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RESEARCH ARTICLE

AN INVESTIGATION OF A TWO-STAGE ASYMMETRIC DAMPER' EFFECT ON THE RIDE COMFORT OF AN INNER-CITY BUS BY USING 3-DOFS VEHICLE MODEL SUBJECTED TO RANDOM ROAD PROFILES

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ABSTRACT

The effect of the asymmetric damper on the vertical acceleration of the driver's body, suspension deflection and tire dynamic load were studied thoroughly in order to provide suggestions for choosing damping parameters while building a bus's suspension system. The vehicle model with three DOFs exposed to random road profiles was employed to investigate the dynamic responses for both two cases of linear symmetric and two-stage asymmetric dampers. The investigation was carried out in the time domain by simulation, then the root-mean-square of oscillatory parameters was calculated and examined by using a program made in the MATLAB software. The results of the analysis show that a two-stage asymmetric damper ensures good oscillatory comfort of the driver but provides less handling stability of the bus when compared to a linear symmetric one.

KEYWORDS

Bus ride comfort, equivalent damping coefficient, linear symmetric damper, two-stage asymmetric damper, random road profiles

1. INTRODUCTION

As a result of the fast growth of the economy and the improvement efforts of the automotive production chain, the number of automobiles in all of society is rising continuously. It facilitates people's work and daily lives, but has a harmful effect on traffic congestion as well as pollution. Priority to public transportation, improvement of bus service quality, especially enhancement of bus ride comfort are crucial strategies of encouraging passengers to travel by public transit in order to lessen pollution and traffic jams (Bao et al., 2015). Due to the bus's restricted structural design, cheap cost, and other factors, its ride comfort is often poorer to that of a sedan or SUV. Hence, automotive manufacturers should pay a lot of attention to reducing these kinds of discomfort for an inner city bus.

Vibrations from the road pavement are transmitted to the vehicle's occupants throughout the journey. Vibrations induce the perception of discomfort, diminish performing abilities, and their prolonged effect might have adverse health effects (Dedovic, 2004). There are evidences from investigations that bus drivers are exposed to strong vibrations (Kompier, 1996). The most typical health issues among drivers as a result of prolonged exposure to extreme levels of vibration include musculoskeletal illnesses, mental disorders, and etc. (Alperovith-Najenson et al., 2010).

The vehicle's suspension system is one of the key components for achieving comfort, stability, and safety. This part is critical in ensuring the movement of the vehicle's structure and keeping the vehicle's connection to the road surface. Also, the vibrations sent from the road surface to the vehicle are absorbed thanks to the damper, so it plays an essential role in defining the passenger's driving experience and comfort. In recent years, several research programs have been focused on enhancing the ride comfort of vehicles that is ranging from simulation to getting signals from realistic models for analysis and evaluation, and then people may increase the suspension system's quality. The vibration levels of a vehicle have been measured in its actual operating condition based on the signal obtained from the vehicle-mounted sensor, then the assessments were conducted (Nahvi, 2009). Another study used Wi-Fi to gather vibrational signals from passenger's cellphones and send them to a server. After the signal has been processed and analyzed in accordance with ISO 2631-1:1997, the results will be shown on LCD screens along the bus, and the system will sound an alert if the value exceeds the acceptable threshold (Zhao et al., 2016).

In addition to collecting data, analysis may be carried out by simulations utilizing a vehicle oscillatory model (Peceliunas et al., 2003; Peceliunas et al., 2005). In circumstances when measurements are seldom performed due to various restrictions, simulations become more important for reducing design cost. Many researchers have sought to determine appropriate damper values to achieve better trade-offs between characteristics like as ride comfort, suspension deflection, and road-holding stability (Sekulic and Dedovic, 2011; Sekulic et al., 2013; Sun, 2012). Despite the fact that these investigations have offered sufficient insight into suspension's damper design, the majority of the conclusions were based on limited performance metrics, while the complicated asymmetric characteristic of damper were mostly disregarded despite of the nonlinear behaviour of damper in traditional suspension system (Kasprzak, 2016).

This study seeks to elucidate the different reactions of linear symmetric and two-stage asymmetric dampers of an inner-city bus subjected to random road profiles. Using the specifications of a typical bus, an oscillatory model with three degrees of freedom was used here to analyze the user's oscillatory comfort. The comfort level of the driver's seat was also evaluated based on the criteria published by (ISO 2631-1:1997). And

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the effect of a two-stage asymmetric damper on vibrational behaviour should be thoughtfully investigated in this study for getting a deeper understanding of suspension's performance of bus.

