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MODELLING AND EXPERIMENTAL INVESTIGATION OF CLUTCH DAMPER SPRING STIFFNESS ON TRUCK DRIVING COMFORT

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ABSTRACT

In recent years, the engine power and torque levels in heavy commercial trucks have shown a significant increase that corresponds to commercial activities. Increasing demands for driving comfort and fuel efficiency in trucks require the design of more efficient powertrain systems. The optimum selection of these parameters is required for power transmission. The aim of this study is to investigate the effect of the damper spring stiffness on truck driving comfort. For this purpose, a truck powertrain system was modelled, and the experimental test results were compared with the modelled powertrain system results. A clutch, which helps to increase the lifetime of the various components in a powertrain system of the vehicle and helps to meet the requirements of driving comfort, has an important role in powertrain systems by regulating the torque transmission. Realistic driving conditions of a vehicle were simulated by 1-D modelling; the response of the powertrain system to the vibrations was investigated on the basis of frequency, and a comparison was made with real vehicle test results. The conclusions considered both the experimental and numerical results, and the importance of the clutch spring stiffness during the design of the clutch and powertrain system was investigated in detail.

Keywords: *Clutch damper spring stiffness, vehicle vibration, powertrain system modelling, vibration simulation, clutch disc design, truck driving comfort*

INTRODUCTION

The clutch disc, which enables gear shifting by a driver by cutting the torque transmission, is a high-strength structure that allows a torque transmission between the flywheel and clutch pressure plate by friction. In addition to providing the torque transmission, the clutch disc is expected to dampen vibrations originating in the vehicle engine. The oscillating motion of a system around its equilibrium position is called vibration. The damper spring used in the disc is the most important damping element in clutches. A typical clutch used in vehicles is shown in Figure 1.

Figure 1. Clutch disc assembly [14]

Damping is a reduction in or an elimination of the amplitude of a mechanical energy wave. The mechanical vibrational energy attains another form by damping and changes in amplitude over time. The damper springs in a clutch disc are used for vibration damping of the vehicle. Therefore, damper springs in the clutch are aimed to increase the comfort of the vehicle and protect the thermomechanical systems against the problems caused by vibration.

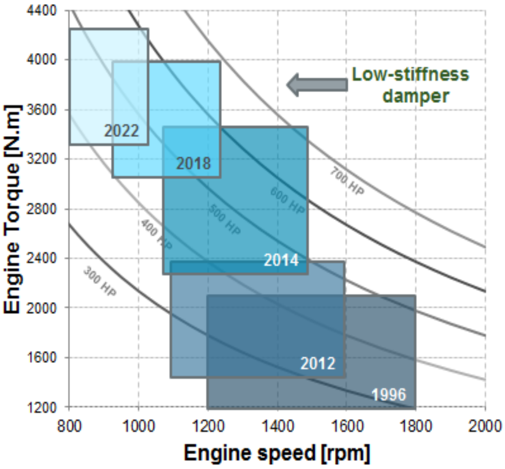

Figure 2. Truck engine torque – Resonance RPM based on years [14]

In recent years, many novelties in the automotive sector have proven that as the engine power and engine torque increase, the maximum vibration value of the vehicle decreases, and the resonance frequency which represents the maximum vibration at a specified RPM (revolution per minute), is reduced to lower values. This future trend forces vehicle designers to use low-stiffness dampers year by year (Figure 2).

Damper springs in vehicle clutch systems have been investigated thoroughly in many studies. Lu and Zeng [1] evaluated the RMS (root mean square) vibration value to optimize vehicle driving comfort in their study. They compared the RMS results acquired by vehicle testing to provide an optimized suspension design. Shi et al. [2] studied the modal analysis of a bus body. In their study, an engine excitation analysis was conducted with different engine firing order. Additionally, they used FEA software to observe the frequency response based on the engine excitation and provided proposals to bus designers based on the vibration optimization. Velmurugan et al. [3] used a GA (genetic algorithm) to estimate the vibration values and compared these values to experimental test data for a further analysis of driving comfort related to the health risks in a suspended cabin tractor semi-trailer. Szadkowski and Morford [4] investigated the importance of the proper disc geometry, spring preload and torque compensation angle in the determination of the damper spring stiffness in their work. Smith [5] examined the natural frequency of the vehicle components and determined the optimum weight increments to increase the moment of inertia of the transmission system that reduced the natural frequency to improve vehicle comfort. When the critical damping value was reached, an increase in the amplitude at the resonance frequency did not continue. It has been observed that this reduction in the natural frequency improves comfort by reducing vehicle vibrations. Acar et al. [6] proposed improvements to the clutch design by analyzing the frequency levels using MATLAB software and performed vibration level optimization studies for a 3- cylinder engine, which has a more effective design and more comfort requirements than those of 4-cylinder engines. In this context, the design of a three-stage clutch spring, which meets the vehicle vibration requirements at different stages, has been studied. Sofian et al. [7] examined the frequency of the gearbox vibrations and compared their vibrations to different gearbox types. They have observed that the engine vibrations must be in the range specified by the gearbox manufacturers. As a result, if the vibration levels are out of the transmission vibration limit, then low vehicle comfort and a reduced lifetime of the gearbox mechanical components are evident. Riedel et al. [8] examined clutch functions by optimizing the stiffness of the clutch damper spring. In their study, the importance of disc damper stiffness and disc design geometry compliance was mentioned.

