Hội nghị Khoa học toàn quốc Cơ học Vật rắn biến dạng lần thứ XII
Đại học Duy Tân, TP Đà Nẵng, 7/8/2015

A Study to Evaluate the Effects of Semi-Trailer Truck Vertical Vibration on Driver Ride Comfort under Different Operating Conditions

Le Van Quynh and Nguyen Khac Tuan

Faculty of Automotive and Power machinery Engineering, Thai Nguyen University of Technology, Thai Nguyen, Viet Nam

Email: lequynhdl@yahoo.com

Abstract

Semi-trailer truck vertical vibration not only affects the durability of parts of a vehicle and road surface, but it also affects the driver's comfort and health. Thus, the aim of this study is to evaluate the effects of the vertical vibration on driver comfort and health under the vehicle different operating conditions. To achieve this goal, a 2-D vibration model for a semi-trailer truck with 10 DOF was is established to simulate. Based on the vertical weighted R.M.S. acceleration responses of driver's seat and the international standard ISO 2631, the vehicle different operating conditions were evaluated respectively, such as speed, road surface, load and working time. The results show that the road surface condition has the greatest influence on driver's comfort and health, this study has proposed the intervention limit for road surface to improve driver's comfort and health.

Keywords: Heavy Truck, Vertical Vibration, Vibration Model, Ride Comfort, Evaluation

1. Introduction

In recent years, heavy vehicle market has required increasingly not only on vehicle performance and safety but also vehicle ride comfort and road friendliness. Thus, the optimal design for vehicle suspension systems is becoming increasingly important for designers as well as researchers to improve driver comfort, road friendliness as well as safe movement of vehicle, such as the optimal design for conventional suspension systems (Lu Sun(2002), M.J. Mahmoodabadi, (2013), Guglielmino E. (2008)); the optimal design for suspension systems by semi-active or active control systems(Tsampardoukas G., Stammers C.W. and Guglielmino E.(2007)).

Four methods to objectively evaluate ride comfort and health (human response to vibration) are used throughout the world today. The ISO 2631 standard is used mainly in Europe and the British Standard BS 6841 in the United Kingdom. Germany and Austria use VDI 2057 while Average Absorbed Power or AAP is used by the United States of America and by NATO in the NATO Reference Mobility Model(P.S. Els (2005)).

The major goal of this study is to improve a 2-D vibration models with 10 DOF for a semi-trailer truck as Fig.1. Matlab-Simulink software is applied to simulate the vehicle vibration model with road surface roughness of national highways according to the international standard ISO 8068. Based on the vertical weighted R.M.S. acceleration responses of driver's seat and the international standard ISO 2631, the vehicle different operating conditions were evaluated respectively, such as speed, road surface, load and working time.

2. Semi-trailer truck vibration model

A Semi-trailer truck with the dependent suspension system is selected for establishing vehicle vibration model. A vibration model with 10 DOF was developed from Tsampardoukas G.'s half-truck model[6] to evaluate the driver comfort and health, as shown in Fig. 1.

In Fig.1, K_i and C_i are the suspension stiffness coefficients and damping coefficients of vehicle, fifth wheel (where, the tractor and the trailer are linked through an articulated connection known as the fifth wheel (Guglielmino E., Sireteanu T., Stammers C.W., Ghita G. and Giudea M(2008)), cab and seat, respectively, $N.m^{-1}$ and $N.s.m^{-1}$; K_{Tj} and C_{Tj} are the stiffness coefficients and damping coefficients of tires, respectively, $N.m^{-1}$ and $N.s.m^{-1}$; m_k are the sprung mass of the cabin, tractor and trailer and driver's seat (including seat mass driver's body), respectively, kg; m_{aj} are the unsprung mass of the the steering axle, the tractor drive axle and the trailer axle, respectively, kg; I_m are the moments of inertia of tractor, trailer and cabin, respectively, $kg.m^2$; l_n are the distances, m; z_{aj} and z_k are vertical displacements at the centre gravity of the axles and tractor, trailer, cabin, driver's seat, respectively, m; φ_m are angle deflection at the centre gravity of tractor, trailer and cabin, respectively, rad; q_j are road surface roughness; v is the speed of vehicle, m/s (i=1-7; j=1-3; k=b,t,c,s; n=1÷11; m= b,t,c).