2. Theory and Simulation Model

2.1 The 3 DOFs Vehicle Model

Figure 1 illustrates a three-degrees-of-freedom oscillatory model of the bus utilized in simulation. Table 1 shows the characteristics used in the simulation along with the explanation of the parameters from the Figure 1.

The vibrational system's differential motion equations in matrix form are written as follows, Eq. (1):

$$M\ddot{x} + C\dot{x} + Kx = f(t) \quad (1)$$

where: $x(t) = (x_u \ x_s \ x_d)^T$ represents the dynamic response vector:

$$M = \begin{bmatrix} m_u & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_d \end{bmatrix}, \quad C = \begin{bmatrix} c_s + c_t & -c_s & 0 \\ -c_s & c_s + c_d & -c_d \\ 0 & -c_d & c_d \end{bmatrix},$$
$$K = \begin{bmatrix} k_s + k_t & -k_s & 0 \\ -k_s & k_s + k_d & -k_d \\ 0 & -k_d & k_d \end{bmatrix}, \quad f(t) = \begin{bmatrix} k_t y + c_t \dot{y} \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

Define the system's mass, damping, stiffness and external force matrices, in that order.

In the two-stage asymmetric damper model, the suspension damping coefficient c_s varies among distinct values. A typical bus's parameter is shown in Table 1 below.

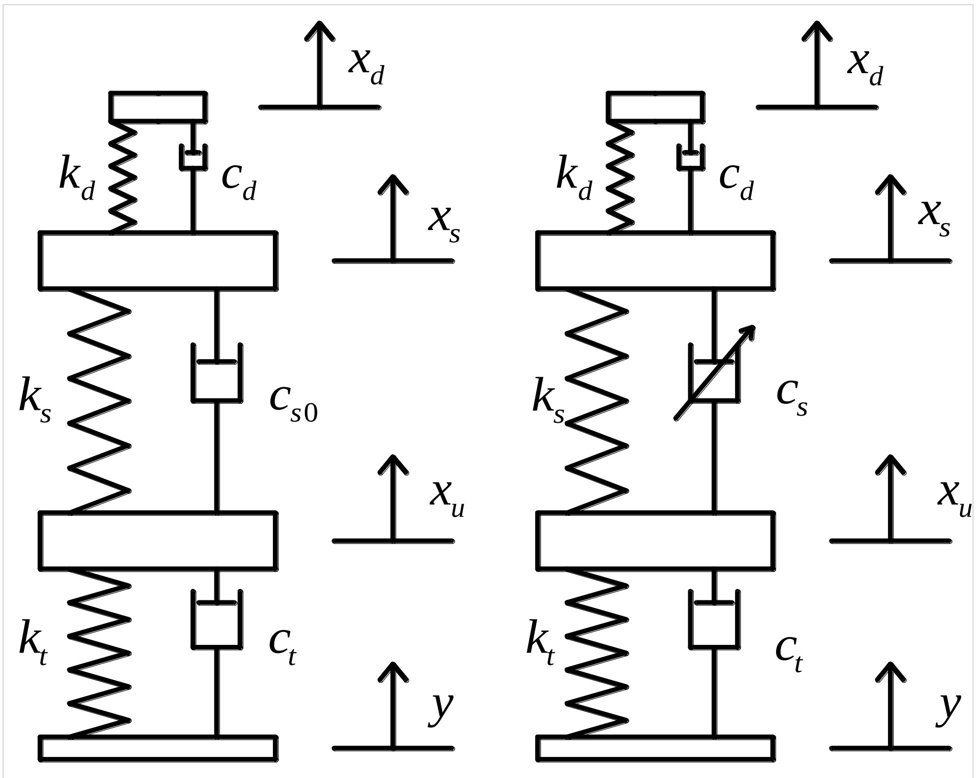


Figure 1: The 3 DOFs Vehicle Model with Asymmetric Damper (Jazar, 2008)

Table 1: Bus's Parameter

Bus parameter	Symbol	Value
Mass of the driver and the seat	m_d	100(kg)
Driver's seat spring stiffness	k_d	25000(N/m)
Driver's seat damping coefficient	c_d	1000(N/m)
Sprung mass	m_s	2000(kg)
Spring stiffness	k_s	100000(N/m)
Equivalent linear damping coefficient	c_{s0}	10000(Ns/m)
Two-stage asymmetric damping coeficient	c_s	Dependence on asymmetric characteristic
Un-sprung mass	m_u	250(kg)
Tire stiffness	k_t	1000000(N/m)
Tire damping coefficient	c_t	150(Ns/m)

Due to the small value of driver's seat and tire damping coefficient, this study ignore the asymmetric charateristic of the driver seat's and tire's damper as well.

