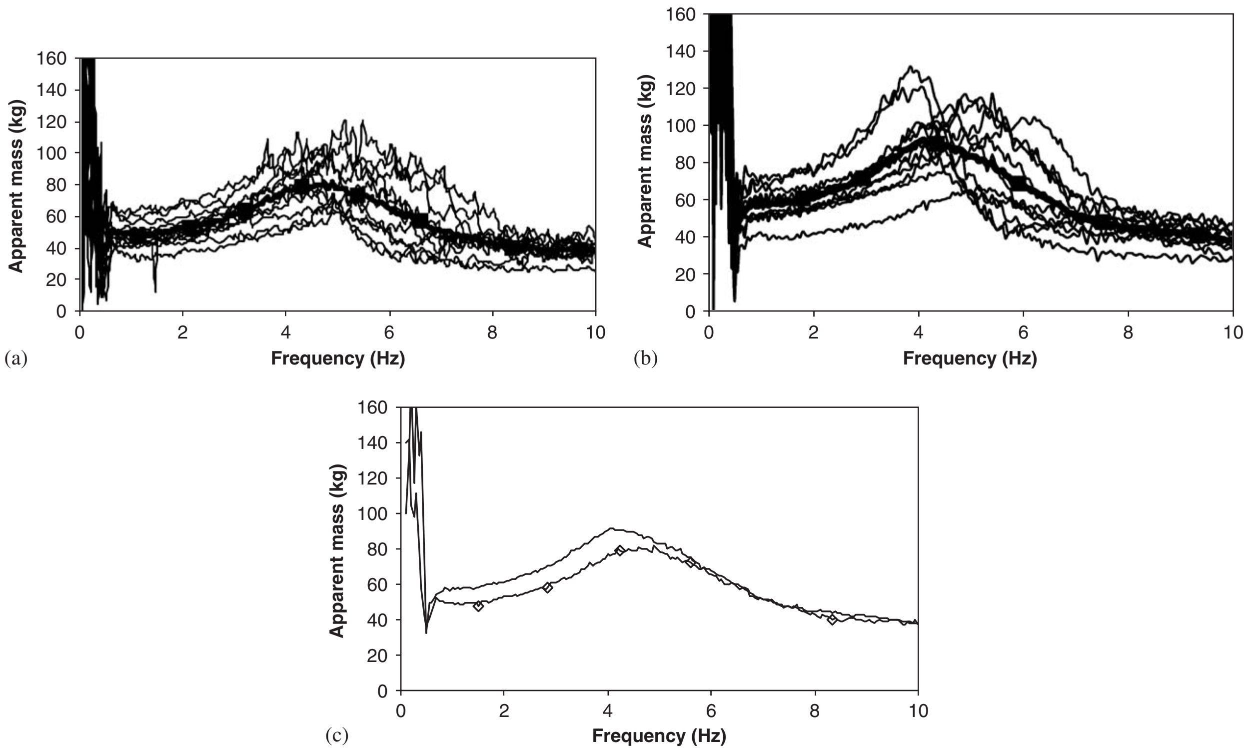

Fig. 4. Magnitude of apparent masses of 12 seated subjects measured with the suspension free (a) and with the suspension blocked (b) under limited bandwidth excitation. Mean values of magnitude of apparent masses (■) are reported for each configuration in (c). (◇) Suspension free; (—) suspension blocked.

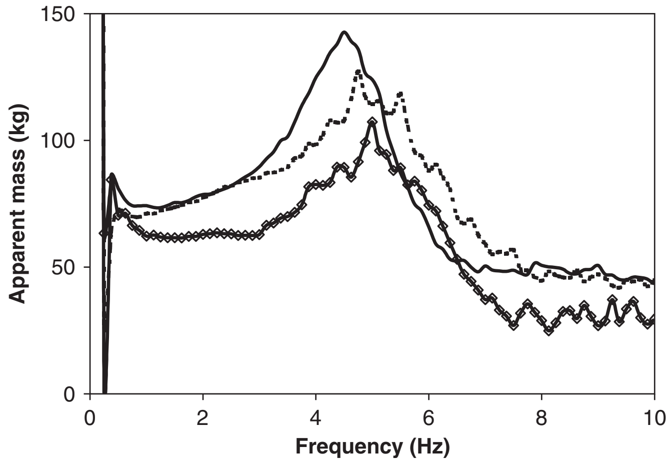

Fig. 5. Magnitude of apparent mass of seated man: (—) limited bandwidth excitation with suspension blocked, (◇) limited bandwidth excitation with suspension free, (- -) narrow band excitation with suspension blocked.