The vehicle vibration equations can be formulated in different ways. One of the most popular methods is the Lagrange equation type II. For the vibration model showed in Fig. 1 the vehicle vibration equations can be derived as Eq.1.

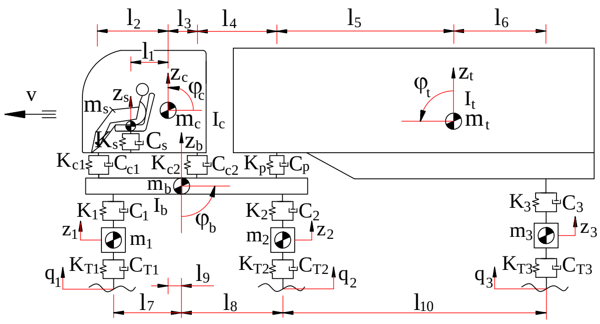

Fig 1. 2-D vibration model for Semi-trailer truck

$$\begin{cases} m_s\ddot{z}_s = -F_7 \\ m_c\ddot{z}_c = F_7 - \sum_{i=5}^{6} F_i \\ I_c\ddot{\varphi}_c = \sum_{i=5}^{7} (-1)^i F_i l_{i+4} \\ m_b\ddot{z}_b = \sum_{i=4}^{6} F_i - \sum_{i=1}^{2} F_i \\ m_b\ddot{z}_b = \sum_{i=1}^{2} (-1)^{i+1} F_i l_i + \sum_{i=5}^{6} (-1)^{i+1} F_i l_i + F_4 l_4 \\ m_t\ddot{z}_t = -\sum_{i=3}^{4} F_i \\ I_t\ddot{\varphi}_t = \sum_{i=3}^{4} (-1)^i F_i l_{i+4} \\ m_{a1}\ddot{z}_{a1} = F_1 - F_{T1} \\ m_{a2}\ddot{z}_{a2} = F_2 - F_{T2} \\ m_{a3}\ddot{z}_{a3} = F_3 - F_{T3} \end{cases} \quad (1)$$

In Eq.1, F_i and F_{Tj} are the vertical forces of suspension systems, respectively which is determined by the following formula:

Driver's seat suspension system (i=7)

$$F_7 = K_7(z_s - z_c + \varphi_c l_{11}) + C_s(\dot{z}_s - \dot{z}_c + \dot{\varphi}_c l_{11}) \quad (2)$$

Cab suspension system (i=5,6)

$$F_i = K_i\left[z_c - (-1)^i l_{i+4}\varphi_c - z_b - (-1)^{i+1} l_i\varphi_b\right] + C_i\left[\dot{z}_c - (-1)^i l_{i+4}\dot{\varphi}_c - \dot{z}_b - (-1)^{i+1} l_i\dot{\varphi}_b\right] \qquad (3)$$

Vehicle suspension systems (i=1-3)

$$F_i = K_i\left[z_k + (-1)^u l_n\varphi_m - z_{aj}\right] + C_i\left[\dot{z}_k + (-1)^u l_n\dot{\varphi}_m - \dot{z}_{aj}\right] \qquad (4)$$

The fifth wheel(i=4)

$$F_4 = K_4\left[z_t - l_8\varphi_t - z_b - l_4\varphi_b\right] + C_4\left[\dot{z}_t - l_8\dot{\varphi}_t - \dot{z}_b - l_4\dot{\varphi}_b\right] \qquad (5)$$

Vehicle tires (j=1-3)

$$F_{Tj} = K_{Tj}\left[z_{aj} - q_j\right] + C_{Tj}\left[\dot{z}_{aj} - \dot{q}_j\right] \qquad (6)$$

where, $\begin{cases} u=1 \\ u=2; \end{cases} \quad when \begin{cases} i=1;\ n=6;\ m=b \\ i=2,3;\ n=5,3;\ m=t \end{cases}$

3. Road surface roughnees

Road surface roughness plays an important role in evaluating driver ride comfort. The random excitation of road surface roughness can be represented with a periodic modulated random process. The general form of the displacement PSD of the road surface roughness is determined by the experimental formula:

$$S_q(n) = S_q(n_0)\left(\frac{n}{n_0}\right)^{-\omega} \qquad (7)$$

where, space frequency n is the reciprocal of the wavelength λ. It means wave numbers in a meter. n_0 is reference space frequency, it's defined as 0.1m^{-1}. $S_q(n)$ is PSD of road surface under the reference space frequency $S_q(n_0)$ known as the road surface roughness coefficient and ω is the frequency index which decides the frequency configuration of PSD of road surface $(\omega = 2)$.