In addition, a powertrain system was modelled in 1-D, and the system behaviors were examined. Brandt et al. [9] analyzed time-dependent vibrations at a frequency level by an FFT method and interpreted the dynamic optimization of the power transmission system using harmonic analysis. The harmonic values were used in the vibration and noise analysis by classifying the components found in the vehicle according to their natural frequencies. Skup [10] studied component-based transmission functions of the clutch and power transmission system and interpreted the effects of the damping elements functionally and graphically. They have mathematically examined the damping function of the clutch in their studies. Keeney and Shih [11] conducted harmonic investigations in order to reduce the noise that occurs due to radial vibrations in the power transmission system and investigated the causes of the vibrations and noise originating from the engine by order track analysis. Orzelowski [12] studied the importance of the clutch damper spring stiffness to reduce the resonance values of the vehicle under dynamic conditions. In this study, the gear dynamic properties chosen under driving conditions were mentioned in terms of the NVH effects. Rajapakse and Happawana [13] investigated driver seat comfort based on a frequency analysis using powertrain vibration analysis. In this study, the powertrain model was divided into subgroups, and the vibration on the seat felt by a driver was evaluated.

In this study, the effects of the clutch disc spring stiffness on truck vibrations were studied at the frequency level [15]. For this purpose, a 1-D model was created using AMESim software to obtain results at different damper stiffness values. These results were confirmed by the vibration values obtained during vehicle testing, and the correlation between experimental and analysis results was established. In this study, the importance of damper stiffness in the clutch design was revealed, and an approach was shown to improve vibration-related driving comfort.

2. MATERIAL and METHOD

2.1. Clutch and Torque Transmission

The clutch provides torque transmission through friction between the flywheel and the clutch pressure plate. In addition, the clutch disc is expected to dampen engine vibrations during torque transmission [16]. The main elements in this damping are helical compression springs. These springs are placed in a circular manner into the disc assembly. In designing these springs, engine vibration characteristics are taken into consideration. Typical helical damper springs are shown in Figure 3.

Figure 3. Clutch damper spring [14]

The torque capacity of a clutch can be calculated from Equation (1):

$$T = \mu F N R_m \quad (1)$$

The torque (T) transmitted by friction between the flywheel and the pressure plate is directly proportional to the coefficient of friction (μ), the applied compressive force (F), the number of friction surfaces (N) and the average diameter of the area on which torque transmission occurs (Rm).

2.2. Comfortable Driving Range, Frequency Analysis and Vibration

A comfortable driving range represents the engine revolutions per minute (RPM) most frequently used by drivers under normal driving conditions. The vibrations caused by an engine in a comfortable driving RPM range should be low; therefore, a suitable comfortable RPM range is one of the most important issues regarding the vibrations and acoustics during vehicle design [17]. This range is more limited in heavy trucks compared to passenger cars. For instance, in a gasoline passenger car, the most commonly used RPM range is between 1500 and 3500 RPM, while the average comfort RPM range of a truck ranges from 1000-1800 RPM. When the vibrations from the engine are high, vehicle comfort is reduced, and in the long term the mechanical system components can be damaged. The damped natural frequency in dynamic systems provides benefits of increased lifetime and reduced mechanical system costs in addition to improving vehicle comfort. To rotate the crank while a vehicle engine is running, explosions occur in a certain row in the cylinders, causing sinusoidal vibrations in the vehicle. When the force of the vibration frequency is equal to the natural frequency of the vibrating structure, the vibration amplitude tends to increase. This increase in vibration level prevents the system from operating correctly and causes damage to the mechanical systems. For this purpose, the damper spring stiffness is determined by a frequency analysis to reduce vibrations in the resonance regions [18].

