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Trains for tomorrow's travellers

Attractive Train Interiors: Minimizing Annoying Sound and Vibration

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Stockholm 2013

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ISSN 1651-7660

TRITA-AVE 2013:28

KTH Railway Group, publication 13-01

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SUMMARY

Rail vehicle passengers demand comfortable journeys. A passenger who wishes to work or read during her or his journey needs to be able to focus without being distracted by disturbing sounds or vibrations that makes writing difficult. In addition to the direct disturbance effect, such sounds and vibrations significantly affect passengers' perception of product quality and are therefore important factors to attract and keep passengers from other less energy effective modes of transportation. In this perspective the acoustic and vibrational interior comfort of rail vehicles is an important factor when seeking to promote travel with relatively low energy and environmental impact.

A study of annoying sounds and vibrations generated by train interiors is reported. A number of different types of annoying sounds are discussed with respect to the effects they have on the passengers and a notation for distinguishing annoying sounds of different character is defined. Annoying sounds in vehicles are categorized with respect to the underlying generation mechanisms and measures for mitigation are discussed in general terms as well as the state-of-art regarding metrics for analysis of disturbing sounds. Furthermore, a literature survey of annoying sounds and vibrations in cars is presented together with procedures and methodologies to reduce the occurrence of such sounds. It is suggested that pro-active methodologies to minimize annoying sound and vibration in cars could be transferred and adapted to be used in rail vehicle design and manufacturing, for example component testing in shaker rigs.

An investigation of disturbing sounds and interior vibrations on Swedish intercity trains is also reported. It is found that a large majority of the annoying sounds onboard a Swedish intercity train is of tapping and rattling type, originating from components like ceiling panels, light covers, cabinet doors, interior sliding doors and foldable tables. A number of case studies are presented based on observations on operating vehicles. From the survey it is found that for some vehicles the number of annoying sounds and vibration issues related to interiors is substantial. Also for vehicles with less than 10 year operation. This observation underlines the need for systematic abatement procedures and proactive activities from the manufacturers to ensure comfortable train journeys.

Finally, best practice design solutions to reduce interior vibrations and annoying sounds from train interiors are presented. The solutions discussed include:

- Monitoring and reporting programs in operating vehicles.
- Systematic application of vibration testing in the component and system quality assurance programs.
- Effective source isolation systems for important vibrating systems like compressors and propulsion systems.
- Squeake and rattle free mounting techniques for interior panels, doors and lighting system.
- Low vibration design and mounting strategies for passenger chairs and interior tables.

Contents

1 INTRODUCTION

1.1 Disturbing sound and vibrations in rail-vehicle interiors

According to the Merriam Webster dictionary 0 the term “noise” is defined as *”any sound that is undesired or interferes with one's hearing of something”.* In this perspective sounds of relatively low energetic level can be very annoying. Such sounds and, in addition, disturbing vibrations of rail vehicle interiors are in focus in the present report.

Rail vehicle passengers demand comfortable journeys. A passenger who wishes to work or read or just relax during her or his journey needs to be able to focus without being distracted by disturbing sounds or vibrations that makes writing, reading or relaxing difficult. In addition to the direct disturbance effect, such sounds and vibrations significantly affect the perception of product quality **Error! Reference source not found.** and are an important factor to attract and keep passengers from other less energy effective modes of transportation, such as air- and car travel. In this perspective the acoustic and vibrational interior comfort of rail vehicles is an important factor to promote travel with relatively low energy and environmental impact **Error! Reference source not found.**.

Regarding interior vibrations it has been shown that the present international standards for rating vibration comfort do not effectively assess the ability for passengers to write on board rail vehicles. In a field study performed on three Swedish Inter-City trains **Error! Reference source not found.** it was found that about two thirds of the 330 randomly selected passengers reported to experience moderately or much difficulty in performing a short written test. In all three trains the measured vibration levels were found to be acceptable according to the applicable international comfort vibration standards 0.

1.2 Purpose of investigation

The purpose of the present work is three-folded. The first aim is to illustrate and analyze typical sound and vibration phenomena with a high degree of annoyance observed in Swedish InterCity trains. The second aim is to survey methods and procedures applied in the automotive industry to eliminate Buzz Squeak and Rattle (BSR) sounds and also other sounds like knocking sounds. Finally, the third aim is to discuss annoying sound and vibration on rail vehicles in a design context, in particular addressing design measures and maintenance procedures to avoid the occurrence of annoying sound and vibration on railway vehicles.

2 ANNOYING SOUNDS IN VEHICLES

What kind of sounds do we consider as annoying? This question is very complex and is in itself a research topic in psychoacoustics. The complexity is due to the fact that the perception of sound is different from person to person. Even a single individual perceives sounds differently depending on situation and mood. Familiar sounds are less annoying than unfamiliar. Sounds we connect with unpleasant experiences are usually more annoying. A sound in one particular context is more annoying than in a different context. Expectation is yet another factor influencing our perception. If we have bought an expensive car we expect it to be free of sounds indicating low quality like for instance a rattling instrument panel. Finally, to make it even more complicated, it has been found that our reactions depends on how the acoustic disturbance is combined with other types of disturbances for instance vibration, light and heat.

What kind of annoying sounds and vibration do we find in vehicles? As passengers we become annoyed when the general noise level is so high that we have difficulties in communicating with other passengers. We become annoyed when suddenly appearing sounds make us lose focus on a demanding task, on reading or writing or a discussion with friends. Hence in vehicles we find both stationary and non-stationary annoying sounds. Ventilation noise and rolling noise from the wheel-rail interaction are examples of stationary sounds that can be annoying if they are sufficiently loud. Squealing brakes, or a door bouncing against its doorpost, are examples on non-stationary annoying sounds. Most people find non-stationary sounds more annoying than stationary since we have an ability to adapt to stationary sounds. In this investigation we focus on non-stationary sounds caused by interior furnishing.

When we discuss annoying sounds we need to share a common notation to facilitate discussion. A large variety of terms, often sound-mimicking, have been developed to characterize annoying sounds. The term *buzzing* sound is used for low-frequency sounds often radiated from resonantly vibrating surfaces, like the 50 Hz plus harmonics sound generated by electric lights. With *knocking* or *tapping* sounds we mean a sound consisting of distinct, often regularly repeated, series of soft impacts, like when we knock on a door or a table. *Rattle* is a more complex sound consisting of a series of more or less random impacts followed by reverberant sound with wide frequency content, like that generated when shaking steal beads in a tin can. *Squeal* is a high frequency, typically 600 Hz – 2000 Hz, tonal sound with long duration, like a squealing railway wheel during braking or curving. *Squeak* is a short duration high frequency tonal sound, like when the rubber sole of a shoe rubs a polished floor. A *hissing* sound is a long duration high frequency broad-band sound, like when gas flows out from a small leak. *Scratch* is a short duration high frequency sound, like two sandpapers in sliding contact. *Grunt*, *hum* and *moan* are all low frequent sounds, typically from say 100 Hz to say 500 Hz, like a door slowly turning on its hinges. And so on …

A conclusion drawn by several researchers, see for instance reference [6], is that the probability of annoying sounds to appear in a built-up structure increases in proportion to the structural complexity and the number of components. A second conclusion is that most of the

annoying sound problems are directly related to the product assembly process. Hence to reduce the probability of annoying sounds to be generated in built-up structures, like vehicles, the designers have to work with the component design and, possibly even more important, with the methods and processes used to assemble the components.

In the following sections we discuss annoying sounds in vehicles based on the character of the generating mechanisms. This basis of characterization is motivated by the fact that successful noise abatement procedures are dependent on well understood generating mechanisms.

2.1 Sounds caused by impact forces

Common for many of the annoying sounds we find in vehicles is that they are caused by interacting components in relative motion. Tapping, knocking and rattling sounds are caused by components vibrating with a relative displacement directed towards each other. The moving part in a sliding door interacting with its carbody-fixed door-frame is one example. If the sliding door vibrates with an amplitude larger than the clearance to the door frame it will repeatedly bounce between the fixed stops and the impacts may generate a disturbing tapping sound.

2.1.1 *Generating mechanisms*

As described above, two adjacent vibrating components will impact each other repeatedly if their relative motion has a component directed normal to the components' surfaces, and if the clearance between the components is small enough. If the vibration amplitude is sufficiently large the two components will repeatedly impact each other and excite vibration that will radiate a tapping sound. Typically one of the components vibrates in resonance with amplitudes larger than the clearance (gap) between the components. The impacting components' total motion will, in the linear regime, be a superposition of the original vibration and the vibration response caused by the impacts.

The impact force duration and magnitude influence the vibration response of the impacting components. An impact with long duration will excite primarily low-frequency vibrations whereas short duration impacts excite vibrations also at high frequencies. In the linear regime the responding vibration magnitude is proportional to the impact force amplitude. The dynamic properties of the impacting components also have large influence on the response to the impacts. Lightly damped vibration modes sounds different than strongly damped modes. Also, the position of the resonance frequencies along the frequency axis has large influence on how we perceive the sound generated.

Tapping and rattling sounds are both generated by impact forces. The question is then - what are the differences between tapping and rattling sound? One difference is that tapping sounds are clearly distinguishable from each other whereas the impacts forming rattle merge into each other. Another difference is that tapping sounds appear as relatively damped in contrast to rattles that often appear reverberant. Finally the energy contents of rattling sounds are generally higher at high frequencies than that of tapping sounds. There is of course a transition zone in between tapping and rattling sounds where classification is difficult.

2.1.2 *Measures to reduce impact generated sound*

When the generating mechanisms are understood various measures to avoid impact generated sounds can be suggested in general terms.

- Avoid or reduce the clearances between components. Note that the impacts may also be eliminated with a larger clearance.
- Reduce the vibration amplitude to a value lower than the clearance.
- Reduce the mass of the impacting component.
- Change to a softer material at the impact point. This will shift the frequency contents of the impact sound to lower, less annoying, frequencies.

A reduced clearance means that the impact velocity, and hence the impact force, is reduced. Alternatively, the impacts can be eliminated if the clearance is made larger than the largest possible vibration amplitude. Vibration amplitudes can be reduced in several ways. If the vibrations are resonant, either the system losses can be increased or the system eigen-frequency can be shifted away from the exciting frequency. The idea of changing the contact surface is to shape the spectrum of the radiated sound to one that is less disturbing. Basically this means that the major part of the acoustic energy is shifted to low frequencies where the human auditory system is less sensitive.

2.2 Sounds caused by friction forces

Squeal, squeak, squelch and moan, in contrast to tapping and rattling sounds, are all caused by two components in sliding contact, i e with parallel relative motion components. When the components slide over each other a time-varying friction force will excite vibration that will generate sound of different types. Time-varying friction forces can be caused by various phenomena. The most common is known as stick-slip but a time-varying normal force or contact area also cause time-varying friction forces. Some researchers have classified stick-slip generated sounds as either squealing sounds or rubbing sounds. Squealing sounds are of tonal character and rubbing sounds are of broadband character.