The road surface roughness is assumed to be a zero-mean stationary Gaussian random process. It can be generated through an inverse Fourier transformation:

$$q(t) = \sum_{i=1}^{N} \sqrt{2S_q(n_i)\Delta n}\cos(2\pi n_k t + \phi_i) \qquad (8)$$

where, ϕ_i is random phase uniformly distributed from 0 to 2π.

In this study, typical road surface roughness is adopted according to the standard ISO 8068 and computer simulation result of the typical road surface roughness ISO 8068 level A, B, C and D is shown in Fig.2.

4. International standard ISO 2631

The most widely used international standard for whole-body vibration (WBV) is ISO 2631-1:1997E. This standard defines the methods to quantify WBV in relation to human comfort and health, perception and motion sickness. The standard has given two methods for evaluation human body comfort and health as follows

4.1 Basic Evaluation Method

As per ISO 2631-1, vibration evaluation based on the basic evaluation method always includes measurements of the weighted root-mean-square (r.m.s) acceleration dened by:

$$a_w = \left[\frac{1}{T} \int_0^T a_w{}^2(t)dt \right]^{1/2} \tag{9}$$

where, $a_w(t)$ is the weighted acceleration (translational and rotational) as a function of time, m/s^2; T is the duration of the measurement, s.

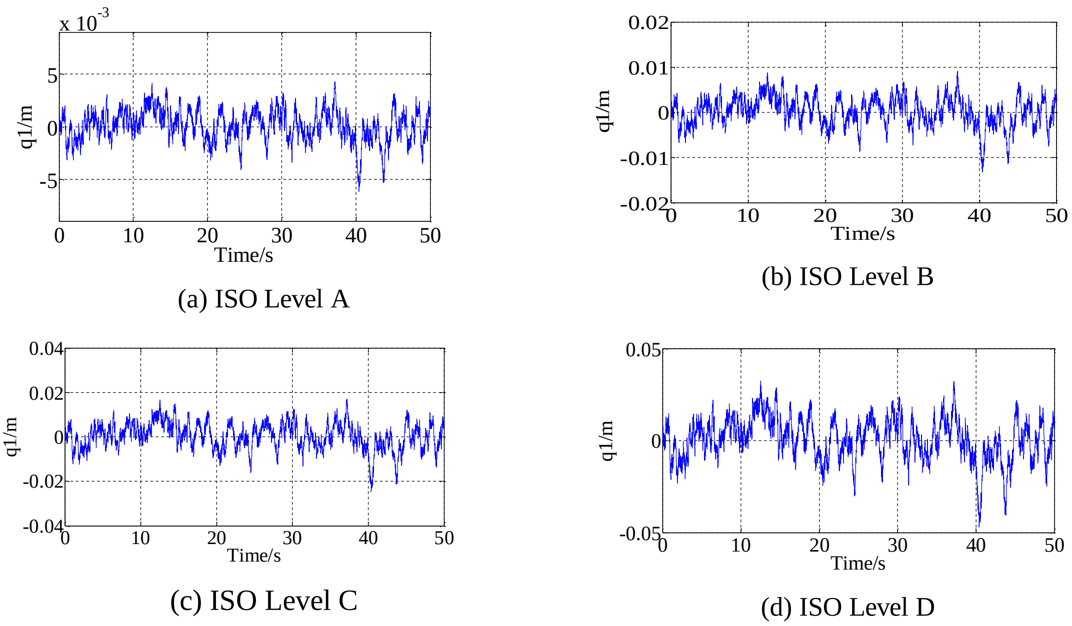

Fig 2. Road surface roughness at ISO 8068 level A, B, C and D

In the case where vibration enters the system in more than one direction, the vibration total value of weighted r.m.s acceleration, determined from vibration in orthogonal coordinates is calculated as:

$$a_w = \left(k_x^2 a^2{}_{wx} + k_y^2 a^2{}_{wy} + k_z^2 a^2{}_{wz} \right) \tag{10}$$

where, a_{wx}; a_{wy}; a_{wz} are the weighted r.m.s accelerations with respect to the orthogonal axes x, y, z respectively. k_x; k_y; k_z are the multiplying factors. The exact value of the multiplying factors depends on the frequency weighting selected to either predict the effects of vibration on comfort or health and also on the point where vibration enters the human body (feet, buttocks, back).

In this way, a synthetic index-called vertical weighted r.m.s acceleration, a_{wz} can be calculated from formula Eq.(8) and the r.m.s. value of the vertical acceleration in vehicle would be compared with the values in Tab 1, for indications of likely reactions to various magnitudes of overall vibration in the public transport.

4.2 Estimated vibration dose value

In order to consider the influence of working time on human health in vibration environment,WBV standard ISO 2631 has given the estimated vibration dose value and it is defined as follows:

$$eDVD = a_w \left[\frac{T}{T_8} \right]^{1/4} \tag{11}$$

where, a_w is the weighted r.m.s. acceleration, $m.s^{-2}$; T is the exposure time, s and T_8 is the reference duration of eight hours (T_0=2880s).

The limits of the evaluation show in Tab.2.

Tab. 1 Comfort levels related to a_w hreshold values

$a_w/(m.s^2)$	Comfort level	$a_w/(m.s^2)$	Comfort level
< 0.315	Not uncomfortable	0.8 ÷ 1.6	Uncomfortable
0.315÷0.63	A little uncomfortable	1.25 ÷ 2.5	Very uncomfortable
0.5 ÷ 1.0	Fairly uncomfortable	> 2	Extremely uncomfortable

Tab. 2 Human health levels related to eVDV threshold values

$eVDV/(m.s^{-2})$	Human health levels
< 0.95	It has no harm to human health
0.95÷1.30	It is certain to make harm to human health
> 1.30	It is harmful to human health

5. Simulation and analysis results

In order to solve Eq.(1) presented in section 2 for evaluating the effects of the vehicle operation conditions on driver ride comfort and health, Matlab/Simulink software is used with a specific set of parameters of semi-trailer truck as Tab.3.

Tab.3 Parameters of the semi-trailer truck

Para.	Values	Para.	Values	Para.	Values	Para.	Values
K_{T1}	$847x10^3$	C_5	$0.75x10^3$	K_3	$1.56x10^5$	I_b	$1.83x10^4$
K_{T2}	$2x10^6$	C_6	$0.75x10^3$	K_4	$2x10^7$	I_t	$2.52x10^5$
K_{T3}	$2x10^6$	C_7	$3.560x10^3$	K_5	$1x10^5$	m_{a1}	$0.27x10^3$
C_{T1}	$1.5x10^3$	m_s	$1.2x10^2$	K_6	$1x10^5$	m_{a2}	$0.52x10^3$
C_{T2}	$3x10^3$	m_c	$5x10^2$	K_7	$4.4x10^3$	m_{a3}	$0.34x10^3$
C_{T3}	$3x10^3$	m_b	$3.78x10^3$	C_1	$1x10^4$	l_{1-3}	1.2;4.8;10.3
K_1	$3x10^5$	m_t	$1.25x10^4$	C_2	$2.76x10^4$	l_{4-6}	3.73;0.4;4.73
K_2	$9.67x10^5$	I_c	$0.15x10^3$	C_3	$4.45x10^4$	l_{7-8}	4.0; 6.9
C_4	$2x10^5$	L_9	1.0	l_{10}	1.1	l_{11}	0.2

Simulations are carried out under vehicle different operating conditions to acquire the vertical weighted r.m.s acceleration responses of driver's seat. For example, a simulation result of the vertical acceleration responses of driver's seat while the vehicle moves on the ISO level B road surface at v=60 km/h with fully loaded, is shown in Fig.3.

