Identification and Evaluation of Perceptual Attributes for Periodic Whole-Body and Hand-Arm Vibration

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Abstract. When a systematic tactile design of a product is to be conducted, it is necessary to understand important perceptual properties of vibration from a user perspective. In everyday life humans are exposed to whole-body and hand-arm vibration, e.g. when driving a vehicle. Vibration of the steering wheel and seat is transmitted to the driver and conveys information about the condition of the road and vehicle. Depending on the spectral and temporal properties of the vibration signal certain attributes are elicited in the driver, e.g., "bumpy". Such verbalisea-ble attributes describe the vibration from a perceptual perspective. In this study periodic whole-body and hand-arm vibration were presented to test subjects. The most common tactile attributes were collected using a free interview. Afterwards, these attributes were rated for their suitability to characterize the signal patterns. The results show a systematic relationship between physical parameters (level, carrier frequency and modulation frequency) and this suitability.

Keywords: tactile perception · whole-body vibration · hand-arm vibration

1 Introduction

When designing a product, it is necessary to understand the relationship between the produced vibration and the tactilely perceivable properties from a user perspective. Therefore, such properties need to be quantified. A quantification by experts often leads to different results compared to the targeted product user because their knowledge, expectations tastes might differ. In order for the properties to be rateable by average product users i.e. laymen, they need to be comprehensible without a technical background or vibroacoustics knowledge.

In everyday life humans are exposed to whole-body vibration (WBV) and hand-arm vibration (HAV), as e.g. occurring in vehicles. Vibration on the seat is introduced into the driver of a car and conveys information about the condition of the road or about the properties of the car. One possibility to convey tactile information is spatial coding. [11] and [16] demonstrated that directional information for driving assistance systems can be communicated by exciting different locations with an actuator matrix. However only one sinusoidal signal with a frequency was utilized. Another possibility would be

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to utilize temporal and spectral properties of vibration to convey tactile information. Depending on these properties of vibration certain perceptual attributes would be elicited in the driver which he is able to verbalize in laymen’s terms, e.g. "bumpy", "rattling". Thus, such signal describing perceptual attributes might be beneficial since laymen are familiar with them from their everyday experience. Therefore this work investigates the potential of temporal spectral properties of vibration to convey information without prior training. A systematic approach to assess important tactilely perceivable temporal and spectral properties doesn't exist yet. Therefore, this study’s aim is to find important signal describing perceptual attributes to enable the analysis of relevant tactilely perceivable properties and the synthesis i.e. the design of a vibration signal with certain desired perceptual properties. Such perceptual attributes would make an effective communication about the perception of vibration possible.

Assessing the perception of temporal and spectral properties of vibration has mostly focussed on psychophysics e.g. perceptual threshold or differential threshold. An overview was presented by [8] which was extended by [7] and [13]. Traditional signal-based descriptors as signal root mean square or centre frequency as well as psychophysical attributes as perceived vibration intensity have been used to characterize vibration. They fail to capture the variance of naturally occurring vibration in a way which can be used by layman to describe their expectations. Perceptual attributes of vibration have become a topic of interest only recently [1, 4, 10]. However, each of these studies considered only a fraction of the tactile perceivable frequency and level range. To unify all the findings of the previous studies, this study tried to find important signals describing perceptual attributes which are suitable for describing the whole perceivable frequency and level range of WBV. By comparing perceptual attributes of WBV to perceptual attributes of HAV the influence of the location of the introduction on the elicited perceptual attributes was to be evaluated.

A common set of such perceptual attributes can form the basis for the systematic assessment of tactilely perceivable properties on whole-body and HAV occurring in everyday life. One area in which perceptual properties can be important is product design [1, 5]. The perceived quality of a product is mainly influenced by the user’s expectations on its perceivable properties. When designing a product, e.g., driving assistance systems, it is beneficial to know its relevant perceptual attributes. If the relevant tactilely perceivable properties are known, perceptual studies can be conducted more effectively. The relationship between vibration and elicited perceptual properties can form the basis for models. Such models might be utilized to predict more complex perceptual properties as quality, comfort or sportiveness. They would also enable the creation of tactile feedback which elicits the desired perceptual attributes in order to convey the necessary information, e.g., about the vehicle’s state. These models might also be utilized in the context of virtual reality applications. The goal of any VR is to achieve the most plausible representation possible in order for the users to react to and to interact with the presented environment as they would in their every-day lives. The plausibility illusion refers to the content of the presented scene and is elicited in the user if the presented scene matches his expectations [20]. It is known, that vibration should be presented in the low as well as in the high frequency range to produce a feeling of presence and avoid unnaturalness [9]. In the auditory domain the work of Foley Artists illustrates the fact that reproducing reality is not enough for meeting user expectations, e.g. spaceships emitting a sound in vacuum. If vibration would be designed to elicit the expected perceptual properties they should be perceived as most plausible.

