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Descriptive analysis of combine cabin vibrations and their effect on the human body

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Abstract

All on- and off-road vehicles are exposed to vibrations caused by unevenness of road or soil profile, moving elements within the machine or implements. A higher prevalence of low back pain is found in drivers of off-road machinery than in other drivers. In this study, significantly higher levels of low-frequency vibrations are found in the cabin of a combine, driving at high speed (20 km/h) on a concrete surface, compared to driving slower on field road. Comfort values indicate that injury can result from long-term driving on the field as well as on a concrete road. As seats with suspension systems are the main transmission paths of vibration towards the spine of the driver, their vibration attenuating characteristics play an important role in comfort assessment. The resonant frequency of seats with passive suspension system, used in agricultural machinery, lies in the low-frequency range most excited in agricultural machinery. A seat with air suspension is found to attenuate better frequencies above 4 Hz and provide more comfort to the driver than a seat with a mechanical suspension.

1. Introduction

All on- and off-road vehicles are exposed to vibrations caused by unevenness of road or soil profile, moving elements within the machine or implements. Increased vehicle speed and capacity, induced by higher labour costs, create a lot of vibration problems, reducing the vehicle lifetime, working precision and driver's comfort [1]. This trend is also noticeable for mobile agricultural machinery. The environmental forces on an agricultural machinery operator have been the subject of extensive research in the past. The important issues related to the tractor driver, useful to farm

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and industrial machinery designers, are: noise, humidity, temperature, clean air and vibration levels. Inadequate design objectives in any of these factors can cause serious deterioration in the operator's ability to perform efficiently. Permanent physiological damages are possible after prolonged exposure of the operator to inappropriate conditions.

There are many factors influencing the transmission of vibration to and through the body. Being a dynamic system, the transmission associated with it will depend on the frequency and direction of the input motion. Transmissibility of vibration will differ between individuals. The transmissibility will also depend on the characteristics of the seat from which the vibration exposure is received. Vibration within the frequency range up to 12 Hz affects the whole human organism, while the vibrations above 12 Hz have only a local effect. Vibration attenuating seats and correct ergonomic layout of vehicle interior may reduce the risk of recurrence [2].

Agricultural machinery workers report performance problems usually associated with back pain and sitting discomfort [3]. Low-frequency (2–20 Hz) cyclic motions like those caused by a vehicle's tyres hitting the road can put the body into resonance. During normal working conditions in a field, high low-frequency vibration levels between 0.5 and 10 Hz are transmitted to the seat [4,5] and affect the health of the conductor. Especially, the backbone is sensitive in this frequency range for severe physical damage in the long-term [6–8]. Just one hour of seated vibration exposure can cause muscle fatigue, weaken the soft tissues and make a worker more susceptible to back injury. Occupations that involve driving transportation vehicles are present more frequently in patients with low back pain than in a reference group without back pain [9–11]. The prevalence of reported back pain is approximately 10% higher in tractor drivers than in workers not exposed to vibration.

The vibration that people are exposed to while sitting and driving is rarely linked to the cause of discomfort or pain since vibration weakens the spine through "cumulative trauma" which is very difficult to assess.

2. Goal and set-up

The purpose of this study is to analyze the imposed vibrations to the cabin in different driving situations. Whole-body comfort parameters are calculated. As seats are the main transmission paths of vibration from the cabin floor to the driver and as most seats of agricultural machinery are equipped with a suspension system, seat vibration attenuation tests on an electro-hydraulic vibration platform are carried out and comfort comparison is performed.

2.1. Field test

Under road and field conditions, acceleration data are received from a new type of combine. The accelerometers are attached on the supporting structure of the cabin for three translational degrees of freedom (d.o.f.) (fore and aft, lateral and vertical). Measurements are taken for different values of the following variables: machine speed, operational condition of the combine (fully operational or only the engine working) and profile of the driven surface. Two specific situations occur: (1) Fully operational combine, driving at speed 4, 6 and 8 km/h on a field as the agricultural worker tend to do when operating in the field; (2) A not fully operational combine (only the engine on), driving with speed 10 and 20 km/h on a concrete road as the agricultural worker tend to do when coming and going to the field. Every time 5 min of vibration data are recorded. The goal is to analyze the frequency content of the vibration signals in three translation directions for the two situations. A comfort interpretation is done.

