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THE NVH ANALYSIS IN RAIL VEHICLES: A LITERATURE REVIEW NVH ANALÝZA V KOĽAJOVÝCH VOZIDLÁCH: PREHĽAD LITERATÚRY

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1 INTRODUCTION

Railway transport represents one of the main transportation kind of transport of these days to transfer both passengers and goods. Every day people commute to work and back home using railway transport in a form of subway systems, light rail transits and other types of rail transport. These types of railway transport can create noise both to the passengers inside of the train as well as to the environment [1, 2].

If the pay is attended to noise when a human is on a board of a train, there are more than one noise source that one can hear. The main sources for interior noise in a rail vehicle are turbulent boundary layer, air conditioning noise, engine (or powertrain), auxiliary equipment, rolling noise and aerodynamic noise from bogie [1, 2]. This is illustrated in *fig. 1*.

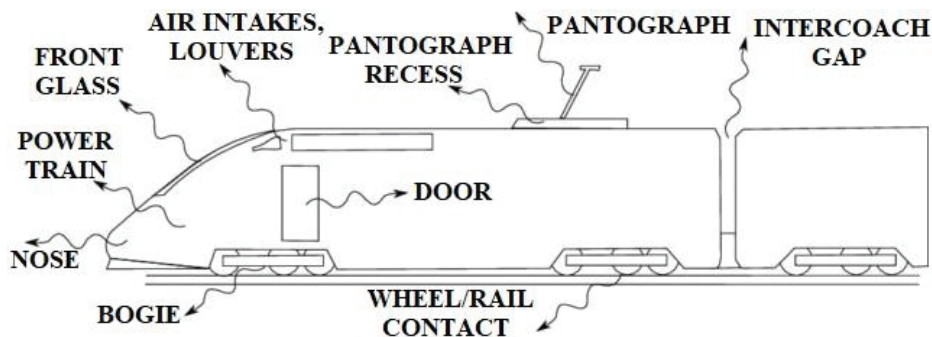


Fig. 1 Noise sources on a rail vehicle [3]

Obr. 1 Zdroje hluku na koľajovom vozidle [3]

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Fig. 2 An illustration of noise measurement [6]

Obr. 2 Ilustrácia merania hluku [6]

internal and external noise. It is stated that aerodynamic sources start to generate significant noise at speeds of approximately of 290 km/h. Below this speed, only rolling noise and propulsion/machinery noise is taken into consideration for external noise calculation. In addition to external noise, machinery noise also contributes to the interior noise levels. This category includes engines, electric motors, air-conditioning equipment, and others [7-9].

Based on the written above, vehicle noise, vibration, and harshness (NVH) is a major problem in the rail vehicle production process [10, 11] and it affects the customer satisfaction rail vehicles owners [12, 13]. The researches of vehicle noise, vibration, and harshness (NVH) are not only suitable for the design process of new rail vehicles (both wagons and locomotives), but they contribute to improve the comfort and performance of current type of rail vehicles [14-16]. Those researches are largely due to the increasing demands of rail vehicle manufacturers. Railway noise, vibration and harshness are the most important issues when the customers assess rail vehicle quality. Some components in the rail vehicles play important roles in reducing NVH, namely rubber dampers, the powertrain, bogie coupling, and elastomeric isolators. In vehicles, the engine/power train mounts affect largely the noise, vibration, and harshness comfort. The mounts are used to provide supports for the power plant, in case of DMUs, or locomotives, and to isolate the vibrations of the power plant from the rest of the rail vehicle [1, 17, 18].

In the past, the engine was considered the most important of the noise source, therefore the first NVH studies were applied to reduce noise and vibrations generated by the engine and powertrain [19, 20]. As over the years, other sources of noise such as track noise have become significant. Moreover, the rail vehicle speed has enhanced the importance of aerodynamic noise [1, 3]. The engine provides a very important contribution to the noise perceived inside a rail vehicle, mainly in case of DMU, representing a one of the internal vibration source. The vibrations derive from the reciprocating and rotational masses such as pistons, connecting rods and shafts. Other sources of vibration come from the drivetrain and other components of the powertrain. Further, the rail vehicle suspension system has an important role in vibration transmission located in the structure-borne transmission path between the wheel/rail interaction and the rail vehicle body. The wheel, or the couple wheel/rail play a dual role in track-noise generation and transmission. Besides the above main phenomena, there are other noise sources, such as brakes [21-24], electrical and mechanical accessories, etc. It is important to consider that internal noise of a rail vehicle depend on the acoustic and vibration sources.

