Overview of Modern Contributions in Vehicle Noise and Vibration Refinement with Special Emphasis on Diagnostics

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This paper presents certain considerations related to noise, vibration and harshness issues on modern motor vehicles. The first, practical aspect was used toward structuring of the acquired knowledge and relationships, required for proper problem diagnosis. On the other hand, advanced signal analyses are considered. The influence on human body is processed and certain noise and vibration analyzers are presented. This synergy of scientific and applicative approach represents a basis for further research related to this important automotive branch.

Keywords: *noise, vibration, harshness, diagnostics, analysis.*

1. INTRODUCTION

Strong market competition with high demanding customers requires appropriate vehicle systems optimization with special emphasis on vehicle noise and vibrations characteristics. Noise and vibrations of motor vehicles are increasingly important for the automotive industry, especially for vehicle manufacturers and component suppliers. The exterior noise is generally regulated by noise pollution legislation, while the interior noise and sense of vibrations are much strictly evaluated by customers themselves. Toward accomplishing extraordinary vehicle performance, there is a tendency in the vehicle design process of utilization of light weight metals in vehicle components manufacturing.

Lighter weight metals decrease the overall vehicle weight that reduce emissions and improve fuel economy, but lighter vehicle components do not absorb noise and vibrations as well as heavier components, what causes many additional concerns for engineers. Noise, vibration and harshness (NVH) have become increasingly important automotive branch as a result of demands for increasing vehicle refinement. In order to achieve desired vehicle performance NVH engineers should collaborate closely with Powertrain, Electrical & HVAC, Body & Trim, Chassis & Suspension Departments as well as with Assembly Plant Engineers and Suppliers [1]. This synergic approach is indispensable in the design process of a new model. But test procedures, either for redesign purposes or during exploitation, are no less complicated. For their proper implementation multidisciplinary knowledge and skills with sophisticated sotware support are required toward identifying the root causes of faults and problems. This paper provides a short overview of some researches related to NVH refinement issues, with professional approach to diagnostic of practical problems.

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2. CHARACTERISTICS OF NOISE, VIBRATION, HARSHNESS

Noise is defined as any unpleasant or unexpected sound created by a vibrating object and has an increasing importance to vehicle users and environments. Vibration is defined as any objectionable repetitive motion of an object, back-and-forth or up-and-down and represents an important issue closely related to reliability and quality of the vehicle. Harshness is customer perception which creates the impression of lack of isolation from the tire/wheel and suspension system. Harshness is related to the quality and transient nature of vibration and noise, because of vehicle incapacity to absorb vibrations produced by road conditions [2, 1].

2.1 Noise

It is well known that sound is a result of mechanical vibrations which act in the elastic medium. Sound source produces a certain amount of sound energy per time, which means that the sound source is determined by sound power, which does not depend on the characteristic of the environment. On the other hand, sound intensity which is measured on a certain spot depends not only from the power of sound source and distance from it, but also from the amount of energy absorbed by the environment [3]. This explains the significance of sound insulation in qualitative assessment of cabin noise, especially to aerodynamic, road and powertrain noise. related Table 1 shows the percentage contribution of different noise sources, originating from powertrain, into total noise [4].

Table 1. Percent contribution of different noise sources into total noise

Sr. No	Source	% Contribution
I	Engine	22 to 30
II	Exhaust system	25 to 35
III	Intake system	05 to 15
IV	Fan and cooling system	07 to 15
V	Transmission	12 to 15
VI	Tires	09 to 15

According to VW Self Study Program [2], that is mostly dedicated to their technicians for the purposes of diagnostics the most common NVH problems, different types of noise which can be felt in the cabin include:

- Droning
- Beat
- Road noise
- Brake squeal

Droning is the ear drums feel caused by sudden changes in atmospheric pressure that occurs during driving into tunnel at high speed, or climbing to a high altitude. Unpleasant droning can be classified into three types according to a speed and frequency range, as it is shown into Table 2 [2].

Table 2. Speed and Frequency Ranges of Droning

	Speed range [km/h]	Frequency range [Hz]
Low-Speed Droning	Up to 50	30-60
Middle-Speed Droning	50-80	60-100
High-Speed Droning	80 and up	100-200

Beat sounds are the type of noise caused by two sound sources producing sound waves with similar pitches. Pitch is the physical quality of sound, related to the frequency of the wave, estimated by personal perception. The beat sound intensity is the most noticeable within frequency difference 1- 6 Hz. If the difference is less, resulting sound seems as one sound and if the difference is greater than 6 Hz each tone is distinguishable.

Road noise originates from road roughness and tires and because of their harsh interaction, and transmission of generated vibrations to the suspension and body, a resonance can occur. The resonance characteristic of the passenger compartment amplifies the vibration and generates annoying road noise. Road noise can occur at any speed and has a frequency range of 30 to 500 Hz.

Brake squeal is the most common NVH problem related to brake systems. It is high-pitched noise caused by inadequate interaction of brake surfaces [2].

But, the most pronounced noise in vehicle cabin at relatively high speeds is aerodynamic noise. It originates from flow separation what causes strong pressure fluctuations and depends from the vehicle's external geometry including A-pillar, the windshield, seals, cavities, any small openings on vehicle body and geometry of transmission paths through the vehicle structure [1].