2 Determining Important Perceptual Attributes of Vibration

2.1 Experimental Design

Building on two studies by Altinsoy [1, 3], the first goal was to extend the found perceptual attributes to the whole perceivable range of WBV. Periodic vibration which is among the most frequently encountered vibration in everyday life were chosen as a starting point for the focus of this study. In order to find all relevant perceptual attributes a free interview was to be conducted for all stimuli. Test participants were instructed to name all descriptors which characterize the presented vibration. In order to find attributes with a direct and clear relationship to the physical domain, test subjects were also instructed to avoid association which are too specific (e.g. "cobble stone road") or too general ("vibration"), affective terms ("annoying") and terms relating mainly on other modalities. All stimuli were presented in random order. In order to facilitate the difficult free elicitation task, participants were not limited by their aptitude to come up with associations. A printout with the list of attributes which were commonly used in [1, 3] was given to the test subjects. Thus participants could name new attributes as well as previously identified attributes.

2.2 Stimuli

Physical excitation processes which occur in everyday life cause certain vibration. Complex vibration could be interpreted as a superimposition of basic signals. Periodic movements can cause sinusoidal vibration, broad band structural excitation can cause noise signals and collision can cause impulse like signals. Due to the limited frequency selectivity of tactile receptors (just noticeable difference in frequency (JNDF) is about 30% [7, 14]) and masking effects [19] more complex temporal spectral vibration are likely difficult to resolve. Therefore, such basic vibration signals would likely elicit the same perceptual attributes as more complex vibration possibly with a slightly lower perceived suitability. The generalization of complex vibration into basic signals (sinusoidal signals, amplitude modulated sinusoidal signals, noise signals and impulse signals) allows the systematic variation of signal parameters across the perceivable level and frequency range. Therefore, sinusoidal and amplitude modulated sinusoidal signals were chosen because they can be interpreted as a generalization of the periodic vibration encountered in everyday life (see Fig. 1).

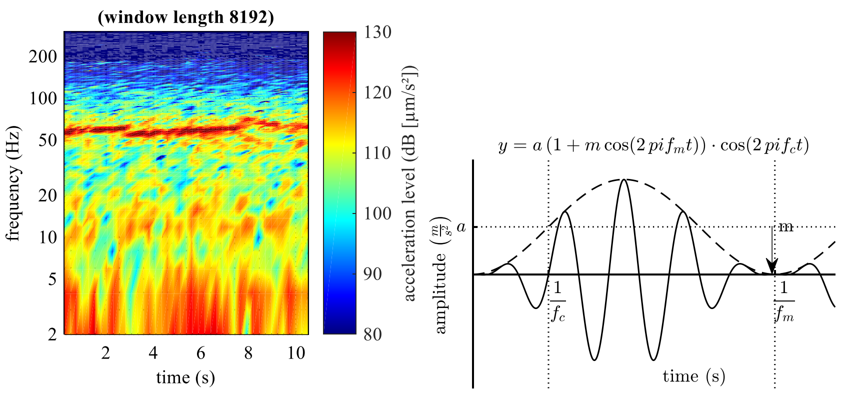

Fig. 1. Example of whole-body vibration (measured on the driver's seat in a car riding on a cobblestone road at 30 km/h) with a dominant periodic component at approximately 60 Hz (a) could be generalized to periodic vibration (b).