Fig. 6 shows the coherence function for each of these three series of tests. For each series, it should be noted that the coherence is close to 1 in the frequency band [0.5–5 Hz], which means that the signal/noise ratio is very low and that the transfer function is therefore correctly estimated.

The resonance frequency of the subject's apparent mass lies between 4 and 6 Hz. Comparing curves (-) and (- -), for which only the acceleration imposed on the testing platform differs, we observe the nonlinear behavior of the human body with respect to the amplitude of the excitation acceleration.

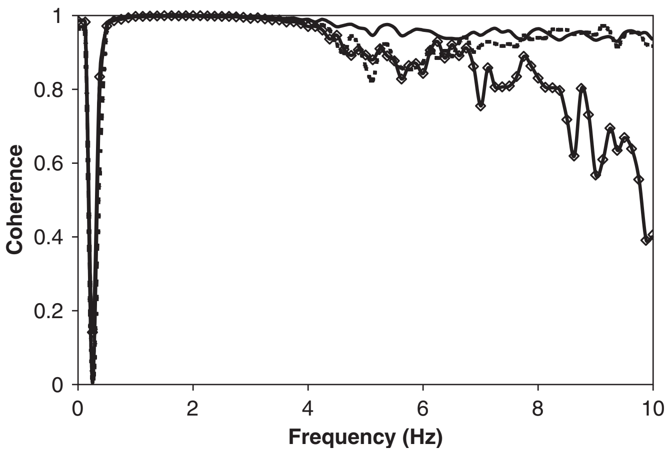

Fig. 6. Coherence function of apparent mass measurements: (—) limited bandwidth excitation with suspension blocked, (◇) limited bandwidth excitation with suspension free, (- -) narrow band excitation with suspension blocked.

Fairley's calculation-based results [10] are also confirmed: relative movement of the lower limbs effectively reduces the magnitude of the apparent mass of the whole body. This reduction is very significant at low frequencies and below the resonance frequency. This results in reducing the resonance peak value by approximately 15% (difference between curves (◇) and (- -) in Fig. 5. Fairley's calculations had led to a reduction of the order of 12%.

On the other hand, the movement of the lower limbs appears to have no significant effect on the whole body resonance frequency.

4. Analysis and modeling

The subject and suspension seat were modeled using multibody mechanical software to understand which exact physical mechanism can explain lower limb influence on vibration transmission through the whole body of the seated man.

4.1. Modeling of seated man

The seat was modeled as a one-degree-of-freedom system with mechanical characteristics previously derived from tests with an inert mass (cf. Section 2).

The subject seated on the seat with its suspension system blocked was identified by a one-degree-of-freedom system, whose mass, stiffness and damping parameters were fitted with apparent mass curve (- -) in Fig. 5. The single degree of freedom allows the subject's dynamic behavior to be simulated up to approximately 8 Hz. Beyond this frequency, it would be necessary to introduce other degrees of freedom to take into account other human body mode shape. In practice, three degrees of freedom are required to describe the behavior of the seated man in the [0–20 Hz] frequency band, the mechanical parameters for the study population being specified in standard ISO 5982 [6]. However, because vibration excitation signals specified in suspension seat testing codes all have a spectral content within the [1–8 Hz] frequency band, it was not considered helpful to complicate the model beyond a single degree of freedom (cf. Fig. 7). Under these conditions, it may be noted in Fig. 8 (cf. curves (▲) and (■)) a good agreement between calculation and measurement for this frequency range.

The suspension was subsequently released. The lower limbs were introduced into the model, whilst respecting joint simplified kinematics: hip, knee and ankle joints were modeled as pivot joints. Body masses in motion (bone and soft tissue) were modeled as homogenous rigid solids, whose mass properties were estimated and adjusted using their density parameters. Lengths between joints were respected (pelvis–knee distance 55 cm, knee–ankle distance 60 cm).