2.2. *Seat tests on the vibration platform*

Performance tests are carried out on a seat with a mechanical suspension and a seat with an air suspension. Both seats are commonly used in combines. As most comfort and health damaging frequencies are situated between 0.5 and 12 Hz, as input signal a sweptsine going linearly from 0.5 to 15 Hz was imposed to the seats using an electro-hydraulic vibration platform. The input signal was obtained after several test runs concerning period length and amplitude in function of frequency, in order to have the best system performance. The result is a signal with an approximate constant acceleration level of $0.5g$. One period of the input signal contains 8192 points as an integer number of points diminishes leakage when using a Fourier transform. Accelerations were recorded (1) on the platform; (2) on the seat (mounted on the platform) above the suspension but under the seat cushion and (3) on the seat cushion: the purpose is to investigate vibration transmission from the vibration source to the point of entering the body. The measurement of vibration at a body–seat interface requires that transducers are located between body and seat. The accelerometers must move with the interface, they must not alter the dynamic properties of either the seat or the body and they must offer little impedance to movement over the frequency range of interest. For this reason, a SIT-BAR is used (seat interface for transducers indicating body acceleration received). It is a contoured rigid device that compresses the seat in a similar way, as do human buttocks [12]. As only the vertical direction is excited, only vertical accelerations are measured. Both human subjects and a dummy were used and compared in the tests, as it is not known if a dummy is a good replacement. Both were placed with straight back and the hands placed on the upper legs. The human subject did not perform any kind of activity. The sampling frequency was 200 Hz, the anti-aliasing filter used had a cut-off frequency of 40 Hz and the analogue amplification was 5. More than 5 periods (one period takes 40.96 s) were recorded to increase the reliability of the vibration transmissibility.

The goal is to investigate the efficiency of the two seats in attenuating comfort decreasing vibration frequencies. The additional vibration diminishing effect of the seat cushion is visualized and differences between dummy (75 kg) and human (80 kg) as sitting object are discussed. As it is the purpose only, to have a first impression of the performance of the used combine seats, taking the tests with one subject is found adequate.

3. Data processing

3.1. *Field measurements*

To compare the different situations in great detail, power spectral densities (PSD) are calculated from the cabin acceleration data to describe the energy distribution over the frequency band of interest (0–25 Hz).

The best methodology for comfort evaluation, giving a single number value, is looked up. A single number estimate of vibration severity requires that the motion be weighted according to the relative importance of different physical variables: magnitude, frequency and duration. Using filters $W_i(f)$ for all three translational d.o.f. as proposed in the British Standard BS 6841 (equivalent to the ISO 2631 filter vertical vibration filter) for whole-body vibration evaluation [13], all frequencies from the cabin acceleration data with lower contribution to the discomfort feeling are lowered in value, where frequencies with high contribution are raised in value. The former are mainly the frequencies under 2 Hz and above 10 Hz (Fig. 1). This frequency weighted data is converted into a comfort value using root mean square (r.m.s.) and vibration dose value (VDV) (Eqs. (1) and (2)). The weighting for duration has received less consideration than frequency weighting. There are two methods for duration weighing. One is the time dependency according to the ISO 2631 [14]. This is a very complex procedure and it is not appropriate for signals containing shocks:

$$\text{r.m.s.} = \left[\frac{1}{N}\sum x^2(i)\right]^{1/2}. \tag{1}$$

The other method is using the vibration dose value (VDV). The VDV calculation performs the duration weightings as it is accumulated and so automatically incorporates a method of giving greater weight to occasional peaks (shocks) in the motion. As large off-road machinery produces large amounts of shocks (crest-factor greater than 6) and as time dependency is incorporated in the *VDV* it is found to be the best comfort value to use. The VDV is defined by Eq. (2) with the measured time period T_s, the number of points in one time period N and the frequency weighted vibration data $x(i)$:

$$\text{VDV} = \left[\frac{T_s}{N}\sum x^4(i)\right]^{1/4}. \tag{2}$$

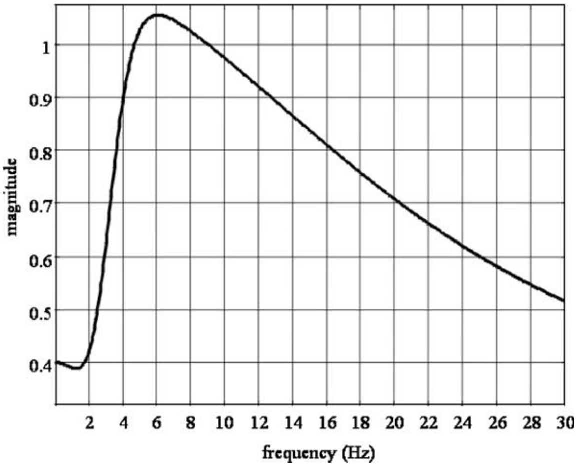

Fig. 1. Close up magnitude bode plot versus frequency of the BS 8641 frequency weighting filter (weighting W_b, digital filter with linear phase shift) used when considering the effect of vertical d.o.f. vibrations on comfort and health.