2.2.1 *Generating mechanisms*

Sound from friction is a complex area and research is still performed to better understand and describe its generation mechanisms, see for instance references [7 – 11]. Stick-slip is a phenomenon where the sliding component repeatedly sticks and slips on the contact surface. Suppose two components, one deformable and one for simplicity rigid, are connected over a surface. If one of the components, for instance the deformable, starts to move relative to the other a friction force sticking the contacting surfaces together develops in the contact surface. The friction force balances the spring force caused by the deformation of the deformable component. As the displacement of the deformable component increase the spring force also increase. This continues until a point where the static friction force has reached its maximum value. When the spring force increases above the maximum static friction force, the components starts to slide and the friction force drops

sharply to the lower dynamic friction force. Since the spring force is now larger than the counteracting friction force the contact surfaces will slide with an accelerating speed until a point where the friction force again balances the spring force. When the spring force is smaller than the friction force the sliding speed will decrease to a point where the surfaces stick again. Then the spring force starts to increase again and the stick-slip process repeats.

The period of the stick-slip repetition is determined by the several factors,

- the relative component speed,
- the friction coefficient's speed-dependence,
- the normal force in the contact surface and
- the stiffness and mass properties of the deformable component.

In cases where the stick-slip frequency is sufficiently close to one of the component's eigen-frequencies the stick-slip deformation amplitude will grow large and possibly cause radiation of tonal sound. In reality both components are deformable meaning that structural modes of any of the interacting bodies may be excited by the forces generated. However, the basic description above still holds. Also, the process described above is a repeated stick-slip motion superimposed over a relative motion of the two components. The relative motion serves as a energy reservoir supplying the sound generating mode(-s) with energy. When the supplied energy is balanced by the dissipated energy a steady-state vibration is reached. In a vehicle the overall relative motion is typically caused by either one of the two components vibrating relative to its equilibrium position.

In the case described above the stick-slip phenomenon gave rise to a series of periodic forces which excited a resonant vibration and a tonal squealing or squeaking sound. In practice the complexity of the interacting surfaces may be such that the stick-slip forces will have a more complex character and the vibration and sound generated will be more or less random in character, i e a scratching sound. As a model for this generation process one can imagine a sandpaper in contact with a rough sandy surface. When the surfaces with their randomly distributed grits slide over each other the asperities will stick and slip randomly. The vibration and sound generated will be similar to squeak but instead of tonal character it will have high-frequency random character.

2.2.2 *Measures to reduce friction generated sound*

From the list of factors influencing the stick-slip motion we can find some measures to reduce or even prevent its appearance.

- Avoid contact between components if not necessary.
- Prevent relative motion between the components.
- Change friction coefficient characteristics by surface treatments or change of materials, see Section 6.1.1 below for further information.
- Change dynamic properties of components to avoid locking to a structural vibration mode.
- Increase the normal force.

2.3 Objective metrics for annoying sounds

Traditionally the A-weighted sound pressure level in dB(A) or one of its close relatives have been used as a measure on both the risk for hearing impairment and annoyance. It is known since long that the A-weighted sound pressure level works well in many situations but is not capable of dealing with other situations. Therefore much work has been spent in the area of psychoacoustics on developing new metrics that capture the sound characteristics that influence human hearing sensation in a better way. Pioneering work in this topic has been carried out by Zwikker and Fastl whose book [12] is the source of most information in this section.

2.3.1 *Loudness*

The loudness [sones] [12] is used as a psychoacoustic measure of the sound strength. The influence of tones and broadband contributions are both readily accounted of. The overall sound strength in a train compartment can be specified using loudness.

2.3.2 *Tonality*

The sound's tonal character is described with the tonality indicator [13]. The tonality accounts for narrow-band frequency components more than 7 dB higher than the neighboring components. The squealing noise generated in narrow curves or during braking are examples of tonal sounds for which the tonality indicator is useful to specify and limit in order to reduce the annoyance of the sound.

2.3.3 *Sharpness*

Sounds with a higher degree of high frequency content is generally perceived as more annoying than those with high degree of low frequency content. The sharpness [acum] is an indicator of the relative high frequency (where the human audible system is particularly sensitive) content in a sound. In the passenger compartment of a train excessive high frequency contents is not likely to be a problem.

2.3.4 *Fluctuation strength and roughness*

Sounds with time varying (fluctuating) strength are known to be annoying. There are two different psychoacoustic features that measure the effect of modulation – fluctuation strength in vacil and roughness in asper.

Fluctuation strength is developed to describe our sensitivity to low-frequency modulation (eg coin whirling on bench), in particular the region around 4 Hz. Roughness on the other hand focuses on higher modulation frequencies. Typically fluctuation strength is the most sensitive of the two up to ca 20 Hz. Above 20 Hz fluctuation strength gradually becomes smaller and roughness with a maximum around 70 Hz takes over. Since sounds modulated at around 70 Hz is perceived as sporty by humans roughness is used in sound quality analysis of cars.

In a train passenger compartment rattle noise created by loose components (eg panels and cabinet doors) and fluctuating pressure in ventilation systems are examples of sounds possible to describe with fluctuation strength.

2.3.5 *Combined features – Acoustic annoyance indices*

In some specific situations a combination of psychoacoustic features can provide a single numerical value that correlates well to the psychoacoustic annoyance reported by human listeners. Jury investigations with members selected from different target groups form the basis for these annoyance indices. For high speed trains the investigation reported in [14] is an illustrative example. Another example is [15] who proposed an annoyance index *AI* for train passengers as a combination of the A-weighted sound level L_A [dB(A)], the sharpness *S* [acum] and the fluctuation strength *F* [vacil],

$$AI = L_A + 47 \cdot S + 163 \cdot F - 80 . \qquad (1)$$

One example of a general purpose annoyance index is the sensory pleasantness [12] that combines the psychoacoustic features loudness, sharpness, tonality and roughness. Investigations have shown that in terms of sensory pleasantness sharpness and roughness are important features. An empirical model for the relative sensory pleasantness P/P_0 is,

$$P / P_0 = e^{-0.7 \cdot \frac{R}{R_0} - 1.08 \cdot \frac{S}{S_0} - (0.023 \cdot \frac{N}{N_0})^2} \cdot (1.24 - e^{-2.43 \cdot \frac{T}{T_0}}) , \qquad (2)$$

where *P* is the sensory pleasantness, *R* [asper] is roughness, *N* [sones] is loudness, *T* is tonality and index 0 indicates reference value. Another possibility is to use the psychoacoustic annoyance *PA* [12] defined as,

$$PA = N_5 \cdot (1 + \sqrt{w_S^2 + w_{FR}^2}) , \qquad (3)$$

with $w_S = (S - 1.75) \cdot 0.25 \cdot \log(N_5 + 10)$ for $S > 1.75$ acum

and $w_{FR} = \frac{2.18}{N_5^{0.4}} \cdot (0.4F + 0.6R)$.

Here N_5 [sone] is the 5th percentile loudness, *S* acum] is the sharpness, *F* [vacil] is the fluctuation strength and *R* [asper] is the roughness.

2.3.6 *Objective BSR metrics in automobile industry*

In automobile industry much effort has been spent on finding a metrics for annoying sounds of buzz, squeak and rattle type. In a number of jury investigations the correlation between different objective metrics and subjective annoyance ratings from the juries were compared, see for instance [16 and 17]. In one of the investigations, where the A-weighted sound level, the psychoacoustic annoyance and the Zwikker loudness was compared as objective metrics for rattle and tapping sounds it was shown that the A-weighted sound level correlated with subjective jury ratings with an adjusted coefficient of determination, R^2_{adj}, equal to 80.1 %, the 95th percentile psychoacoustic

annoyance with R^2_{adj} equal to 98.6 % and the 95th percentile Zwikker loudness N5 with R^2_{adj} equal to 99.4 %.

Similar investigations have been performed to find useful objective annoyance metrics for friction type sounds like squeak. The results are less good but the Sharpness seems to be useful for high frequency squeak sounds [16 chapter 2].

Based on the results from various experiments both Ford and GM have decided to use Zwikker loudness based metrics for objective evaluation of annoying sounds of BSR type. GM for instance [16, 18 and 19] use a non-stationary version of the Zwikker loudness and the acceptance criteria are formulated in the 90th percentile Zwikker loudness N10.

3 HOW IS ANNOYING SOUND PROBLEMS TREATED IN CAR INDUSTRY?

In car industry annoying sound and vibration have been in focus since the early 1980s [16]. The interest for annoying sound issues increased when vehicle acoustics and vibration comfort reached a level where the contributions from interacting interior furnishing components could be discriminated (picked up) from the contributions from the driveline and wheel-road interaction. Nowadays car industry pays a lot of attention and effort to avoid annoying sounds in their products. The rest of this chapter tries to summarize how the automobile producers deal with the annoying sound problem. Part of the methods used in car industry may become useful in railway industry as well.

3.1 Present situation

A review o f the public literature indicates that the car industry certainly has a strategy to reduce the problems connected with annoying interior sound and vibration:

- In the development phase of a new model extensive component testing is performed to detect and eliminate possible annoying sound problems in the final product.
- Sample tests with respect to annoying sounds are performed during end-of-production-line inspection, [6 and 20]

The overall aim is to bring the number of customer complaints down to a minimum. More specifically the aim is to detect, diagnose and eliminate annoying sounds from components and the final product.

3.2 Component vibration testing

Shaker tests are used in car industry to test alternative components, component combinations and component mountings with respect to possible annoying sound problems in the final product. Typical tested components are belt retractors, instrument panels, doors and seats. Examples from the rail vehicle industry could be folding tables, seats, cabinet doors and sliding doors. After the tests the product design team can choose between component alternatives, identify and solve annoying sound problems and verify that components satisfies specifications etc.

3.2.1 *Component annoying sound detection*

An important task for a design team is to choose between different component alternatives. One factor important for the choice is if and how much the component alternative contributes to the annoying sound in the final product. Shaker testing is one possible method to compare different alternatives in the design phase. The idea is to mount and shake the tested component in a way such that the vibration is representative for the component vibration in the final product. The shaker is fed with a random signal from a control system. The frequency characteristics of the signal are such that the component vibrations during different operating conditions are reproduced. The frequency range of interest is typically from 5 Hz to maximum 200 Hz and the root mean square acceleration is typically in the range 1 m/s^2 to 5 m/s^2. During the test sound signals are captured with microphones located close to (typically 1 dm) the suspected sound source. Finally the sound signal is analysed and processed for an objective sound annoyance feature. Two of the major American car producers, General Motors and Ford, use the N10 Zwikker loudness measured in sones [18 and 19]. N10 is the Zwikker loudness level that is exceeded by only 10 % of a running Zwikker loudness measurement. Based on the sound annoyance results the alternative components are ranked and the ranking list is used when the final design is set.

3.2.2 *Component annoying sound diagnosis*

Sometimes it is necessary to diagnose and eliminate an annoying sound source. Also in these cases the controlled shaker test is a feasible choice. When a component annoying sound is to be diagnosed a sine is a frequently chosen excitation signal. The sine frequency is swept from low to high frequencies. When an annoying sound is detected the frequency sweep is stopped and actions to identify its origin are taken. The diagnosis task relies heavily on the experience and skills of the test operator. Basically the diagnosis procedure can be summarized as listen – touch – feel – and see what happens to the sound. Sometimes so many sound sources contribute to the emitted sound that it is difficult to distinguish any specific sound source. In such cases the recommendation [16] is to reduce the excitation level a factor 2. If this does not help reduce it another factor of 2 and so on … . Finally the most important sound source will be dominant and the investigation can start. This procedure is known as “peel the onion” [16] and it allows to identify the contributors in order of severity.