In a rail vehicle there are two different categories of transmission paths, related to different mechanisms of energy transmission: structure-borne and airborne paths (**fig. 3**).

Rolling noise is caused by wheel and rail vibrations induced at the wheel/rail contact [4, 5] and it is one of the most important components of railway noise (**fig. 2**). This noise type depends on both wheel and rail's irregularities. The rougher surface of these components will create higher noise level inside and outside of a rail vehicle. To be able to estimate the airborne component from the rolling noise, it must be considered wheel and track characteristics and irregularities. Another noise component is aerodynamic noise. It can be caused by more than one sources.

These types of sources may contribute to

Commonly in a vehicle, the structure-borne noise transmission path dominates at low frequency (< 200 Hz) and the airborne noise transmission path grows up above 500 Hz [7].

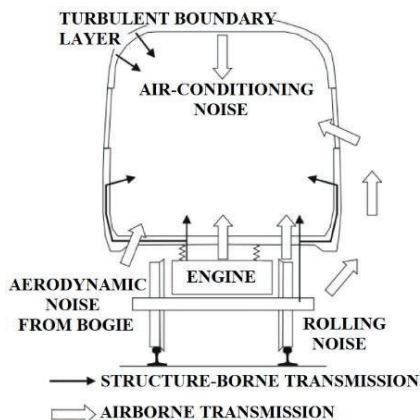


Fig. 3 Ways of noise transmission [2]

Obr. 3 Spôsoby prenosu hluku [2]

In the mid-frequency range, both transmission paths have usually the same level of importance. In order to implement an improvement process of NVH performance of a rail vehicle, the knowledge of the main noise sources and the transmission paths represents a basic aspect.

In the case of railway track noise analysis, the track-induced forces on the body originate from the interaction between rails and wheels. This wheel/rail contact induces forces at the wheel centers, which are transferred to the suspension system and then to the rail vehicle body. Those forces generate

the vibrations and they act as the excitation mechanism.

2 SIMULATION METHODS OF A RAIL VEHICLE NVH ANALYSIS

Rail vehicle NVH became more important in the past decades, since the regulations concerning environmental protection (pass-by noise) and also rail vehicle comfort expectations became more severe. Not only the production quality, the perfect material selection in the passenger compartment, etc., but also the acoustic comfort became an important criterion of the quality of a rail vehicle. Also the NVH experts have recognized soon that simulation methods enhance the development process of a rail vehicle [25].

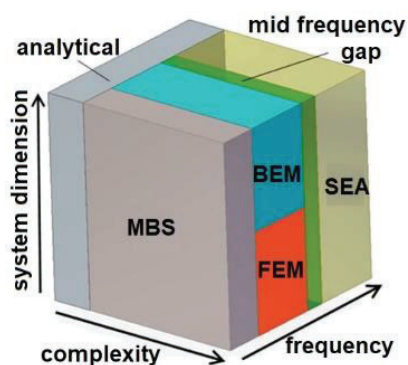


Fig. 4 Methods of the rail vehicle NVH simulation depending on the complexity, boundary conditions and frequency range [25]

Obr. 4 Metódy NVH simulácie koľajového vozidla v závislosti od komplexnosti, okrajových podmienok a rozsahu frekvencií [25]

The goal of the numerical simulations is to calculate, or to predict of the NVH behavior of full rail vehicles or their components. The selection of the proper simulation method is based on the investigated frequency range. It is not possible to apply a certain method for the full acoustic frequency range (0–20 kHz). Generally, the simulation methods are currently not able to predict the perceived noise of the passengers even for a single operating condition. A general brake down of the simulation methods used for rail vehicle NVH simulation depending on the frequency range of interest, complexity and system dimensions is shown in **fig. 4**. There are mentioned the following numerical methods: multibody simulation (MBS), finite element method (FEM), boundary element method (BEM), statistical energy analysis (SAE) [25].

In the case the wheel/rail interaction is calculated with MBS. The obtained forces are serving as excitations for the FEM calculation of the bogie. The vibration of the bogie exciting the rail vehicle body and the internal passenger cavity. The sound pressure level can be finally calculated by the SEA model.