The perceivable range of whole-body vibration covers frequencies from the fraction of one Hz up to about 500 Hz with the perceptual threshold rising from approximately 80 dB(µm/s²) to 120 dB(µm/s²) [15]. The exposure limits for one hour exposure as stated in [12] can be interpreted as a reasonable upper boundary for every-day vibration. Other psycho vibratory research findings like just noticeable difference in level (JNDL) [7] and JNDF [7, 14] were taken into account in order to create clearly distinguishable stimuli. In the area limited by the aforementioned boundaries sinusoidal stimuli were distributed evenly. The frequencies of the stimuli were selected in such a way that they extended the stimuli used in the study in [3]. Two vibration levels were chosen. Weak vibration had a level of 10 dB above the perceptual threshold (sensation level, SL). Strong vibration had a level of 36 dB (SL) which was just below the one-hour exposure limits. The resulting stimuli are shown in Fig. 2a. Due to limitations of the reproduction system 5 and 7 Hz needed to be omitted for the 10 dB (SL) level.

Starting from the sinusoidal stimuli AM stimuli were created. In order for them to be clearly distinguishable from sinusoidal stimuli a modulation depth value of one was chosen. The modulation frequency was selected to be well below the carrier frequency since this resembles the typical everyday amplitude modulated vibration e.g. from combustion engines. The AM stimuli are shown in Fig. 3a.

Stimuli for the HAV were selected to be comparable to WBV. The level was chosen in relation to the perceptual threshold of vertical HAV [15] at 10 dB(SL) and at 26(dB) due to limitations of the reproduction system. This was also the reason for the carrier frequency only starting at 15 Hz. The resulting stimuli are shown in Fig. 2b and Fig. 3b.

2.3 Experimental Setup

The aforementioned WBV were presented in the Multimodal Measurement Laboratory [2] of the Chair of Acoustics and Haptics (Fig. 4a). Low frequency vibration was

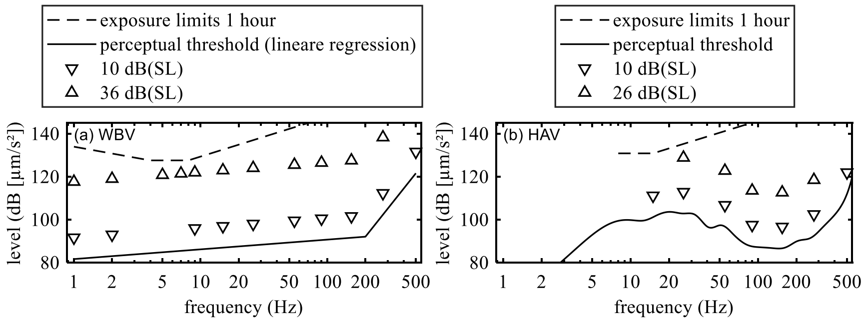

Fig. 2. The sinusoidal stimuli which are shown for whole-body vibration (a) and hand-arm vibration (b) were chosen for the experiment.

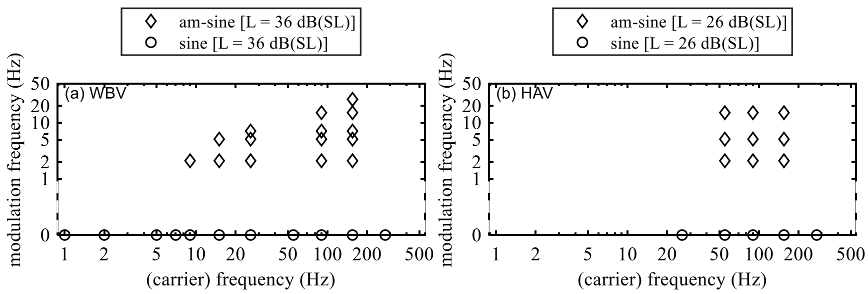

Fig. 3. The amplitude modulated stimuli which are shown for whole-body vibration (a) and hand-arm vibration (b) were chosen for the upper sensation levels for the experiment.

presented vertically with a hexapod platform and high frequency vibration with an electrodynamic shaker. Due to the properties of the reproduction systems stimuli with a sensation level of 10 dB were presented with the shaker starting from 7 Hz and stimuli with a sensation level of 36 dB were presented with a shaker starting from 15 Hz. The reproduction system is linear in the level and frequency range of the stimuli. The individual transfer functions of the subjects were not flat. Therefore, they were compensated with an FIR filter of the inverse transfer function [6].