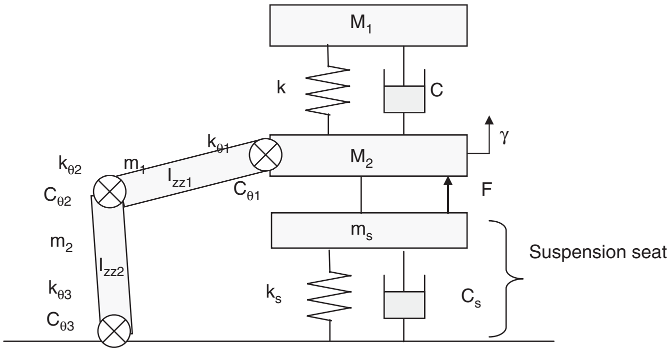

Fig. 7. Mechanical model of seated subject. Seat parameters : $m_s = 23\,\text{kg}$; $k_s = 9000\,\text{N/m}$; $C_s = 500\,\text{N/m/s}$. Upper body parameters: $M_1 = 40\,\text{kg}$; $M_2 = 12\,\text{kg}$; $k = 50000\,\text{N/m}$; $C = 700\,\text{N/m/s}$. Lower limb parameters: $m_1 = 25\,\text{kg}$; $I_{zz1} = 0.65\,\text{kg/m}^2$; $m_2 = 8\,\text{kg}$; $I_{zz2} = 0.25\,\text{kg/m}^2$; $k_{\theta 1} = 0\,\text{N/rad}$; $C_{\theta 1} = 15\,\text{N/rad/s}$; $k_{\theta 2} = 0\,\text{N/rad}$; $C_{\theta 2} = 0\,\text{N/rad/s}$; $k_{\theta 3} = 0\,\text{N/rad}$; $C_{\theta 3} = 0\,\text{N/rad/s}$.

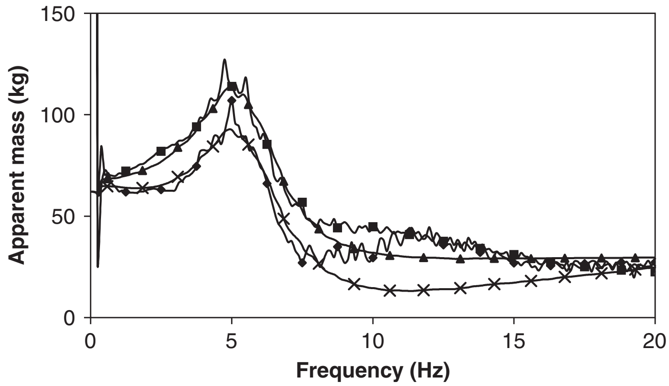

Fig. 8. Magnitude of apparent masses of the seated subject measured with the suspension free (♦) and with the suspension blocked (■). Same magnitude of apparent masses calculated with the fitted equivalent mechanical model suspension free (×) and suspension blocked (▲).

Lower limb masses were readjusted to obtain the static apparent masses measured in both test configurations (curves (◇) and (- -) in Fig. 5) and obviously identical. The readjustment process involved transferring part of mass M_2 to the lower limbs (m_1 and m_2), whilst maintaining the subject's overall mass balance ($M_1 + M_2 + m_1 + m_2 = 85\,\text{kg}$).

Knee and ankle joints were considered to offer negligible stiffness and damping.

Hip stiffness was neglected. On the other hand, damping was introduced to take into account possible internal damping in the hip joint or friction due to contact between the subject's buttock and the seat pan. The whole model of the suspension seat and seated subject is illustrated in Fig. 7.

In the blocked configuration, the single-degree-of-freedom model presented above could be derived from the articulated model of Fig. 7 just by blocking the joints between the three parts m_1, m_2 and M_2 and attributing to the resulting rigid part a mass of 25 kg.

Good agreement between the measured and the model-calculated magnitude of the apparent mass may be observed in the [1–8 Hz] frequency band (cf. Fig. 8 (♦) and (×)). The model does not allow seated subject behavior to be predicted beyond 8 Hz for the same reasons as those previously stated.