Normally, the accelerations used for the calculation of VDV values are taken at the seat with a SIT-BAR. As different seats are in use, the choice is made to use the vibrations as transmitted to the driver's feet. Consequently, the calculated VDV will be an overestimation but will be more general information, independently of the seat type. The overall (VDV) comfort value is calculated using Eq. (2) with the VDV values of the three d.o.f. replacing x and without T_s and N.

3.2. Seat tests on the vibration platform

Power spectra are calculated for the two sets of data acquired on the electro-hydraulic vibration platform. Also worked out is the transfer function $H(\mathrm{j}\omega)$ for single-input systems using the non-parametric equation:

$$H(\mathrm{j}\omega) = \frac{S_{xy}(\mathrm{j}\omega)}{S_{xx}(\omega)} \tag{3}$$

with $S_{xy}(\mathrm{j}\omega)$ the cross-spectral density with x the input and y the output vibration acceleration.

To assist the interpretation of the transfer function the coherence function $\gamma(\mathrm{j}\omega)$ is used (Eq. (4)) [15]. With ideal linear systems and no noise, the coherence function will have its maximum value of unity at all frequencies. Common possible causes of lower coherence values are that the output motion is not linearly related to the input, the presence of noise, or the rapid change in the magnitude of the input and output spectrum with frequency:

$$\gamma(\mathrm{j}\omega) = \frac{\mathrm{abs}(S_{xy}(\mathrm{j}\omega))}{S_{xx}(\omega)}. \tag{4}$$

But the transfer function depends only on the vibration spectra. It is solely an estimate of the physical response of the seat–person combination. Therefore, the seat effective amplitude transmissibility (SEAT) value by the following equation is introduced:

$$\mathrm{SEAT}\,\% = \left[\frac{\int S_{yy}(\omega) W_i^2(\omega)\,\mathrm{d}\omega}{\int S_{xx}(\omega) W_i^2(\omega)\,\mathrm{d}\omega}\right]^{1/2} \times 100, \tag{5}$$

where $S_{yy}(\omega)$ and $S_{xx}(\omega)$ are the seat and floor acceleration PSDs and $W_i(f)$ is the frequency weighing for the human response to vibration which is of interest as mentioned before.

A SEAT index of 100% indicates that, although the seat may have amplified the low frequencies and attenuated the high frequencies, there is no overall improvement or degradation in vibration discomfort produced by the seat. The degree to which the SEAT value is less than 100% indicates the amount of useful isolation provided by the seat. It must be commented that the input signals from the vibration platform are not representative for the amplitude function of frequency as experienced in the field or road.

4. Results

4.1. Combine cabin vibration characteristics

Great differences can be seen between the two situations of driving slow, with the combine fully operational on the field and driving fast on the concrete road with only the engine working. In

