Noise and vibration generation for laboratory studies on sleep disturbance

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INTRODUCTION

The research project TVANE is aimed at studying the effects of noise and building vibrations from railway traffic, and is sponsored by the Swedish railway infrastructure manager Banverket. The project includes many studies performed both in the field with questionnaires and noise and vibration measurements, and in the laboratory. This paper describes the design of a low cost vibrating bed used in laboratory sleeping experiments, and also the sound and vibration signals that the subjects were exposed to. The results of the experiments are under evaluation, but details on the outcome of a previous similar study without vibrations are presented in a parallel paper in these proceedings, Öhrström et al. (2008).

There are several technical possibilities for vibrating beds in sleep experiment setups. In Arnberg et al. (1990) hydraulic actuators were used (often called vibrating tables), but these are typically rather large and noisy systems, so the bed must be suspended a certain height above the floor and some form of sound insulation introduced. Preferably the whole laboratory room should be built on top of the vibrating table itself. Another approach is to use electrodynamical actuators, where the main concern is that it is difficult and expensive to build actuators with high power output and low distortion levels at low frequencies.

The vibrations being studied here correspond to building vibrations caused by a heavy train passage, where the vibrations are transmitted through relatively soft soil such as clay. For Swedish conditions this tends to cause vibrations in the 5 – 10 Hz range, and the predominant vibration direction is typically vertical for low buildings and horizontal perpendicular to the tracks for buildings with more than one floor, see for example (Hannelius 1978; Bahrekazemi 2004; Hassan 2006). For stiffer ground types the transmitted vibrations are at higher frequencies (> 25 Hz), and may cause complex interactions between vibrations and low frequency sound, but this is not the focus of the TVANE project. A typical example of this situation is a railroad tunnel in an urban area that generates vibrations that are then radiated as low frequency sound inside the nearby buildings.

METHOD

In the experiment setup discussed here three identical rooms are equipped with loudspeakers and vibrators for noise and bed vibration generation. The subjects sleep in the rooms, and a computer located in an adjacent control room generates audio and vibration signals during the night. The sleep quality of the subjects is evaluated using questionnaires. As can be seen in the photo in Figure 1, the bed-rooms have been decorated to resemble a normal room, and the speakers, cables and vibration actuators have been hidden as much as possible. Before the start of the study presented here the rooms were already equipped with a sound system and had been used for other sleep experiments, but the vibration system was added during this study.

Figure 1: Photo of the bedrom interior with the bed and some furniture

Generating the noise

Each bedroom is equipped with 22 roof mounted panels, each with four ten inch speakers, for generating the low frequency part of the sound field in the room. The high frequencies are handled by two small speaker cabinets in the corners, with a crossover frequency between the two systems of 125 Hz.

The reverberation time of the room is around 0.3 s for high frequencies, which corresponds to a fairly damped room, but below 200 Hz standing wave patterns are present in the sound field. Therefore a 1/3 octave band equalizer is used to adjust the sound levels and spectrum in the receiver positions close to the bed, for more details see Ögren et al. (2007).

During the night the sound system plays train passages that are based on recorded real passages of different train types. The recording position was around 30 m from the nearest track and the maximum train speeds at the location were about 130 km/h for passenger trains and 90 km/h for freight trains. All recordings were filtered to correspond to indoor levels with a window towards the railway slightly open (about 30 mm open).

Apart from control nights when no audio was played, two sets of sounds were used, one with the maximum (FAST) A-weighted sound pressure level (L_{AFmax}) of 54 dB and one with the same traffic but with the overall audio volume lowered to 48 dB. The traffic pattern was modeled to fit Västra Stambanan, the main railroad between Stockholm and Göteborg in Sweden, and the total number of passages during the sleep period between 23:00 and 07:00 were 44 (25 freight, 9 high speed and 10 commuter trains). The equivalent A-weighted level (L_{AEq}) and maximum levels are given in 5 minute intervals during the night in Figure 2. The 1/3 octave band spectrum of the total exposures is given in Figure 3. Since the background sound level is as low as 13 dB(A) in the rooms at night an artificial background was added that raised the background to 25 dB(A).

