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Identification of sources, propagation and structure of vibrations affecting men in means of transport based on the example of automotive vehicles

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IDENTIFICATION OF SOURCES, PROPAGATION AND STRUCTURE OF VIBRATIONS AFFECTING MEN IN MEANS OF TRANSPORT BASED ON THE EXAMPLE OF AUTOMOTIVE VEHICLES – Vol. 1

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Summary

Vibration problems are very important for vehicle dynamics, especially due to safety and comfort. The range of impacts vibrations exert on a vehicle driver is very broad, starting from the feeling of discomfort to safety hazards caused by vibrations at resonant frequencies of specific organs, thus affecting the driver's responses. Therefore, it is important to study the paths of vibration propagation from their sources into the human organism and to assess the vibration exposure for different input function conditions.

In a decided majority of cases, modelling of the vehicle vibration dynamics is based on the assumed input functions reflecting sources of vibrations, e.g. the random ones caused by road irregularities, and they are identified at testing stations featuring vibration inductors characterised by sinusoidal or random input functions. The range of applications of models thus developed is very broad, however, the selection of publications addressing the impact on men is definitely more limited, the reason for which is the difficulty in reflecting biodynamic phenomena taking place in the human-vehicle-road (HVR) system as well we the fact that input functions are brought down to a single source, namely the road irregularity.

This book provides a discussion on the results of studies the author was conducting for several years, addressing the impact exerted by operating parameters of the engine and the power transmission system as well as the vehicle's technical condition and service factors of the suspension system components on the vibrations being generated. The author proposed specific methods dedicated to identification of the vibration structure in the function of time, frequency and time-frequency distributions, compared characteristics of the vibration structure of wave propagation in three orthogonal axes as well as identified the vibration distribution in a vehicle structure. Ultimately, such a wide range of experimental studies and analyses enables accurate assessment of the human exposure to vibrations in means of transport based on multidimensional analysis of the vibration exposure time for successive frequency bands. It may also initiate a new approach to experimental modelling and identification of the oscillatory wave propagation in a vehicle structure.

In terms of the vibration propagation analysis from the perspective of safety aspects, the publication addresses methods of testing oscillatory phenomena taking place in the vehicle suspension system, being responsible for the contact between the wheel and the road pavement. Oscillatory comfort was studied based on vibration signals in points of the impact exerted on the human organism by general vibrations propagating through the feet and the lumbosacral spine section. However, the objective nature of the feeling of comfort and discomfort may lead to disturbances in the human organism, and consequently to safety hazards related connected with vehicle driving. It is exactly for this reason that studies and collective analyses should be conducted in the fields of safety and comfort.

Results of the studies discussed in the book were obtained in the course of numerous experiments conducted with actual vehicles by application of three types of vibration input functions: kinematic, at a harmonic station of programmable frequency and amplitude structure, input functions caused by road irregularities and aerodynamic phenomena as well we those isolated from the road irregularity-induced and aerodynamic input functions caused by the engine and the power transmission system. The quantities recorded each time were the vibration accelerations measured simultaneously at several points of the vehicle structure in three

orthogonal axes (X – in parallel to the vehicle's longitudinal axis, Y – horizontally and perpendicularly to the vehicle's longitudinal axis, Z – vertically and perpendicularly to the vehicle's longitudinal axis).

In the first part of the book, the author has discussed the results obtained while studying the impact of the vehicle operating parameters as well as technical condition of the suspension system components on vibrations, and special emphasis has been put on describing how passengers are affects through feet. Studies of the impact exerted by the technical condition of the suspension system components and the chosen operating parameters of a vehicle on the propagation of vibrations generated by a road wheel vertical motion to the vehicle structure are particularly important in cognitive terms for the analysis and identification of the vibration sources and propagation in vehicles. The purpose of the said studies was to identify factors affecting the propagation of vibrations caused by the dynamic impact of road irregularities on wheels of a moving vehicle. The aspects analysed included the accelerations of vibrations of the suspension system components and of the vehicle floor panel generated by the kinematic input function and affecting the vehicle wheel. For the sake of accurate analysis of both the stationary and non-stationary parts of signals, an algorithm for automatic identification of the signal's stationary characteristic and a division into successive time windows were developed. The research methodology proposed and a dedicated analysis of results enable comparison of the vibration dynamics between specific frequency bands. Also mathematical and programming algorithms were developed, allowing for in-depth analysis of automotive vehicle structure vibrations. The influence exerted by selected factors on vibrations was assessed based on energy and frequency measures. Furthermore, the author developed time and frequency measures for the vibration structure as a function of time of exposure to vibration for defined frequency bands and a frequency resonance function for the sake of studying the influence of technical condition of suspension elements and of the vehicle operating parameters on vibrations. These measures demonstrated a considerable susceptibility to changes in the technical condition of suspension elements and in the vehicle operating parameters with regard to the assessment of human exposure to vibrations.