The calculations showed that the effect of distributing mass is not enough to explain the differences between the apparent masses measured with and without suspension system. Assuming zero damping at the hip joint, the inertial influence of the lower limb degrees of freedom in fact results in attenuating the resonance peak by only 7 kg (107 kg, not shown in Fig. 8, instead of 114 kg for the curve (▲) maximum value). The 22 kg discrepancy observed between the resonance peaks in the apparent mass curves with the suspension free and blocked (curves (▲) and (×) maximum values) therefore originates mainly from the a dissipative phenomenon rather than an inertial effect. The torsional damping coefficient $C_{\theta 1}$, introduced into the model, may be interpreted as simulating the friction phenomenon between the subject and the seat pan or internal damping in the joints. These two plausible phenomena occur when lower limb relative movement is allowed, i.e. when the suspension system is in action. Conversely, absence of relative movement implies zero dissipation.

5. Calculation of S.E.A.T. factors

The influence of considering lower limb mobility was subsequently evaluated by calculation: the value of the S.E.A.T. transmissibility coefficient was calculated for several excitation classes (IT1, IT2, IT3, IT4, cf. standard EN 13490 [2], EM3, cf. Standard ISO 7096 [1]).

Initially, calculations were performed based on the seat and subject models defined in Section 4.1 (cf. Fig. 7). The subject model was then modified to exclude taking into account lower limb mobility, i.e. by removing the two sub-parts (representing the anatomical sections of the legs) of weights m_1 and m_2 and the three degrees of freedom associated with the hip, knees and ankles, and by transferring to mass M_2, the equivalent of the static mass contribution of these sub-parts to the overall apparent mass. In this case the mass transfer amounts to 13 kg (i.e. $M_2 = 25$ kg). This model simulates effectively the dynamic behavior of the dummy designed from data acquired under standard ISO 5982 conditions [6].

Fig. 9 is the estimated suspension seat transfer functions (γ_s/γ_i) calculated when using these two types of models of the subject. We note that lower limb mobility has the effect of slightly attenuating seat resonance and reducing the slope of the transfer function beyond the cut-off frequency. The very slight differences in the range of the natural frequency of the seat (about 1.8 Hz) were attributed to the fact that, because of higher resonance frequencies, the seated subject models behaved there more as pure masses and then the mobility of the lower limbs was less involved.

Fig. 10 illustrates the seat responses to various vibration excitation classes. These classes are defined in standard EN 13490 [2] for industrial trucks or standard ISO 7096 [1] for earthmoving machinery and they each correspond to one type of mobile machine. They are excitation signals whose power spectral densities are specified with analytic formulations.

Suspension seat response was calculated using both subject models (taking into account lower limb mobility and considering lower limbs inert) for each excitation class studied.

All response curves are weighted according to filter w_k defined in standard ISO 2631-1, reflecting the health effect of vertical vibration. The main effect of filter w_k is to attenuate the response outside the [4–10 Hz] frequency band.

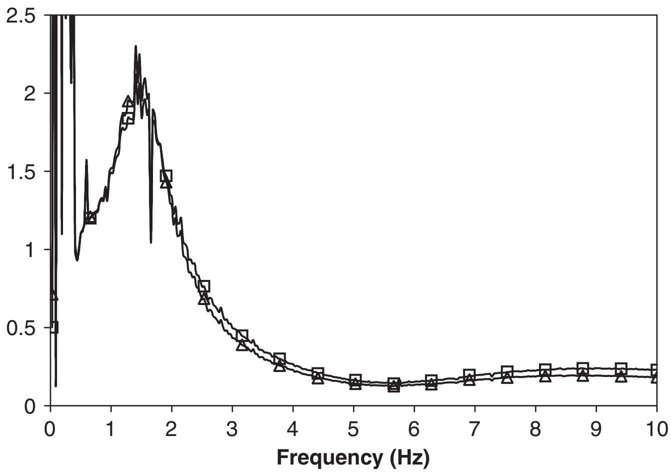

Fig. 9. Suspension seat transfer function calculated with the numerical model of seated subject: (△) lower limbs modeled as an inert mass, (□) lower limb mobility taken into account.