3.3 End-of-production-line-inspection

Basically, the end-of-production-line inspection procedure aims to perform three steps [6 and 23]

(i) to detect
(ii) to diagnose and localize and
(iii) to classify possible noise problems.

Based on the problem classification a decision is taken on whether to take actions or not.

Today (2012) acoustic quality control during end-of-production-line-inspection is performed using specially trained human auditors [6]. For practical reasons, only samples of the production can be inspected. Typically, when the sample car leaves the production line it is run in different operation conditions on a test track with various road surface qualities to provoke excitation of annoying sounds. The auditor tries to detect, localize and classify any appearing annoying sound. When the test driver reports a noise problem a second auditor, usually more experienced, takes the sample car on a second test run to give a second opinion and verify the reported problem. If the problem is verified the car is brought to a repair area where it is subject to more extensive investigations, involving for instance shaker excitation on four-pole stands [18], to identify the root cause of the problem. When the root cause is identified repair actions are decided and performed. Finally, the second auditor is responsible for verifying the effectiveness of the repair and approving shipment. In the end each reported case is filed for later analysis.

3.4 Trends for future

Clearly the present procedures for avoiding annoying noise and vibration in car interiors are costly. In many places efforts are made to find more cost efficient ways to improve the driver's and passenger's comfort. The efforts have been directed towards both product development and to end-of-production-line-inspection.

During the first decade of the 21st century software and methodologies to simulate the occurrence of annoying rattle and squeak sounds have been developed. Dassault Systems, for instance, introduced software for rattle simulation within the ABAQUS FEA portfolio in 2008. Basically the software uses information on assembly tolerances and clearances between components to estimate the probability for rattle sound generation in the contact between components. Experimental tests on an instrument panel showed acceptable correlation with simulation results [21]. One problem was, however, that the simulation detected more rattle areas than was actually found during experiments. More recently a dedicated acoustic buzz, squeak and rattle (BSR) toolbox has been introduced by the software vendor ESI. The toolbox is based on a combination of deterministic and statistical methods with the potential of both determining the probability of buzz, squeak and rattle problems to occur as well as analysing associated sound radiation and psychoacoustic quantities such as loudness [22].

The system with human auditors for end-of-line inspections is another area where car industry tries to find more efficient methods. Apart from the high costs associated with human auditors it has also proven difficult, if not impossible, to train auditors to assess and classify annoying sounds objectively and consistently. However human auditors also have advantages that are difficult to ignore. Human auditors are

- far more sensitive to subtle changes in the sound character,
- far more sensitive to signals in background noise,
- far more sensitive to unfamiliar sounds,

than any existing experimental equipment. Also, a human auditor is likely to react in a similar way as a potential customer.

In reference [6] Caryer and Ali discuss the possibility of an automatic end-of-production-line inspection system. This development relies on the recent advances in psychoacoustic research on assessing annoyance from different sounds and how to extract sound signatures from high background noise. The conclusion is that measurement and analysis systems based on beam-forming techniques using microphone arrays are the most promising future techniques for sound signature extraction in a typical car interior. It remains to investigate whether or not this conclusion also is true for a typical railway car interior. For acoustic annoyance assessment descriptors such as loudness, sharpness, fluctuation strength, roughness and tonality or combinations thereof, see section 2.3 above, are foreseen as useful.

4 ANNOYING VIBRATION – VIBRATION COMFORT

Vibration comfort in rail vehicles is a multifaceted concept. In general terms comfort is about "a conscious well-being" [24]. More specifically it may concern being able to sit comfortably during the journey, relax without being disturbed, being able to get some sleep without being awakened, being able to read and write without problems or being able to drink a cup of coffee without risk of getting wet. Since excess of vibration is also a health risk for drivers of tractors, wheel-loaders, logging machines etc a lot of research have been performed on vibration and its effects on seated persons [25]. Clearly the dynamics of the seat with a seated person is crucial for vibration comfort [26 and 27].

Particularly notable contributions, covering the whole field of human response to vibration, come from the Human Factors Research Unit at the ISVR, University of Southampton, led by Professor Michael Griffin. Over the years the unit has been working with a number of research projects of interest to the topic of this investigation.

- Apparent mass of the human body.
- Biodynamic responses.
- Combined effects of noise and vibration on drivers and passengers.
- Discomfort caused by horizontal (fore-and-aft and lateral) and rotational (roll and pitch) vibration.
- Discomfort caused by low-frequency translational and rotation oscillation.
- Dynamic performance of car seats.
- Effects of seat inclination of seat backrests on vibration discomfort.
- Methods for measuring and predicting seat transmissibility.
- Modeling the dynamic response of the human body.
- Modeling the dynamic responses of seats.
- Motion sickness caused by low-frequency translational and rotational oscillation.
- Motion sickness in tilting trains.

- Non-linearity in subjective and biodynamic responses to vertical vibration.
- Perception of health differences between the seat, the feet and the hands.

Much information on passenger vibration comfort in the following paragraphs is obtained from research produced at the ISVR Human Factors Research Unit.

4.1 How is passenger vibration discomfort assessed?

Stevens' power law, see reference [24], forms the basis of most existing methods to assess vibration discomfort. The power law was formulated as a general law that coupled a physical, objective, magnitude φ to a psychological, subjective, magnitude ψ,

$$\psi = k \cdot (\varphi - \varphi_0)^n , \tag{4}$$

where n is a frequency dependent exponent that Stevens assumed to be constant for each type of stimulus and φ_0 is a value that represents the threshold of perception. During the latter half of the 20th century large effort was spent on how we perceive various vibration stimuli. This work resulted in a number of standards for assessing discomfort caused by vibration. For railway cars whole-body vibration comfort for standing and seated passengers are regulated in the standards SS-ISO 2631-1 and SS-ISO 2631-4 [28 and 29]. The present versions of these standards assumes that

- the overall discomfort can be estimated as a root-sum-of-squares of discomforts evaluated at the seat, the back and the feet and that
- the influence from different frequency components and directions of motion can be taken into account using frequency weighting factors and axis multiplying factors.

For a seated passenger the overall weighted acceleration total value a_v [m/s^2] becomes,

$$a_v^2 = \sum_m \sum_n (k_{mn} W_{mn}(f) a_{mn}(f))^2 , \tag{5}$$

where n is the measurement position, i e the seat, the back and the feet, and m is three translational (vertical, lateral and fore-aft) and three rotational (roll, pitch and yaw) axis. W_{mn} is the frequency weighting factor and k_{mn} is the axis multiplying factor selected according to the measurement position and axis.

The standard SS-ISO 2631-1:1997 gives guidance to the effects of vibration on comfort. In the guide effects on activities like reading writing and drinking are excluded. The reason is that the effects on this kind of activities are very dependent on details, like body posture and supporting table, over which we have limited control. "Approximate indications of likely reactions to various magnitudes of overall vibration total values" are stated in table 1,

Table 1 *Likely passenger reactions to various overall vibration total values according to ISO 2631-1:1997 [28].*

Overall vibration total value a_v	**Likely passenger reaction**
Less than 0,316 m/s^2	Not uncomfortable
0,316 m/s^2 - 0,63 m/s^2	A little uncomfortable
0,5 m/s^2 - 1 m/s^2	Fairly uncomfortable
0,8 m/s^2 - 1,6 m/s^2	Uncomfortable
1,25 m/s^2 - 2,5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

Among manufacturers of railway vehicles the German standard DIN EN 12299 [30] is used for passenger vibration comfort evaluation. The basis of the method is the same as for the method proposed in SS-ISO 2631 but with slightly different weighting filters *W* and different multiplying factors *k*. Also the way to introduce the multiplying factors is different. The main reason DIN EN 12299 have become the de facto standard among rail vehicle manufacturers is most likely the fact that it proposes a method to assess the vehicles contribution to the vibration comfort. It should be noted that, due to the different weightings and multiplying factors, it is not possible to compare vibration comfort values obtained using the different standards.

During the first decade of the 21st century effort has been spent on trying to improve the methods to assess human vibration discomfort. One possible improvement concerns the influence of seating posture. Several experiments have shown that the inclination of the backrest influences the passenger sensitivity to vibration. In [31], for instance, it is shown that discomfort and frequency for maximum discomfort increase as backrest inclination approach upright position. Other investigations have focused on how human body parameters like mass and length etc interact with seat dynamic parameters like impedance and transmissibility, see references [32-36].

4.2 Vibration effects on passenger activities

As mentioned above the standard ISO 2631-1:1997 does not include guidelines for assessing vibration influence on passenger activities such as reading, writing, typing and drinking. There are, however, investigations aiming to determine this influence [4, 37-40]. Sundström's research [41] showed that even at low overall vibration total values according to SS-ISO 2631 railway passengers have difficulties in writing. It is clear that writing ability sets stronger demands on low vibrations than general vibration discomfort.

According to Griffin and Hayward [38] reading, writing and typing difficulties are due to relative vibration. Reading becomes problematic when the head with the eyes vibrates relative to the text or vice versa. Writing becomes problematic when the hand vibrates relative to the paper. Typing and drinking becomes problematic when the hands vibrate relative to the keyboard or the

mouth. Having this in mind it is clear that body resonances, in addition to structural resonances in tables etc, are important for passenger activity disturbances. Hence, reading performance is particularly sensitive to horizontal vibration around 4 Hz [38] where the vibration transmissibility from the seat-backrest system to the head is high [38]. Writing and typing performance is highly dependent on the existence of an effective support that stabilizes the hand-arm system with respect to the paper or keyboard. Of particular significance for passenger seat design is the fact that the seat backrest often increases the vibration transmission from the seat to the head-shoulder system.

Another interesting fact demonstrated by jury investigations is that a subjective task performance evaluation by the passenger often underestimates an objective evaluation [38, 37 and 40]. For example, a passenger's estimation of the number of typing errors performed in a test is often significantly higher than the true number. A framework for understanding this behavior is given by Hockey's compensatory control model [42 and 37]. According to the model

- the activity's goal (performance) is given high priority,
- the resources spent on reaching the goals (maintaining the performance) is managed in a self regulatory process and
- this regulatory process implies physiological and psychological costs to the passenger.

In the case with the passengers participating in activity performance tests the performance, for instance reading accuracy, was given high priority and the participants unconsciously activated a high level of concentration and mental effort to maintain a high performance level. This mental effort caused increased costs in terms of increased heart rate, fatigue etc that cause discomfort and a low self-evaluated subjective performance level. If the caused discomfort is too large a reduction in performance level will be accepted. Similarly an ordinary passenger, not taking part in any test, trying to read a text will more or less unconsciously compensate reading difficulties due to whole-body vibration by increasing concentration, correlating the head and eye motion with the text motion etc to the cost of fatigue and irritation leading to a decreased comfort level.

5 ANNOYING INTERIOR SOUND AND VIBRATION IN SWEDISH INTERCITY AND REGIONAL TRAINS

In this chapter measurement and analysis of interior sound and vibration in some Swedish Intercity and regional trains are reported.

5.1 Measurements and analysis

Ten measurement sessions on four different train types in operation, were performed. During the measurement sessions the trains were searched for annoying sounds and vibrations. When an annoying sound or vibration was detected and roughly localized a microphone and an accelerometer, were placed close to, say in the order of a decimeter, the supposed origin of sound. The acquired sound pressure and acceleration signals were used for later analysis. The instruments used were,

- one 1/2 inch microphone: BSWA, model MPA206,
- one 4.8 g accelerometer: Bruel & Kjaer model 4507B 005,
- one two channel external data acquisition card: PCP-880 and
- a laptop with software SpectraPlus 5.0 for controlling the data acquisition and storing the measurement data.