2.3. Damped Natural Frequency and Vibration

The damped natural frequency in dynamic systems should be properly treated due to lifetime, cost and comfort issues in vehicles. When the clutch damper stiffness decreases, the oscillation amplitudes that occur because of engine forced vibrations are reduced. As a result, the RPM values at which high vibrations occur will decrease and wider comfort ranges will be enabled. The system‘s damped natural frequency Wd, critical damping ratio δ, and undamped natural frequency Wn, is given in Equation 2. Additionally, the same equation was illustrated by means of a different approach in Equation 3;

$$w_d = Wn\sqrt{1-\delta^2} \quad (2)$$

$$w_d = \sqrt{Wn^2 - (\frac{c}{2m})^2} \quad (3)$$

The angular acceleration (rad / s^2) is the change in the angular velocity per unit time. The angular acceleration is defined as the first derivative of the angular velocity with respect to time and the second derivative with respect to time of the angular displacement. In a power transmission system, the vibrations originating from the engines are represented by the angular acceleration (Figure 4). The amount of vibration can be expressed by amplitude. The amplitude is the greatest amount of motion that is separated from the average value or an equilibrium point in a harmonic vibration. The vibration amplitude can be examined in 3 groups: peak-to-peak (P-P), zero-to-peak (0-P) and RMS (root mean square) (the square root of the sum of the squares). In this study, the peak-to-peak (P-P) and RMS values were considered. The RMS value is the value that represents the effective value of the vibration, and the vibration that is felt in the vehicle by the passengers. The RMS value is equal to 0.7 times the value of 0-P in simple harmonic motion (Figure 4).

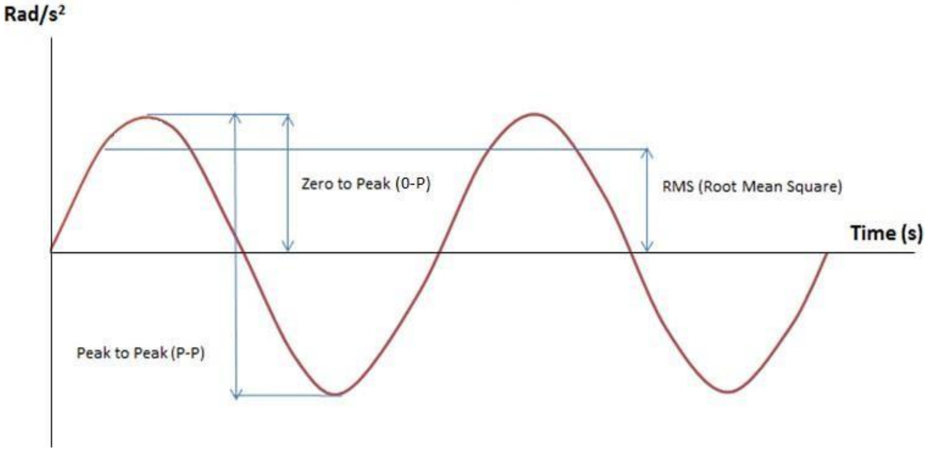

Figure 4. RMS (Root mean square) amplitude values

2.1. Truck Torsional Vibration Test

Torsional vibration testing was performed to evaluate the oscillation limits and damping capability of the powertrain system components. As mentioned in the previous sections, the damper springs used in a clutch disc are highly important for the dampening of vibrations originating from the vehicle engine. In this section, the torsional vibration test stages and targets are presented generally.

A powertrain system, in which power and torque flow occurs, is the main part of a vehicle. A clutch provides torque transmission by friction between the engine and gearbox. Additionally, high vibrations are expected to be dampened by the clutch to prevent mechanical damage to the gearbox. Gearbox producers share the vibration limits of their gearboxes with vehicle producers to prevent possible mechanical damage. Otherwise, a gearbox can be damaged in time, which results in noise, vibration and mechanical problems. In recent years, low-stiffness dampers have been widely demanded by many vehicle brands. In Figure 5, owing to the use of low-stiffness dampers, gearbox vibrations have decreased drastically, and the resonance frequency has also decreased.

This graph shows that by using low-stiffness dampers in clutch discs, lower vibration values and wider RPM comfort ranges are acquired.

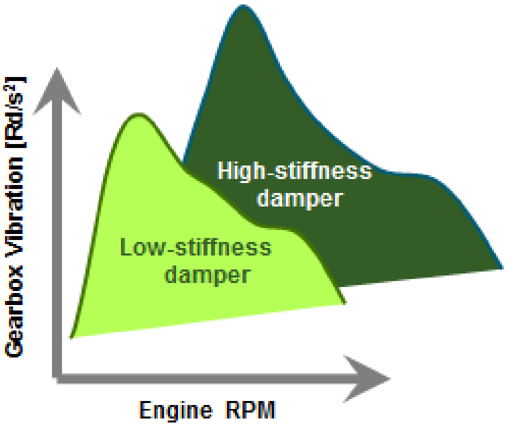

Figure 5. Low- and high-stiffness damper comparison [14]

Torsional vibration tests were initiated with speed sensor equipment installed at defined locations on the engine and gearbox. The sensors used for the vibration tests had high precision and sensitivity, so the assembly process required great experience during sensor fixation on the vehicles. One sensor, generally fixed near the flywheel, is positioned to obtain a signal from the engine cranks, while the other sensor is attached to the gearbox (Figure 6). The main idea is to record the angular acceleration of the engine and gearbox that exhibits the damping capability of clutch. If the engine vibrations are higher than the gearbox vibrations, then the clutch is able to dampen the vibrations from engine, whereas if the gearbox vibrations are higher than the engine vibrations, then the clutch is not able to dampen the engine vibrations.