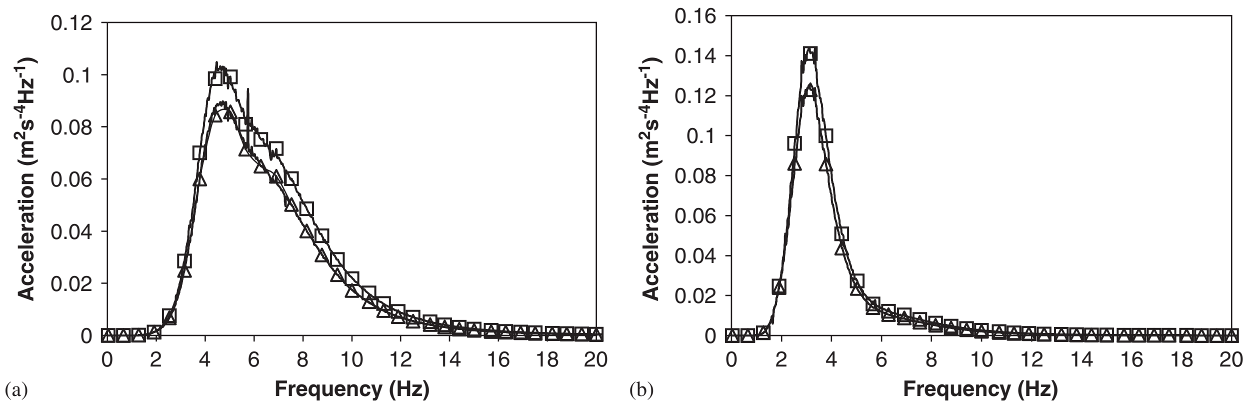

Fig. 10. Weighted response (weighting defined in standard ISO 2631-1 [11]). (w_k) of suspension seat for an excitation signal corresponding to IT1 (classes IT1 and IT2 defined in standard EN 13490 [2]) (a) and IT2 (b) vibration classes. (△) Lower limbs modeled as an inert mass, (□) lower limb mobility considered for response calculation.

Table 1

Vibration excitation class	S.E.A.T value Model with lower limbs considered inert	S.E.A.T value Model with lower limb mobility considered	Difference (%)
IT1	0.145	0.167	13.3
IT2	0.396	0.453	12.7
IT3	1.983	2.028	2.3
IT4	1.983	2.028	2.3
EM3	1.983	2.028	2.3

As a result, it may be noted that the double filtering due to w_k weighting and type of input amplifies effectively the differences between responses calculated using the two model subjects (cf. Fig. 10).

The value of the S.E.A.T. factor was then calculated from suspension seat frequency responses and excitation frequency spectra, for each excitation configuration and each subject model used. Results are consolidated in Table 1.

It can be observed that the suspension seat studied allows criteria to be satisfied only for classes IT1 and IT2. For other excitation classes corresponding to heavier machinery, the S.E.A.T. value is effectively greater than 1, which means that the seat amplifies the platform vertical acceleration.

For the two machinery categories in which the studied seat is efficient, a difference of around 13% with respect to the S.E.A.T. value was calculated, irrespective of whether lower limb mobility is considered or not. This value should be compared with results of interlaboratory tests performed by Riedel and Kinne [8]. Suspension seat tests conducted using their dummy, designed based on DIN 45676 impedance data [7] (i.e. neglecting the effect of lower limb relative movement as for ISO 5982), then using human subjects, have in fact revealed systematic differences of around 10%. Just as with the results shown in Table 1, the tests performed by Riedel and Kinne showed that consideration of lower limb mobility resulted in an increase in the suspension seat transmissibility factor.

6. Conclusion

The aim of this study was to highlight the role of the lower limbs in transmitting vertical vibration through the body of the seated man. The significance is to improve the level of accuracy of models describing the dynamic behavior of the seated man to design ultimately, equivalent mechanical systems (dummies) to be used to test suspension seat efficiency in the laboratory.

This study allowed the dynamic properties of the seated man to be measured in two types of configuration: with (seat suspension system in action) and without (suspension system blocked) relative movement of the lower limbs. Measured data enabled the setting up of a mechanical model of the subject, which takes into account movement of the lower limbs and their interaction with the rest of the body.