The detected sounds and vibrations were documented for later use with photographs and a rough annoyance rating on a scale 1, 2 and 3, with 3 being the most annoying.

5.2 Measurement data analysis

Some conclusions can be drawn from visual inspection and listening to the acquired signals. For instance, a visual inspection reveals that the acceleration signals is much more favourable for further analysis than the sound pressure signal. The reason is that, in contrast to the acceleration signal, a large part of the energy in the sound pressure signal originates from other sources like talking passengers etc. This is clearly shown in figure 1 where measurements on a scratching sound are shown both as sound pressure signal and acceleration signal. The relative contribution from background noise is much higher in the sound pressure signal than in the acceleration signal.

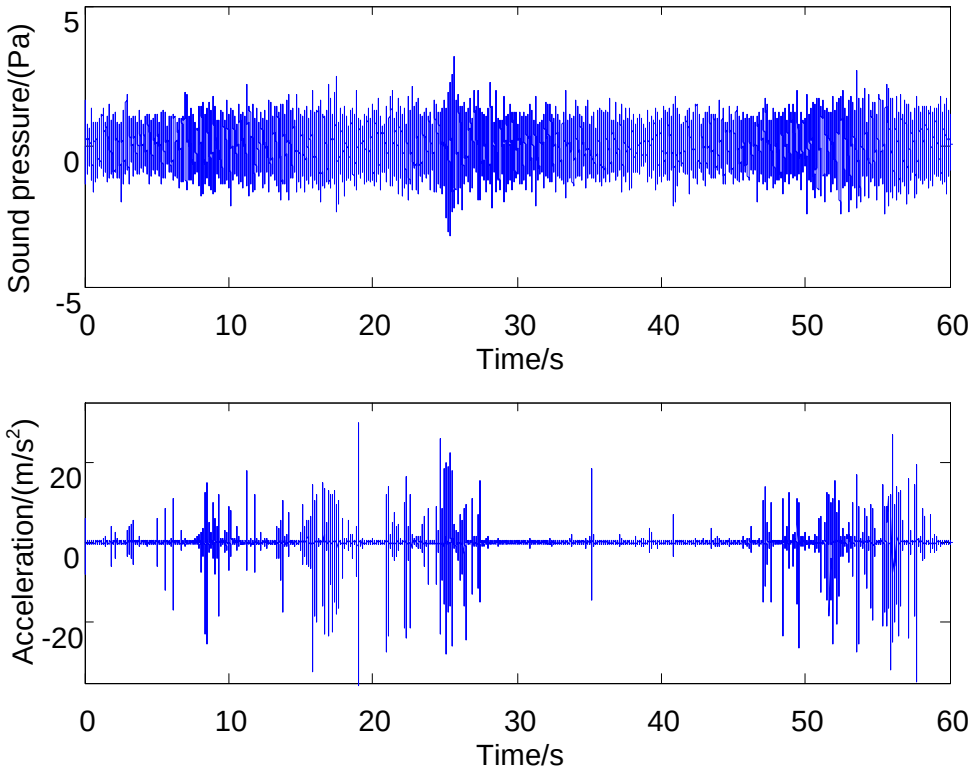

Figure 1 *Sound pressure and acceleration signals measured on scratching light cover panel. The signal to noise ratio is much higher for the acceleration signal.*

A conclusion from inspecting the list of measurements is that there are mainly three types of annoying sounds in the passenger compartments of the investigated trains – knocking or tapping sounds, - rattling sounds and – scratching or rubbing sounds. Examples of these sound types are treated in more detail below.

5.2.1 *Knocking sound*

From listening and visually inspecting the signal time histories we can conclude that a large part of the sounds considered as annoying are excited by mechanical impacts. A typical tapping sound example from the measurements is a cabinet door in a coach, see figure 2. Figure cc shows the acceleration signal picked up from an accelerometer mounted on the door. From the shorter segment of the acceleration signal plotted in figure 3 the impacts are clearly visible.

Figure 2 *Accelerometer placed on cabinet door. Strong bursts of vibration are excited when the door impacts the door frame.*

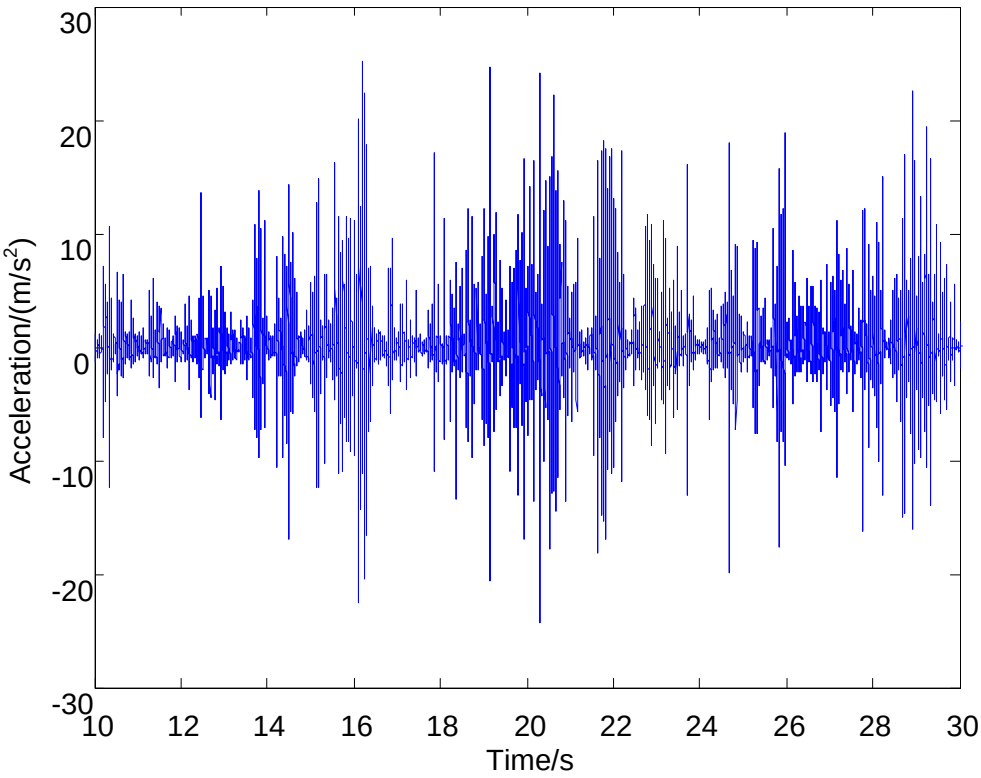

Figure 3 *Acceleration signal measured on cabinet door. Strong bursts of vibration are excited when the door impacts the door frame.*

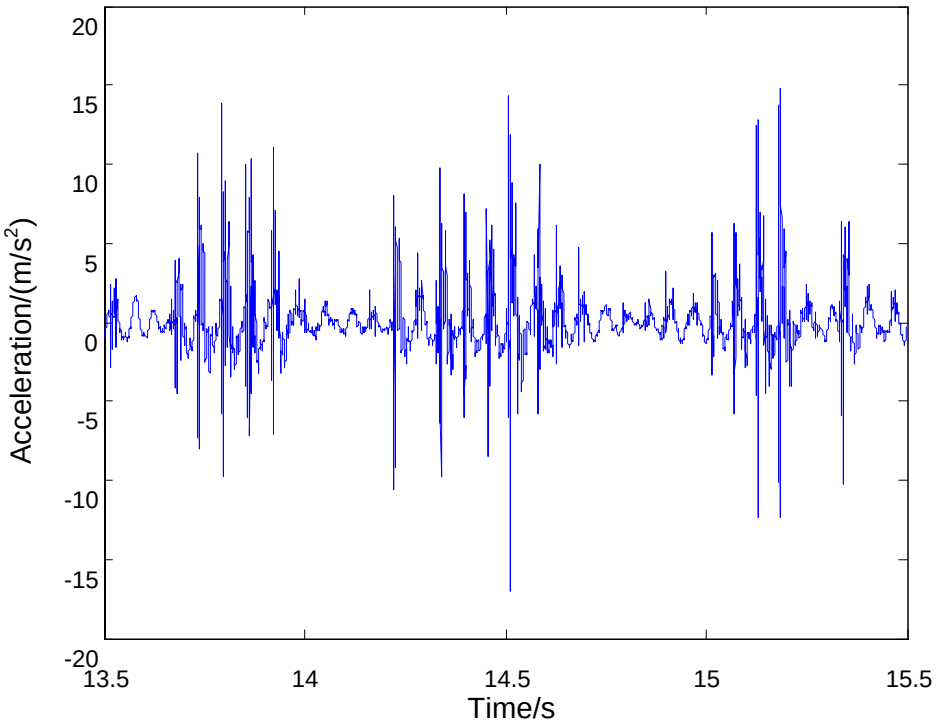

Figure 4 *Detail of acceleration signal measured on cabinet door. The door impacts are superimposed on a nearly sinusoidal 16 Hz signal possibly originating from the door's ordinary vibrations.*

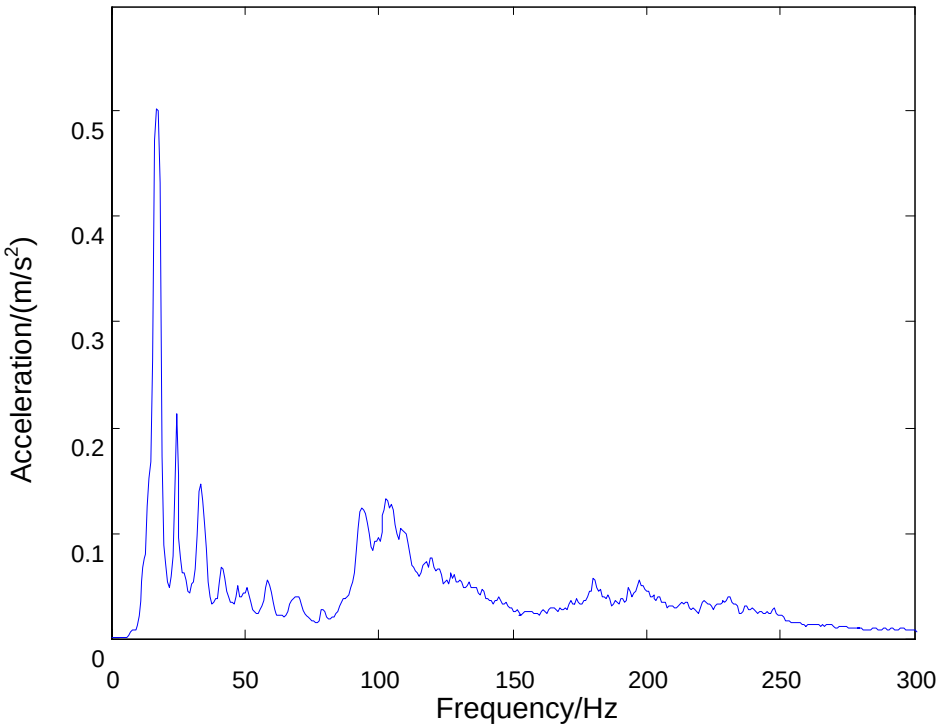

Figure 5 *Acceleration spectrum measured on cabinet door. The spectrum is dominated by low frequencies.*

5.2.2 *Rattling sound*

The acceleration signal acquired on a rattling light cover panel on a train, see figure 6, is shown in figure 7. The acceleration signal clearly shows the impacts exciting the cover panel vibrations that cause the rattling sound. It is also clear that the decay times of the vibration response to the impacts are significantly longer than the time between the impacts. Similar to the tapping sound described above the rattling sound is caused by components impacting due to vibration amplitudes larger than the clearance between the components. In this case it is probably the light cover that vibrates and impacts the frame in which it is mounted.

