Numerical and Experimental NVH Testing of Vehicle Components – from Simple Part to Complex Assembly

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Abstract. Increased demanding in the fields of noise pollution, human comfort and health finds its prints in the development of automotive components. The paper presents general problems of noise and vibration in the vehicles. Main sources and transfer paths are identified. The sound quality – psychoacoustic aspects are also described. In the second part of the article, authors presents an example of numerical and experimental approach to the undercarriage components testing in the field of noise and vibrations problems. Presented examples leads through the basic investigations of particular component to the investigations of complex subassemblies.

1 Introduction

Issue of noise and vibration in machine design is not only the mater of safety and performance of the machine/structure itself. As this is very often the fundamental requirement to fulfil, in some industrial branches the human perception of noise and vibration energy is a big issue. This take place mostly in cases where human comfort is one of the key marketing factor, so e.g. house hold equipment, residential construction and automotive industry.

One can see (figure 1) that noise and vibration in cars is the complex issue. This is caused by the fact of broad band excitations generating shocks, low and high level vibration as well as acoustic emission.
From one point of view, human body can be treated as the mechanical structure with specific dynamic characteristics of its components. In figure 2 there is presented diagram of human body as a multibody model and related to it dynamic model 7.

Literature provides resonant frequencies of some human body organs. The values differ with respect to the source, however in general the frequency bands are comparable. Cempel in his book 2 presents the following list of human body organs resonance frequencies (table 1). Relatively short exposition to vibrations in harmful ranges should not result in nothing more than feel of discomfort. However, long time exposition for vibrations (machine operators, truck drivers, etc.) are the cause of occupation diseases11.
Table 1. Human body resonance bands.

<table>
<thead>
<tr>
<th>Human Organ</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>4-5; 17-25</td>
</tr>
<tr>
<td>Eyes</td>
<td>60-90</td>
</tr>
<tr>
<td>Jaw</td>
<td>6-8</td>
</tr>
<tr>
<td>Larynx, trachea, bronchi</td>
<td>12-16</td>
</tr>
<tr>
<td>Chest</td>
<td>5-9</td>
</tr>
<tr>
<td>Upper Limbs</td>
<td>3</td>
</tr>
<tr>
<td>Spine</td>
<td>8</td>
</tr>
<tr>
<td>Abdominal cavity organs</td>
<td>4.5-10</td>
</tr>
<tr>
<td>Liver</td>
<td>3-4</td>
</tr>
<tr>
<td>Bladder</td>
<td>10-18</td>
</tr>
<tr>
<td>Pelvis</td>
<td>5-9</td>
</tr>
<tr>
<td>Lover limbs</td>
<td>5</td>
</tr>
<tr>
<td>Standing human</td>
<td>5-12</td>
</tr>
<tr>
<td>Sitting human</td>
<td>4-6</td>
</tr>
</tbody>
</table>

Another aspect, which is especially important in the mentioned households and automotive industry, is the relative human perception of surroundings sounds. Psychoacoustics is the field of knowledge which covers the aspects of human feeling under sound exposition. This is a step further than fundamental acoustic measurements of sound pressure level, sound power or intensity while allows to distinguish the sound from noise. The main measure of psychoacoustic level is loudness which is the measure of human perception of sound pressure level with respect to the sound frequency. This is one among many other which are based on it or developed separately.

Selected psychoacoustics metrics:
- loudness – measure of human perception of sound pressure level with respect to the tone frequency,
- sharpness – measure of high frequency tones components in noise spectrum,
- booming – measure of low frequency tones in noise spectrum,
- roughness – measure of high frequency modulation,
- fluctuation strength – measure low frequency modulation,
- tone to noise ratio – measure of tonal component with respect to the background/noise,
- prominence ratio – measure of characteristic band with respect to defined bands of background/noise,
- tonality – measure of tonal to non-tonal components of noise.
2 Structural vibrations and noise - investigation methods

Among multiple possible approaches to the NVH application and structural dynamics problems, authors on the basis of own experience, selected most common accessible. The experimental testing can be divided into modal testing and response testing 1610. The experimental modal analysis should be distinguished into classical experimental modal analysis where the input and output signal is known. This requires the set up with use of hammer or modal shaker. However, in some cases where the operational loads plays the crucial role in dynamics of investigated object, the operational modal analysis (no input signal required) should be used. Similar situation is when there is no reasonable technical solution for excitation of the investigated object due to its mass (heavy mining machinery)3 or accessibility during operation (planes).