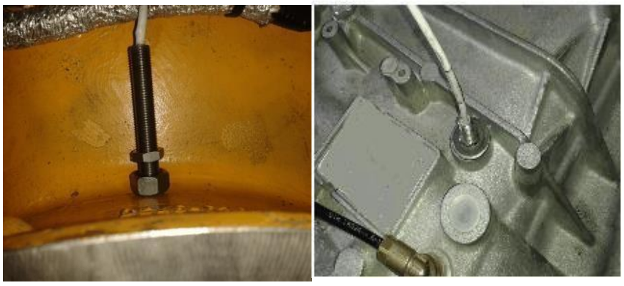

Figure 6. NVH test equipment fittings during truck torsional vibration testing [14]

The torsional vibration tests were conducted with the most used gear in general. For instance, a truck that has 12 different gears is tested between gears 6 to 12 because these gears have wide usage during the lifetime of the truck. The test began at low RPM, then continued until a maximum RPM was reached at the selected gears. A key point is to give full throttle to the gas pedal to observe the maximum vibration ability in the truck. These events were repeated for each of the selected gears, and the results were recorded with a signal converter and a post-processing analysis program. When the test was completed, the obtained data from the test equipment and software were initiated for each parameter, and then the results were reported in the vibration test documentation.

3. MODELLING and ANALYSIS

3.1. Modelling

To investigate the effects of clutch damper spring stiffness on vehicle comfort, the effects of spring stiffness on the vibration damping and resonance frequency were investigated by modelling the vehicle powertrain system with LMS AMESim software. The vibration damping reaction in the gearbox was analyzed by assigning values to the clutch damper spring stiffness in a certain range on the model, and the effect of the damper spring on the vibrations was evaluated. Example power transmission system components are shown in Figure 7.

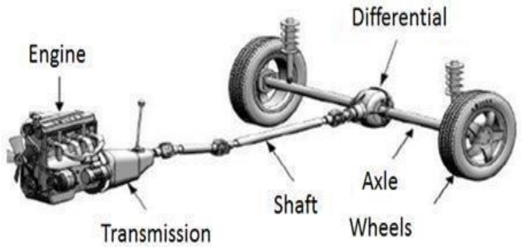

Figure 7. Vehicle powertrain system

The vehicle power transmission system consists of an engine, clutch, gearbox, main shaft, connecting elements, wheel and equivalent vehicle mass. By specifying the engine speed and torque level of the vehicle, the natural frequency and damping behavior of the vehicle components were examined, and the power transmission system was modelled to obtain a comfort analysis during vehicle usage.

The one-dimensional physical model of an example powertrain system created using AMESim software is given in Figure 8. To construct the model, parameters such as stiffness, inertia, and damping were selected from the application library according to vehicle requirements. The system modelling was conducted by assigning such properties. In the model, the starting signal of the system was provided to the engine, and the variable system outputs were obtained from the power transmission system.

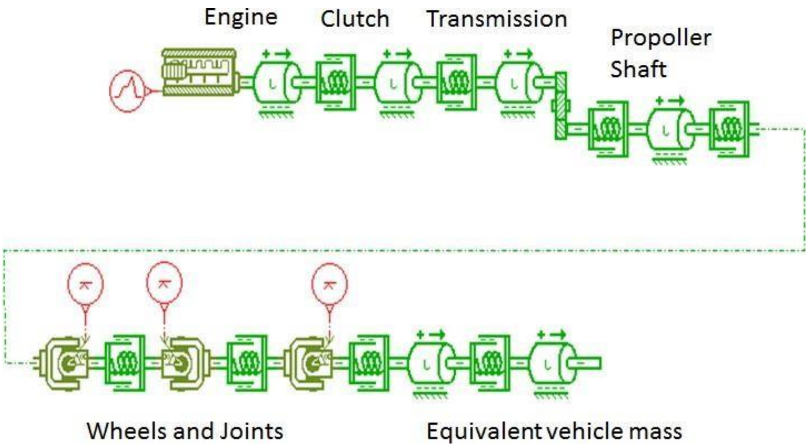

Figure 8. Modelled truck powertrain system

In the model shown in Figure 8, the dynamic behavior of a heavy vehicle power transmission system excited by a 6-cylinder engine was investigated. By describing the stiffness and mass of the system elements, the behavior of the vibrations originating from the engine subjected to variable clutch damper spring stiffness was interpreted in the system.