Figure 6 *Rattling light cover.*

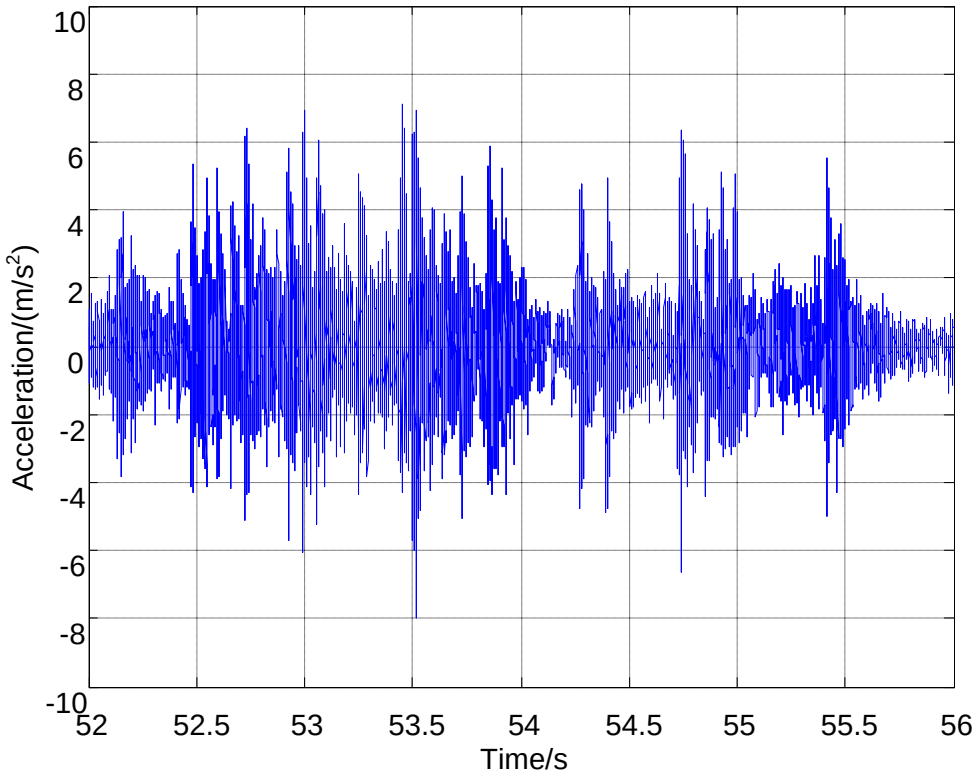

Figure 7 *Acceleration signal measured on rattling light cover. Note the impacts appearing with roughly 0,1 s time interval and the long reverberation time. This sound is rattling with a metallic sound.*

The frequency spectrum of the rattling light cover panel is shown in figure 8. As commented above the tonal high frequency content is relatively large especially when compared to the acceleration spectrum, in figure 5, measured on the tapping cabinet door.

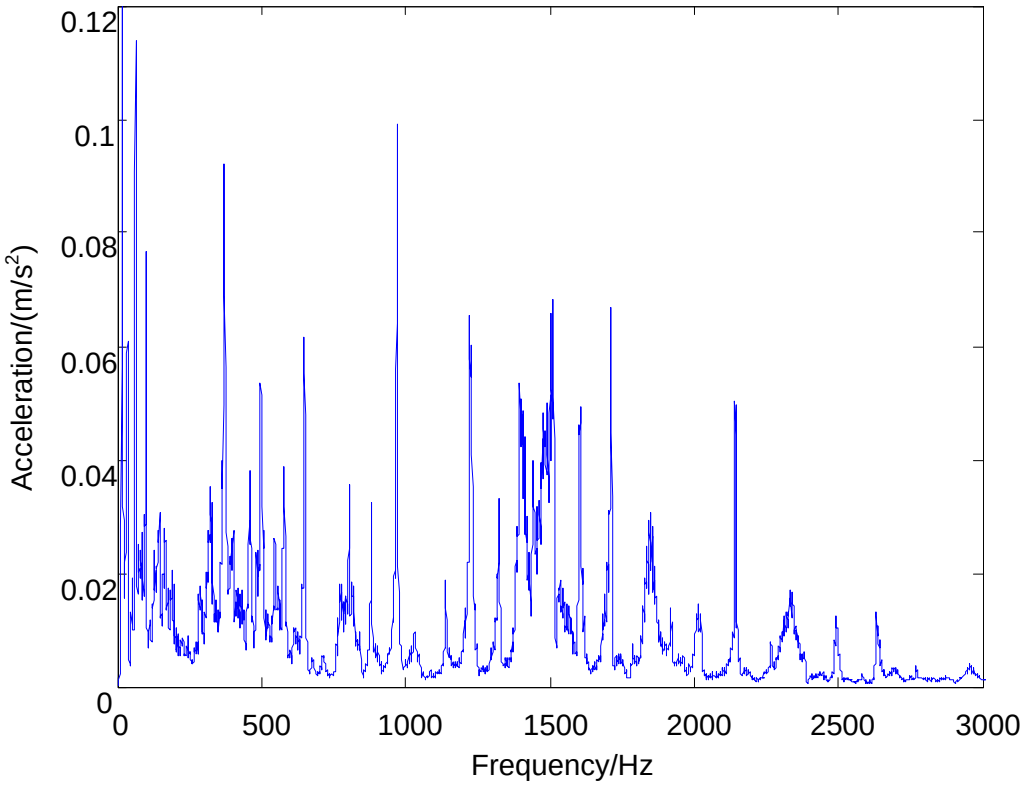

Figure 8 *Acceleration spectrum measured on rattling light cover.*

5.2.3 *Rubbing sound*

An example on a rubbing sound is shown in figure 10 and in a single event zoom in figure 11. From figure 10 it can be noted that the rubbing or scratching sound is a more or less regularly appearing outbursts of vibration. The section with intense sound between 25 s and 26 s in figure 10 consists of several overlapping single events. From figure 11 it is seen that in contrast to the similar looking knocking sound the burst amplitude increase gradually to a maximum from which it decrease to zero again. This is typical for stick-slip generated sound generated by to surfaces in sliding oscillating contact. Hence this sound is caused by two components in continuous but sliding contact.

Figure 9 *Accelerometer and microphone during measurements on scratching light cover.*

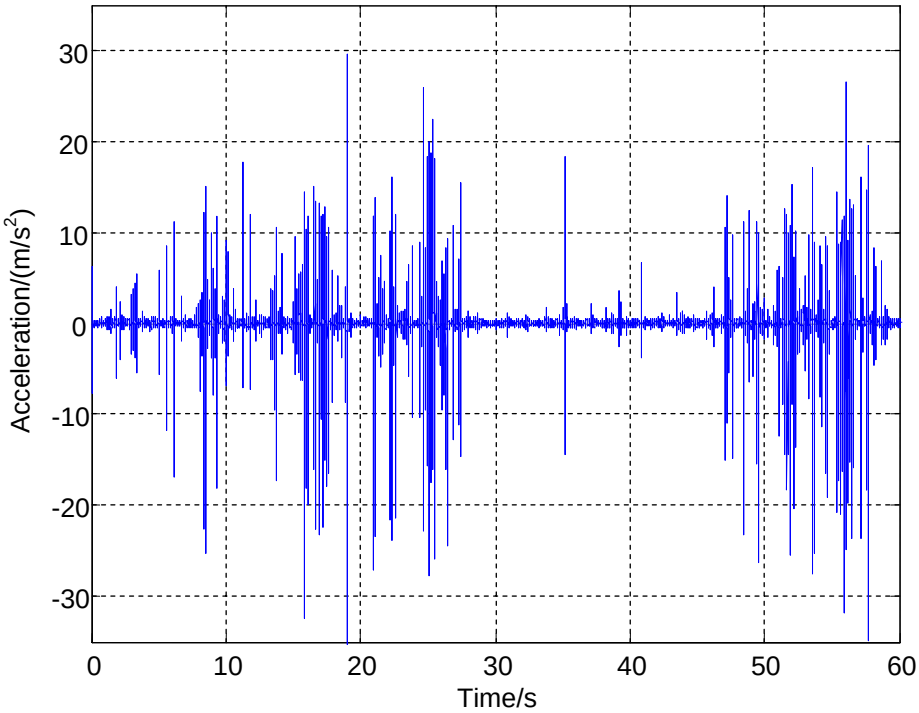

Figure 10 *Acceleration signal measured on scratching light cover. Several outbursts of scratches are captured in 1 minute measurement time.*

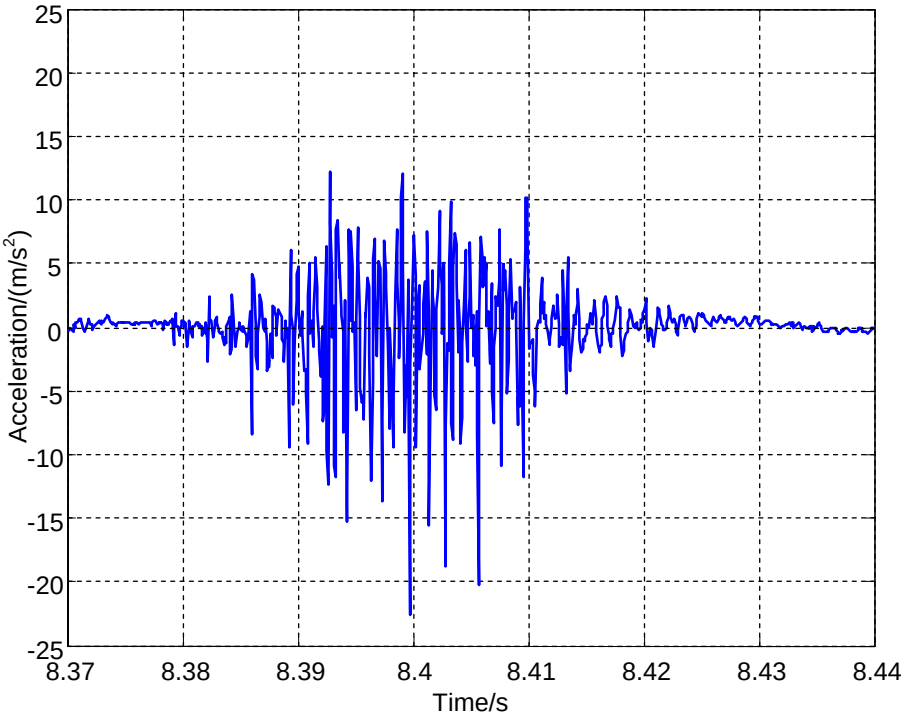

Figure 11 *Acceleration signal measured on scratching light cover. Note that the acceleration starts at a low value the sticks and slips with increasing amplitude and finally gradually decays to a low value.*