The second part of the book addresses studies of the engine and the power transmission system considered as sources of vibrations in automotive vehicles. With regard to differences in the human perception of vibrations depending on the action direction, the engine was analysed as a directional vibration source. Having assumed such an approach, one could assess the energy fraction of vibrations propagating in 3 directions as well as analyse their dynamics and determine the predominant direction and frequency components of the vibration source. The author has also described propagation paths for whole-body vibrations (WBV) starting from the source (i.e. the engine) towards the driver and passengers, at points where lower limbs as well as the lumbosacral spine section are affected.

What is required in order to consider the engine as a source of vibrations in a moving vehicle is an analysis of the impact exerted by other mechanisms of the power transmission system on the vibration propagation from the source. And bearing the vibroacoustic emission in mind, one of the most crucial mechanisms is the transmission.

This part of the book provides results obtained in the studies of the influence exerted by basic operating parameters of the engine, namely rotational speed, and of the transmission, i.e. gear ratio at successive gears, on the propagation and impact of vibrations in a vehicle-human system. For this purpose, a series of measures was compared and some additional new measures were developed as energy estimators of the vibration spectrum and energy estimators of the vibration TFR, which represent frequency as well as time-frequency distributions of vibrations.

For the sake of verification of the methods developed for the vibration source identification in vehicles, results of vibration studies conducted in a moving vehicle have been discussed. The method proposed for identification of components of road irregularity induced vibrations for a moving vehicle may be brought down to comprehensive laboratory and road tests of the same vehicle while maintaining identical engine and power transmission operating parameters. It can be achieved by isolating components correlated with the signals obtained in the course of laboratory tests of a motionless car, excited to vibrate by an engine operating at a constant rotational speed and with the given transmission gear ratio, from the recorded signals of directional vibration propagation of a moving vehicle's load bearing structure. The foregoing is most evident in the difference spectrum function defined, one which represents the frequency distribution of absolute values based on the difference of vibration spectra obtained in road and laboratory tests.

The book also addresses an experimental approach to exposure to WBV penetrating the human organism through the floor panel via feet. Different evaluation methods have been compared for the assessment of the influence exerted by technical condition of the vehicle and the power transmission system on the human exposure to whole body vibration. Attempts to use the acceleration dose and equivalent static compressive stress for the assessment of health effects of WBV transferred from the floor panel, according to methods described in ISO 2631-5, have been discussed as well.

Based on an analysis of such a vast selection of study results, bearing in mind that the research purpose was to identify sources, propagation and structure of vibrations affecting men in means of transport based on the example of automotive vehicles, a decision has been made to extend the studies with an analysis of the vibration energy dissipation across the vehicle structure. It will enable assessment of the damping properties of the vehicle structure and its equipment, and may prove to be a valid source of information to be applied while designing eliminators and dampers of vibrations propagating into the human organism. The notion of vibration energy dissipation is inextricably linked with the wave propagation phenomenon, being most commonly described by means of wave propagation velocity derivatives. What matters more in terms of the vibration related phenomena and their impact on men is the energy-oriented approach. Having established a correlation between energy measures and dynamic properties of vibrations or their TFR distribution, one can develop dedicated measures of propagation and dissipation of vibrations in a vehicle structure from the perspective of their impact on the vehicle passengers. Based on satisfactory results of the efficiency assessment for the measures proposed in the book with reference to the studies of propagation of vibrations and how they are affected by technical parameters of the suspension system, the engine and the transmission, specific measures of the vibration energy dissipation at structural points of a vehicle have been proposed.

The measures developed enable observation and assessment of the energy and amplitude dissipation of vibrations in the domains of time, frequency and TFR. The dissipation measures are correlated with vibration signals of the vibration sources envisaged as int signals. In order to verify the efficiency of the measures proposed for the vibration dissipation in a vehicle structure, analytical experiments were conducted, comprising assessment of the susceptibility of the said measures to changes of the input function parameters. The source of vibrations was assumed to be the engine and the transmission. The measures of vibration dissipation in automotive vehicles have been defined and verified. They enable the vibration propagation and damping to be analysed and assessed by application of simple energy measures in the domains of time and frequency. The measures envisaged can also be used in experimental studies, which has been confirmed by the results of validation experiments. Directional distributions of the said coefficients make it possible to determine the vibration damping characteristics and the directional propagation, whereas by comparing the values obtained at the selected structural points in the propagation path, one can assess the dynamics of vibration damping or suppression as well as determine the most exposed locations.