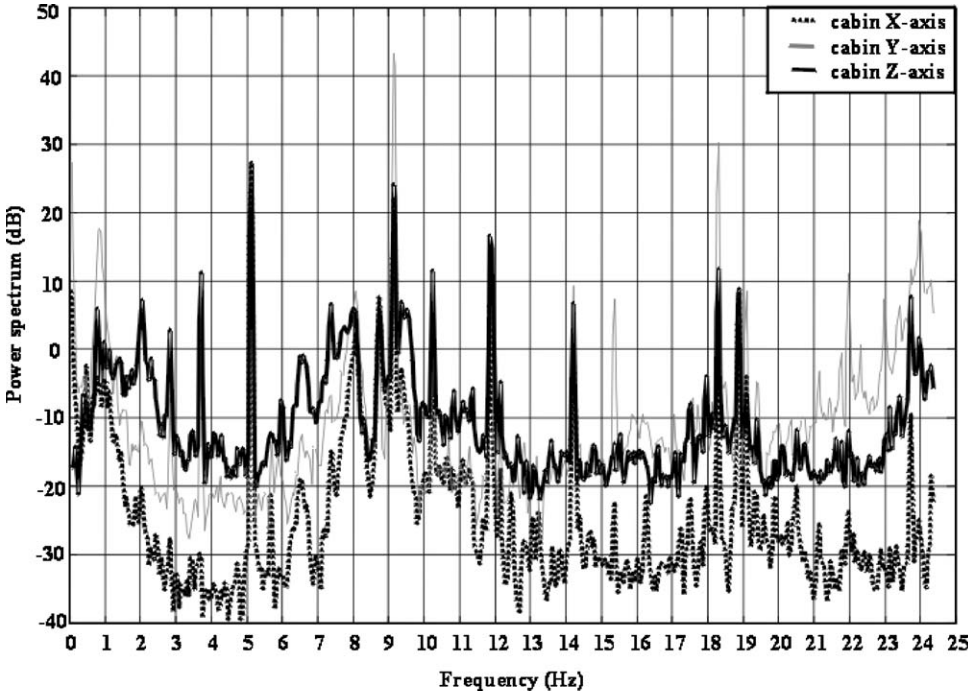

Fig. 2. Power spectrum of a 5-min drive on the field, with the combine fully operational, at 8 km/h for three translational d.o.f.

Fig. 2, the power spectra of the three translational d.o.f. (vertical, fore and aft and lateral) for driving in the field are shown for the frequency range 0–25 Hz. The unit in the y-axis is 20 log 10 (W/Hz), which means that the value of 0 in the power spectrum stands for 1 W/Hz. The different working sections of the fully operational combine produce most of the clear and high magnitude peaks seen. For example the trashing mechanism is responsible for the 5 Hz peak, the elevator for the 14 Hz peak and the cutterbar for the 18 Hz peak. Lower peaks than 5 Hz are present but seem not as harmful.

The 5 Hz peak is situated in the resonant range of the low back. The possibility of fatigue development in the low back after exposure during long working hours is real [7]. A totally different spectrum can be seen when the combine is driven with high-speed on a concrete surface. Fig. 3 shows very high energy levels in the frequency range 1.5–3.5 Hz and with values above 30 dB (approximately 31.5 W/Hz); this may give serious problems in driving ability and comfort failure. A passenger car is the most used vehicle for transportation. Comparing the vibration data of an off-road machine and a car gives a better idea of the relative weight of certain frequencies. Therefore, in Fig. 4 the power spectra from vertical acceleration data of a 5 min drive are presented for a mono-volume car driven on a paved road with bad profile and for the studied combine driven at 8 and 20 km/h.

In both vehicles, the same instrumentation was used and measurements were performed on the same place on the floor of the vehicle near the feet of the driver. The comparison makes clear the increased load to the driver caused by the 2–3 Hz amplification for the combine at 20 km/h.