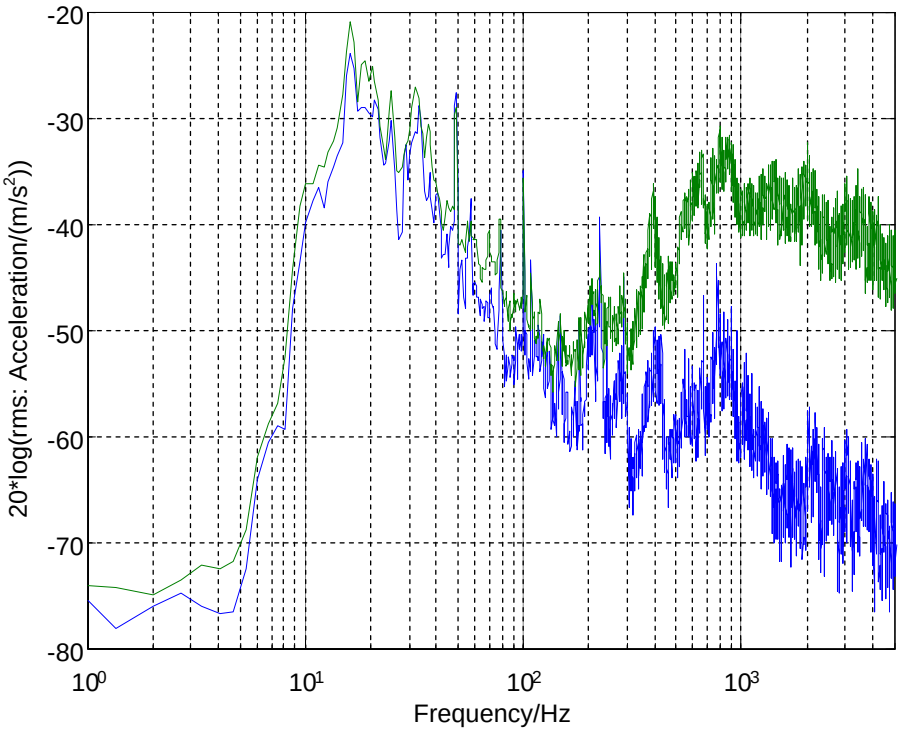

Figure 12 *Acceleration spectrum measured on scratching light cover. Solid (blue) – Weak scratch sound. Dashed (green) – Strong scratch sound.*

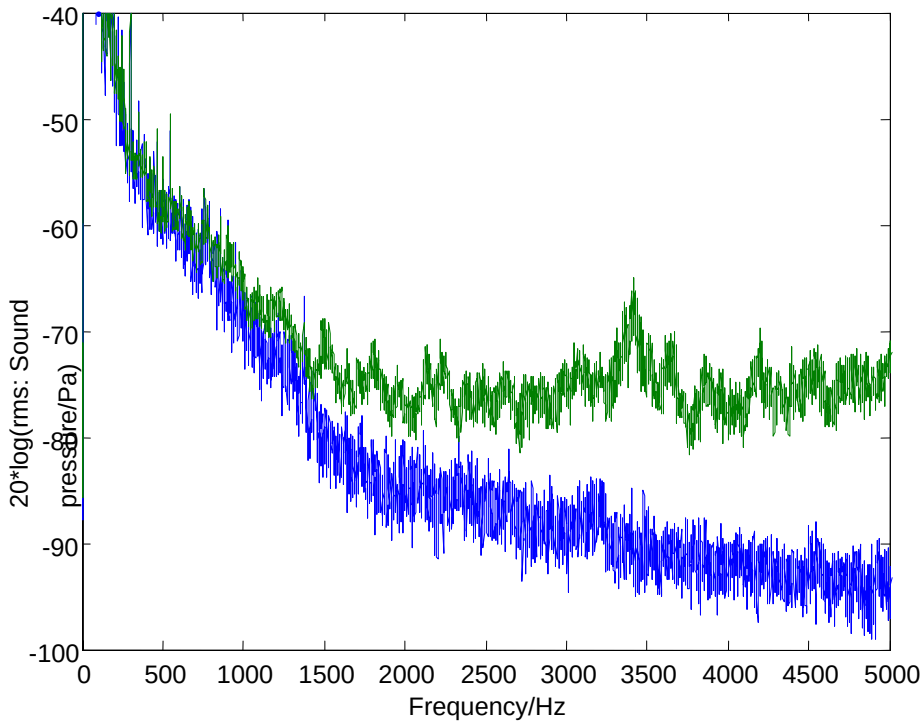

Figure 13 *Sound pressure spectrum measured on scratching light cover. Solid (blue) – Weak scratch sound. Dashed (green) – Strong scratch sound.*

Figure 12 compares the spectrum of a “scratchy” part of the acceleration (0 – 27 s in figure 10) with the spectrum “non-scratchy” part of the acceleration (27 – 35 s in figure 10). The measured sound pressure spectrum is compared in the same way in figure 13. From the diagrams we can draw some conclusions.

- The light cover scratch sound is a broad-band high frequency sound with energy contents from 1000 Hz and above.
- The cause of the sound is two surfaces in sticking and suddenly sliding contact. The contact surface structure is rough and the friction force will be of broad-band random character. The sound generating friction force is between the light cover panel edge and a textile material of the adjacent surface. The generated vibration and sound is similar to that of two sandpapers in oscillating sliding contact.
- The light cover panel is vibrating with large amplitudes at low frequencies. Now and then the friction force will be smaller than the accelerating panel sliding force and the random character impacts between passing small scale asperities will excite a burst of random character vibration and sound.

5.3 Interior vibration

5.3.1 *Table vibration*

Some cases of strong passenger table vibrations were found. One example is single passenger tables mounted to the seat in front of the user, see figure 14. Figure 16 to figure 18 show a series of acceleration spectra measured on the floor and on the table in different conditions – train speed, seat in front occupied or free. From the spectra a number of conclusions can be drawn.

- The floor vibrations are magnified roughly a factor 3 along the path to the table, see figure 16.
- The system seat-table has a couple of resonances that are the main contributors to the table vibrations, see for instance figure 17.
- The seat loading strongly influences the table vibration amplitude, see figure 17. The heavier the seat load the smaller the table vibration.
- The train speed has strong influence on the table vibration amplitude. The amplitude increase with speed, see figure 18.

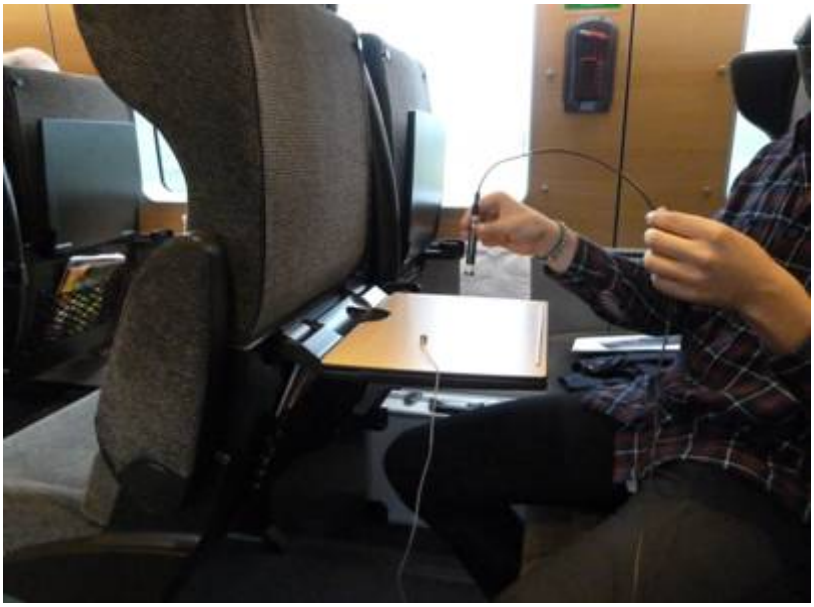

Figure 14 *Sound and acceleration measured on table mounted on seat. Seat in front free.*

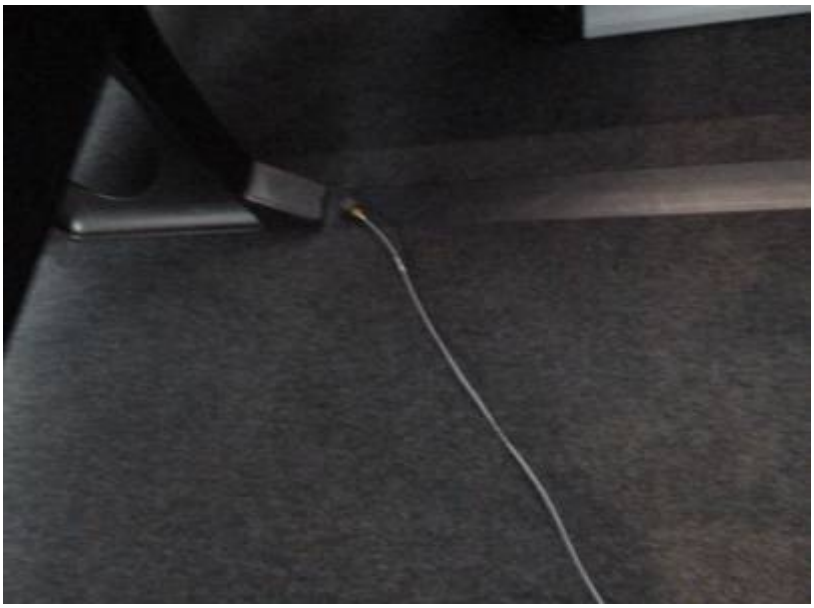

Figure 15 *Acceleration measured on floor close to seat.*

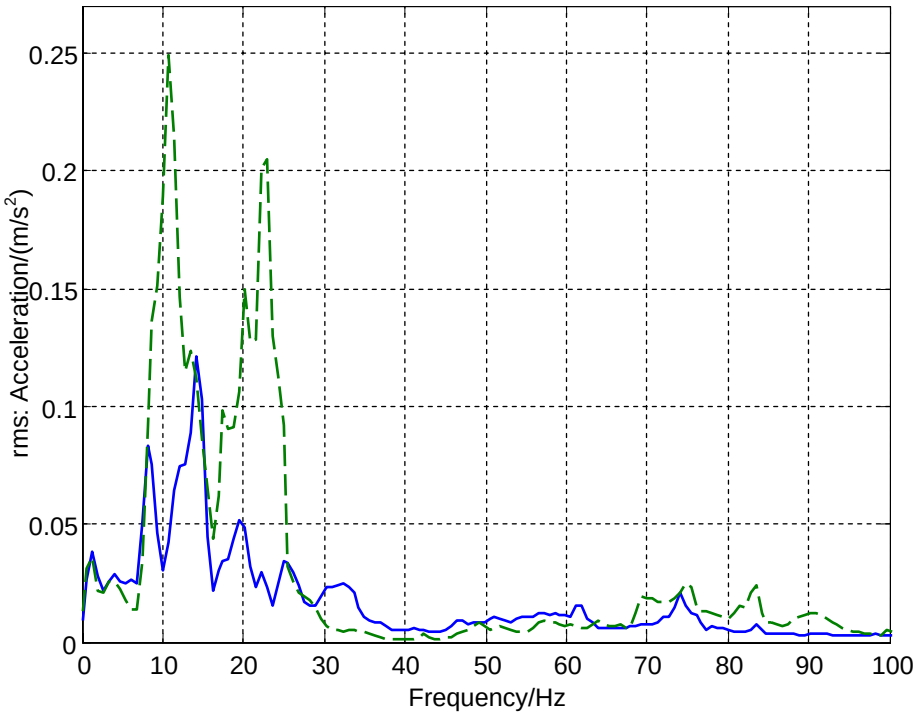

Figure 16 *Table at seat. Seat in front occupied. Solid (blue) – Acceleration spectrum measured on floor. Dashed (green) – Acceleration spectrum measured on seat mounted table.*