A problem manifested by undesired noise in the cabin frequently comes from powertrain noise. From acoustic point of view, powertrain system is an extremely complex source of noise, because it is consisted of a large number of sub-systems, components and parts, whereby all of them generate specific sounds during operation. The most complex "acoustic block" of powertrain system is an internal combustion engine because of different nature of noise sources [3].

Generally, noise of internal combustion engines can be divided into three categories:

•Tonal noises (e.g. generated by turbo-charger, generator, bearings),

•Impulsive noises (e.g. combustion process, injectors),

•Flow noise (e.g. intake flow noise, exhaust flow noise).

These noise components have different characteristics in the time domain as well as in the frequency domain. Impulsive noises of a combustion engine are characterized by a short temporal extension with a high repetition rate. On the contrary, tonal noise segments are usually singular events with a large temporal extension. Impulsive and tonal noise components are typically defined by a deterministic phase structure, whereas flow noise components have more a stochastic character, because of the many physical phenomena caused by fluid flowing, especially expressed during non-stationary working regimes of the engine [5].

Another general division of sound generation and its propagation can be made according to mechanisms of energy transmission, on structure-borne and air-borne paths. While air-borne noise involves a physical mechanism from which sound is generated and radiated (e.g. the hot displacement of fluid mass in the exhaust tailpipe), structure-borne noise is caused from a vibrating source that induces the acoustic energy to travel through solid structures and then to be released as air-borne noise (e.g. the engine structural vibrations). Commonly in car, the structure-borne noise transmission path dominates at low frequency (<200 Hz), while the air-borne noise transmission path dominates above 500 Hz. In the mid-frequency range, both transmission paths have usually the same level of importance. Only an accurate identification and characterization of noise and vibration sources could benefit in NVH refinement [6].

2.2 Vibration

Vibrations are result of acting of compelling force upon an object. Because of a complex structure and many rotating components, there are many sources and types of vibrations on a vehicle. Because of the "telegraphing effect", transmission of vibration to other components, determination of the main source of vibrations is sometimes very difficult.

Inside the cabin, vibrations can be classified as:

- Shake
- Shimmy
- Shudder

The appearance of shake can be felt at the steering wheel, seat, or at the floor. Shake generally has a frequency of 10 to 30 Hz and can be vertical or lateral. Vibration that causes the steering wheel to oscillate is known as “shimmy”. It is characterized by frequency range of 5 to 15 Hz. There are two types of shimmy:

- High-speed shimmy
- Low-speed shimmy

High-speed shimmy occurs when driving on smooth roads at high speeds, within a certain range. Low-speed shimmy occurs when the steering wheel begins to vibrate as a consequence of driving across a bump at low speeds.

Shudder can be explained as brake vibration, transmitted across the brake hydraulic lines to the suspension system, steering system, and the brake pedal. Very often brake shudder can cause a vibration of instrument panel, and sometimes the vibrations of the entire body during braking. It has a frequency of 5 to 30 Hz, within a speed range 60-80 km/h [2].

Vibration order is the number of disturbances created in one revolution of a component and its determination is from essential role in the trouble–shooting process. It is helpful in definition of a component that produces undesired vibrations, but to achieve that, sometimes beside the vehicle speed and engine rpm is necessary to know transmission ratios or pulley ratios, depending on the component whose frequency should be ascertained.

2.3 Harshness

The causes of harshness may be deterioration of vehicle components, damage, or modification of the original equipment. In most cases, harshness is related to chassis components. The impact force from the road surface causes the tires to vibrate. The tires transmit the vibration through the suspension system to the car body. Harshness has a frequency of 30 to 60 Hz [2].

3. CAUSAL RELATIONSHIP OF FACTORS RELATED TO NVH CONCERNS

Systematic approach to NVH concerns is crucial in efficient problem diagnostics. Generally effective diag–nosis technique is "symptom-system-component-cause" [7]. This means that verification of problem is the first step, after that, by using a diagnostic tool it is necessary to determine the system that causes the symptom. The third step is determination of worn or damaged component and final is the identification the cause of the failure.

According to VW Self Study Program [2] and Mustang Workshop Manuals [7] examples of the most common causal relationship of NVH factors, for front wheel drive vehicle with manual transmission, are listed below.

1. Vibration causing concern;

1.1. Engine speed related;
1.2. Vehicle speed related;

1.1.1. Engine assembly;
1.1.2. Engine accessory;

1.1.1.1. First order engine imbalance;
1.1.1.2. Second order engine imbalance;
1.1.1.3. Half order engine imbalance;

1.1.1.1.1-4. Harmonic balancer, Flywheel or torque converter imbalance, Cylinder to cylinder mass differences, Crankshaft imbalance;

1.1.1.2.1. Up and down motion of the pistons;
1.1.1.3.1. Camshaft imbalance;

1.1.2.1-7. Engine pulley, Coolant pump, Generator, A/C Compressor, Power steering pump, Vacuum pump, Accessory drive belt;

1.2.1. Tyre and wheel assembly;
1.2.2. Drivetrain;

1.2.1.1. Rough or irregular road surface;
1.2.1.2. Condition of tires and wheels;

1.2.1.2.1-6. Imbalance, Excessive radial force variation, Excessive radial runout, Excessive lateral runout, Improperly mounted wheel, Tread patterns;