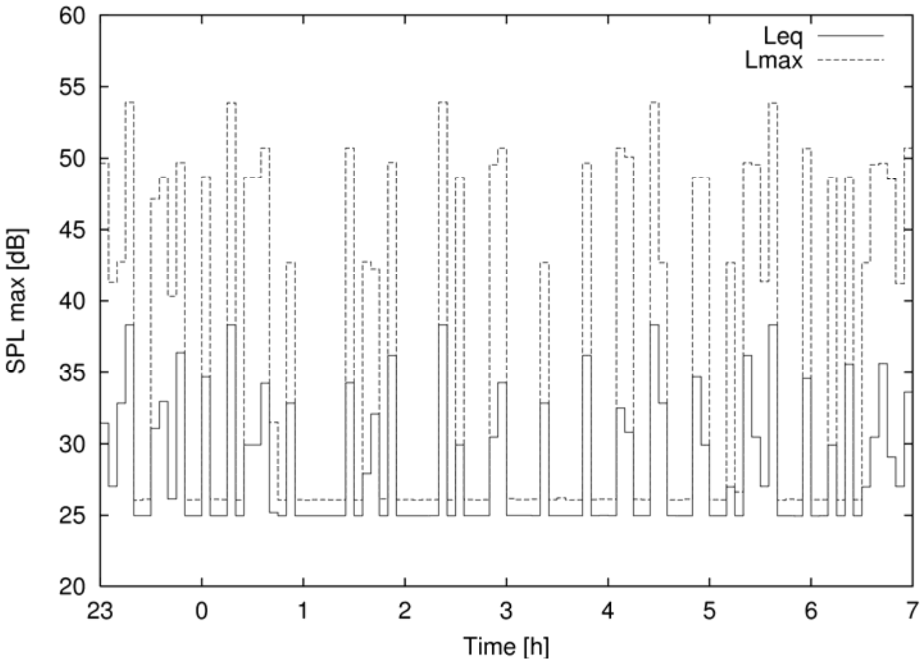

Figure 2: Equivalent and maximum A-weighted sound pressure level in 5 min intervals

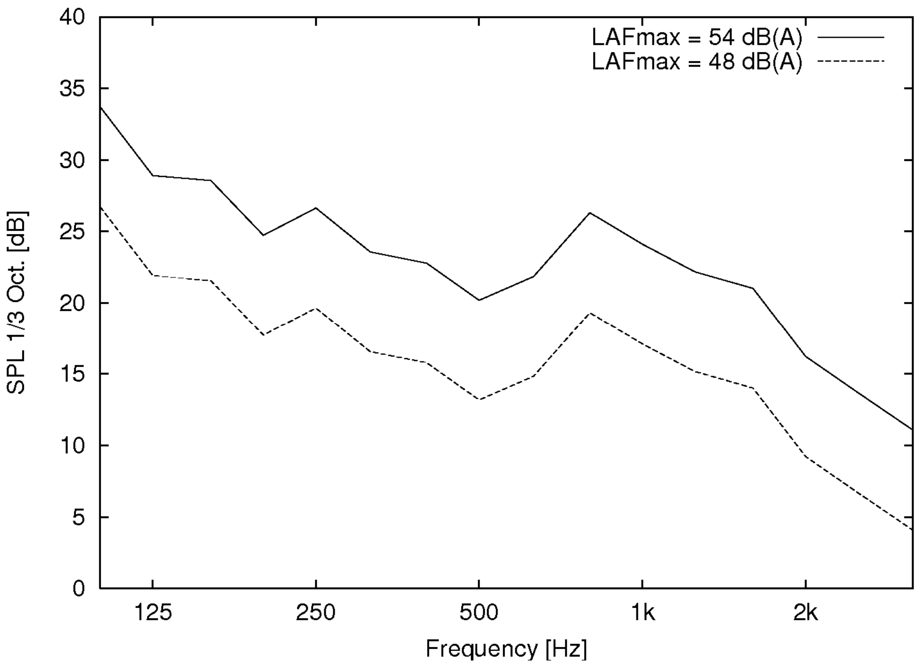

Figure 3: Equivalent level in 1/3 octave bands of the total exposure from 23:00 to 07:00

Generating bed vibrations

For the experiments presented here electrodynamical actuators were selected, since the vibrating beds where to be introduced into the already existing laboratory built for sound exposure, with limited space available for hydraulics or sound insulation under the beds. Another important aspect was that electrodynamical actuators can be controlled from the already present sound system, simply treated like audio signals to speakers, whereas a hydraulic system would have needed a new control system altogether.