2.2 Two-Stage Asymmetric Damper Model

The suspension damper with two-stage asymmetric characteristics in the compression and rebound is taken into consideration, as shown in Figure 2 (Balike et al., 2011)

c_{s0} : Linear equivalent damping coefficient.

c_s^- : Compression damping coefficient. c_s^+ : Rebound damping coefficient.

The damper's asymmetric ratio β can be defined as:

$$\beta = \frac{c_s^+}{c_s^-} \tag{3}$$

Assuming that the linear and bilinear asymmetric dampers dissipate energy similarly, the linear equivalent damping coefficient c_{s0} is attained by formula (Balike et al., 2011):

$$c_{s0} = \frac{c_s^-(1+\beta)}{2} = \frac{c_s^+(1+\beta)}{2\beta} \tag{4}$$

The formula for the damping force is (Balike et al., 2011):

The compression force

$$F_{d-c} = \begin{cases} \dfrac{2c_{s0}(\dot{x}_s - \dot{x}_u)}{\beta+1}, \text{ if } \alpha_c \le \dot{x}_s - \dot{x}_u < 0 \\ \dfrac{2c_{s0}}{\beta+1}\left[\alpha_c + \gamma_c\left(\dot{x}_s - \dot{x}_u - \alpha_c\right)\right], \text{if } \dot{x}_s - \dot{x}_u < \alpha_c \end{cases} \tag{5}$$

And

The rebound force

$$F_{d-r} = \begin{cases} \dfrac{2\beta c_{s0}(\dot{x}_s - \dot{x}_u)}{\beta+1}, \text{ if } 0 \le \dot{x}_s - \dot{x}_u < \alpha_r \\ \dfrac{2\beta c_{s0}}{\beta+1}\left[\alpha_r + \gamma_r\left(\dot{x}_s - \dot{x}_u - \alpha_r\right)\right], \text{ if } \dot{x}_s - \dot{x}_u \ge \alpha_r \end{cases} \tag{6}$$

where:

α_c, α_r : saturation factors.

γ_c, γ_r : high-speed damping reduction factors.

2.3 A Method for Creating Random Road Profile inTime Domain

Roughness features of motorways, secondary roads, and poor roads have been described as zero-mean, and Gaussian distribution in several research. In accordance with ISO 8086, the Power Spectral Density data are used to characterize road roughness (ISO 8608, 2016). We employ the sinusoidal approximation technique to study the dynamic response by solving the equations of motion at continuous sample times. If the vehicle is anticipated to keep a consistent speed v_0 along a given road section of length L, a random profile of a single track may be estimated by using the accumulation $N(\to\infty)$ sine waves (Tyan and Hong, 2009):