Fig.3 could be determined the values of vertical weighted r.m.s acceleration of driver's seat a_{wz}=0.2678 m.s^{-2} and this value of a_{wz} is satisfy the conditions for driver comfort (according to Tab.1).

In order to evaluate the influence of the operation conditions of the heavy truck on driver ride comfort and health, they will be continued to discuss in the following section.

5.1 Effect of road surface condition

Road surface condition not only affects the durability of the part of vehicle, but also affects the vehicle ride comfort. In order to analyze its effects on driver's seat ride comfort, five road conditions from level A (very good) to level E (very poor) in ISO/TC 80686 are applied while the vehicle moves on the different road surface conditions with v=60 km/h and different loaded conditions (as half loaded, fully loaded and over 50% loaded). Fig.4 shows the value of a_{wz} increases quickly while the vehicle moves on the bad road surface condition which is the main problem to make the negative effects on driver's comfort. The value a_{wz} increases 1.82 times while the vehicle changing road surface condition moves from the ISO level D to level E road surface with fully loaded condition. And we see that vehicle load conditions have no large influence on driver's comfort while the vehicle moves on the good road surface condition.

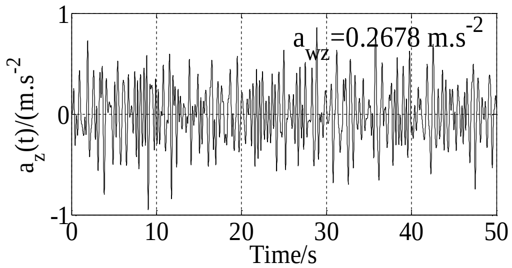

Fig 3. The vertical acceleration responses of driver's seat

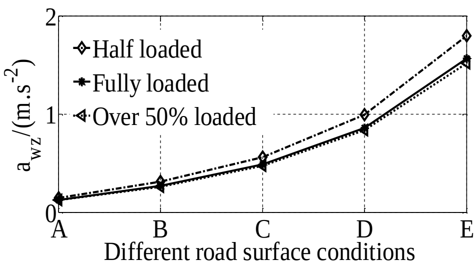

Fig 4. Effect of road surface conditions on a_{wz}

In order to ensure the driver's comfort for heavy vehicle, the road surface condition of ISO level C (the value of a_{wz}<0.5606m.s^{-2}) is chosen as the intervention limit for road surfaces. In this circumstance, traffic management need to intervene quickly to repair the road surface.

5.2 Effect of vehicle speed

In order to analyze the effect of the vehicle speed on driver ride comfort, the speed values of vehicle v=[10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120] km.h^{-1}are applied while the vehicle moves on different road surface conditions with fully loaded condition. The effects of vehicle speed on the vertical weighted r.m.s acceleration responses of driver's seat shows in Fig.5. Fig.5 shows that the driver of the subjective feeling is very uncomfortable while the vehicle moves at high speed and especially when vehicle moves on the poor road surface. While the vehicle moves the road surface ISO level E and at speed v≥70km/h, the values of a_{wz} increased very quickly which makes the driver feel so uncomfortable.

5.3 Effect of vehicle load

In order to analyze the effect of the vehicle loads on driver's seat ride comfort, the values of $0.2m_t$, $0.4m_t$, $0.6m_t$, $0.8m_t$, $1.0\ m_t$, $1.2m_t$, and $1.4m_t$, where m_t is used to designate the sprung mass of trailer shown inTab.3 are applied while the vehicle moves on the road surface at v=72 km/h. Fig.5 shows the variation a_{wz} with different sprung mass of the trailer. Fig.6 shows that with sprung mass of the trailer increases, the value of a_{wz} does not change significantly and the driver of the subjective feeling is comfortable when vehicle moves good road surface ISO level A. When the value of sprung mass of the trailer reduced, the values of a_{wz} increase very quickly which makes the driver feel very uncomfortable and especially when vehicle moves on the poor road surface.