The model highlighted the role of dissipative effects (interpreted as friction between subject and seat or internal damping in the joints), which is dominant in relation to lower limb inertial effects.

The model also enabled the effect of considering the lower limbs as mobile on the design of bio-dynamic dummy to be predicted and the effect on suspension seat vibration response to be quantified. Calculations revealed a difference of around 13% in the transmissibility of the suspension seat studied, whether the lower limb mobility being considered or not. These results corroborate noted differences between suspension seat tests conducted with human subjects and dummies (results published by Riedel and Kinne [8]), knowing that the dummies concerned were designed based on subjective tests that did not involve lower limb movement.

In conclusion, this study provides scientific justification for the experimental differences referred to above. Two approaches are feasible in relation to defining performance criteria for the design of dummies simulating the dynamic behavior of the seated man. One approach would involve establishing new apparent mass and impedance target curves that can be substituted for standard ISO 5982-based data [6] and measured using populations of individuals under conditions allowing lower limb mobility. This is not really feasible because this type of experiment requires accurate definition and control of the flexible component (suspension system) mechanical characteristics to be introduced at the lower limbs. Neither is implementation of these tests easy because platform vibration excitation signals are themselves the result of suspension mechanical characteristics.

The other approach would involve adapting threshold values of suspension seat test criteria for use in biodynamic dummies. Knowing that a 10% systematic difference can effectively be observed between subject- and dummy-based test results and that this difference tends invariably towards an underestimate for dummy-based tests, weighting the transmissibility coefficients would be conceivable under these conditions.

In the case of the first approach and from the designer's standpoint, taking the lower limbs into account by adding an articulated system, such as that shown diagrammatically in Fig. 7, offers little interest: as previously stated, the inertial effect of introducing joint-connected masses has been shown to be negligible with respect to damping effect. Moreover, such a system does not allow a realistic damping value to be controlled in a simple way.

References

[1] International Standard ISO 7096, Earth-moving machinery—laboratory evaluation of operator seat vibration, 2002, 22pp.

[2] European Standard NF EN 13490 Mechanical Vibration, Industrial trucks—laboratory evaluation and specification of operator seat vibration, 22pp., publication date: 15 January 2002.

[3] Commission Directive 83/190/EEC 28 March 1983 adapting to technical progress Council Directive 78/764/EEC on the approximation of the laws of the Member States relating to the driver's seat on wheeled agricultural or forestry tractors. *Official J.* L 109, 26/04/1983, pp. 0013–0024.

[4] C.H. Lewis, *The Implementation of an Improved Anthropodynamic Dummy for Testing the Vibration Isolation of Vehicle Seats, Presented at the UK Group on Human Response to Vibration Held at the Health and Safety Executive*, Buxton, Derbyshire, England, 1998.

[5] B. Richter, S. Werdin, Summary of research project F1687, Bundes austalt für arbeitsschutz und arbeitmedizin, Design review and realization of a mechanical vibration model representing the sitting human, Federal Institute for Occupational Safety and Health, 1999.

[6] International Standard ISO 5982, Mechanical vibration and shock—range of idealized values to characterize seated-body biodynamic response under vertical vibration, 2001.

[7] Standard DIN 45676, Mechanical impedances at the driving point and transfer functions of the human body, publication date: June 2003.

[8] S. Riedel, J. Kinne, *Prüfung von schwingungsisolierten Fahrzeugsitzen mit mechanischen Mensch-Modellen—Laborversuche*, GfA-Press, Dortmund, 2002.

[9] H. Politis, S. Rakheja, P.E. Boileau, D. Juras, J. Boutin, Limits of application of human body dynamics in assessing vibration comfort of seats, *SAE 2003 Transactions Journal of Passenger Cars—Mechanical Systems, 2003, SAE Paper 2003-01-0953*, pp. 973–979.

[10] T.E. Fairley, *Predicting Seat Transmissibilities: The Effect of the Legs, Paper Presented at the Joint French– British Meeting on Human Response to Vibration*, INRS, Nancy, France, 1988.
[11] International Standard ISO 2631-1, Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements, 01-05-2001.