The study results discussed in the book as well as the methods developed for the sake of analysis and assessment of vibrations have displayed a considerable application potential. The author has proposed several concepts of vibration monitoring systems to be used in vehicles for diagnostic purposes, for monitoring the state of comfort and safety as well as for vibration "management" by means of active insulation and damping systems.

The overall body of problems discussed in the book is also crucial in cognitive and utilitarian terms, which stems from an increasing share of forced stops while travelling with means of transport due to larger traffic volume and growing congestion. These factors are responsible for intensification and growth of the fraction of exposure to vehicle vibrations at stops, experienced by all vehicle users, the sources of which should not be sought in road irregularities and aerodynamic phenomena but exactly in the operation of the engine and the power transmission system.

Nomenclature

A_{wmax}	Maximum transient vibration value
$D_{TabsTFR_i}$, $D_{S_{TabsTFR}}$	TFR directional dispersion factor for i-direction, total TFR dispersion factor
D_{Tabs_i}, $D_{S_{Tabs}}$	Frequency directional dispersion factor for i-direction, total frequency dispersion factor
D_{RMSi}, D_{SRMS}	RMS directional dispersion factor for i-direction, total RMS dispersion factor
D_k, D_{kd}	Acceleration dose, average daily acceleration dose
$F_d(\omega)$	Differential spectrum
F_f	Coulomb friction
R_{xy}	Cross-corelation function
S_{RMS}	Total energy estimator (sum of RMS for X, Y, Z axes)
S_{Tabs}	Total energy of vibration spectrum estimator (sum of T_{abs} for X, Y, Z axes)
$S_{TabsTFR}$	Total energy of TFR of vibration estimator (sum of t_{abstfr} for X, Y, Z axes)
S_{Tavr}	Function of average value of time period vibration in frequency domain
S_{avr}	Function of average values of frequency bands vibration in time domain
S_e, S_{ed}	Equivalent static compressive stress and its daily equivalent dose
S_f	Time function of separate frequency bands
S_t	Function of frequency distribution for determined time period
T_{abs}	Estimator of energy of vibration spectrum
T_{absTFR}	Energy of TFR of vibration estimator
X_{RMS}, RMS	Root-mean-square
a_l	Acceleration of vibration of lumbar response (lumbar spine acceleration)
$H[s(t)]$	Hilbert transform of the signal $s(t)$
$A(8)$	Daily exposure to vibration
EMA	Experimental modal analysis
$F(\omega)$	Fourier transform
FFT, DFT	Fast fourier transform, discrete fourier transform
FRF	Frequency response function
I	Vibration intensity
IRI	International roughness index (metric to describe road roughness)
M, C, K	Mass, damping, stiffness matrix
NDN	Vibration limit value
Q	Quantity of the energy transferred
R	Risk factor
$STFT$	Short time fourier transform
TFR	Time-frequency representation
VDV	Vibration dose value
WBV, HAV, HVR	Whole-body vibration, hand-arm vibration, human-vehicle-road
WSA	Vibroacoustic signals analyzer
WT, $\Psi(t)$	Wavelet transformation, wavelet family
WVD	Wigner-ville distribution
X, Y, Z	X – longitudinal, Y – lateral, Z – vertical (direction, axes)
$n-DOF$	The n degrees of freedom
rpm	Revolutions per minute
λ	Wave length
ω, f	Frequency

1. Introduction

The complex distribution of oscillatory motion and force within the body during whole-body vibration produces complex sensations. The location and character of the sensations vary greatly according to the vibration frequency, axis and other factors. The term “iscomfort” is applied to the sensations arising directly from the vibration. A wider term is sometimes used in transportation systems to include reactions to other aspects of the environment (e.g. vibration, noise) and the effects of motion on common activities. Whether a degree of discomfort is acceptable will depend on many factors. Vibration is the mechanical phenomena caused by machines in operation. Generally the vibration is undesirable, wasting energy and creating unwanted effects. The vehicle vibration are one of the most important unwanted effects. It causes decrease of safety and comfort factors and increase of fuel consumption. Vibration transmission to human has a large influence on comfort, performance and health. Comfortable ride is essential for a vehicle in order to obtain passenger satisfaction.

Ride quality and comfort increasingly begins refer to vibration and noise in terms of sensation or feel of the passengers. Lower range of vibration frequencies mostly are correlated to vibration comfort and higher (more than 80 Hz) to noise [137, 155]. Vibration and noise are perceived differently by humans, so there is a need to adopt methods that help quantify and control them. Independent of method it is important to define the sources of these phenomena.