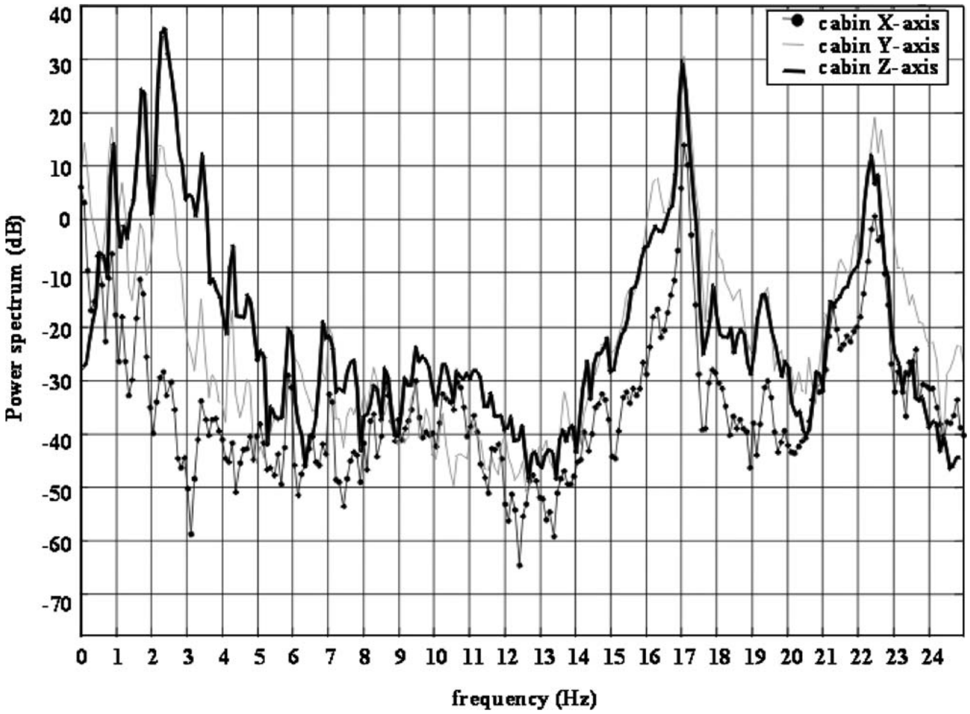

Fig. 3. Power spectrum of a 5-min drive on the road at 20 km/h with the combine not fully operational for three translational d.o.f.

The magnitudes at the frequency range 2–14 Hz when driving at 8 km/h with the combine are significantly higher than for the car.

As the VDV is calculated for all situations, the impact of the vibration frequencies together with the time effect and the influence of large shocks on comfort and health can be evaluated and compared among road and speed differences (Table 1). The British Standard BS 6841 states that: there is currently no consensus of opinion on the precise relation between VDV and the risk of injury. It is known that vibration magnitude and duration which produce VDV in the region of 15 $\mathrm{m/s^{1.75}}$ will usually cause severe discomfort and above which it is reasonable to believe that increased exposure to vibration will be accompanied by increased risk of injury [9]. Assuming this statement, driving in the field and on the road does not produce severe discomfort by vibrations in the lateral and vertical direction in the time that measurements are performed. Comparing the comfort values is difficult, as the measuring time is different for every test.

Knowing the sampling time and its corresponding VDV value it is possible to calculate the driving time needed to reach 15 $\mathrm{m/s^{1.75}}$ with the following equation:

$$time.to.15\ \mathrm{m/s^{1.75}, s} = \frac{15^4 \times (measurement.time, \mathrm{s})}{(measured.VDV, \mathrm{m/s^{1.75}})^4}. \tag{6}$$

The resulting figures show that the speed in the field influences comfort as felt in the vertical direction. Higher speed results in fewer hours needed to experience severe discomfort. When driving on the road the same conclusion can be drawn. But as driving at 10 km/h will only harm

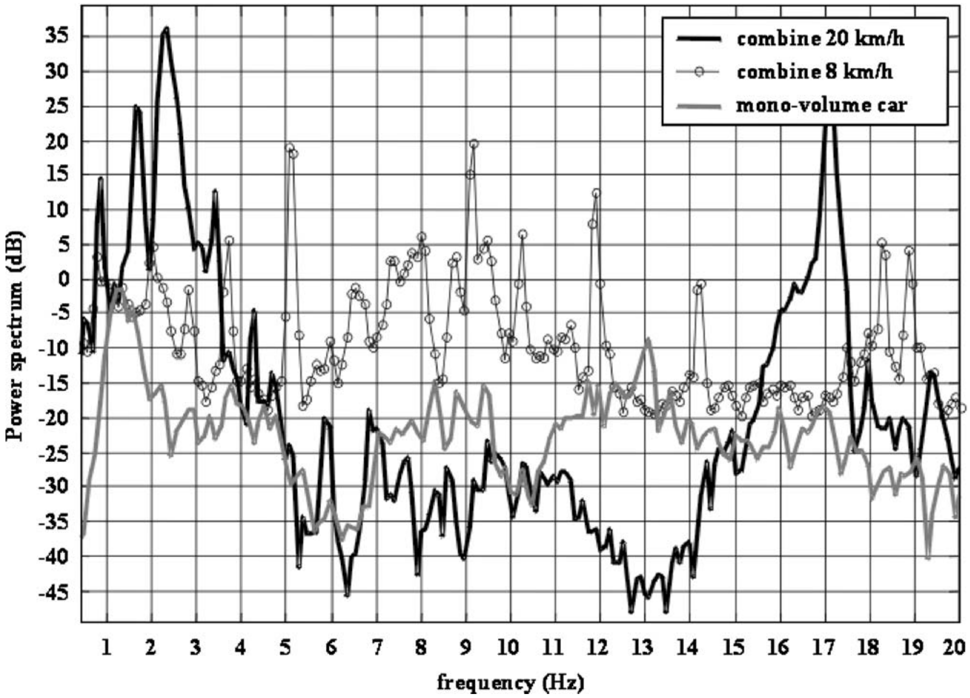

Fig. 4. Power spectra of vertical acceleration data for a 5-min drive in a mono-volume car on a paved road at 50 km/h and a 5-min drive in the combine at 8 km/h in the field and 20 km/h on the road.