$$y(t) = \sum_{i=1}^{N} A_i \sin(\Omega_i vt + \varphi_i) \tag{5}$$

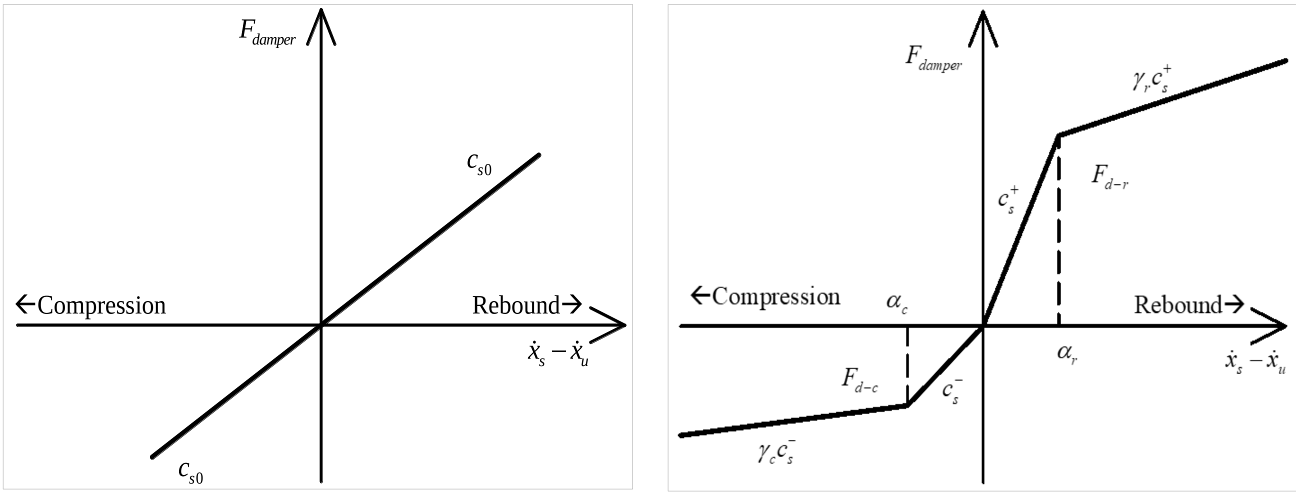
where: A_i is the amplitude, Ω_i is the angular spatial frequency, and the phase angles $\varphi_i, i = 1,\ldots, N$ are provided as random variables inside the $[0, 2\pi)$.

The nominal parameters of the road are taken to be *L*=100(m), *N*=512(waves) and the frequency is chosen from 0.5 to 50(Hz). An average-quality excitations (Class C) throughout the normal working velocity (5-120 (km/h)) will be taken as input parameter. A typical C-Class random road profile is shown as Figure 3.

2.4 Frequency Weighting and IIR Filter

Acceleration data obtained from simulation must be multiplied by frequency weighting to properly assess how vibration influences human health at the bands to which people are most sensitive (Mansfield, 2005). The first step in using ISO 2631-1:1997 for vibration evaluation is to find the acceleration taking into account the influence of frequency weighting. But the acceleration data obtained from the simulation is in the time domain, and using the frequency filter requires complex calculations. If these filters are used in the time domain, the computation becomes more straightforward, hence a weighting filter should be designed to carry out this procedure.

Generally, there are many methods of creating filters in time domain based on frequency filters. However, this paper will use the design method according to the bilinear transform. A Matlab's user-defined function will help to obtain weighted accelerations from the simulation.