For the reproduction of the HAV a similar electrodynamic shaker was chosen. A wooden handle bar was attached to the shaker (see Fig. 4b). Subjects were seated next to the electrodynamic shaker in a way that their upper arm was orthogonal to their lower arm and their hand was resting comfortably on the shaker. The transfer function was also compensated individually.

2.4 Subjects

A total of 23 German native speakers (15 male, 8 female) with an average age of 35 years (23 to 71 years) took part in the WBV experiment. A total of 20 German native speakers (13 male, 7 female) with an average age of 37 years (19 to 67 years) took part in the HAV experiment. All test subjects were laymen.

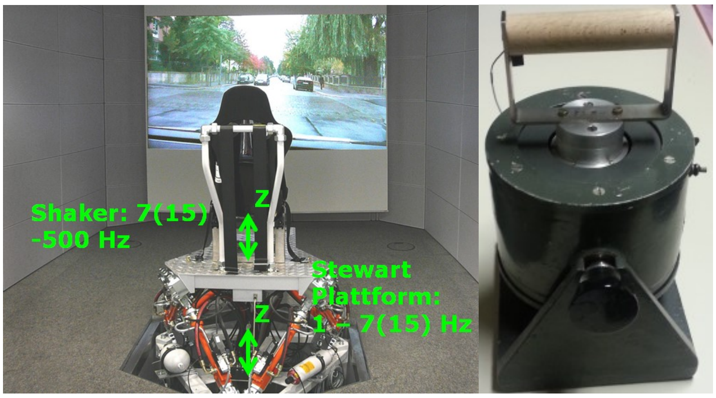

Fig. 4. The tactile stimuli were presented on the depicted whole-body reproduction system (a) (with frequency range for low sensation level (and high sensation level)) and hand-arm reproduction system (b). No auditory or visual context was presented.

2.5 Results

The free elicitation interview of the WBV resulted in 117 unique perceptual attributes which matched the task of the experiment. 52 unique perceptual attributes were found for the HAV experiment. Due to the extended stimulus range, additional unique attributes were identified compared to [1, 3]. Such a large number of perceptual attributes would not constitute an effective tool for communicating efficiently about vibration. However not all attributes need to be utilized for that purpose. Since the associations of the test subjects contained many synonyms and antonyms the redundancy could be reduced. Therefore, in the first step, all antonyms and synonyms were identified with the help of a machine generated thesaurus ("Wortschatz" of the University of Leipzig). If two attributes were identified as a synonym or antonym their occurrences were summed up and the more frequent attribute was kept and the less frequent was discarded, e.g. the occurrences of "strong" were added to the occurrences of "weak". This reduced the WBV set to 39 and the HAV set to 51 attributes.

Another potential for reducing the number of perceptual attributes lies in the different frequencies of the associations. The most frequent attribute for describing WBV occurred 178 times (127 for HAV) while more than 50 % of attributes only had less than 20 occurrences. Since test subjects are more familiar with the more frequently occurring perceptual attributes, these attributes are also more likely relevant for describing vibration. First a local occurrence filter of 15 % for at least one stimulus was applied to discard attributes with very low intersubjective agreement. Therefore, if one attribute was not mentioned more often than this threshold for none of the stimuli, it was omitted. After this step a global occurrence threshold of 2 % of the total judgements (n stimuli times n test subjects) was applied to exclude attributes which were mentioned only very rarely across all stimuli. The resulting set of the most relevant perceptual attributes is displayed in Table 1.

The German attributes were translated by a bilingual language expert for this paper. The translations were verified by presenting stimuli with high and low suitability ratings (see section 3) of each perceptual attribute to the expert. Three attributes ("uniform", "wafting" and "fast") fell below the occurrence threshold for WBV but not for HAV. The occurrences of each attribute were not constant over the stimuli. In order to differentiate the suitability of each attribute in describing a specific vibration simply comparing the number of occurrences for different stimuli is not enough. A failure to come up with an attribute does not equal disagreement regarding the suitability of this attribute for describing a specific vibration. Therefore, a second experiment was conducted where all subjects rated the suitability of each attribute in describing each stimulus.