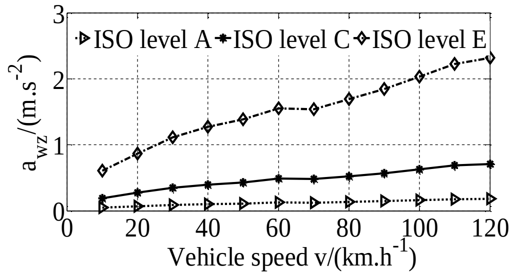

Fig 5. Effect of vehicle speed on a_{wz}

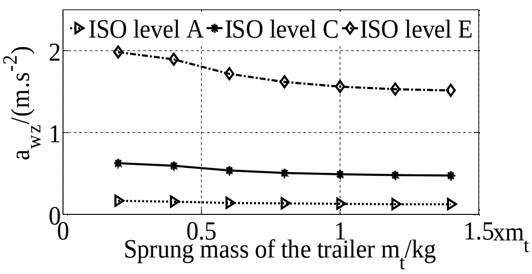

Fig 6. Effect of sprung mass of the trailer on a_{wz}

5.4 Effect of driver working time

The effect of the vehicle operating conditions on driver ride comfort has been carefully analyzed in the section above. Based on the eVDV values in International standard ISO 2631-1, the influences of driver working time on health of driver were analyzed respectively.

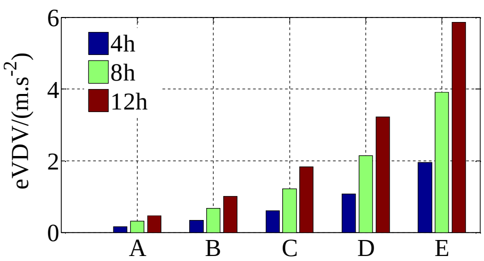

Fig 7. Effect of road surface condition and driver working time on health of driver on eVDV

In order to analyze its effects on health of driver, the driver working time T=4h, 8h, and 12h are applied for calculating the estimated vibration dose values while the vehicle moves on the different road surface conditions at v=60km.h^{-1} with fully loaded. Calculation results are shown in Fig.7. From Fig.7 shows that when the vehicle moves on road surface ISO level E when driver works four hours for one day, ISO level D when driver works eight hours for one day and ISO level C when driver works twelve hours for one day, respectively, these cases will do harm to driver's health (according to Tab.2).

6. Conclusion

In this study, A 2-D vibration model is developed for simulating and evaluating the influence of the operation conditions of the semi-trailer truck on driver ride comfort and health. The major conclusions that can be drawn from the evaluation results as follows:

i) Road surface conditions have very large influence on driver's comfort and health. In order to ensure ride comfort and health of the driver, the road surface condition ISO level C is proposed to be the intervention limit for road surfaces.

ii) Vehicle load, speed and driver working time conditions have a negligible influence on driver ride comfort and their health when the vehicle moves the good road surfaces.

References

Lu Sun(2002). Optimum design of "road-friendly" vehicle suspension systems subjected to rough pavement surfaces, *Applied Mathematical Modelling* 26(5), pp635 – 652.

M.J. Mahmoodabadi, A. Adljooy Safaie, A. Bagheri, N. Nariman-zadeh(2013). A novel combination of particle swarm optimization and genetic algorithm for pareto optimal design of a five-degree of freedom vehicle vibration model, *Applied Soft Computing*, 13(5), pp 2577-2591.

Guglielmino E., Sireteanu T., Stammers C.W., Ghita G. and Giudea M(2008); *Semi-active Suspension Control Improved Vehicle ride and Road Friendliness*, New York: Springer Publishing Company.

Tsampardoukas G., Stammers C.W. and Guglielmino E.(2007). Hybrid balance control of a magnetorheological truck suspension, *Journal Sound and Vibration*, 317, pp514-536.

P.S. Els (2005). The applicability of ride comfort standards to off-road vehicles, *Journal of Terramechanics 42* (2005), pp47–64.

Dodds C J, Robson J D (1973). The description of road surface roughness, *Journal of Sound and Vibration*, Vol. 31(2), pp175-183.

ISO 8068(1995). *Mechanical vibration-Road surface profiles-reporting of measured data*, International Organization for Standardization.

ISO 2631-1 (1997). *Mechanical vibration and shock-Evanluation of human exposure to whole-body vibration, Part I: General requirements*, The International Organization for Standardization.