Group of interesting problems are relating to the understanding of vibration in complex mechanical structures such as means of transport. One of the usual reason to seek such understanding is to control the vibrations. The book presents research on identification of sources, propagation and structure of vibration in complex mechanical structure of passenger car. The vehicle vibration are results from many kind of dynamic interactions. The proper identification of the vibration is very difficult research and scientific problem. It requires good knowledge fundament and correct measurement tools and signal processing. An automotive vehicle, being a complex mechanical system, includes a set of specific natural vibrations frequencies depending on the direction of the oscillatory wave propagation.

Model representation of an automotive vehicle as a complex mechanical object requires that various aspects should be taken into consideration from the perspective of statics and dynamics, bearing the random phenomena in mind as well. In the study discussed in the monograph, the author focused on non-linear vibration related phenomena occurring in vehicles [34, 35, 63, 70-72, 74, 80, 114, 115, 133]. What is characteristic about dynamic vehicle models is that they entail a set of simplifications, applied across quartile models, several point masses, to finally mention full vehicle models of numerous degrees of freedom and non-linear characteristics.

The main areas of the author’s interest under the past studies undertaken included an assessment of vibration damping from the perspective of safety and comfort based on vibration signals recorded in a direct vicinity of shock absorbers, at points of shock absorber mounting to both unsprung and sprung masses [56]. Furthermore, the author conducted a series of studies pertaining to identification of other vibration sources occurring in vehicles, such as the engine and the power transmission systems. The range of impacts vibrations exert on a vehicle driver is very broad, starting from the feeling of discomfort to safety hazards caused by vibrations at resonant frequencies of specific organs, thus affecting the driver’s responses. Therefore, it is important to study the routes of vibration propagation from their sources to the human organism and to assess the vibration exposure for different input function conditions. The studies discussed in papers [39, 47] illustrate the outcomes of the influence of input parameters on the distribution of the vibrations being generated as well as their propagation.

The scope of studies of vehicle vibration dynamics, identification of sources and propagation paths have to be extended by stationary empirical tests of oscillatory wave propagation in a vehicle structure as well as identification of natural vibrations. One must also bear in mind that a detailed analysis of vibration related phenomena requires that other properties and mechanical phenomena taking place in the course of degradation as well as the impact of external factors should be taken into consideration.

During operating of vehicles there are many vibration generated by the different sources. Motor engine should be considered as the vibration generator as well. This kind of machine generate a disturbing force of one sort or another, but the frequency of the disturbing force should not be at, or near, a natural frequency of the structure otherwise resonance will occur, with the resulting high amplitudes of vibration and dynamic stresses, and noise and fatigue problems. There are two basic types of structural vibration: steady-state vibration caused by continually running machines such as engines, air-conditioning plants and generators either within the structure or situated in a neighbouring structure, and transient vibration caused by a short-duration disturbance such as a lorry or train passing over an expansion joint in a road or over a bridge. Vibration from engines can agitate the body to the point of causing micro fractures in the vertebrae, disc protrusion, nerve damage and acute lower back pain.

Ride comfort is extremely difficult to determine because of the variations in individual sensitivity to vibration. Therefore many researchers have concentrated their efforts on reducing the amount of vibration from vehicles. Some interesting researches were conducted for the low frequency discomfort for human analysed [88, 89]. Ride vibrations are transmitted to the driver buttocks and back by the seat. The floor panel, pedal and steering wheel transmit additional vibrations to the feet and hands of the driver. These vibrations are producing a level of discomfort for driver and passengers.

With advancements in transportation, we often travel longer distances at faster speeds. Whole-Body vibration research is now focusing on determining the vibration and exposure levels that initiate physical and mechanical changes in the body. The results of current research could provide helpful guidelines for vehicle manufacturers. To reach this purpose it is extremely important to define all sources of vibration in driving vehicle and paths of propagation into the occupants.

The book address the results of large scope research on identification of sources, propagation paths and structure of vibration affecting on human in means of transport. According to scope of the research others authors and the current state of art the book is focused on consideration on combustion engine as source of vibration affecting on occupants. For fulfilment of the engine working condition during drive the investigation were conducted on vibration generated by working engine and powertrain system with different gear ratio. For the identification of vibration propagation paths there were developed some estimators of vibration energy dissipation. As the second main source of vehicle vibration the impact of vertical movement of wheels on vibration propagation into car-body were investigated. The influence of technical condition of suspension system and operating parameters of the vehicle on vibration caused by forcing a wheel were described in the book. The author discussed the influence of vibration sources on exposure to whole-body vibration.

Basing on the conclusions some mathematical and software application for vehicle vibration comfort and safety were developed. Thus it allowed to describe the systems for monitoring and control of vibration propagation in means of transport in terms of comfort and safety.

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