Table 1
Vibration dose value and the time to reach 15 m.s$^{1.75}$, a value known to cause severe discomfort, is presented in function of speed and operational condition of the combine for two translational d.o.f.

Speed (km/h)	Fully operational	Sample duration (s)	True VDV Y-axis (m/s$^{1.75}$)	True VDV Z-axis (m/s$^{1.75}$)	Time to 15 m/s$^{1.75}$ Y-axis (h)	Time to 15 m/s$^{1.75}$ Z-axis (h)
4	Yes	164	1.10	4.40	> 24	6.11
6	Yes	205	1.36	4.86	> 24	5.16
8	Yes	205	1.69	4.99	> 24	4.65
8	Yes	205	2.03	4.99	> 24	4.77
10	No	246	2.00	4.50	> 24	8.41
20	No	41	1.06	4.27	> 24	1.74

after a working day, at 20 km/h less than 2 hours are needed. More than 24 hours are needed in any situation for the lateral direction to cause severe discomfort. Combines normally drive up to 25 km/h on normal roads. These values, therefore, show that severe levels of discomfort can be reached easily when driving in off-road machinery. As a comparison, for a passenger car, in all d.o.f., more than 24 hours are needed to reach the 15 m/s$^{1.75}$ [9].

4.2. Combine seat vibration characteristics

Improved knowledge of cabin vibrations transmitted to seat and driver, makes better interpretation of the combine seats performance possible.

A first comparison between human and dummy, seated on the mechanical-suspended seat, is performed. For both human and dummy, the resonant frequency of the suspension system is situated around 2–3 Hz, but overall differences are great although they may be partly explained by the difference in weight (Fig. 5). At 7.5 Hz, a second resonant peak is visible for the seat with the dummy where the seat with the person on top still attenuates the vibrations. The conclusion can be made that for human vibration behaviour simulation a normal crash-dummy is not adequate. In the seat comparison tests the dummy is not used.

In Fig. 6, the spectra of the vertical acceleration at the cushion–person interface for both mechanical and air-suspended seat and the spectrum of the input excitation are presented. Both seats have the same behaviour towards the imposed sweptsine under 4 Hz with the resonant frequency around 2 Hz. The spectra of the combine cabin accelerations in Fig. 3 showed the production of significant energy levels at the low-frequency range 1.5–3.5 Hz, responsible for high discomfort when driving at high speed on a concrete surface.

In this situation both seats will behave, in terms of comfort, insufficiently, as their resonant frequency will be excited frequently. From 4 Hz onwards, the attenuation of the air-suspended