(a) Linear Asymmetric Damper (b) Two-Stage Asymmetric Damper

Figure 2: The Relationship Between Velocity and Damping Force

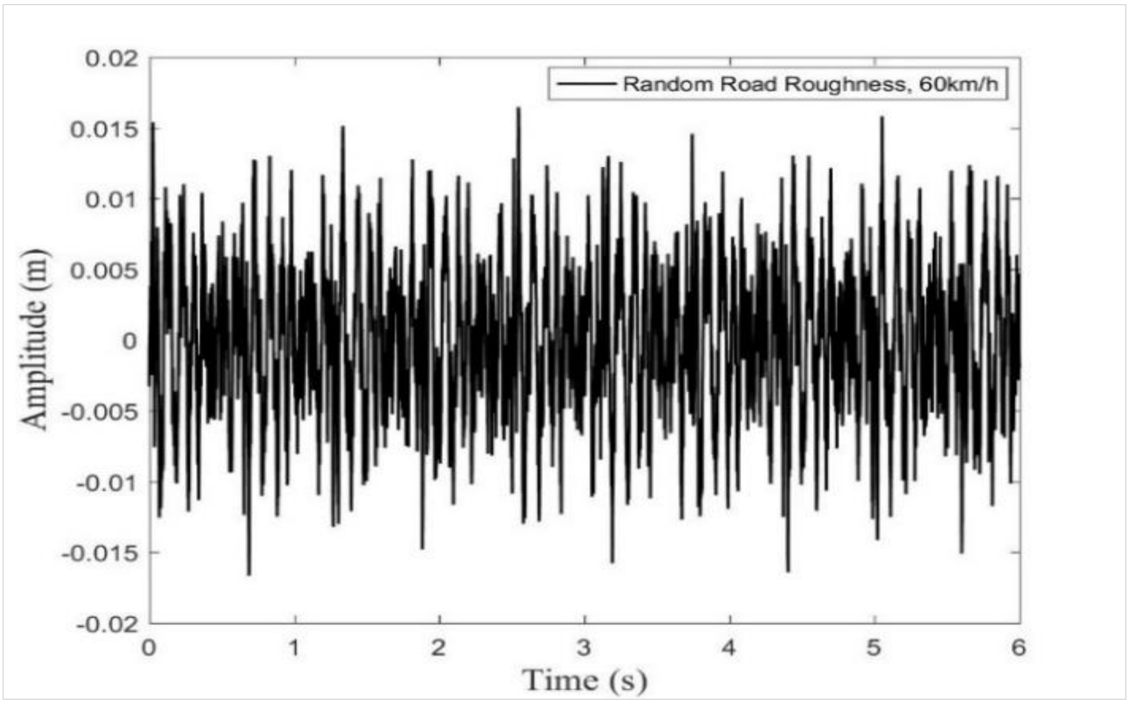


Figure 3: A Typical C-Class Random Road Roughness at Velocity Of 60(Km/H)

2.5 MATLAB Program

The software used in this paper is MATLAB version R2016a, files are organized as Figure 4.

where:

MAIN.m: contains the main code that calculate the required variables and write data to *.mat files.

INPUT.m: contains input parameters of quarter-car system (suspension system)

PLOT.m: plots out result from *.mat files.

Others user-defined function files: are presented in Table 2.

3. Results of the Simulation

The parameters of the two-stage asymmetric damper are selected as follows: $\beta = 70/30$ represents most of the asymmetric dampers in reality (Dixon, 2007); $\gamma_c = 0.5$, $\gamma_r = 0.25$, $\alpha_c = -0.2$ (m/s), $\alpha_r = 0.1$ (m/s) which has been illustrated to reach a satisfactory compromise between the evaluation criteria for the suspension deflection, road-holding, and ride under bump inputs (Balike et al., 2010). On the other hand, $\beta = 1$, $\gamma_c = \gamma_r = 1$ for linear symmetric damper.

The paper analyses the effects of two-stage asymmetric characteristic on four oscillatory parameters – the Driver's Vertical Acceleration (DVA), the Body's Vibration Acceleration (BVA), the Suspension Dynamic Deflection (SDD) and the Tire Dynamic Load coefficient (TDL), at a working bus's working velocity of 5-120(km/h). All the values of dynamic response mentioned above will be attained by root-mean-square calculation as:

$$\text{DVA} = \left[\frac{1}{T} \int_0^T \ddot{x}_d(t)^2 \, dt \right]^{1/2} \tag{6}$$

$$\text{BVA} = \left[\frac{1}{T} \int_0^T \ddot{x}_s(t)^2 \, dt \right]^{1/2} \tag{7}$$

$$\text{TDL} = \left[\frac{1}{T} \int_0^T \left(\frac{k_t\left(x_u(t) - y(t)\right) + c_t\left(\dot{x}_u(t) - \dot{y}(t)\right)}{\left(m_s + m_u + m_d\right) g} \right)^2 dt \right]^{1/2} \tag{8}$$

$$\text{SDD} = \left[\frac{1}{T} \int_0^T \left(x_s(t) - x_u(t) \right)^2 dt \right]^{1/2} \tag{9}$$