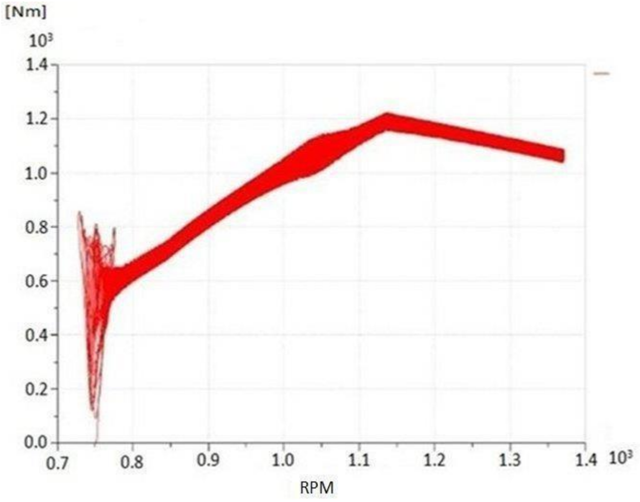

Figure 9. Torque-RPM graph modelled with AMESim

After modelling the powertrain system, the desired data can be obtained and visualized with the graph using the 'model graphics' tab in the analysis program. In the torque-cycle diagram shown in Figure 9, the model reaches a torque value of 1200 Nm at an engine speed of approximately 1150 RPM, and this torque value decreases afterwards. The simulation time was selected as 45 seconds, and the analysis requires the vehicle to accelerate from an initial engine speed of 750 RPM. A comfortable use range is accepted as 1000-1800 RPM. The effect of the spring stiffness on vehicle vibrations was observed by examining the clutch damper spring stiffness values of 300 Nm / °, 200 Nm / ° and 100 Nm / ° in the model by considering a heavy vehicle power transmission system. In this study, the road factor and gear ratio were assumed to be constant, and the losses in the power transmission system were neglected.

2.1. Analysis

In this section, three different clutch disc assemblies were modelled with three different damper spring stiffness values: 300 Nm / °, 200 Nm / ° and 100 Nm / °. The models built by using a variable spring stiffness were accelerated from a 750 RPM engine speed to a 1400 RPM engine speed in 45 seconds. The simulation results were obtained with a rad/s^2 total amplitude (peak-to-peak) and a rad/s^2 RMS (root mean square) methods. For the 3 different stiffness values, the results are shown as follows.

In Figure 11, the highest vibration amplitudes for 300 Nm / ° stiffness values occurred at the 26th second, and the amplitude was measured to be +600 / -600 rad/s2. In Figure 11, the vibrations are converted to rad/s2 – the RPM graph by an RMS method. By using an RMS method, the effective vibration value that is felt in the vehicle by the passengers was obtained. The RMS value is equal to 0.7 times the value of 0-P in simple harmonic motion. This value was found to be 400 rad/s2 at a 1050 RPM engine revolution.

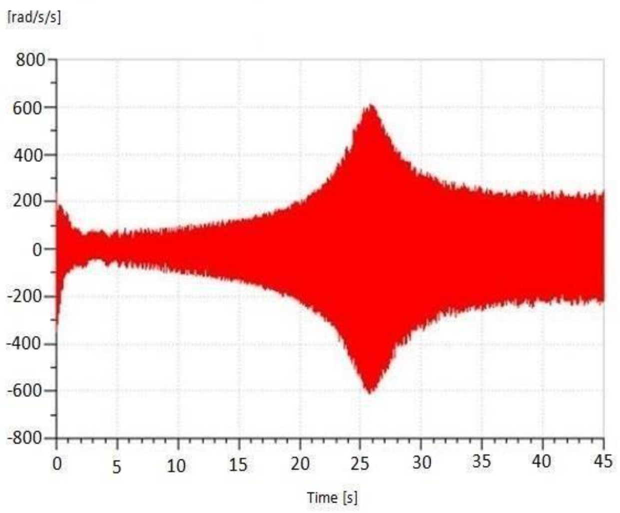

Figure 10. Rad/s^2 vs. Second (Peak-to-peak vibration graph versus time at $k = 300\ Nm/°$)

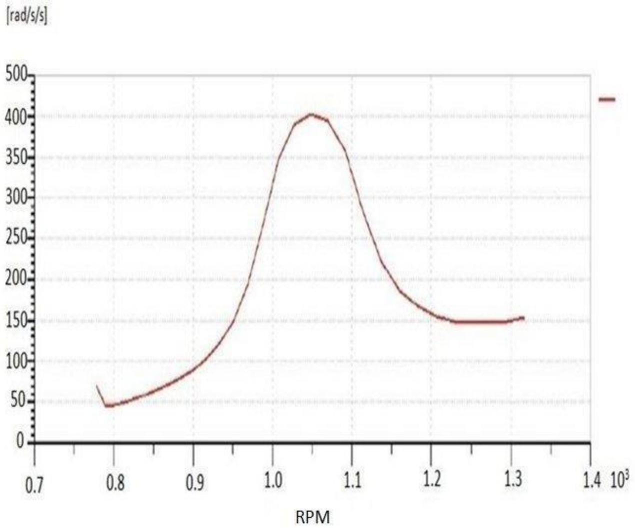

Figure 11. Rad/s^2 vs. Second (RMS (root mean square) graph results at $k = 300\ Nm/°$)