Table 1. Most common elicited perceptual attributes and their number of occurrences (occurrences in brackets mark attributes which fell below the defined occurrence threshold)

Attribute (Translation)	Attributes (German)	number of occurrences WBV	number of occurrences HAV
weak	schwach	178	53
trembling	wackelnd	143	73
jolting	schlagend	136	127
bumpy	holprig	124	62
buzzing	summend	113	106
tingling	kribbelnd	108	53
pulsating	pulsierend	108	57
calm	ruhig	101	97
humming	brummend	99	71
rattling	ratternd	92	58
grinding	rauschend	78	36
shaky	rüttelnd	70	28
shuddering	zittrig	54	34
throbbing	wummernd	47	48
up and down	auf und ab	32	21
uniform	gleichmäßig	30	54
ticking	tickend	17	30
wafting	wabernd	14	21
fast	schnell	9	31

3 Correlation of Vibration Signals with Attribute Suitability

3.1 Experimental Design

Knowing which attributes are elicited by vibration in general is not enough for the characterisation of vibration. It is equally important to know how suitable each relevant attribute is for describing vibration with specific characteristics. In order to get a general overview about the relationship between vibration parameters and the attributes suitability, all stimuli from the previous section were presented again in a second experiment. Each of the most common perceptual attributes (see Table 1) was rated for each stimulus. For the rating of the suitability of the perceptual attributes subjects indicated their judgement on a quasi-continuous Rohrmann scale. This rating scale includes the verbal anchors "not at all – slightly – moderately – very – extremely" which are perceived to be at equidistance [17] (Fig. 5). A unipolar rating scale was used for all attributes since only a few attributes had clear antonyms. The rating scale was implemented as a MATLAB graphical user interface. Before the experiment there was a short training phase in which all participants were first presented different stimuli from across the full stimulus range. All stimuli were presented in random order. Again, the experimental setup from the previous section was used.

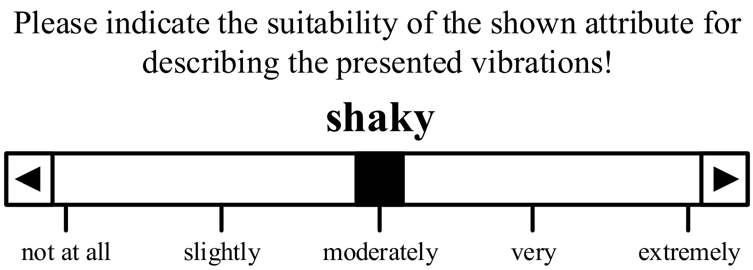

Fig. 5. The rating scale was shown in the graphical user interface which was used for rating the suitability of a perceptual attribute for describing the presented stimuli.

3.2 Subjects

A total of 29 German native speakers (21 male, 8 female) with an average age of 36 years (22 to 72 years) took part in the WBV experiment. A total of 29 German native speakers (21 male, 8 female) with an average age of 31 years (20 to 67 years) took part in the HAV experiment. Again, all test subjects were laymen. No difficulty in understanding the task were encountered.

3.3 Results

Before further examination of the suitability ratings a Shapiro-Wilk test was conducted in SPSS. Since not all suitability ratings of each attribute for each stimulus were normally distributed a non-parametric statistical test was chosen for each attribute. But even the Friedman test showed a significant ($p < 0.05$) influence of stimulus on the suitability rating of each attribute. When visualizing suitability ratings of each attribute three main attribute groups with similar rating patterns with regard to signal parameters could be observed.

Perceptual attributes used for describing the level of a signal. The perceptual attributes "calm" and "weak" are in the first group. Their mean suitability ratings and the standard deviations for sinusoidal WBV signals with 10 dB (SL) and 36 dB (SL) are shown in Fig. 6a. For the low SL the suitability rating is high and vice versa. The suitability ratings seem to be quite independent from the frequency of these signals, with only a slight increase towards high frequencies. Thus, these attributes were primarily used to express the level of the vibration. The standard deviation for the suitability ratings was approximately 10 to 20 points on the 100-point suitability scale, for the ratings of these two attributes and the majority of the other suitability ratings. A similar suitability trend can be observed for HAV (Fig. 6b). Understandably the suitability ratings of WBV for 36 dB (SL) are lower than the suitability ratings of HAV for 26 dB (SL). However, a steeper decline for HAV below 50 Hz compared to WBV can be observed. The reason for this can be seen in the lower perceptual threshold of WBV compared to HAV (see Fig. 2). Assuming a linear influence of level on the suitability ratings of "weak", WBV ratings could be interpolated to absolute acceleration levels used for the 26 dB (SL) HAV. This transformation enables the comparison of WBV ratings to HAV ratings for identical absolute acceleration levels. Fig. 7 shows that similar absolute levels seem to produce similar suitability ratings with the exception of 275 Hz. Therefore, it seems to be more suitable to use absolute vibration levels for such a comparison.