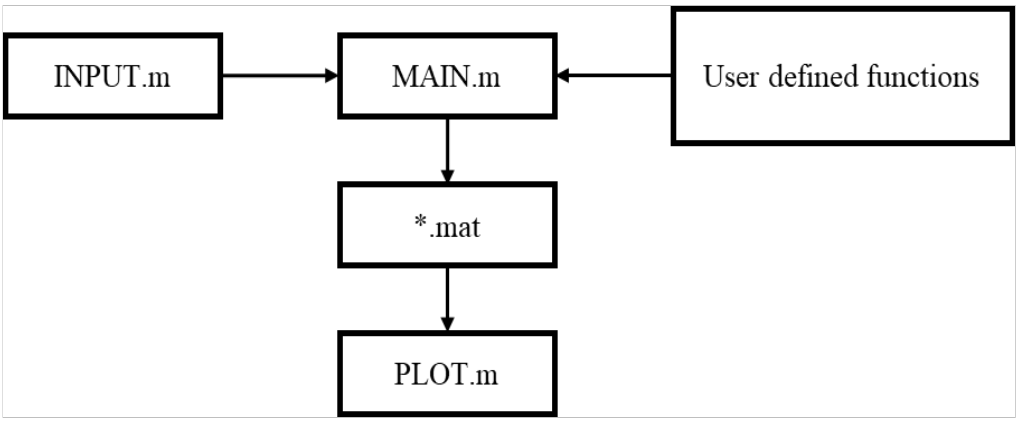


Figure 4: Organization of MATLAB Program Files

Table 2: User-Defined Functions		
File Name	**Inputs**	**Outputs**
RANDOM_Road_Profile.m	Road number	Parameters of excitation
RANDOM_road_generate.m	Creating random road profile based on the sinusoidal approximation approach	
Myrungekutta.m	Using Runge-Kutta Method to solve differential equations	
ISO2631_Wk.m	Creating IIR filter & converting acceleration into weighted acceleration	