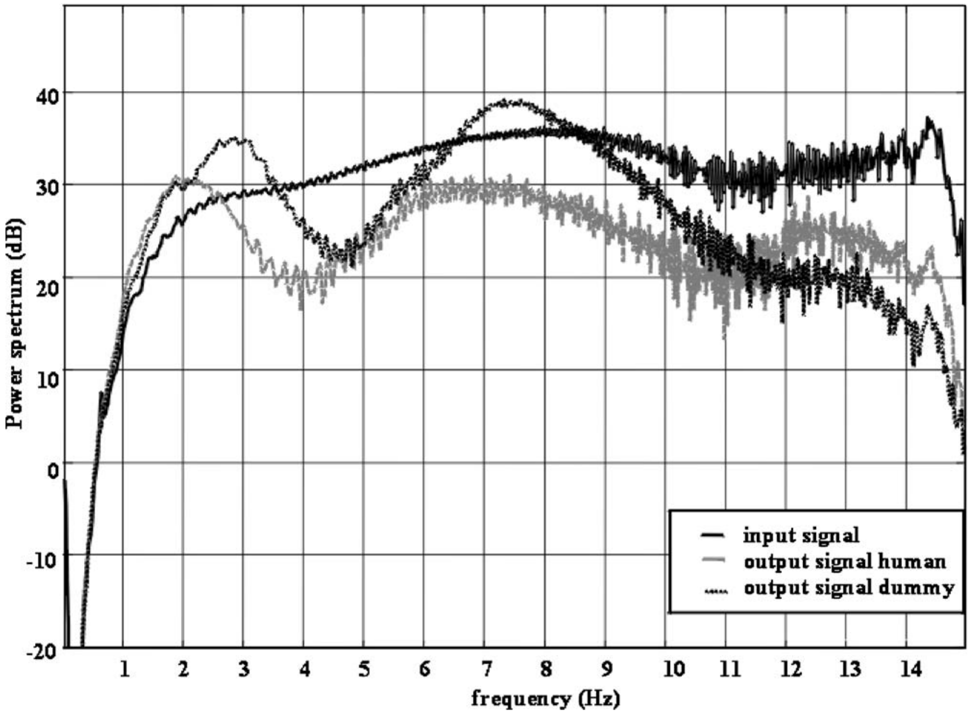

Fig. 5. Power spectrum of the input sweptsine (0.5–15 Hz) and of the vertical accelerations at the cushion–person interface (SIT-BAR) for human and dummy as sitting object.

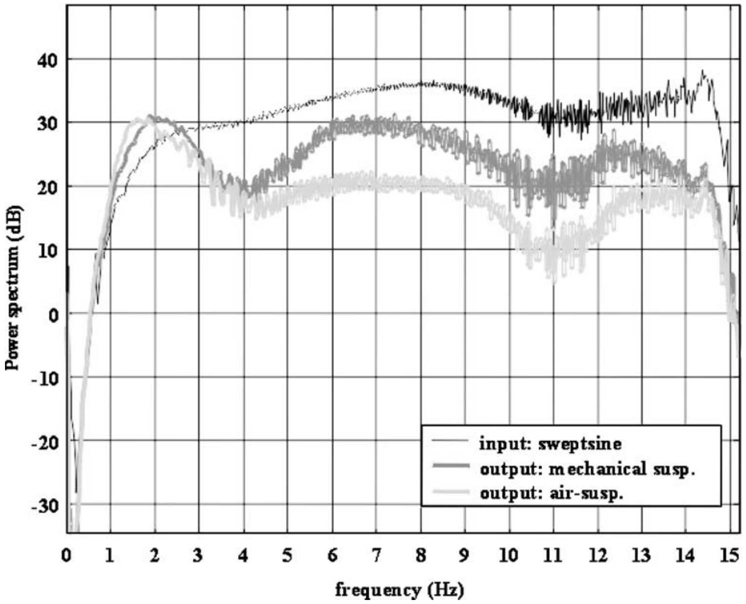

Fig. 6. Power spectrum of the input sweptsine (0.5–15 Hz) and of the vertical acceleration at the cushion–person interface for the mechanical- and air-suspended seat.

seat is significantly higher than the mechanical-suspended seat. The former will in field driving provide much more comfort than the latter. The coherence function for both seats indicates good reliability of the transfer functions, as values under 0.9 were not reached for the whole frequency range.

The transfer function given for both suspension types shows again that from 4 Hz onwards the air-suspension has greater attenuation performance. The transmissibility of vibration at the 2 Hz resonant frequency is however more pronounced for the air-suspension (Fig. 7). The SEAT values give a better idea of the comfort improving capabilities of both seats. For the same subject the SEAT value was **77.5** and **63** for, respectively, the mechanical- and air-suspended seat. A second subject showed a value of **61** when seated in the air-suspended seat. It proves that the air-suspended seat provides more comfort to the sitting person.

To have an idea of the attenuation contribution of the cushion the transfer functions of accelerations, taken at the cushion–person interface (SIT-BAR) and taken under the cushion but above the suspension system with input the sweptsine for the mechanical-suspended seat, are plotted (Fig. 8). At frequencies lower than 7 Hz, the energy passing through is higher on the SIT-BAR, but at frequencies higher than 7 Hz is lower. So the seat-cushion of this mechanical seat combined with the human dynamics attenuates vibrations above 7 Hz but amplifies under 7 Hz.

For the air-suspended seat where attenuation starts only from 9 Hz, no major improvement can be seen. At frequencies underneath 9 Hz, higher transmissibility is observed. The reason is mainly that the cushion of the air-suspended seat is not as thick as the cushion of the mechanical-suspended seat.