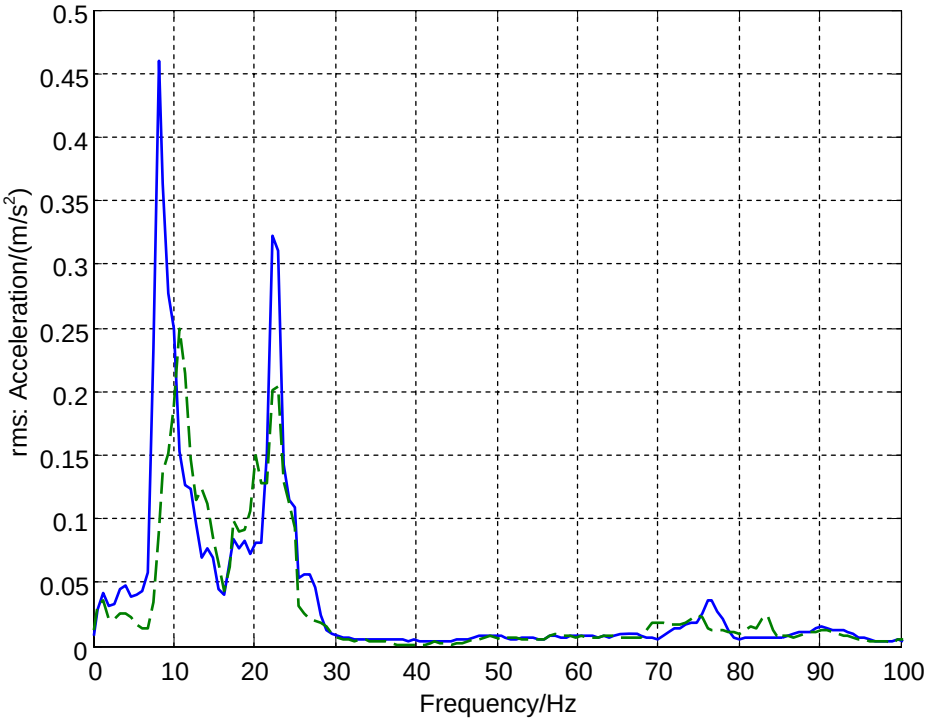

Figure 17 *Acceleration spectrum measured on table. Table at seat. Solid (blue) –Seat not occupied. Dashed (green) – Seat occupied.*

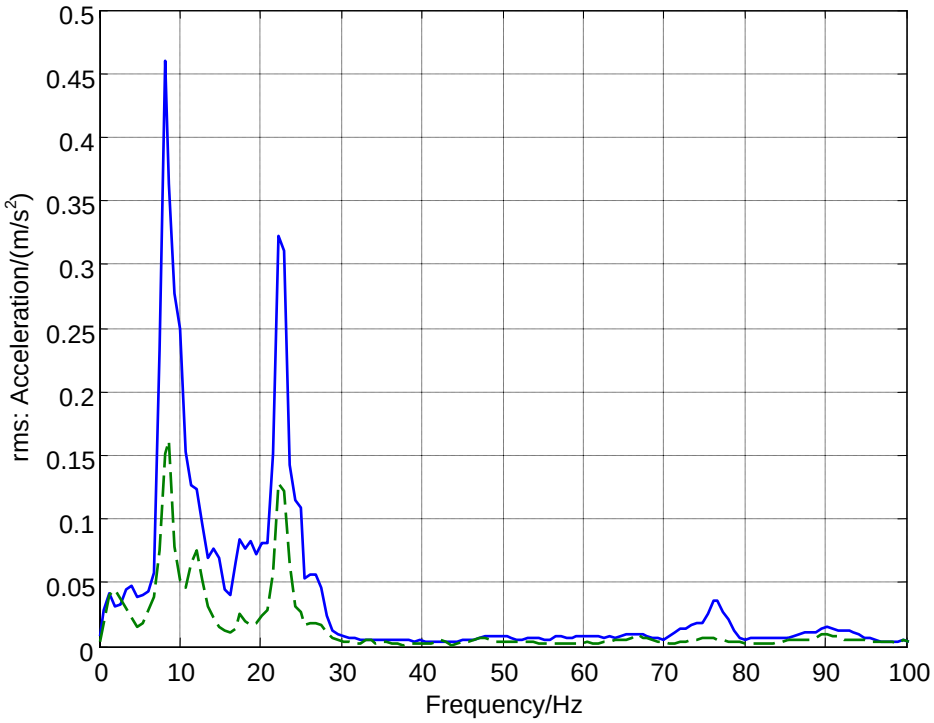

Figure 18 *Acceleration spectrum measured on table. Table at seat.*
Solid (blue) – Train speed 190 km/h. Dashed (green) – Train speed 90 km/h.

6 MEASURES TO REDUCE ANNOYING INTERIOR FURNISHING SOUND AND VIBRATION

To reduce BSR type sounds and annoying vibration in train cars, two areas of design measures can be identified. The first area is associated with the mounting and design of interior systems like panels, doors and cabinets for which primarily tapping, rattling and squealing sound must be controlled. The second area is related to the design of chairs and tables to reduce effect of vibrations. Here, the main objective is to avoid resonant amplification of the vibrations transmitted by the carbody structures from the bogie and traction system. In the following both these areas are addressed.

6.1 Lessons from automotive industry

As outlined in Chapter 3 the area of BSR sound abatement has become increasingly important in car design and manufacturing. In some aspects the production process and the materials used significantly differs from those of rail-vehicle production but certain experiences and methodologies can be transferred to the design and production of rail vehicles. Of significant difference is the fact that cars are produced in much larger numbers than rail vehicles and it is fairly straight forward to test new vehicles on a test track when they are just out of the production line. Generally speaking, methods based on prototype in-situ testing are not practical for rail cars because prototypes are very seldom produced. The first railcar is sold to the customer as is.

6.1.1 *Material combinations at component interfaces*

One important design rule from car design that can directly be transferred to other applications, like train interior design, is the knowledge and methodology applied to determine how certain material combinations are more prone to squeak and rub sound generation than others. In Figure 19 below a material compatibility matrix is displayed, illustrating how hard plastic materials can be combined to avoid squeak and rub. Material combinations that are marked in red in the table should be avoided wherever rubbing contact may occur. Further details on material compatibility and the likelihood of annoying sound generation as a function of stiffness or Shore hardness for various materials are found in reference [16]. In the same reference the methodology applied to test material sample pairs is discussed. This methodology may also be adopted in the design of rail vehicles.

	ABS	PC	PC/ABS	POM	PPO	PET	PBT	PA 6	PA 4,6	PA 6,6	PP	PVC	PS	PE
ABS (acrylonitrile butadiene styrene)							PBT with 23% gf or less	PA6 with 23% gf or less	PA46 with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
PC (polycarbonate)							PBT with 23% gf or less	PA6 with 23% gf or less	PA46 with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
PC/ABS							PBT with 23% gf or less	PA6 with 23% gf or less	PA46 with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
POM (poly oxymethylene, or acetal)							PBT with 23% gf or less	PA6 with 23% gf or less	PA46 with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
PPO (poly phenylene oxide)							PBT with 23% gf or less	PA6 with 23% gf or less	PA46 with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
PET (poly ethylene terethphalate)							PBT with 23% gf or less	PA6 with 23% gf or less	PA46 with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
PBT (poly butylene terethphalate)	PBT with 23% gf or less	PBT with 23% gf or less	PBT with 23% gf or less	PBT with 23% gf or less	PBT with 23% gf or less	PBT with 23% gf or less	PBT with 23% gf or less	PA6 with 23% gf or less	PA46 with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
PA 6 (polyamide 6, or nylon 6)	PA6 with 23% gf or less	PA6 with 23% gf or less	PA6 with 23% gf or less	PA6 with 23% gf or less	PA6 with 23% gf or less	PA6 with 23% gf or less	PA6 with 23% gf or less	PA6 with 23% gf or less	Both PA46 & PA6 each with 23% gf or less	Both PA66 & PA6 each with 23% gf or less	PP with 23% gf or less			
PA 4,6 (polyamide 4,6, or nylon 4,6)	PA46 with 23% gf or less	PA46 with 23% gf or less	PA46 with 23% gf or less	PA46 with 23% gf or less	PA46 with 23% gf or less	PA46 with 23% gf or less	PA46 with 23% gf or less	Both PA6 & PA46 each with 23% gf or less	PA46 with 23% gf or less	Both PA66 & PA46 each with 23% gf or less	PP with 23% gf or less			
PA 6,6 (polyamide 6,6, or nylon 6,6)	PA66 with 23% gf or less	PA66 with 23% gf or less	PA66 with 23% gf or less	PA66 with 23% gf or less	PA66 with 23% gf or less	PA66 with 23% gf or less	PA66 with 23% gf or less	Both PA6 & PA66 each with 23% gf or less	Both PA46 & PA66 each with 23% gf or less	PA66 with 23% gf or less	PP with 23% gf or less			
PP (polypropylene)	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	PP with 23% gf or less	
PVC (poly vinylchloride)											PP with 23% gf or less			
PS (polystyrene)											PP with 23% gf or less			
PE (polyethylene)														

Figure 19 *Hard plastic compatibility matrix. From reference [23 Martin Trapp, Ford Motor Company, 5-18-06].*

To reduce the risk for squeak noise generation it can be effective to cover the surfaces at risk with low-friction adhesive tape. See for example reference [43] for an example of a dedicated low friction tape product. In Figure 20 the mounting of flock tape is used to prevent squeak between vinyl and sheet metal surfaces in a car interior assembly.

Figure 20 *Example: Add Flock tape (or increase retention) to prevent vinyl to sheet metal squeak. From reference [23 Martin Trapp, Ford Motor Company, 5-18-06]*

6.1.2 *Component vibration testing*

Another area of potential methodology transfer is that of component vibration testing, see section 3.2 above. Such methods can be applied to various interior systems such as tables and chairs, sliding doors and ceiling panels to identify potential BSR problems before the component is mounted in the vehicle.

Increased use of specific BSR focused component vibration testing may reduce the problems in operating rail vehicles. However, the approach is fairly complex as several individuals of each component need to be tested and usually an experienced BSR engineer needs to be present at the tests. It is essential to mount the system in a similar manner as applied at the vehicle. In Figure 21 a candidate instrument panel from a car is mounted in a test bench with electro-dynamic shakers for vibration testing. The shakers applied need to be very silent not to mask the sounds originating from the test object.