Generally, the main task the numerical simulation is to convert a real object, a complex system or a physical problem into a simplified mechanical, and then a mathematical model. Thereby the following terms should be fulfilled, which is basically a balance act between model accuracy and prediction quality:

- idealized assumption,
- as accurate as possible,
- as simple as possible.

Depending on the described aspects, the following methods can be used for the NVH simulation [25].

2.1 Multibody simulation

Multibody Simulation method (MBS) is established as a non-continuous method for low frequency calculations. Generally, the MBS is applied for the calculation of the dynamic system performance in the railway engineering. The field of applications is the rail vehicle dynamic [26-28], ride comfort for passengers (NVH) [29], powertrain and others. Typically, this approach uses discrete masses (either rigid or flexible bodies), which are interconnected to each other as well as to the environment by means of linear or non-linear coupling elements (spring or damper), kinematic constraints and joints. The bodies may undergo large translational and rotational displacements. In general, a body has 6 independent degrees of freedom. They can be restricted by means of joints or constraints. The displacement conditions are described with generalized coordinates with the number of the degrees of freedom [25]. Mathematically described the system contains regular 2nd order differential equations as seen below:

$$\mathbf{M} \cdot \ddot{\mathbf{q}}(t) + \mathbf{B} \cdot \dot{\mathbf{q}}(t) + \mathbf{K} \cdot \mathbf{q}(t) = \mathbf{Q}(t), \quad (1)$$

where \mathbf{M} is the mass matrix, \mathbf{B} is the damping matrix, \mathbf{K} is the stiffness matrix, $\ddot{\mathbf{q}}(t), \dot{\mathbf{q}}(t), \mathbf{q}(t)$ are vectors of accelerations, velocities and deflections, respectively, and $\mathbf{Q}(t)$ is the vector of external loads (excitation forces).

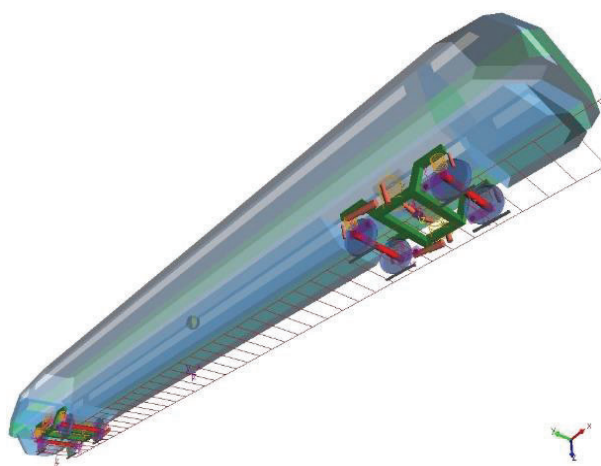


Fig. 5 An illustration of the MBS rail vehicle model
Obr. 5 Ukážka MBS modelu koľajového vozidla

The authors team uses for the research of dynamics of rail vehicle the Simpack software package (**fig. 5**). This software includes a specialized module called Simpack NVH (Noise, Vibration, Harshness). It enables to carry out vibration analysis in Simpack. One can use Simpack NVH to linearize and solve complex models analytically within the frequency domain, saving vast amounts of CPU time. In addition, there are calculation methods in the time domain which take the models nonlinearities into account. In the frequency do-

main, one can use the Linear System Analysis calculation method. In the time domain, one can use the Operating Deflection Shapes of the Non-Linear Frequency Pass (NLFP) calculation method [30].

2.2 Finite element method

The finite element method (FEM) is well known since several decades, and it is widely used in the engineering [31-33]. This approach delivers reliable absolute results in the buckling, strength, heat transfer and fatigue analysis. It is also a state of the art method of the vehicle NVH simulation. Further, it provides reliable results concerning natural frequencies, transfer functions for a single part or for a not too complex system as well as in the higher frequency range (approx. 1000 Hz). However, by a complex rail vehicle FEM model, which contains a structure (body, frame, etc.) and also air cavities (passenger compartment, etc.) a coupled simulation (acoustic-structure) calculation is needed. In such a case, the frequency range is limited to a few hundred Hz (< 300 Hz). The complexity of the model is already enormous, the model can have several million degrees of freedom, which makes the computational effort expensive [25]. The general mathematical description of FE model is well-known as following:

$$\mathbf{K} \cdot \mathbf{u} = \mathbf{F}, \quad (2)$$

where \mathbf{K} is the stiffness matrix, \mathbf{u} is the deflection vector and \mathbf{F} is the vector of external forces.