1.2.2.1. Clutch;
1.2.2.2. Gearbox;
1.2.2.3. Final drive;
1.2.2.4. Differential;
1.2.2.5. Drive shafts;

1.2.2.5.1. Drive shafts first order vibrations;
1.2.2.5.2. Drive shafts second order vibrations;
1.2.2.5.3. Drive shafts fourth order vibrations;

1.2.2.5.1.1. Bent drive shaft;
1.2.2.5.1.2. Out of balance;

1.2.2.5.2.1. Inadequate drive shaft angle;
1.2.2.5.2.2. U-joint cancellation;
1.2.2.5.2.3. Worn CV joints or U joints;

1.2.2.5.3.1. Worn CV joints or U joints;

2. Unpleasant droning;

2.1. Transmission of engine and drive line vibrations to the body panel;
2.2. Bending resonance of exhaust pipes;
2.3. Resonance of auxiliary equipment;
2.4. Bending resonance of propeller shaft;
2.5. Resonance of suspension links;
2.6. Transmission of engine vibration;
2.7. Transmission of exhaust noise;
2.8. Transmission of intake air noise;

3. Beat sounds;

3.1. Engine and air-conditioning compressor;
3.2. Engine and power steering hydraulic pump or other accessories;
3.3. Engine and vibrations of the drive shaft;
3.4. Tire non-uniformity;
3.5. Tire and drive shaft vibrations;

4. Brake squeal;

4.1. Worn brake shoes;
4.2. Non-uniform thickness of brake disc or drums;
4.3. Excessive runout;
4.4. Damage or contamination of friction surfaces;

5. Shake vibrations in cabin;

5.1. Roughness of road;

5.2. Tire imbalance;
5.3. Non-uniform tires;
5.4. Bent or out-of-round wheels;
5.5. Driveline;
5.6. Engine;

6. Shimmy vibrations in cabin;

6.1. Roughness of road;
6.2. Tire imbalance;
6.3. Non-uniform tires;
6.4. Bent or out-of-round wheels;

7. Brake shudder vibrations;

7.1. Extended periods where the vehicle is not in operation;
7.2. Brake disc surface irregularities due to foreign agents (oil or grease, antifreeze, etc.);
7.3. Deformation of brake disc or drum due to poor installation;
7.4. Thickness variation;
7.5. Improper wheel tightening procedure;

8. Harshness;

8.1. Front suspension;
8.2. Rear suspension;

9. Undesired engine noise;

9.1. Abnormal combustion;
9.2. Friction (Poor lubrication characteristics);
9.3. Tolerance slap (Wear of moving parts);

9.1.1. Detonation;
9.1.2. Backfiring;

9.1.1.1. Inadequate fuel;
9.1.1.2. Incorrect ignition timing;
9.1.1.3. Carbon deposits in the combustion chamber;

9.1.2.1. Excessively lean fuel mixture;
9.1.2.2. Incorrect valve timing;
9.1.2.3. After fire;

10. Exhaust noise;

10.1. Exhaust gas sounds;
10.2. Exhaust system misalignment;

10.1.1. Pulsating;
10.1.2. Air column resonance;
10.1.3. Air stream sounds;

10.2.1. Mounting brackets;
10.2.2. Failed hangers;

As to the examples above, it can be concluded that many NVH problems may possess the same causes (shake/shimmy vibrations in cabin). The corresponding structure of cause-consequence rules is essential for proper diagnosis of technical systems and for the prospects of building an expert system. According to the recommended diagnostic procedure "symptom-system-component-cause", second step is determination of system that causes the problem. But, related to NVH issues, it is a very complex term. For example, compelling force of exhaust system is generating a pulsating pressure in the exhaust manifold what causes production of acoustical energy. That energy is transmitted across exhaust pipe and with certain engine firing frequency and vibrations caused by reciprocal motion of pistons, the resonant behaviour of body may occur what presents a complex NVH concern.

So in this case, the problem is not within the chassis system than in the exhaust system, which is a source of vibrations. Second example is vibrations of instrument panel caused by shudder of rear brakes. Because of that, vibration transfer characteristics, as the relationship between vibration transmissibility and excitation frequencies, should be extensively taken into account. Accordingly, supplemented diagnostic procedure can be proposed, which predicts the second step as the most comprehensive due to determination of functional system which involves definition of the source, transfer and reactive factors. The proposed new diagnostic technique can be presented as "symptom-functional system-source system-component-cause", which will be examined in the future work.

4. RELATIONSHIP OF NVH CHARACTERISTICS WITH ERGONOMICS

Exposure to noise and vibrations affects people in different ways, from reduction of work efficiency, increased health risks from potential diseases. Serbian legislation does not strictly define regulated permissible values of vibration exposure. Consequently, ISO standards, such as ISO 2631 are used for whole-body vibration (WBV), ISO 5349 are related to hand arm vibrations (HAV) and ISO 8041 provides regulations for design and classification of measuring equipment. Directive 2002/44/EC defines daily exposure limit values standardized to an eight hour reference period as 1.15 m/s^2 for WBV and 5m/s^2 for HAV.