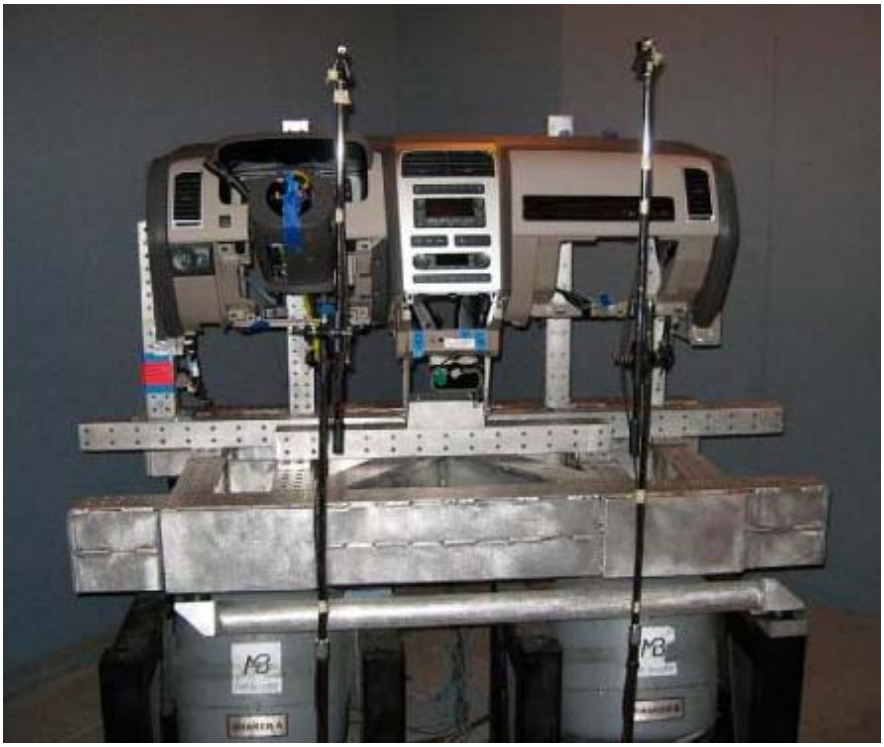

Figure 21 *Component testing in environmental test bench. From reference [16 Martin Trapp, Ford Motor Company, Text book].*

The approach developed within Ford Motor Company is described in the book by Martin Trapp [16] where also step-by step procedures to systematically provoke, rank and evaluate potential BSR issues from the components tested are described. Certain advances to automatically sort out poorly performing components have been developed, see for example reference [44], where the feasibility of an automated system of detection of BSR events that can replace the "subjective" detection is demonstrated.

To provoke BSR issues on new cars at *End-of-production-line-inspection*, dedicated test roads are developed for which the road surfaces are chosen to represent bumpy and irregular surfaces as expected by the customers driving patterns. When component testing is applied to automotive parts, like instrument panels, the test is made with excitation spectra and levels measured at the BSR test tracks. For rail vehicles no such procedures are standardized and the excitation spectra and levels to be applied for component testing need to be adapted to the operating conditions of railway vehicles. A starting point may be to use the vibration standards applied for vibration testing of e.g. electronic equipment on rail vehicles (EN 61373), but the levels may need to be modified to systematically provoke BSR issues. Another aspect is that the vibration spectra may vary significantly depending on the propulsion system, as diesel drive systems cause rather strong interior vibrations.

6.2 Design solutions in the railway industry: Best practice and outlook

Most of the interior design principles for railway cars are based on experience, meaning that design solutions proven to be successful in operation regarding robustness, maintainability, cleanability etc, are kept for future vehicle generations. Please note that the choice of rail vehicle interiors are to a large extent made by the customer and is therefore mainly governed by the experiences by him or her. The BSR aspect is clearly not negligible, but is definitely not the only design driver. One important difference between rail cars and automobile is the design life. Whereas a car is typically driven 10-20 000 km/year during 10-15 years life span, an intercity rail-car is typically in service for 30-40 year with an annual operation distance of 350 000 km/year, or about *40 times* longer operational distance during the life cycle than a standard car. Even though the interiors are refurbished one or two times during the vehicle life cycle, the design life of rail interiors is still much, much longer than that of an automobile and the need for robust solutions is therefore even more pronounced. In this respect the interiors are more comparable with other mass transit vehicles like busses and aircraft.

The control of annoying sound and vibrations is mainly dealt with by application of proven design practices. A general risk with such procedures is that the principles may become outdated due to increased vehicle speed, by other means altered operating conditions or by systematic changes in the infrastructure, e.g. from ballasted track to slab track. A few such practices as applied in the train manufacturing industry are discussed below.

General:

- Reduce the vibration excitation at the sources:
  - wheel-rail excitation: keep the wheel-rail surfaces smooth and make sure the roundness of the wheels is well maintained to reduce.
  - Equipment on carbody (main compressor, diesel engine, HCAC compressor). Make sure that the vibration isolation systems are well designed including adequate arrangements to keep the local dynamic stiffness of the carbody sufficiently high.
- Reduce the vibration transmission from the sources. For instance design the secondary suspension system with sufficient insertion loss to reduce the vibration transmission from the bogie to the carbody.
- Monitoring and reporting programs in operating vehicles can be effective to improve quality of component specification and give feedback to production and maintenance regarding mechanisms producing annoying sounds.
- Tolerances between design elements that may be at risk for BSR sounds must be large enough; It is advisable that critical tolerances are checked with a measuring guide during assembly.
- Improved follow up of the sub-supplier design.

Doors, hatches, lids:

Make sure that rubber trim sealing system is well designed. Rubber seals have to be replaced according to maintenance procedures. Silicone is more expensive than EPDM materials but has longer life span and greater tolerances can then be allowed. An alternative is mounting systems with spring loaded locking devices providing high pressure. Interior sliding door systems are frequently rattling after a few years use. Component testing of such systems are recommended to find and control potential door rattle problems.

Interior trim panels:

- Velcro tape much better then rigid mounting.
- T-profiles can be mounted on the backside of interior panels.
- Mounting of panels in C-profiles: Rubber profiles or self-adhesive plastic/rubber elements can be used to reduce risk for rattle an also vibration transmission from carbody structures.
- Avoid flat surfaces (low resonance frequency) Panels with a large radius are less likely to vibrate in resonant vibration than perfectly flat panels.
- Local blocks of foam (e.g. divinycell material) behind inner wall panels can be used to support inner panel structure.
- Mounting of interior doors and end-sections: pre-stress can be applied to minimize BSR risk.
- Extra care should be taken for panels used for mounting of PA systems for which rattle problems are rather common.

Interior lighting systems:

Light fitting systems are fairly common to rattle. Service requirements lead to special solutions.

- Lamps and lighting tubes can be mounted using spring loading devices to increase pressure and thereby reduce the risk for squeal. Train manufacturer should specify such functional requirements to sub-suppliers to avoid squeal.
- Light fitting systems are candidates for component vibration testing, see Sections 3.2 and 6.1.2.

Seat vibration:

The two most important sources of passenger vibration discomfort are seat and table vibrations. Clearly the seat dynamic properties and how they combine with the carbody and in particular the passenger dynamic properties are important for the vibration comfort.

During recent years substantial research effort has focused on trying to find dynamic models for the components of the passenger-seat system. The objective is to design a seat with desired properties based on input data in terms of vibration excitation and passenger properties. The dynamic properties in terms of mechanical impedance, apparent mass or transmissibility have been measured for both seats and passengers in different postures [31], different hand-arm support conditions and different seat stiffness [32]. The objective is to design a mechanical model able to

simulate the response of a seated passenger to various vibration excitations for different seat designs.

From the literature it is clear that one single seat design will not fulfill comfort requirements for all passengers and all passenger activities. Seats with properties adjustable for body weight and body length can provide a better vibration comfort for a majority of passengers. For specific passenger activities like reading, writing and typing that require even lower vibration levels, special solutions can be applied. A passenger that wants to write can be equipped with a special hand-arm-paper supports that stabilizes the hand position relative to the paper etc.

Some suggested solutions to vibration discomfort due to chair vibration are stated below:

- Fundamental resonance frequencies of chairs should be above 30 Hz in view of measured vibration spectra on floor as reported in Section 5.3.1.
- Vibration isolation of wall mounted chair system. It is generally advisable that manufacturers take the responsibility for vibration isolation of chairs as they normally have more experience and competence in this area than the sub-suppliers.
- Reduce the vibration transmission from the seat-passenger interface to the critical and sensitive parts of the body. In the case of reading, for example, the transmission to the head should be low. In the case of writing the transmission to the hand is critical.

Passenger table vibration:

- Fundamental resonance frequencies of passenger tables should be above 30 Hz in view of measured vibration spectra on floor as reported in Section 5.3.1.
- *Chair mounted tables:* Tables can preferably be mounted in the same chair as the seated person. This solution is effective as the table essentially will follow the motion of the user of the table, at least for low frequencies.
- *Foldable tables:* Pay special attention to risks for rattle. Plastic/rubber spacer elements can be applied.
- Discomfort due to reading, writing and typing difficulties can be reduced if seats and tables etc are designed to minimize relative motion between relevant parts of the body and the work-piece. For reading the head motion relative to the hand motion should be small if the book is held in hand. For writing the hand motion should be small relative to the table motion etc.

7 CONCLUSIONS

From the measurements and the literature survey performed in the present investigation we can conclude:

- From the survey of Swedish intercity trains in operations it is found that for some vehicles the number of annoying sounds and vibration issues related to interiors is substantial. Also for vehicles with less than 10 year operation. This observation underlines the need for systematic abatement procedures and proactive activities from the manufacturers to ensure comfortable train journeys.
- The sound and vibration measurements have shown that a large majority of the annoying sounds onboard a Swedish intercity train is of tapping and rattling type. The annoying sounds are most often caused by furnishing components in relative motion. One example is the cabinet door tapping against its frame. To reduce the number of appearances of this type of sound measures to fix doors and hatches and avoid relative motion between components should be taken during production and during service and maintenance.
- A large number of annoying sounds can be avoided by production and maintenance routines designed to avoided relative motion between components. To quote Trapp [16] – " a few not fully torqued fasteners among the thousands of fasteners in a car are bound to, sooner or later, come lose and cause annoying sounds". The routines, tools etc used in production and maintenance must be designed to avoid this.
- The probability for stick-slip induced squeak noise can be reduced if material combinations in rubbing contact are chosen from a material compatibility matrix.
- In the interior design process vibration testing of component and component assemblies should be systematically applied to provide early warnings for noisy components and component assembly solutions.
- When different design solutions are compared it is important to use objective metrics or systematic listener tests to assess the passenger annoyance.
- Several authors conclude that the probability of annoying sounds to appear in a built-up structure increases in proportion to the structural complexity and the number of components. Most annoying sound problems are directly related to the product assembly process. Hence to reduce the probability of annoying sounds in built-up structures, like vehicles, designers have to work with component design and, more important, with methods and processes to assemble the components.
- For seat mounted tables high vibration levels are common. The table vibration is related to a few system resonances and the levels typically increase with train speed and but reduced by loading the seat to which the table is mounted.
- The vibration comfort of a seated passenger is highly dependent on the passenger activity (resting, reading writing etc), body and seat dynamic properties. Hence, it is a difficult task to find a single seat that is found comfortable by all passengers in all situations.

ACKNOWLEDGMENTS

The in-situ testing of disturbing sounds on in operating Swedish IC trains as reported in Section 5 was conducted by KTH students Max Zapka and Claes Kastby. The authors are grateful for their valuable support to the project. Furthermore, Susanne Rymell and Jonas Strömblad, SJ AB, are kindly acknowledged for their assistance in making the trains available for measurements.

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