Professional electrodynamical actuators are expensive, but recently several variants have become available for the home theater/stereo market. The difference in price can be as much as a factor of 20. They are typically also a lot smaller than the corresponding professional variants. Therefore it was decided early on to try out those cheaper vibrators in this project.

One of the major drawbacks with using cheaper actuators turned out to be distortion; they do not give a perfect sine wave output when the driving signal is a sine wave. If they are mounted stiffly into the bed frame they generate lots of audible frequencies even if the driving signal contains no energy above 10 Hz. This interferes with the well controlled sound exposure situation of the experiment and is unacceptable. Therefore we designed a mechanical resonant filter, which makes the mechanical system receive more power at frequencies close to the resonance and filters out higher frequencies. The principle is illustrated in Figure 4.

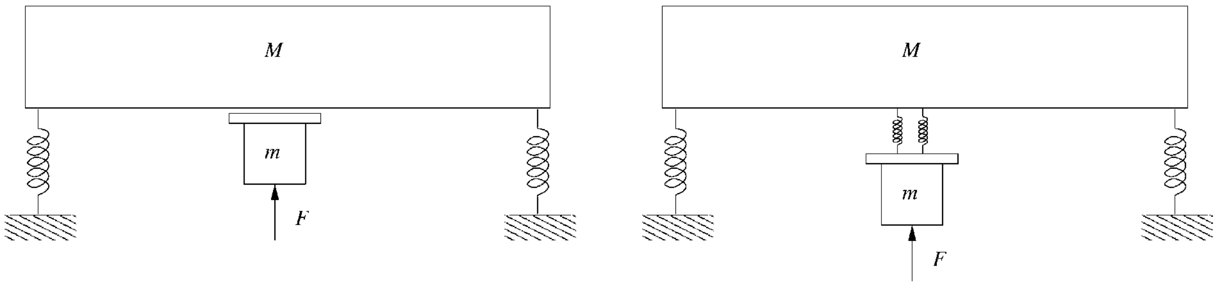

Figure 4: Sketch of the mechanical system with the actuator directly coupled to the bed (left) and indirectly via the resonant mechanical filter (right)

The mechanical filter together with the introduction of sound insulation around the actuator itself reduced the sound level at a position 5 cm above the pillow to 29 dB(A) when the shaker was driven at the maximum amplitude. This was deemed acceptable since the noise from the train masks the vibrations, but it is still possible to hear the low frequency part, especially if lying on the side with the ear pressed against the pillow.

As mentioned earlier the typical frequency of building vibrations due to railway traffic is in the region of 5 – 10 Hz, but the vibrators had trouble reproducing frequencies lower than 10 Hz without reaching the excursion limit (maximum movement of the coil). Therefore the frequency 10 Hz was chosen for the driving signal. Real vibrations are of course more complex than a simple steady state sine wave, therefore a modulation was introduced. By looking at the many time signals for freight trains at speeds around 80 – 90 km/h published in Hannelius (1978), a modulation at 0.2 Hz was introduced together with an extra deep minimum once each 15 s, see Figure 5. This signal was then ramped up when a freight train audio signal was played and repeated periodically until the audio signal was turned off, see Figure 6.