Also, signal values are standardised to an eight hour reference period as 0.5 m/s^2 for WBV and 2.5 m/s^2 for HAV [8]. The list of regulatory acts, Directives and Regulations, related to European legislation for vehicles is specified in the paper "The influence of Slovenian traffic safety agency on motor vehicle legislation" [9].

The occurrence of resonance has a significant role in both many physical processes and in the assessment of harmful effects on human health. The human body is composed of subsystems that have different natural frequencies. Because of the subsystem interaction, various subsystems vibrate with different amplitudes, depending on their resonant frequencies in certain body position. One of the most important subsystems is the stomach that has a resonance frequency of 0.8-8 Hz [10, 11]. Figure 1 shows resonance frequencies of various body parts in different positions.

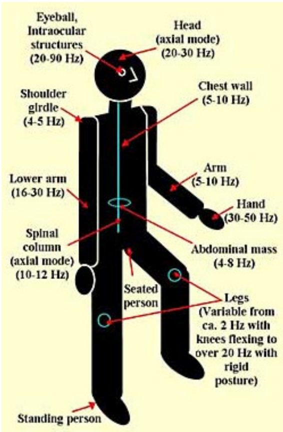

Figure 1. Resonance frequencies of various body parts [21]

According to the research, it has been found that people are more sensitive to the whole body vibrations (WBV) [12]. Their negative impacts are mostly noticeable on comfort characteristics, perception and human health. According to the standard ISO 2631 the sense of discomfort is more dominant with increasing duration of vibration and their random appearance, especially from different directions. With increasing frequencies above 10Hz the sense of discomfort is less noticeable. Negative impacts on the perception of the driver are caused due to the displacement of the image in the retina of the eye, as the result of vibrations. When an object, or an eye, is vibrating at frequency less than 1Hz, the eye can follow the movement and the picture is clear. Problems occur at frequencies above 2-3 Hz, when object tracking becomes difficult and picture in the eye becomes muddy. Related to the human health, the most dangerous are the vibration frequencies of 45-100 Hz with amplitudes above the 100□m, while the vibrations less than 30Hz may seem pleasant and soothing [8]. Likewise, some other study has examined operator's reaction time in addiction to the whole body vibrations and the most detrimental influence was observed at vibration frequency of 5Hz, with reaction times typically increasing between 50 and 70 ms [13].

As vibrations, noise also has complex negative impacts on human health. It was believed that the effect of noise is confined to the organ of hearing, but today on the basis of extensive tests it has been found that the effect is more complex. Influence of noise on human body is reflected through a wide range of operations at most on the central nervous system. Besides, noise affects on senses of voice and speech and cause poorer colour recognition [14]. Because the sense of noise is strongly individual assessment, the perceived noise quality is predominantly influenced by the occurrence and characteristics of individual disturbing noise components. Related to that, the Institute for Combustion Engines of the RWTH Aachen University developed a methodology, which allows the extraction of audible noise components so that they can be listened separately with the quantification of the annoyance level of these components [5].

Noise and vibrations, as the most important catalytic parameters of safety possess the essential significance for effectiveness of the global system consisting of the driver, the vehicle and the environment.

5. NVH DIAGNOSTICS

Vibration analysis is used to determine the operating and mechanical condition of equipment. From numerous techniques of predictive maintenance, vibration monitoring is undoubtedly the most effective technique to detect mechanical defects in rotating machinery within industrial facilities. Predictive maintenance, basically a condition-driven preventive maintenance, utilizes a combination of the most cost-effective tools to obtain the actual operating conditions of the equipment, so on the basis of collected data, the maintenance schedules can be precisely determined. Vibration analyses are mostly applied for diagnosis of rotating equipment such as steam and gas turbines, pumps, motors, compressors, paper machines, rolling mills, machine tools and gearboxes [15].

But generally, in industrial purposes reliability of just vibration analysis is disputable for large or complex machines, or in noisy parts of a plant. In these circumstances, complex monitoring systems, comprised of advanced signal preprocessing and feature extraction tools with sophisticated analysis software, are required. Very often, these systems include comparative analysis of vibration and acoustic emission toward disturbance elimination in order to achieve high effectiveness of designed system in non-stationary working conditions.
Related to the above mentioned, it can be concluded that benchmarking between industrial and automotive engineering can be very helpful in developing new sophisticated systems and automotive diagnostic devices based on vibrations.

This chapter also provides a short overview of some special tools for diagnosis and testing of NVH concerns on motor vehicles. Two most used non-electrical automotive vibration analyzers are resonant reed tachometer and sirometer (vibratach) [16]. Both should be hold against a vibrating component. The first one displays a frequency of a component by the vibrations of reed on the scale, with measuring range of 10-80 Hz. The operating principle of sirometer is based on adjustment of wire's length, untill finding its resonant frequency. The ChassisEAR is a versatile electronic listening tool that allows the user to listen amplified sounds through a professional set of headphones. The tool has multiple microphone inputs that can be placed in different sections of the vehicle. During road testing, while the vehicle is in operation and when many components under load produce specific noise, distinct from sounds in non-load conditions (e.g. bearings), microphones should be placed on parts or areas in the vehicle, suspected as being the possible fault source [2].