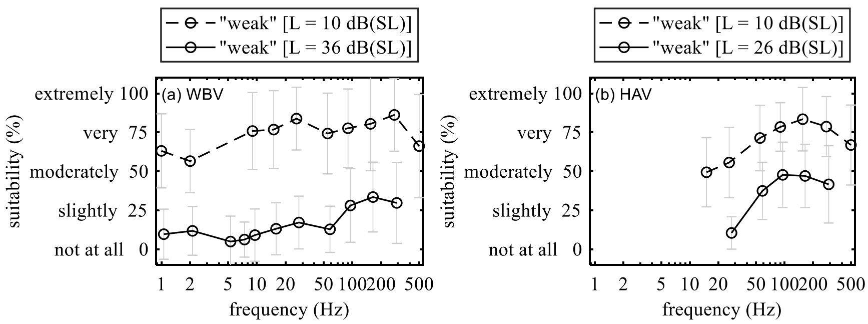

Fig. 6. The mean suitability ratings and standard deviations of the attribute "weak" for sinusoidal whole-body vibration (a) are similar to the ratings of hand-arm vibration (b). Both demonstrate a major level dependence.

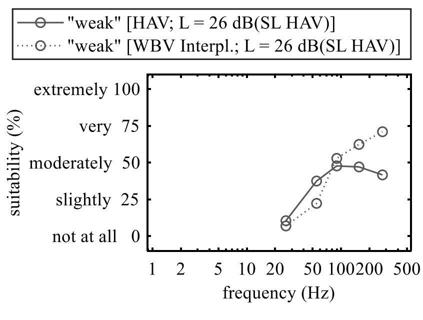

Fig. 7. The mean whole-body vibration suitability ratings of the attribute "weak" are interpolated to the level of the 26 dB (SL) the hand-arm vibration stimuli. They approximate the mean hand-arm vibration ratings for 26 dB (SL).

Perceptual attributes used for describing the frequency range of a signal. Another set of perceptual attributes was used for describing the frequency of the vibration. Attributes in this group are: “up and down”, “trembling”, “rattling”, “bumpy”, “shaky”, “shuddering”, “tingling”, “humming” and “buzzing”. All attributes in this group are exhibiting similar suitability ratings vs. frequency. The suitability ratings for sinusoidal WBV stimuli of one of these perceptual attributes of this group are displayed in Fig. 8a. Depending on the attribute there is a certain frequency at which it is rated as most suitable. This trend is most obvious for 36 dB (SL) suitability ratings (solid line). However, the 10 dB (SL) suitability ratings (dashed line) show a similar trend although at much lower overall suitability. This means: besides the frequency dependency a level dependency can also be observed for these attributes. Again, a similar suitability trend can be observed in the case of HAV (Fig. 8b) with the lower suitability rating for HAV below 50 Hz. Again, minor differences at lower frequencies can be explained by the different perceptual thresholds.

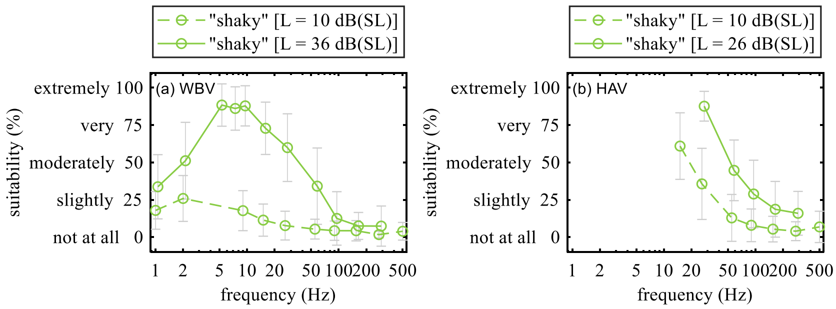

Fig. 8. The mean suitability ratings and standard deviations of the attribute “shaky” for sinusoidal whole-body vibration (a) are similar to the ratings of hand-arm vibration (b). Both demonstrate a major frequency dependence.

