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Definition and determination of the bus oscillatory comfort zones

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ABSTRACT

The paper defines *"equal oscillatory comfort zones"* as a novel concept in the sphere of the bus vertical dynamics. Oscillatory zones are determined using the original and validated oscillatory model of the intercity bus and comfort criteria according to the international ISO 2631/1997 standard requirements. The bus spatial oscillatory model with 65 degrees of freedom (DOF) was built in the *ADAMS/View module* of the multibody software package *MSC.ADAMS*. The model was excited by two different real road surfaces: poor asphalt-concrete and good asphalt-concrete pavements, registered at the speed of 64 km/h and 90 km/h respectively. It was found by simulation that oscillatory zones with different comfort assessments exist in the bus. The most comfortable oscillatory zone is in the middle part of the bus (between the front and the rear axle), whereas the least comfortable oscillatory zone is on the rear bus overhang. For the purpose of the ride comfort harmonization, using *Design of Experiments (DOE)* analysis, new oscillatory parameters are proposed for passenger seats which do not ensure satisfactory oscillatory comfort level. It is concluded that harmonization of oscillatory comfort for all bus passengers could be achieved for good asphalt-concrete excitation. For the poor road excitation it is possible to achieve significant improvement of comfort, especially for the assistant driver and passengers in the bus rear overhang. On a poor asphalt-concrete pavement, by using the proposed seat oscillatory parameters, the allowed exposure time for vertical whole body vibration would be considerably extended.

Relevance to industry: Oscillatory comfort has a particular importance for users of intercity buses traveling longer distances. Comfort assessment of each bus user and mapping of comfort zones can indicate the individual seat and group of the seats on which the oscillatory comfort is reduced. Proper selection of seat oscillatory parameters can improve users comfort. Results of such an analysis can significantly help bus designers and manufacturers in order to improve and harmonize oscillatory comfort on the whole vehicle platform.

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1. Introduction

Traffic participants, especially vehicle users (passengers and drivers) in all types of transport (road, railway, air and waterway) are affected by vibrations. Vibrations can cause the feeling of discomfort, reduce working ability and if increasingly intense can endanger human health. A particularly risky group includes drivers of construction machinery, farm machinery, heavy-duty vehicles and buses (Alperovitch-Najenson et al., 2010; Eaton, 2003; Griffin, 2007; Kompier, 1996; Leelavathy et al., 2011). Investigations of the whole-body vibrations' (WBVs') effect on the occurrence of low back pain among professional drivers have shown that bus drivers in the USA and in Sweden suffer from this health problem (Magnusson et al., 1996). Musculoskeletal disorders are the most prevalent health problems in bus drivers (Patterson et al., 1986).

Vibrations are transmitted to the bodies of drivers and passengers via their seats. It was found that intensity of vibrations that bus users are exposed to depend on the bus seat position (Sekulić et al., 2013). Also, the intensity and effect of vibrations on users depend on their seats' construction properties. Bus drivers' seat usually has a suspended frame and an elastic cushion, whereas passengers' seats have rigid connection with the bus body and the elasticity needed is achieved by elastic foam cushions only. The characteristics of the seat foam cushion, such as stiffness and damping,

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influence vibration transmissibility and intensity, and apparently passengers' comfort (Zhang et al., 2015). This is also true for the passengers' seats in other means of transport, e.g. an aircraft (Ciloglu et al., 2015).

In previous studies dealing with the problems of bus vertical dynamics, the majority of analyses were directed to determine the effects of WBV on the driver ride comfort and working ability (Blood et al., 2010; Okunribido et al., 2007; Picu, 2009; Sekulić and Dedović, 2011). Also, influence of transient shock vibration on driver's health for two types of city busses is experimentally investigated in (Thamsuwan et al., 2013). This is quite comprehensible, having in mind that the bus driver spends most of his working time driving. A smaller number of papers consider the effect of WBV on the passenger comfort, taking into account only the passengers at distinctive places in the bus (e.g. in the middle part of the bus, and in the bus front/rear overhang) (Diligenski and Demić, 2000; Diligenski et al., 2005; Seidel et al., 2008). These studies have not provided in-depth information necessary for comfort improvement and comfort harmonization for all bus users.

In the PhD thesis (Sekulić, 2013) an extensive research of the effect of vibrations on the comfort of intercity bus users was carried out. Results from this research have not been published until now, and some of them are presented in this paper. The main objective of this study was to improve and harmonize users' vertical ride comfort on the whole bus platform. This is achieved through the mapping of comfort parameters on an intercity bus platform and changing seats oscillatory behavior. A novel concept of *"equal oscillatory comfort zones"* has been defined. In order to accomplish the task, the bus oscillatory model with 65 DOF was built in the ADAMS/View software. When determining oscillatory comfort zones, the criteria of international standard ISO 2631/1997 were used. For the purpose of this paper, mapping of oscillatory comfort zones for two different road pavements – poor asphalt-concrete and good asphalt-concrete – has been selected from a larger set of data. The excitation signal has been registered at the speeds of 64 km/h and 90 km/h respectively. *"Equal oscillatory comfort zones"* is a wording that denotes a novel concept defined in the thesis and in this paper, and it has not been published or presented in any previous study or paper.