Examples of well-known models of electronic auto–motive vibration analyzers are EVA II, Vetronix MTS 4000 NVH and Pico Diagnostics NVH kit. These models and many others, beside vibration measurements provide functions for determination the vibration order of specific components and localization of problem source. In this paper, features of Pico Diagnostics NVH kit (Figure 2), as one of the most sophisticated auto–motive vibration analyzers, is presented. For performing vibration testing, besides Pico Diagnostics NVH kit it is necessary to link a laptop, data link USB conncector, e.g. ELM 327 (for

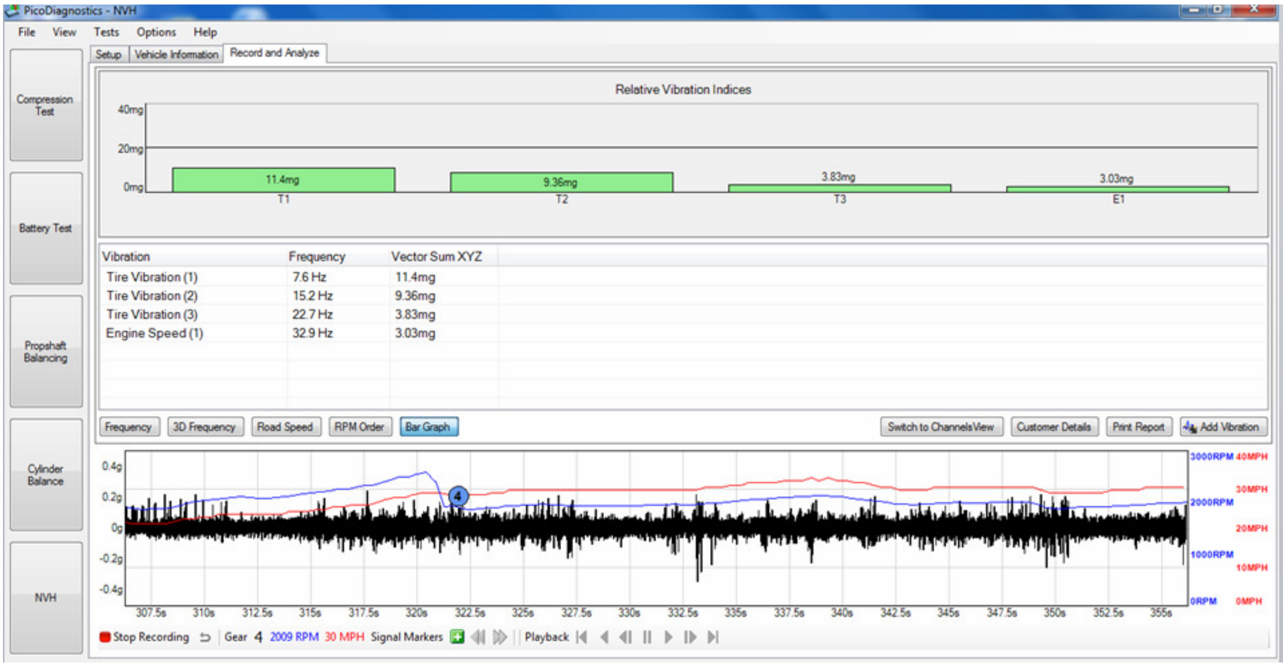

Figure 2. Pico Diagnostics NVH working environment

information about engine rpm) and PicoScope 4000 Series Automotive oscilloscope. After connecting of ELM 327 to OBD II connector in the vehicle, PicoScope software is asking about: engine configuration, type of drivetrain, tyre size, applied sensor type, type of transmission, number of gears, gear ratios and final drive ratio. The sensor is usually mounted on the seat rail, or in the engine compartment. On this basis, software is capable to determine road speed and recognize the selected gear ratio, while recording vibrations. Figure 2. shows working environment of Pico Diagnostics NVH, with selected feature of bar graph, during vibration recording in driving.

According to the calculated road speed, first, second and third orders of tire vibration are presented. Also, according to the engine rpm, frequency of the first order of engine vibration is determined. On the basis of Pico specifications, each amplitude higher than 10 mg, with the customer complaint should be considered [17]. As can be seen from Figure 2, beside bar graph frequency, 3D frequency, road speed and rpm order mode can be selected. This software is highly user-friendly because it enables saving of recorded data, what is very useful for purposes of explanations to the customers before and after the repair. Also it can be used as system for acquisition because it enables exportation of data to CSV (Comma-Separated Values) for advanced analysis.