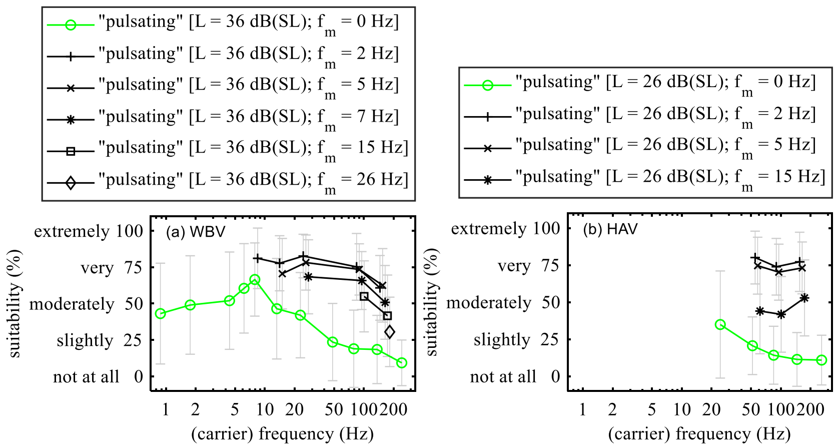

Fig. 9. The mean suitability ratings and standard deviations of the attribute “pulsating” for sinusoidal and amplitude modulated sinusoidal whole-body vibration (a) are similar to the ratings of hand-arm vibration (b). Suitability ratings increase with amplitude modulation.

Perceptual attributes used for describing modulation. When comparing the suitability of sinusoidal vibration to AM-sinusoidal vibration a major difference could be observed for the attributes "pulsating", "throbbing", "jolting" and "ticking". The suitability ratings of one exemplary attribute of this group for WBV and HAV are shown in Fig. 9. The increased suitability ratings for modulated vibration compared to unmodulated vibration can be observed for all attributes in this group but not for the frequency range group or the level group for WBV and HAV.

4 Discussion

Results clearly show that the suitability rating of perceptual attributes are strongly correlating with vibration signal properties as level, frequency and type (sinusoidal, AM-sinusoidal) indicating a systematic relationship. WBV and HAV seem to share the most common attributes elicited by them. Possibly due to smaller frequency range less unique perceptual attributes were found for the HAV experiment.

When judging the suitability of attributes for describing a specific vibration signal WBV and HAV show slightly different rating patterns. These differences can be explained in part by their different perceptual thresholds. Similar results might be obtained presenting the same absolute acceleration levels for WBV and HAV instead of the same sensation levels. Further experiments need to be conducted to verify this relationship. Judging by the similar suitability rating patterns of some attributes it seems reasonable to eliminate some attributes in order to produce more compact models. However periodic vibration is not the only class of vibration occurring in everyday life, but also stochastic, impulsive vibration. The possibility of a lower degree of correlation in the domain of these additional vibration classes needs to be considered. An elimination of seemingly redundant attributes should be conducted only after all vibration classes have been rated for the suitability of the found perceptual attributes.

The promising results justify a more thorough examination of the approach. Therefore, more vibration classes (stochastic, impulse) need to be examined for elicited perceptual attributes. In the next step all perceptual attributes of all vibration classes need to be rated for their suitability. The superimposition of multiple vibration signals might also show interesting interaction effects. The discovered correlations could be utilized to build models for the synthesis or analysis of vibration. If users quantify their expectations using these perceptual attributes a suitability rating profile can be created. A synthesis model could be constructed which can generate vibration from a suitability rating profile in such a way that the expected perceptual attributes would be elicited in the user. This would enable a systematic design of vibration to fulfill user expectations for tactile product design or the tactile design of virtual reality applications. A small pilot study has demonstrated that it is possible to utilize perceptual attributes for the systematic creation of plausible scenes with WBV [18].

Acknowledgements

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