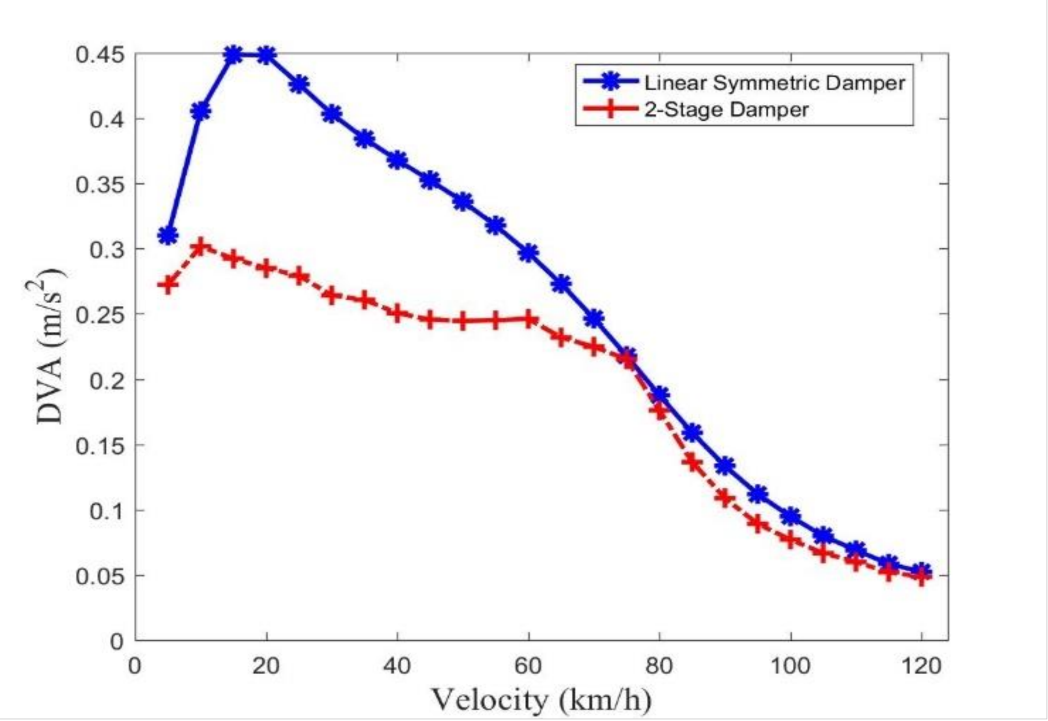


Figure 5: DVA Versus Velocity

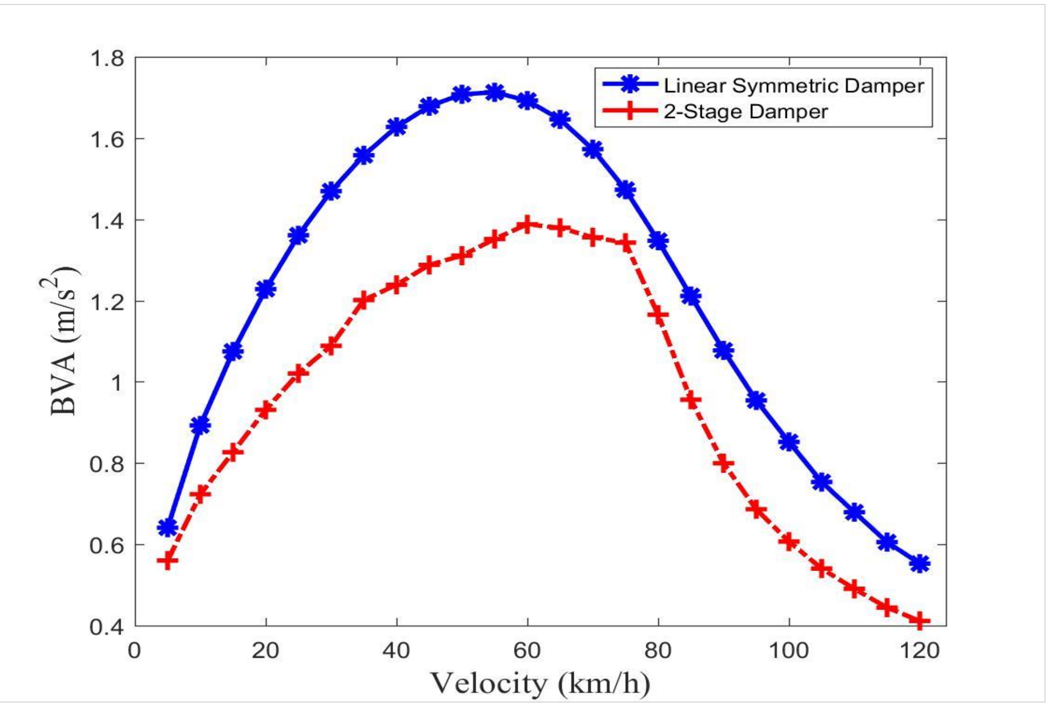


Figure 6: BVA Versus Velocity

As can be seen from Figures 5-6, from the beginning of the velocity range, the values of DVA, BVA increase gradually then reach their peak value at 20(km/h) and 55(km/h), respectively. Then the amplitudes of DVA and BVA drop down sharply as the vehicle is running at high velocity. On the whole velocity's range, the two-stage asymmetric damper yields a significantly better driver's seat comfort level than that of the linear symmetric one (approximately 35% at 20 km/h). According to ISO 2631-1:1997, the RMS values of DVA, in case of the two-stage asymmetric damper, satisfy the comfort level (BVA<0.315 (m/s^2)) in the entire vehicle's running velocity domain, as shown in Figure 5. The two-stage asymmetric damper also produces a considerably higher comfort level for vehicle's body (about 30% at 50 km/h), as shown in Figure 6.

In contrast, the two-stage asymmetric damper produces considerably worse handling control than the linear symmetric damper on the whole range and the most significant difference is approximately 45% at 75(km/h), as shown in Figure 7. In terms of the SDD value, the linear symmetric damper yields better performance throughout most of the velocity domain, and the highest variation between the two types of dampers is up to 100%, as shown in Figure 8. SDD values, however, are quite negligible, SDD is less than 10(mm) so the effect of the two-stage asymmetric damper on the working space could be overlooked.