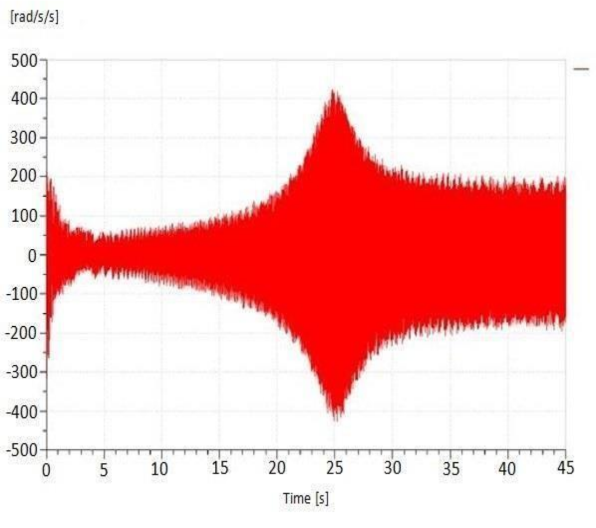

Figure 12. Rad/s^2 vs. Second (Peak-to-peak vibration graph based on time at $k = 200\ Nm/°$)

Figure 12 shows that the highest vibration amplitudes for the 200 Nm / ° stiffness value occurred at the 25th second, and the amplitude was measured to be +400 / -400 rad/s2. In Figure 13, the vibration value felt in the vehicle was found to be 270 rad/s2 by the RMS method. This result shows that the vehicle enters the resonance frequency at lower engine speeds compared to the 300 Nm / ° stiffness value at 1030 RPM. This result shows that the comfort range (1000-1800 RPM) increases.

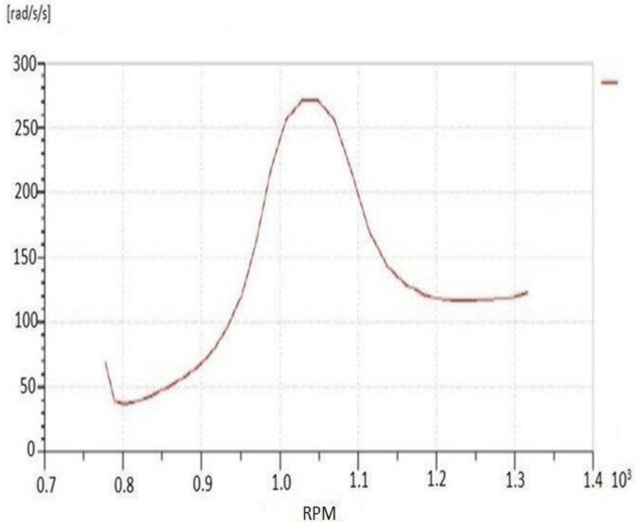

Figure 13. Rad/s^2 vs. Second (RMS (root mean square) graph results at $k = 200\ Nm/°$)

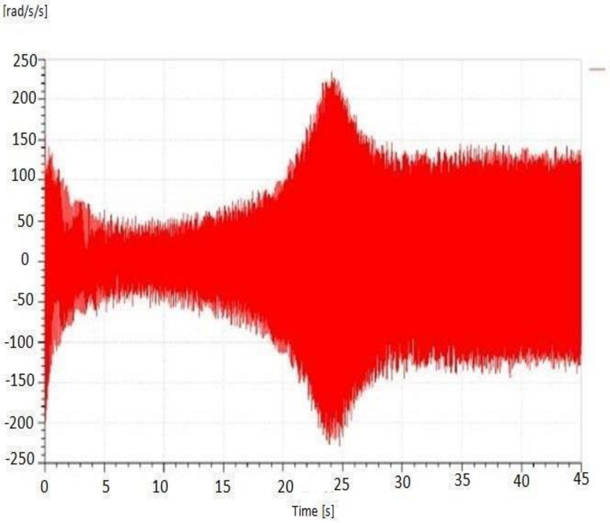

Figure 14. Rad/s^2 vs. Second (Peak-to-peak vibration graph versus time at $k = 100\ Nm/°$)

Figure 14 shows that for a 100 Nm / ° stiffness value, the highest vibration amplitude was achieved at the 24th second and is +220 / -220 rad/s2. In Figure 15, the vibration value felt in the vehicle was found to be 140 rad/s2 by the RMS method. The results clearly indicate that a 100 Nm / ° stiffness value provides a resonance frequency at a lower engine speed (1010 rpm) compared to that of the 200 Nm / ° stiffness value.