2.3 Flexible multibody simulation

For analyses of running dynamics and low-frequency vibrations (0 to 30 Hz) of a rail vehicle looking at riding comfort for passenger in a rail vehicle, the method of multibody simulation (MBS) is state-of-the art. Using this method, the vehicle is split in a defined number of rigid bodies, whose degree of freedom to each other and the surroundings is defined by joints.

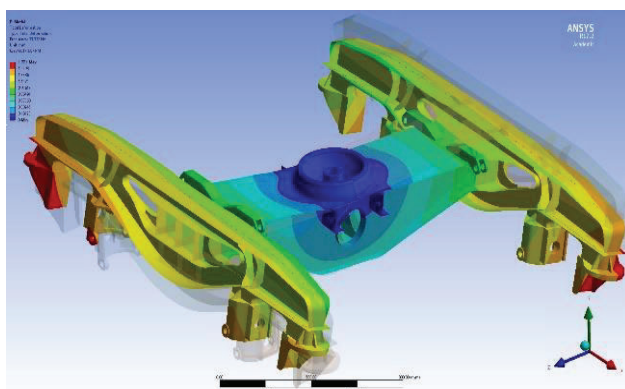


Fig. 6 Eigenmode of a flexible bogie frame
Obr. 6 Vlastný tvar poddajného rámu podvozka

Between these bodies and between bodies and the surroundings force elements can be installed. A big advantage of MBS, for example in comparison to the finite element method (FEM), is the possibility to simulate nonlinear system behaviour in the time domain. To expand the validity to the acoustic frequency range, the structural dynamic behaviour of parts taking part in the transmission of structure-borne sound has to be considered by integrating flexible bodies. To reduce the often very large degree of freedom

of FE-models of flexible bodies, this method uses a modal description of the system [34, 35] and a problem specific selection of eigenmodes (**fig. 6**). Besides the representation of the deformation behaviour of structure-borne sound transmitting bodies a more detailed modelling with nonlinear spatial force elements and modelling of all relevant excitation mechanisms has to be taken into account [36].

2.4 Statistical energy analysis

Through the statistical averaging of the modes the problem can be solved simpler. For that case, the Statistical Energy Analysis (SEA) provides acceptable results for the higher frequency range. The SEA was developed to calculate the dynamic behaviour of complex structures at high frequencies. In comparison with the deterministic methods (e.g. FEM), the SEA derives average energetic values. This is the major limitation of the method. As the method's name indicates, the SEA provides a statistical framework and does not give the exact deterministic solution. In SEA 2 types of averaging will be considered:

- frequency averaging, i.e. averaging of the modes, velocities, powers, and others in a certain frequency band, general in third octave band,
- spatial averaging, i.e. averaging over the points of observation and excitation. All phase relevant information will be lost.

The mathematical description of this method is expressed given by the following power equilibrium equations:

$$\begin{bmatrix} P_i \\ \vdots \\ P_n \end{bmatrix} = \omega \cdot \begin{bmatrix} \eta_i \cdot N_i & \dots & -\eta_{ni} \cdot N_n \\ \vdots & \ddots & \vdots \\ -\eta_{in} \cdot N_i & \dots & \eta_n \cdot N_n \end{bmatrix} \cdot \begin{bmatrix} E_i/N_i \\ \vdots \\ E_n/N_n \end{bmatrix}, \quad (3)$$

where $[P_i]$ is the vector of the input power, $[E/M]$ is the vector of the modal energies of the subsystems, η_n are the internal loss factors (ILF), η_{nn} are the coupling loss factors (CLF) and N_i is the modal density.

In comparison with the FEM, this method is mathematically easy and fast. There is a matrix to be solved and the elements will be directly related to the number of the subsystems. In this method, the number of modes per frequency band (or modal density) acts the major role and the accuracy of obtained results largely depends on it [25].