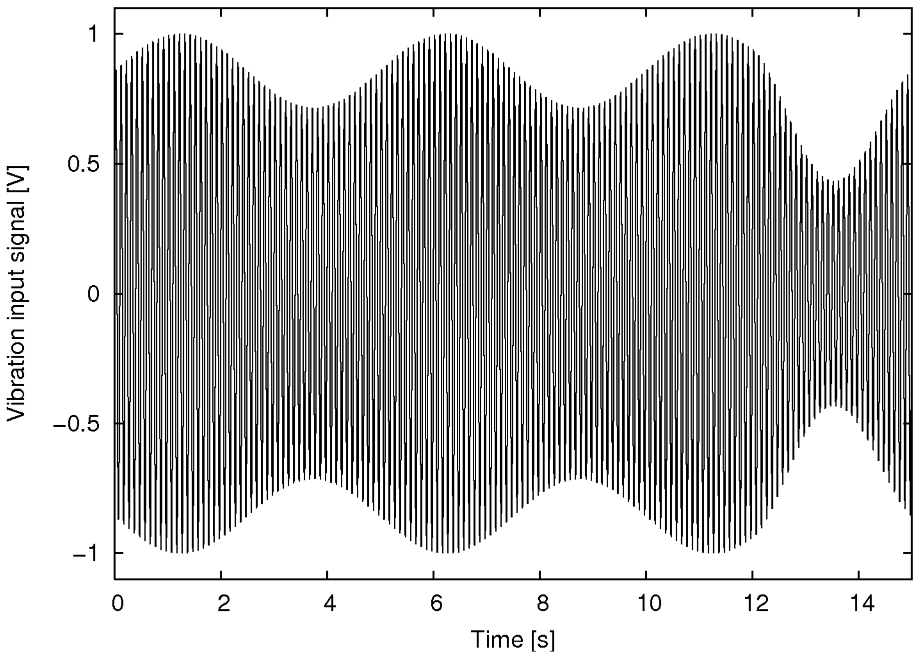

Figure 5: Fundamental vibration input signal. The main frequency is 10 Hz and the modulation frequency 0.2 Hz with an extra deep minimum every 15 seconds

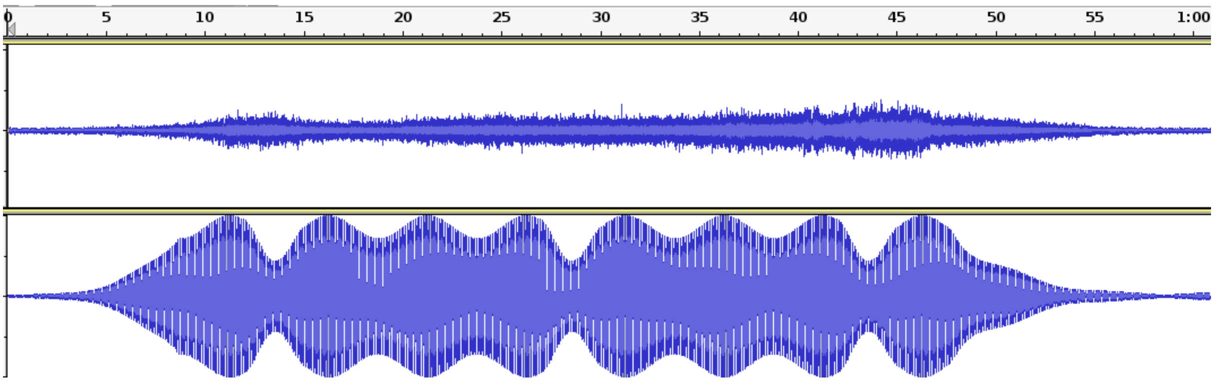

Figure 6: Example of the noise input waveform (top) and the vibration input waveform (bottom) for one freight train passage

The vibration actuators non linear behavior together with the varying mechanical properties of the three beds soft mountings caused us to make further compromises on the vibration reproduction part of the experiment. Since a change in input level on one actuator/bed combination was not the same as the others it would mean an individual calibration for each level used in the experiment for all three beds/actuators. Therefore it was decided to use one single level for all freight trains and no vibrations for the other trains. Under realistic conditions the vibration velocity is more than a factor 10 lower for passenger trains (Bahrekazemi 2004).

In Sweden vibration in building floors from railway traffic is evaluated using a weighted vibration velocity value sometimes referred to as “comfort level”. The weighting is based on the Swedish standard SS 460 48 61 and is expressed as mm/s. In this paper all vibration levels are also given as acceleration without any weighting in order to facilitate international comparisons.