The aim was to identify passengers' seats with reduced oscillatory comfort and to propose new oscillatory parameters of those seats for comfort improvement. Also, the objective was to test whether harmonized oscillatory comfort on the bus platform could be achieved by using the oscillatory parameters defined after the analysis. The effects of oscillatory parameters on users' body allowed exposure time was investigated using standard ISO 2631/1985.

The two earlier versions of ISO 2631 standard (ISO 2631/1985 and ISO 2631/1997) referred to random vibration effects on whole body exposure time and users' comfort, while the new ISO 2631-5, published in 2004, deals with analysis of the effects of transient shock vibration on human body health. The phenomena presented in this paper, referring to random vibration effects on bus users' exposure time and their comfort, have been investigated using criteria that were defined in previous versions of ISO 2631only.

2. Intercity bus oscillatory model

The IK-301 bus (Fig. 1) is intended for passenger intercity transport. Technical data for this bus are given in (Nijemčević et al., 2001). The notations in Fig. 1(a) are as follows: L-wheelbase, a-bus front overhang and b-bus rear overhang. In Fig. 1(b), the users on the seats are noted as follows: D-driver, AD-assistant driver and P-passenger.

The bus is equipped with two rigid axles (Glumac et al., 2002). Suspension on the front axle is provided by two air springs and four telescopic shock absorbers, while on the rear axle it is designed with four air springs and four telescopic shock absorbers. Front axle is attached to the body by means of three longitudinal rods and a single transverse rod, while rear axle is connected by two longitudinal and two inclined rods (Glumac et al., 2002). Two wheels are mounted on the front and two twin wheels on the rear axle. The tire size is 295/80R22.5 (Nijemčević et al., 2001).

The bus has 53 passenger seats, a seat for a driver and a seat for an assistant driver (Fig. 1(b)). The driver's seat beyond polyurethane foam cushion has a suspension system with pneumatic spring and hydraulic damping, whereas assistant driver's and passengers' seats are rigidly mounted to the bus body. Elasticity and damping of passengers' and assistant drivers' seats are achieved through elastic polyurethane foam cushions only.

The bus oscillatory model has been designed in the *ADAMS/View module* of the multibody software package *MSC.ADAMS*. The assumptions made for the bus model are following: characteristics of all elastic and damping elements are linear, bus wheels are in permanent contact with the road surface, the bus is moving along a straight line at constant speed, all bodies that the bus oscillatory model has been formed of are rigid and the bus engine is not taken as a separate rigid body, but included in the bus body.

Fig. 2(a) and (b) show the models of the bus front and rear suspensions. The role of transverse rod in the bus front axle model is given to the revolute joint between the upper (middle) longitudinal rod and carrying structure. Establishment of such connection prevents front axle translational motion in the transverse y-axis direction. Bus axles' lateral motion in the y-axis direction have insignificant impact on the user oscillatory comfort.

The tires of the bus oscillatory model are defined by the BUSHING element. This element enables to define tire linear characteristics in radial, transverse and longitudinal direction. In order to realize motion at the contact point of the tire and road surface, the four rigid bodies are defined and connected with the GROUND part by translational joints. Road roughness is introduced into the translational joints by means of the CUBSPL function.

Driver, assistant driver and passenger seats together with users' bodies are defined as unique rigid bodies (Fig. 3). Driver's seat suspension is defined by the SPRING-DAMPER element. Seat elastic cushion is considered as linear elasto-damping element (Bouazara et al., 2006), characterized by stiffness coefficient $c_c = 20{,}000$ N/m and viscous damping coefficient $b_c = 200$ N/m (Diligenski et al., 2005). When modeling assistant driver's and passengers' seats, equivalent stiffness of the whole seat was considered as by the expression (1):

$$c_{eq} = \frac{c_r \cdot c_c}{c_r + c_c} \tag{1}$$

where c_{eq} is equivalent stiffness of the whole seat, c_r is stiffness of rigid pillar that connects seat structure with the bus floor, c_c is stiffness of the seat cushion. Since stiffness value c_r is much higher than stiffness value c_c, it could be accepted that the equivalent stiffness value c_{eq} is approximately equal to the stiffness value c_c. Stiffness and damping characteristics of the whole seat for all passengers and driver assistant are modeled by SPRING-DAMPER elements (Fig. 3).

Linear characteristics for air spring and telescopic shock absorber elements of the bus suspension system are also defined by the SPRING-DAMPER elements. The force generated by such an element is given by the expression (2):

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