2.5 Hybrid methods

For the low frequency range, the calculation of the modes is for example done using the Finite Element Method. In the high frequency domain, where high modal overlap occurs, SEA is better suited as mentioned. A predicting gap exists in the mid frequency range. Furthermore, the structure-borne transmissions are not well predicted. To cover the mid frequency gap, e.g. a hybrid FEM/SEA method can be applied. (Also other combinations of methods, e.g. FEM/MBS, FEM/BEM, etc. existing.) The subsystem with the low modal density is modelled e.g. with FEM. The results will be coupled to the SEA calculation. The exact shape of the component is built up in FEM, which is fully coupled to neighbouring elements modelled using the SEA [25].

5 CONCLUSION

The article presented simulation methods, which are widely used in the rail vehicle NVH simulation. The FEM is one of the most powerful and all-round method also in the rail vehicle NVH. The SEA is mathematically easy and fast in comparison with the FEM. One of the main advantages of SEA is that it can help to identify the major contributor in the overall energy of the system. Also it is easy to monitor the effects of changes in the design. The main disadvantages of the method are the loss of phase information, the results are valid for a subsystem and not for a certain point and low frequency problems because of the low modal density at low frequencies of the structures. The MBS is widely used in the low frequency range. However, the implementation of elastic parts condensed with the FEM can enhance the frequency range. The future research of the researchers will be focused on the application of the described methods and procedures to perform the NVH analyses. It is

considered, that this approach will help to identify the negative effects of the operation of a rail vehicle and will contribute to improve the quality of the railway transport.

Nomenclature

NVH	Noise, Vibration, Harshness
MBS	MultiBody System, MultiBody Simulation
BEM	Boundary Element Method
FEM	Finite Element Method
SEA	Statistical Energy Analysis
CPU	Central Processing Unit
NLFP	Non-Linear Frequency Pass
CLF	Coupling Loss Factor
ILF	Internal Loss Factor
M	mass matrix (masses, moments of inertia); [kg], [N·m ²]
B	damping matrix; [N·s·m ⁻¹], [N·m·s·rad ⁻¹]
K	stiffness matrix; [N·m ⁻¹], [N·m·rad ⁻¹]
Q	vector of the external loads (forces, torques); [N], [N·m]
t	time; [s]
$\ddot{q}(t)$	vector of accelerations, angular accelerations; [m·s ⁻²], [rad·s ⁻²]
$\dot{q}(t)$	vector of velocities, angular velocities; [m·s ⁻¹], [rad·s ⁻¹]
$q(t)$	vector of deflections, angular deflections; [m], [rad]
u	vector of deflections, angular deflections; [m], [rad]
F	vector of forces, torques; [N], [N·m]
P_i	vector of the input power; [W]
E/N	vector of the modal energies; [J]
η_n	internal loss factors
η_{nn}	coupling loss factors
N_i	modal density; [kg·m ⁻³]
ω	angular frequency; [rad·s ⁻¹]

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Summary

The main purpose of the NVH analysis (noise, vibration and harshness) in the railway engineering is to study and measure harmful effect of rail vehicle operation. The NVH allows to identify a source of a sound as well as the cause of its origin. The task for engineers of rail vehicles is to reduce or eliminate unwanted noises and other negative effects of vibration and noise. This article is focused on an overview of the known researches outputs related with the NVH analysis in rail vehicle. It also presents the possibilities to perform NVH analyses in a commercial simulation software. Further, the article contains a presentation of the most known and the most widely used methods for analysis of the noise, vibration and harshness (NVH) in the field of rail vehicle.

Resum e

Hlavn ym  c elom NVH anal zy (hluk, vibr cie a tvrdosť chodu) v oblasti  elezni n ho in inierstva je št diium a meranie škodliv ch  cinkov prev dzky koľajov ch vozidiel. NVH anal za umo ňuje identifikovať zdroj zvuku, ako aj pr чину jeho vzniku.  lohou konštrukt rov koľajov ch vozidiel je zn i it alebo odstr niť ne iaduce zvuky a in  negat vne vplyvy vibr ci  a hluku. Tento  l nok je zameran  na prehľad v stupov zn mych v skumov s visiacich s NVH anal zou koľajov ch vozidiel. Prezentauje tie  mo nosti vykon vania NVH anal z v komer nom simula nom softv ri.  alej pr spevok obsahuje prezent ciu najzn amej ch a najroz irenej ch met d na anal zu hluku, vibr ci  tvrdosti chodu (NVH) v oblasti koľajov ch vozidiel.