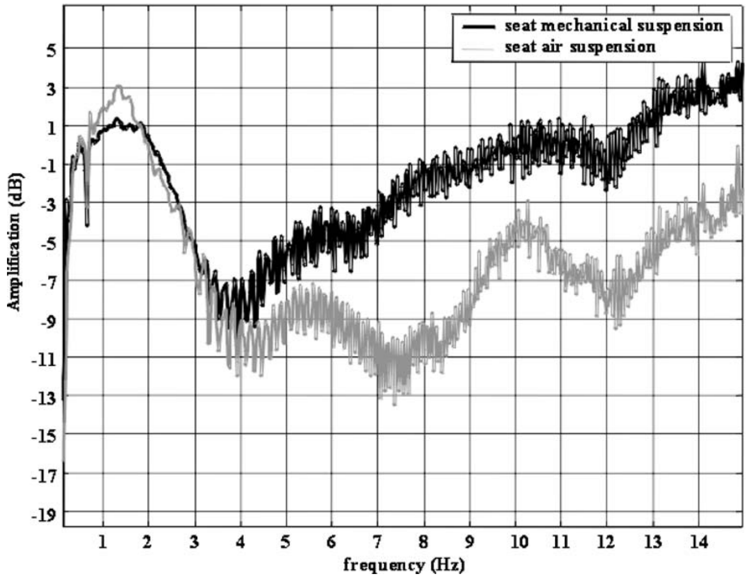

Fig. 7. Transfer function calculated of input sweptsine and output vertical accelerations on seat–person interface (SIT-BAR) for air-suspended and mechanical seat.

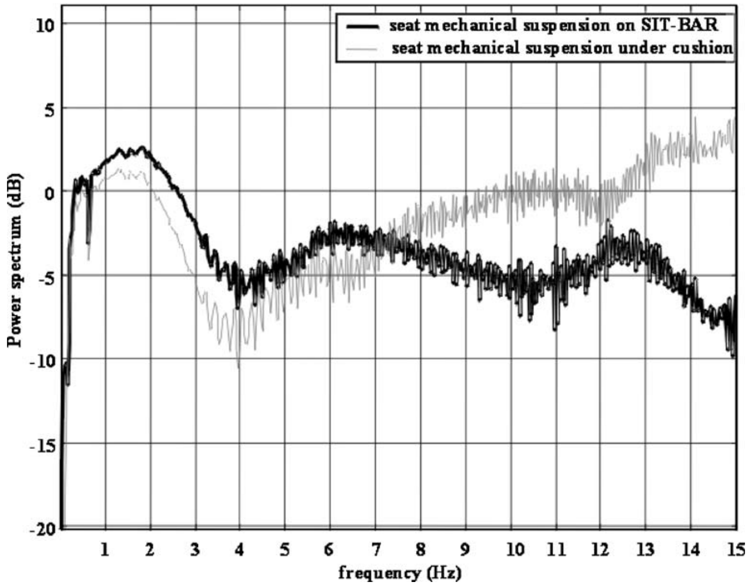

Fig. 8. Power spectra calculated of input sweptsine and output vertical accelerations on seat–person interface and under the cushion for the mechanical-suspended seat.

5. Conclusions

There are great differences in vibration characteristics transmitted to the cabin of a combine as function of vehicle speed, driven surface and whether the combine is fully operational or not. At low speed, with the machine fully operational, vibration levels are in the first place generated by the different machine sections (cleaning, separation…). When driving at high speed (20 km/h), significant energy is transmitted to the combine cabin in the frequency range from 1.5 to 3.5 Hz. The vibration dose values from the vertical vibrations show that risk for injury in long-term driving exists in general and serious risk for injury in driving at high speed on the road (transport to and from the field). From lateral vibrations, no discomfort is felt in long-term driving indicated by the comfort values.

The study and comparison of two commonly used combine seats with suspension system show the main resonant frequency around 2 Hz for both mechanical- and air-suspended seat.

The air-suspended seat provides more vibration attenuation at frequencies above 4 Hz, and more comfort as indicated by the SEAT values. Above the frequency range 7–9 Hz, the seat cushions provide extra vibration attenuation.

Low-frequency vibration is much more present in heavy off-road machinery than in other transportation means and the resonant frequency of nowadays-used seats with passive suspension system lies in the low-frequency area. In future, low-frequency vibration (0.5–5 Hz) need to be given more weight in seat or cabin suspension design and comfort assessment.

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