Finally the spectrum of the acceleration measured on the bed frame is given in Figure 7 and 8. Here the three different directions are given, vertical (the direction the actuator was mounted), horizontal along the long side of the bed and perpendicular to that direction. The difference between the fundamental frequency and the first harmonic is approximately 7 dB measured in the acceleration power spectral density (PSD) diagram, which makes it around 13 dB if measured in velocity instead. The difference between the vertical direction and the horizontal is about 10 dB.

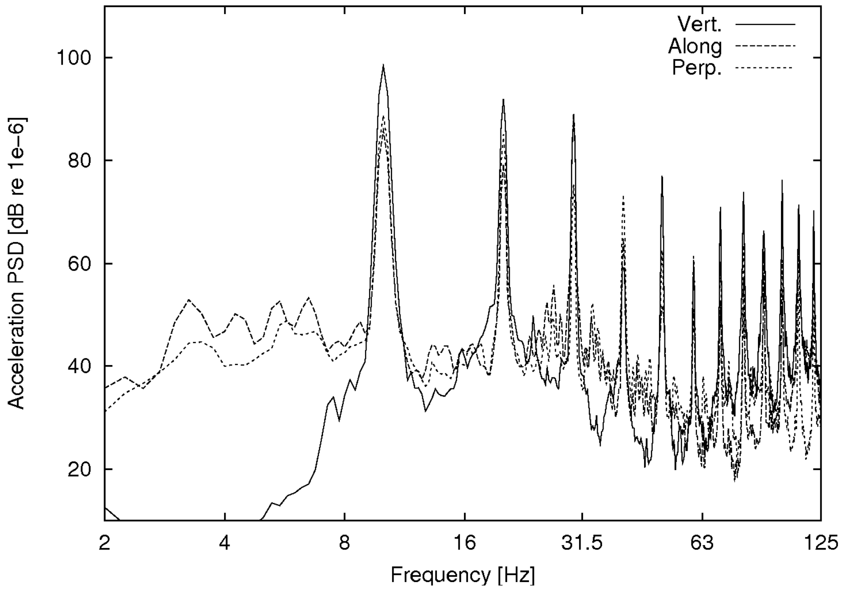

Figure 7: PSD and 1/3 octave spectrum of the acceleration in three directions on the frame of the bed expressed in dB relative to 1e-6 $m/s^{3/2}$

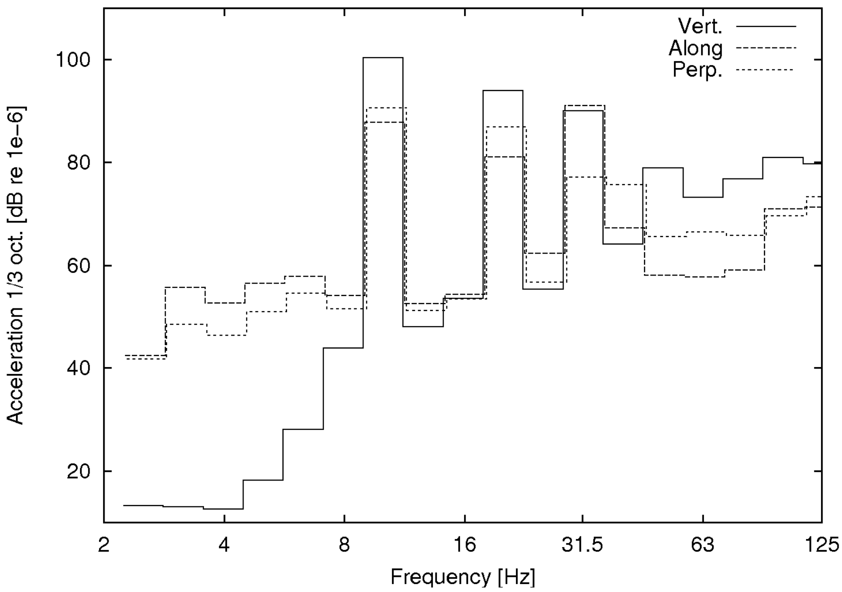

Figure 8: 1/3 octave spectrum of the acceleration in three directions on the frame of the bed expressed in dB relative to 1e-6 m/s^2

The exposure situation during the experiment night is summarized in Table 1, where all vibration levels are given as maximum values with an exponential time weighting of 1 s (known as the SLOW weighting) is applied. The design of the exposure strategy during the week each subject slept in the lab is not described in detail here, but the basics are two nights as habituation followed by the active nights in Table 1 in a randomized order.