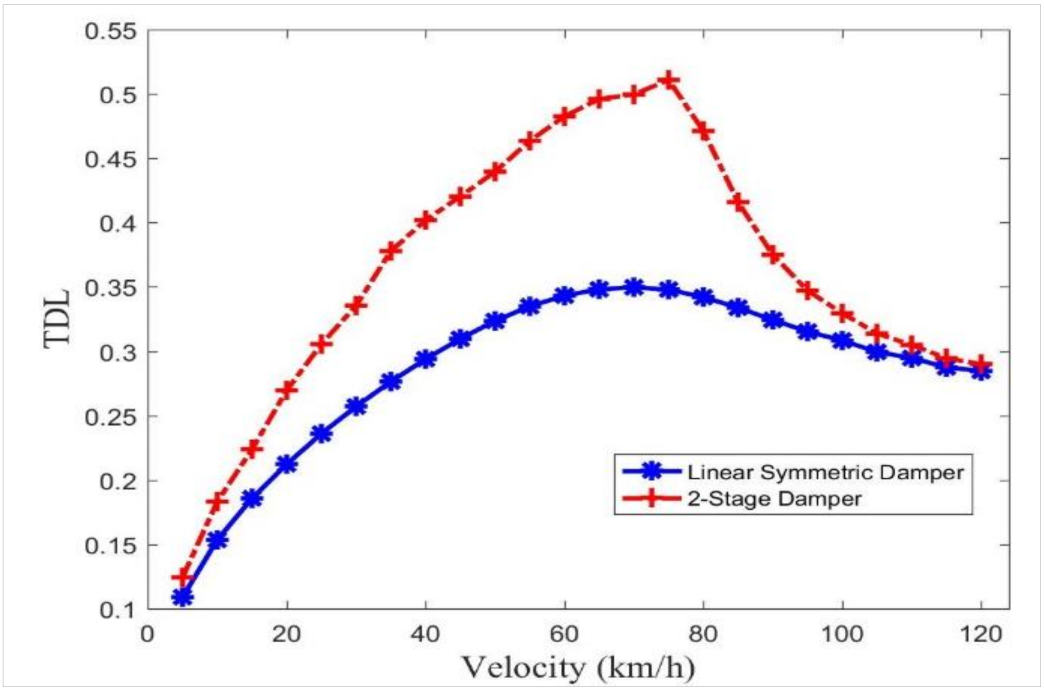


Figure 7: TDL Versus Velocity

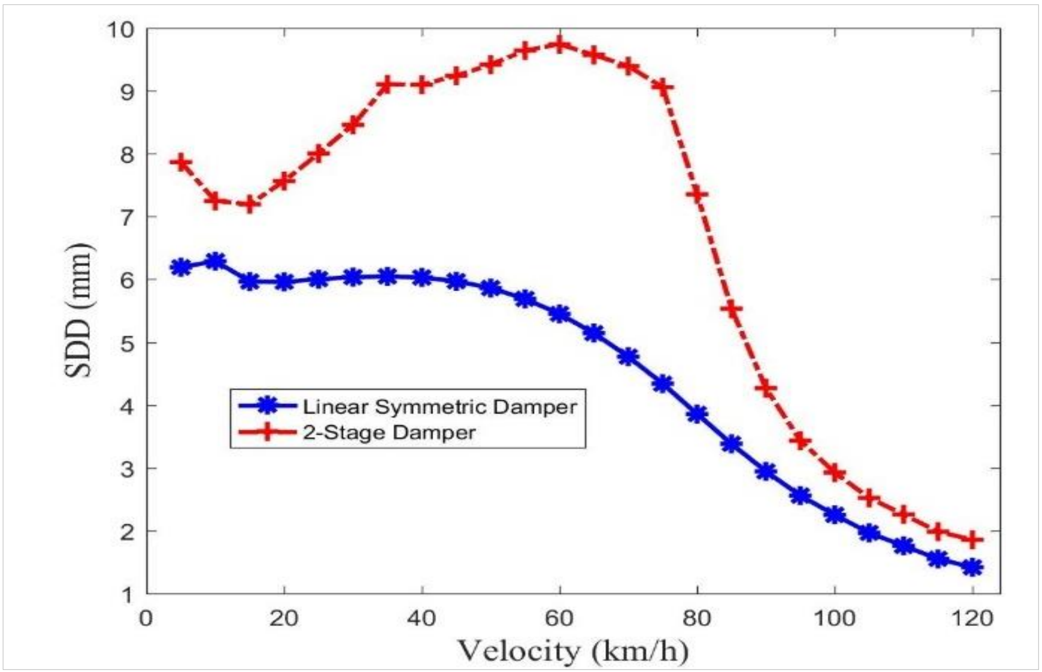


Figure 8: SDD Versus Velocity

4. CONCLUSIONS

The analysis's findings in this research allowed us to think about how the two-stage asymmetric damper would affect the oscillatory bus model's vibration behavior in the time domain when the bus is subjected to random road profiles. The inner-city bus model's four responses - the driver's vertical acceleration, the body's vibration acceleration, the suspension dynamic deflection, and the tire dynamic load - were investigated. The following impact was discovered as a result of the appearance of damper's asymmetric characteristics of:

1) When the bus is subjected to a random road profile, the two-stage asymmetric damper produces greater performance in terms of ride comfort than the linear symmetric one. In the case that the two-stage asymmetric damper is used, the values for the driver's vertical acceleration throughout the entire velocity range satisfy the desired level of comfort according to ISO 2631-1:1997.

2) The linear symmetric damper will aid in lowering the dynamic load on the tires, which will enhance handling control. In addition, the two-stage asymmetric effect on the working space could be ignored due to the small value of SDD on the entire vehicle's working velocity.

This study provides a couple of valuable references for further improving suspension's performances in the manufacturing's design progress. The two-stage asymmetric damper is beneficial to significantly improve the ride comfort, especially for the driver. However, choosing the better damping characteristics needs achieving a compromise between "more comfort" and "safer" because the linear symmetric damper enhances handling control throughout the working velocity.

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