A second branch of the investigations is widely spread vibration measurements which also includes the vibrodiagnostics and/or vibroacoustics 2510. This approach is directly related to the identification of the noise and vibration sources, path analysis and general performance of the object. In this approach a sound/noise measurement can be a separate tool. With development of the equipment, tools like sound brush or acoustic cameras can provide sufficient data for noise analysis.

The final group of tool for structural dynamics and noise/vibration generation are numerical simulations8. In this case authors distinguish, as the most important : numerical modal analysis, implicit dynamics simulations and explicit dynamics simulations. However, when using any of this tools, require specialist knowledge from the user and each of the tool have limited application range with respect to the phenomenon characteristic. Modal analysis is the linear dynamics simulation so the investigated system must be linear or it is possible to reduce it into linear system without introducing significant change in the system behaviour. Implicit dynamics is dedicated to the relatively low frequencies of structural dynamics. Very often use in NVH applications. The explicit dynamics is dedicated to the high speed, impact phenomenon so in cases where wave speed (vibration) is relatively high. This approach finds its limited application in NVH.

3 Selected testing in automotive industry

This chapter presents exemplary testing, modelling and results of particular components and complex assemblies. At first presented is the approach of dynamic characteristics quality control of a brake calliper. The second example briefly describes the complex process of noise source identification of electric power steering. The last example is presentation of noise source identification with acoustic camera and quantification of selected psychoacoustic parameters of noise generated in the engine compartment. All examples considers different cars.

3.1 Dynamic characteristic control of a single component

The proper approach in vibration measurements of structural components, should be in many cases, preceded with the numerical modal analysis. Results of the numerical simulations, provides the fundamental knowledge about the mode shapes of the structure. Thanks to that, proper excitation point as well as proper response point/points can be determined. Figure 3 presents the results of the numerical modal analysis with the indicated of excitation and response point. At the same figure experimental set up with a modal hammer and accelerometer is presented.
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As a result of the experimental testing, 8 modes were selected (figure 4). Those modes will become the references modes for the future quality control of dynamic characteristics of the brake calliper.

![Fig. 3. Numerical modal analysis (left) and experimental modal analysis (right).](image)

![Fig. 4. Brake calliper resonances.](image)
Figure 5 presents exemplary spread of the standard deviation of the mode A and G of the investigated component. With proper knowledge about the operation of the entire assembly in which the calliper is mounted, the particular component can be classified as useful or fault.

3.2 Dynamic analysis of multicomponent element

The presented example of investigations of the electric power steering (EPS) (figure 6) were conducted with numerical and experimental modal analysis as well as the implicit dynamics simulations and experimental measurements of the vibration level.

![Fig. 6. CAD model of the EPS with indicated excitation forces.](image)
Due to the complexity of the model and uncertainty about the parameters of contacts, damping, stiffness of components (some components like bushings, bearings, O-ring were implemented in the model with use of simplified finite elements or connectors) main components dynamic characteristics were validated with use of the experimental modal analysis at first. Figure 7 presents the first mode shape of the rack. The numerically obtained frequency equals 263Hz and the experimentally obtained frequency equals 260Hz, which proves about very good correlation between numerical and experimental model. It is additionally confirmed by the matching mode shapes. Higher modes were also verified and gave correlation on similar level.

![Fig. 7. Rack first mode shape numerical 263Hz (left) and experimental 260Hz (right).](image)

The entire model consisted of main structural components and connections: rack, pinion, worm gear, worm, bearing, supporting springs, dampers and bushing. Some of the components were introduced to the model as simplified elements. The finite element model assembly is presented in figure 8.