7. ADVANCED TECHNIQUES, METHODOLOGIES AND INNOVATIONS IN VEHICLE NOISE AND VIBRATION REFINEMENT

For application any of advanced techniques in vibration analysis it is necessary to know a natural frequency of the examined component or structure. Very simple and extensively used in practise is bump test. To perform this test it is necessary to fix a vibration sensor to the body whose natural frequency is required. The operating principle is based on counting the number of cycles of free vibrations of the body, produced directly after impact by the hammer. In this way, time waveform of a bump test is created. Otherwise, results of bump test may be displayed by application of Fourier analysis. It provides transformation of a time waveform into a spectrum of amplitude vs frequency values. Fourier analysis sometimes is referred as spectrum analysis, and can be done by Fourier transformation (FFT) analyzer [15]. One method that combines application of a bump test and FFT analysis has proved suitable for optimization of dynamic behaviour of modular superstructures of vehicles for special purposes, for example for firefighting vehicles, which are characterized by harsh exploitation conditions and special requirements for this type of vehicles. Therefore a comprehensive, dedicated approach in optimization of superstructures in terms of stress, deformation, fatigue, noise, comfort and effectiveness should be applied [18]. Useful benchmarked techniques and methodologies for vibration vehicle refinement can be taken from aviation industry. Researches reveal that understanding the character of vibrations from propulsion group is very important for modelling adequate response/isolation of initially discovered vibrations. One of papers examines changes in low-frequency vibration spectrum located in the engine of Lasta airplane. The vibration spectrum is induced as a consequence of changing quality composition of air/fuel mixture, while testing on a flying plane equipped, with piston propelled propulsion group. The aim of testing was to establish impact from changes in engine working conditions on low frequency vibration spectrum of the engine and to establish the critical vibration regime toward contribution of lowering vibration level transferred on seat of the pilot and then on the pilot's body. Low frequency vibration spectrum of technical systems expresses a range that has largest impact on the structure fatigue and failure, as well as plane crew fatigue [19].

Taking that into account, comprehensive methodologies of vibration testing in aviation industry can be very applicable to automotive purposes.

According to papers [19, 20] general framework/model of vibration testing can be specified, as follows:

1. Pre-Testing Procedures:
1.1. Theoretical vibroanalysis;
1.2. Selection of testing;
1.3. Determination of limiting vibration levels;
1.4. Selection and itegration of testing and measuring equipment;
1.5. Selection and defining of vehicle profile;

2. Testing:
2.1. Execution of required testing;

3. Post-Testing Procedures:
3.1. Chronological audit of testing process;
3.2. Discussion and interpretation of results;
3.3. Functional verification of recorded results;
3.4. Processing and presenting of recorded results from testing process;
3.5. Results analysis with aim toward system correctness;

In order to achieve high effectiveness of any acoustic or vibration analysis, proper feature extraction is necessary. Feature extraction is the most important step in signal processing, because it provides extraction of the most important information from the original signal. Feature extraction techniques are determined based on the nature of the signals. According to the nature of the original data, there are two types of feature extraction: stationary (frequency-based) feature extraction and non-stationary (time-frequency based) feature extraction. For analyzing acoustic and vibration signals, time-frequency representation is of great interest. Most often, for representation in frequency domain, Fast Fourier transform (FFT) is used. Advantage of time-frequency representation of signal is providing the information about evolving the spectral content of the signal with time. Traditional time-frequency analysis use time-frequency distributions, which represents energy or power of waveform signals in two-dimensional functions of time and frequency. The most popular time-frequency techniques are Short-Time Fast Fourier Transform (STFFT), Continuous Wavelet Transform, Discrete Wavelet Transform and Wigner-Ville Distribution [38, 3].

Short-Time Fast Fourier Transform (STFFT) which is characterized by division of a longer time signal into shorter segments of equal length, multiplied by the Fourier transform separately on each shorter segment, is very often used for representation of signal in time-frequency domain. The magnitude of the STFFT is called the spectrogram. Spectrogram is representation of the signal in three dimensions: time, frequency and amplitude [3]. Example of spectrogram obtained by Pico Diagnostics NVH device is presented on Figure 3.

For 2D spectrogram representation, e.g. in Matlab, time is on the horizontal axis, frequency is on the vertical axis and amplitude of the signal is given by a color and presents third dimension. For automotive NVH analysis, spectrogram can be very beneficial. E.g. various statistical features like Kurtosis, Variance, Skewness, Shape factor, Root mean square, Absolute mean, Zero crossing rate and Maximum Peak can be computed from spectrogram and used for artificial neural network training in order to classify different internal combustion engine faults [39]. On the other hand, T2 control charts, as a powerful statistical tool used to detect failure, can be applied on acoustic signals of internal combustion engines in order to detect fault modes of operation [3]. These comprehensive tools are highly applicable what enables them wide perspectives of application in the future.

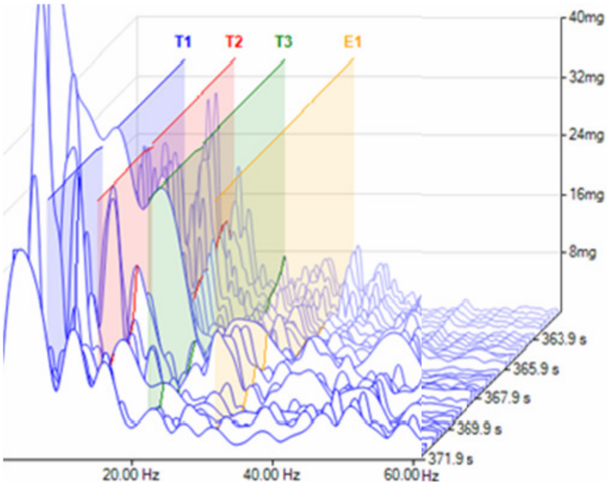

Figure 3. Spectrogram of recorded vibration signals

The essential importance of application of adequate simulation technique for NVH refinement is observable in the vehicle development process also. Due to complexity of NVH refinement and synergic influence of many factors on its performance, it is difficult to single out a particular simulation technique as the most appropriate. Instead, the most optimal technique should be chosen according to the project specifications and availability of resources and time. The most common computer aided techniques (CAE) are:

- Finite element (FE)
- Boundary element (BE)
- Computational fluid dynamics (CFD)
- Statistical energy analysis (SEA)
- Transfer path analysis (TPA)
- Multi-body dynamics

Finite element (FE) methods are characterized by geometric representation of each component, by a set of numerous small sized elements, with defined performance parameters, described by the element mass matrix, the element stiffness matrix and the ‘response’ vector. Application of FE methods, related to NVH issues, is in generating: Trimmed body FE model, (Interior) cavity models, Fluid–structure boundaries, Chassis models, Powertrain model or Bushing and connections [1]. For example, Powertrain FE models generally are not very complicated but demand very long time due to the complexity of powertrain system. Well known methods are powertrain bending analysis, powertrain forced response analysis and powertrain mount vibration analysis. Powertrain bending analysis is very useful mainly due to the fact that it gives accurate information on bending frequencies so that measures can be taken to avoid getting these modes excited by engine or other subsystem operations [21].

Boundary element (BE) methods are commonly used for sound radiation simulation of engine and exhaust shell.

Computational fluid dynamic (CFD) methods are used to simulate and predict aerodynamic and aeroacoustic behaviour of the vehicle.

Statistical energy analysis (SEA) is convenient for noise simulation and prediction, with potential application in optimizing material thickness of sound package. The basic principle of SEA is to solve equations for energy balance between individual sub-structures, that can be described by their acoustical or vibration energy within their boundaries and energy flow to all neighbouring sub-structures [22, 23].

Transfer Path Analysis (TPA) is a well-known method which can help to identify paths and rank them relative to their share in total noise and vibration in vehicle compartment [24]. TPA concerns a product's actively vibrating components (such as engines, gearing systems or turbochargers) and the transmission of these vibrations to the connected passive structures. TPA is particularly useful when the actual vibrating mechanisms are too complex to model or measure directly, as it allows us to represent a source by forces and vibrations displayed at the interfaces with the passive side [37]. The principal concept of TPA is to sum up all individual noise paths, obtained by multiplication of individual noise sources by respective noise sensitivity to the full vehicle noise or vibration response. Identifying the transfer paths of noise and vibration in vehicle helps NVH engineers to find key critical paths which transmit noise and vibration. Each path starts from an active component like engine, continues through the passive component of chassis, and ends up to target points at the passenger position, such as interior noise, seat vibration, steering wheel or compartment floor vibration [25,26].

Depending on the application, TPA techniques are very often basis for some more sophisticated methods. Eisele and Wellmann presented a method of vehicle interior noise simulation (VINS) to estimate interior sound of a car. The simulation is based on the measured or calculated excitation forces and transfer functions for subsequent calculation of the interior noise in the time domain [27,28,29].

Similar approach, which is related to vibrations, is the vehicle interior vibration simulation, known as VIVS method. Sakhaei and Durali applied VIVS method for engine mount optimization [30]. According to VIVS method acceleration amplitude of the vehicle interior can be defined as chain multiplication of transfer functions, apparent mass of the engine mounts and vibration engine measurements, as it is expressed by equation (1):

$$a_{\mathrm{int},j}(N,f) = H_{1,j}(f)\cdot H_{2,j}(f)\cdot H_{3,j}\left(f\right)\cdot a_{engine,j}(N,f) \quad (1)$$

where $a_{\mathrm{int,j}}(N,f)$ is the acceleration amplitude of the vehicle interior, defined by engine speed N and each frequency f.

$H_{1,f}(f)$ is the mount transmissibility function (in frequency domain f), which is the ratio of the acceleration on engine mount body side to acceleration of the engine mount at engine side, as defined in equation (2):

$$H_{1,j}(f) = \frac{a_{body,j}}{a_{engine,j}} \quad (2)$$

$H_{2,j}(f)$ represents virtual mass of the body, according to equation (3):

$$H_{2,j}(f) = \frac{F_{body,j}}{a_{body,j}} \quad (3)$$

$H_{3,j}(f)$ is the body transfer function in vibration transfer from engine mount location to the vehicle interior target point, equation (4):

$$H_{3,j}(f) = \frac{a_{t\arg et,j}}{F_{body,j}} \quad (4)$$

According to experimental results this method needs less analysis time than classical TPA methods [30].

Well known example of multi-body dynamic solution package if ADAMS simulation, which can be also used for optimization of the powertrain mounting system. With respect to ADAMS capabilities such as simulation of powertrain motion and mount deflection due to driveline loads and vehicle accelerations, simulation of the powertrain rigid body and simulation of the motion of major engine components, Kuipers and Powell developed a hybrid model capable to predict interior noise. According to cylinder pressure and engine rpm, firstly dynamic forces at each mount position are predicted by ADAMS and secondly, noise transfer functions are determined for the prediction of vehicle interior noise [31]. Also, in order to achieve prediction of the interior noise, Kim proposed a hybrid transfer path analysis [32] and Plunt used the same instrument to find and fix NVH problems, especially in the later development stages [33]. Another important application of ADAMS/VIEW software was for the analysis of passengers vibration comfort, according to international standard ISO 2631, through an oscillatory model of intercity bus. Comfort was considered in different positions of the interior in dependence of asphalt-concrete conditions. The results of simulation showed that the vibrations mostly endanger the comfort of passengers in the rear end of the bus, while the driver's comfort was not threatened [34].