Table 1: Noise and vibration exposure levels for the three different exposure conditions

	54 dB strong vibrations	54 dB soft vibrations	48 dB strong vibrations
Maximum SPL L_{AFmax} [dB]	54	54	48
Equivalent SPL $L_{AEq,8h}$ [dB]	31	31	27
Max (S) velocity SS 460 48 61 [mm/s]	1.1 – 1.5	0.2 – 0.4	1.1 – 1.5
Max (S) acceleration [m/s^2]	0.09 – 0.12	0.018 – 0.025	0.09 – 0.12
Number of sound events 23 – 07	44	44	44
Number of vibration events 23 – 07	25	25	25

DISCUSSION

The simple electrodynamical shakers used in this project forced us to make two compromises in the design of the study; all freight trains during one night cause the same vibration signal and 10 Hz is at the higher end of frequencies in real situations. We were also forced to build a soft mounting and introduce sound insulation in order to reduce the sound emissions during operation.

On the other hand the low cost shakers were easily available, have proven to be reliable during the experiments, did produce sufficient power output at 10 Hz and were small enough to fit under the beds without increasing the height of the bed construction above the floor by more than approximately 10 cm.

ACKNOWLEDGEMENTS

The advice received from Göran Wallmark is gratefully acknowledged. This study has been funded by the Swedish Rail Administration (Banverket).

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APPENDIX

This appendix is a brief description of the sounds used in a previous set of experiments, where the results on sleep are discussed in Öhrström et al. (2008).

The experiment used three different sound exposures for three different nights. One was the same as the sound described in the section “Generating the noise” above. The other two were based on road traffic, and were recorded and filtered in a similar manner as for the railway sound. In Figure 9 the sound levels are given in five minute intervals in the same way as in Figure 2. The first of the road sounds used a normal traffic pattern with 369 vehicle passages giving the same equivalent level as the railway noise, the other a pattern that tried to emulate the noise pattern of a railway line, i.e. fewer and louder events. In the second case the maximum level was the same as for the railway.

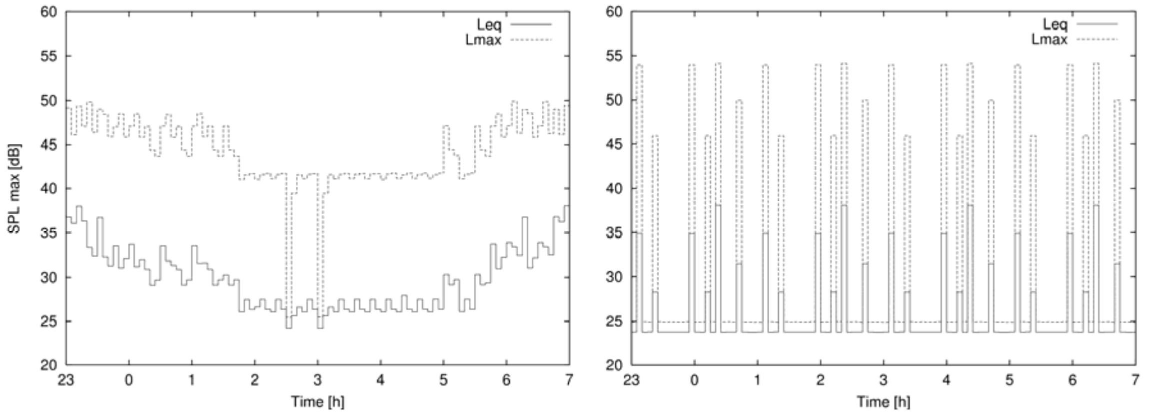

Figure 9: Two nights of road noise exposure similar to the railway noise in Figure 2