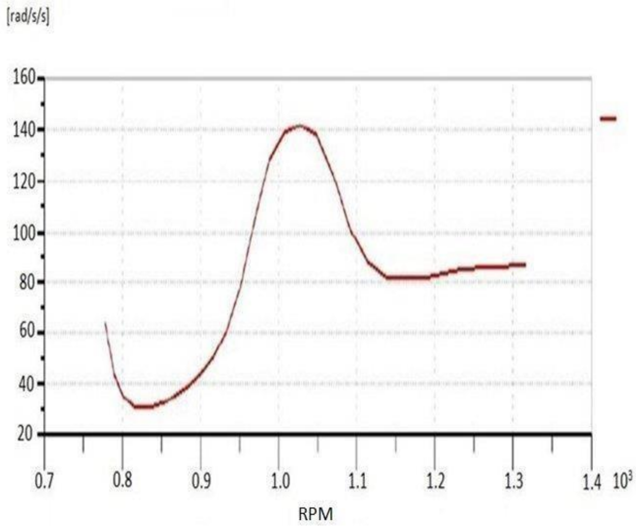

Figure 15. Rad/s^2 vs. Second (RMS (root mean square) graph results at $k = 100\ Nm/°$)

Table 1. Comparative analysis results

Clutch damper spring stiffness (N/°)	rad/s-sec (peak to peak)		rad/s2-RPM (RMS)	
	rad/s2	sec	rad/s2	RPM (rev/min)
300	±600	26	400	1050
200	±400	25	270	1030
100	±220	24	140	1010

Table 1 shows the results of a comparative analysis for three different damper spring stiffness values. The effect of spring stiffness on the vehicle vibrations was examined by showing the analysis results obtained for the different stiffness values using the rad/s2- RPM graph (Figure 16).

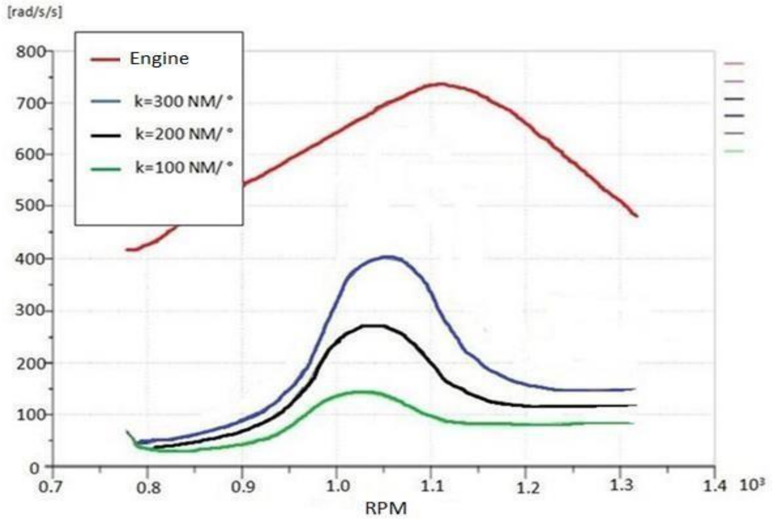

Figure 16. Comparative RMS summary graph at various clutch damper spring stiffness values (Rad/s^2 vs. RPM)

4. RESULTS AND DISCUSSION

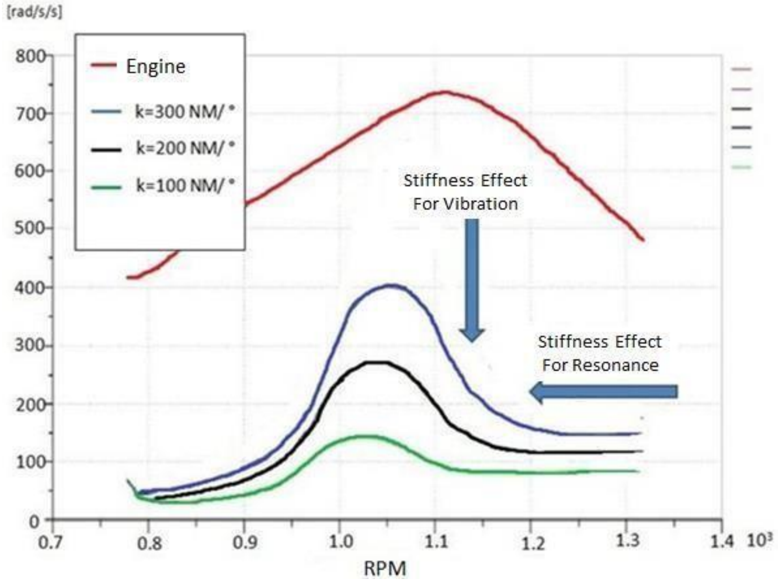

Figure 17. Clutch damper spring stiffness effect at various stiffness levels (Rad/s^2 vs. RPM)

The comparison shows that as the clutch damper spring stiffness decreases, the amount of damping in the system increases; therefore, the oscillation amplitude decreases. By increasing the damping value, the critical damping coefficient increases, and the damped natural frequency slips to the left side of the RPM graph, indicating that the vehicle vibrations reach their highest values at lower engine speeds (Figure 17). In Figure 17, the highest vibrations occur in the engines. It can be seen that the clutch, which has the task of damping vibrations in addition to torque transfer, achieves variable damping ratios and the resonance frequency with the use of damper springs at different stiffness values. As a result of the analysis, it is seen that with the use of high stiffness damper springs, higher vibrations are generated in the vehicle compared to damper springs with low stiffness. However, with a reduction in the damped natural frequency fd, the vehicle enters into a resonance at lower engine revolutions (RPM), and the comfort of the vehicle increases.