![Fig. 8. Finite element model of the internal components of the EPS.](image)

Validation of the simulation results of the entire assembly was performed by experimental testing. The excitation force was applied, both in numerical and experimental testing, through the tie rod slot. The excitation signal was the time trace of the accelerations acquired during test ride. Validation points (accelerometers placement) is presented in figure 9. The most important is the one located in the CRB while that was the main validation signal.
In figure 10, on the right side, graphically presented is the moment of the impact between rack-pinion-CRB. On the left side of the figure the acceleration trace of CRB numerical (top trace) and experimental (bottom trace) is presented. It is easy to observe the characteristic impact shape. In both cases the top pick is close to the 80m/s².

**Fig. 9.** Placement of the accelerometers.

**Fig. 10.** Excitation impact.
Presented results are only exemplary and were preceded by multiple simulations. On the basis of that knowledge authors graphically presented the idea of vibration energy transfer in the presented EPS (figure 11).

As it is visible, the impact generated between rack-pinion-CRB components generates the vibration energy which is transferred through those components and further through bearing and bushings to the housing. Vibration transfer to the housing is the case of separate investigation and it is not presented in the paper.

### 3.3 Acoustic measurements of engine compartment

Development in the field of measuring equipment in recent years, led to relatively common access to the acoustic cameras. The main and crucial component of the measuring system is the microphone array (figure 12). Placement of the microphones is unsymmetrical and it is determined by the algorithms which are recalculating measured sound pressure to the location of noise source.
In figure 13, it is presented the noise generation in the band of 20 to 770Hz. Investigated objects is the engine compartment of the Jeep Cherokee XJ 91’. Information about which mechanical component can generate the noise in this range require detailed and complex investigation of the 4.0 R6 petrol engine.

Fig. 12. Acoustic camera array with 52 microphones.

Fig. 13. Noise source localization in the range of 20 – 770 Hz.
As mentioned in the introduction, psychoacoustic aspects of the noise may play significant role, especially in automotive industry. Table 2 presents selected psychoacoustic parameters of the investigated engine. As the psychoacoustic research touches the individual preferences of human, authors do not justify the obtained values. However, it is known that in some automobile fans groups the 4.0 R6 engine of Jeep Cherokee XJ sound is said to be “nice”.

Table 2. Selected psychoacoustic parameters.

<table>
<thead>
<tr>
<th>Psychoacoustic parameters</th>
<th>Idle no. 1</th>
<th>Idle no. nr 2</th>
<th>Idle no. nr 3</th>
<th>High level rpm no. 1</th>
<th>High level rpm no. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudness [son]</td>
<td>192.42</td>
<td>187.23</td>
<td>176.46</td>
<td>353.54</td>
<td>338.19</td>
</tr>
<tr>
<td>Loudness level [fon]</td>
<td>115.88</td>
<td>115.49</td>
<td>114.63</td>
<td>124.66</td>
<td>124.02</td>
</tr>
<tr>
<td>Sharpness [acum]</td>
<td>1.35</td>
<td>1.34</td>
<td>1.37</td>
<td>1.44</td>
<td>1.49</td>
</tr>
<tr>
<td>Booming [acum]</td>
<td>0.81</td>
<td>0.80</td>
<td>0.81</td>
<td>0.84</td>
<td>0.83</td>
</tr>
</tbody>
</table>

4 Summary and conclusions

In the paper selected examples in the approach of NVH application was presented. Following the paper title, the single component to complex structure investigation was presented.

On the basis of showed examples different drivers for NVH testing can be distinguished. First related directly to the life cycle process of the component/assembly. Presented investigation of the quality control of brake calliper dynamic characteristics takes place in the mass production of already developed product. The main task is to keep the characteristic of the component in the assigned range. This allows to keep the predicted performance of the complex assemblies in the car. Presented investigations were conducted with numerical and experimental modal analysis. However, acoustic control of dynamic characteristic of the components is also common.

The presented investigations of the electric power steering assembly was the example of the product development. This is much more complex and demanding task. Applied tools were numerical modal analysis, experimental modal analysis, implicit numerical simulations and vibration measurements on the test rig. With such a investigations, the main task is to localize and improve all the problematic components in the assembly. Additionally, when the final shape of the assembly is achieved, dynamic characteristics of particular components should be evaluated. In the future quality control, those characteristics should be controlled to keep entire assembly in good performance.

Investigations of the noise in the engine compartment, presents the possibility of the noise source identification with use of the acoustic camera. Additionally, psychoacoustic parameters were defined.

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References