Noise prediction can be practically utilized in the developing of noise cancellation systems. Passive noise control is characterized by good design, well balanced structure, symmetry, avoidance of resonance and good aerodynamics. A poor aerodynamic characteristic causes turbulent noise with unwanted distribution of energy across the frequency spectrum, known as broadband noise. Because of its random nature it is hardly predictable. As it is shown in Table 1, exhaust noise has a significant share in total noise. That is why the application of passive mufflers is justified. They are characterized with sound absorbing materials for attenuation of high frequency noise and enlarged diameters of pipes toward reducing back pressure and discontinuities in the gas flow. The other types are dispersive mufflers whose operating principles are based on dissipation of noise energy, while the reactive mufflers use acoustic resonances to reflect noise energy back to the source [35].

In terms of vibrations one approach of passive control is installation of counter rotating shafts toward cancelling undesired vibrations, originated mostly from components at twice of the engine rotational speed. It may cause in enhancement of weight and friction losses with power reduction up to 10%. According to that, stiffness optimization of the rubber powertrain mounts is more attractive approach. Taking into account tasks of powertrain mounts such as holding the static engine load, limitation of engine movement, isolation of powertrain from chassis it can be concluded that low stiffness of mounts may cause large engine displacement what generates low frequency vibrations with high probability of resonance with suspension system. In that case, handling and stability characteristics of vehicle are disturbed. On the other side, low internal damping may cause unpleasant noise with high resonance peak. [35, 36]. Significance of passive vibration damping has been found remarkably important because of passive safety. For the clearly stricter safety requirements for aviation industry, determination of efficiency of passive vibration damping on the pilot seat of piston propeller aircraft, has found that rubber absorber built in under the pilot seat achieves desired vibration damping on the seat in vertical direction, in all flight profiles. Considerable effectiveness was reached at frequencies below 100 Hz, what is very important in terms of long-term exposure, what negatively affects on mental and physical condition of the pilot and increases body fatigue [40]. Besides, the other approach showed that different potential connections of pilot seat to the cockpit floor may result in passive vibration reduction [41]. These important insights from aviation industry may positively affect on automotive passive vibration control.

Because of many disadvantages of passive noise and vibration control from the mid 70's, comparatively with the development of digital signal processing (DSP), different concepts of active noise and vibration control (ANC/AVC) have been applied. Validity for research and development of sophisticated engineering solutions of active control are less energy losses of usage of electronics than from a soft structure. Basic idea of ANC/AVC systems is to superimpose the unwanted signal with the same amplitude of the opposite phase. For innovations in automotive area, technologies from military and aircraft industry are very often used. The basic element of ANC is loudspeaker, while the AVC system includes actuators, such as active engine mounts for compensation of the displacement between engine and a car body and inertia shakers for cancellation of the disturbing vibrations through generating force of the opposite phase. From well-known companies, ContiTech has implemented prototypes of AVC systems in various test vehicles, while Honda has developed a series production of ANC/AVC system due to cylinder cutoff operation [36].

8. CONCLUSION

This paper provides a brief overview of certain considerations and a review of literature on the analysis techniques and validation methods related to NVH issues on modern vehicles. Due to strong market competition and highly demanding customers there is a tendency for comfort advancement on the one side but also there are needs for production savings on the other side. That is why many new innovations can be expected toward achieving optimal NVH refinement solutions in the future.

In this paper the importance of NVH characteristics in terms of the overall quality of vehicle with impact on ergonomics was considered. Advanced classification of possible NVH problems along with causal relationship of the relevant factors is presented. The above structural review could be helpful for diagnosis of practical problems and could be of great importance for the prospects of building the intelligent decision support systems. Specialized devices used for diagnostic purposes on vehicles are described. Sophisticated engineering solutions and concepts within NVH refinement are shown and numerous methods and tools for noise and vibration analysis are specified.

The paper also presents the starting base for future work, which could be based on the application of certain multivariate analysis for a comprehensive assessment of the NVH characteristics of vehicles. This can be of great importance for improving the methods of predictive maintenance with determination of the reliability of certain vehicle components and systems. One direction of future research could be building of expert system, applied for problem diagnosis by using noise and vibration features. It should be noted that the foregoing considerations and prospects of development are fully adjustable for commercial vehicles with even greater importance of application.

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ПРЕГЛЕД САВРЕМЕНИХ ДОПРИНОСА У ОБЛАСТИ КОНТРОЛЕ И УНАПРЕЂЕЊА КАРАКТЕРИСТИКА БУКЕ И ВИБРАЦИЈА МОТОРНИХ ВОЗИЛА СА ПОСЕБНИМ АКЦЕНТОМ НА ДИЈАГНОСТИКУ

Д. Матијевић, В. Поповић

У овом раду приказана су одређена разматрања везана за карактеристике буке и вибрација савремених моторних возила. Поред научног, проблематика се разматра и са практичног аспекта у циљу структуирања потребних знања, неопходних за правилну дијагностику проблема. Такође се разматрају напредне анализе сигнала буке и вибрација. Ова синергија научног и практичног приступа представља основу за даља напредна истраживања.