A comparison of the analysis results (Figure 17) with the actual vehicle test results (Figure 18) indicate that the data in the graphs are directly proportional to each other. The measurement results come from a heavy vehicle with a torque of 1200 Nm. In the tested vehicle, the vibration tests were repeated using two different discs with 381 Nm / ° and 298 Nm / ° damper spring stiffness values. Vehicle vibration tests were performed to see if the clutch meets the requirements and vibration damping capacity. In these tests, speed sensors are placed in the engine and gearbox, and the angular acceleration was measured and recorded on the relevant program. In the comparative test, it is revealed that if the clutch disc with a 298 Nm / ° damper spring stiffness is used, then the vibrations coming from the vehicle are decreased by more damping; therefore, the damped natural frequency is lowered. As a result, this vehicle enters the resonance at lower engine revolutions, and the highest vibration amplitude value is seen to slip to the left of the RPM graph.

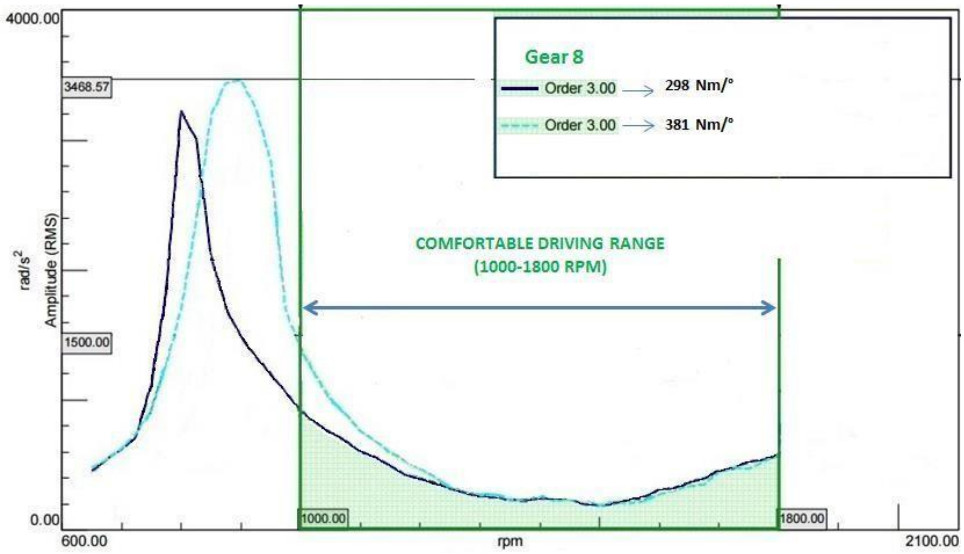

Figure 18. Comparative vehicle test measurement results [14]

Table 2. Torsional vibration vehicle test measurement results

Clutch damper spring stiffness (N/°)	rad/s2-RPM (rev/min) (RMS)	
	rad/s2	RPM (rev/min)
381	3468	730
298	3200	550

5. CONCLUSION

The clutch disc damper spring stiffness was taken as a variable in the model that was established to investigate the effects of spring stiffness on truck driving comfort. The other variables were considered constant in comparative analysis. The simulation effects of the road and driver profiles were neglected. The usage of the desired stiffness in the clutch depends on the suitability of the disc design and vehicle specifications. In this study, it is accepted that the disc geometry is compatible with the damper spring stiffness values. The results clearly indicate that the use of low-stiffness damper springs in clutches damped the vibrations generated by the engines and decreased the vibration levels felt by passengers in the truck. Vibration damping in truck applications is very important due to high torque excitations generated in the engine. The optimized lower stiffness on the truck clutch disc increases the comfort of the truck by reducing the high amplitude vibrations. In addition, it is clearly observed that the use of a low-stiffness spring reduces the damped natural frequency and allows the vehicle to enter into a lower engine resonance RPM. A lower resonance RPM enables a more comfortable driving range for the driver under various road conditions.

NOMENCLATURE

c	damping coefficient (Ns /m)
f	frequency (Hz)
fd	damped natural frequency (Hz)
f_n	undamped natural frequency (Hz)
fs	friction coefficient
k	stiffness $Nm/^\circ$
N	number of facing surface
Rm	torque transmitted mean diameter (mm)
RMS	felt vibration on vehicle (Root mean square)
RPM	revolution per minute (Rev./Min.)
Sec	Second
T	Torque (NM)
δ	Critical damping ratio

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