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Implementation of TMD on Classic Car Suspension Structure

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Abstract. This investigation is aimed at exploring the possibility of energy recovery through the suppression of vibrations. The article describes a new type of regenerative suspension using an electromagnetic tuned mass damper (TMD) approach. The magnetic part of the device performs the function of the TMD, thereby providing both energy regeneration and damping properties to the protected structure. The basic concept and origin of such an approach was introduced. According to existing problems of classical car suspension, the method of revealing extra energy from car vibration was obtained. Then the main properties of the system with and without TMD were compared and finally, the aims of further research and conclusions were determined.

1. Introduction
In recent years, there has been an obvious trend in the increased development of electric vehicles. Novel methods of deriving better performances of such vehicles are continuously developing. In the future, it will likely continue to be a common solution for transportation. Assuming that most of the vehicles will use electric power for movement, the world’s consumption of electrical energy will increase significantly. Certainly, this will cause a problem for humans, as the increased consumption will increase the cost of electricity and likely lead to a shortage. To prevent this problem, scientists should immediately explore the new ways to deriving electrical energy, improving the existing methods of storing and producing energy. As for car production, there are a few main ways to store and produce energy: improve the performance of battery capacity, and increase motor effectiveness and developing recuperation systems. Recuperation systems are automotive systems for recovering a moving vehicle's kinetic energy under braking or vibration [1], such that systems are able to increase their driving range by a supplying an extra amount of energy. The current investigation is aimed at exploring the possibility of energy recovery through the suppression of vibrations. This research provides a new concept of regenerative suspension systems: construction with two degrees of freedom consisting of an electromagnetic damper, recovering the kinetic energy due to vibrations, and a solenoid which transforms it to electrical energy. This concept is predicted to have many advantages. The regenerative suspension system is able to simultaneously provide vehicles with: sufficient damping force and high regenerative efficiency with low energy consumption. This article presents the basic concept and origin of such an approach. In section 2, problems of classic car suspension systems were examined in addition to the opportunity to release more energy from car vibrations. Next section 3 describes particularly tuned mass damper approach and its properties. Further, in section 4 according to plots derived in the previous sections, a comparison of the main characteristics of the system with
and without TMD reveal advantages of using the TMD approach. Finally, aims of further research and conclusions were determined in section 5.

2. Problems of classic car suspension and opportunity to release more energy from car vibration

The current development trend of car suspension systems is to reduce their rigidity through wide application of pneumatic or hydro pneumatic suspension, as well as increasing the rigidity of the tires through the reduction of the height of their profile and further reducing the weight of the wheels. Under these circumstances, the natural frequency of the vehicle body would decrease to 1Hz, and the natural frequency of the wheels would increase to 10-14Hz [2]. It follows that the modern passive vehicle suspension configured for vibration damping bodies however, in the high-frequency range of perceived loads, do not perform their functions, and as a consequence transmit to the body a large force, which deteriorates the smoothness of the car and the stability of its movement at high speeds.

Let's consider the classical car suspension system with two degrees of freedom as shown in Fig.1a.

![Figure 1. a) Classic car passive suspension system. b) Classic car passive suspension with TMD.](image)

Where $M_{ps}$ is a sprung mass (protected structure) with stiffness $K_{ps}$ and damping coefficient $C_{ps}$, $M$ is an unsprung mass with stiffness $K$ and damping coefficient $C$, $X$ and $Y$ are respectively its coordinates, and $n(t)$ is a kinematic exiting with amplitude.

Let’s explore the main characteristics which are able to affect important aspects of suspension performance. Firstly plot the amplitude response of car body mass for four conditions: small damping (under damped system), classic damping system, critically damped system and over damped system with damping parameter $\zeta=0.1, 0.4, 1$ and $2$ respectively as shown in Fig.2a.

![Figure 2. a) Amplitude frequency response of car body mass. b) Acceleration frequency response of car body mass.](image)
The small damping system obviously has a maximum response at the body's natural frequency, but after the resonance region has better characteristics. In turn, a system with critical and large damping observed inverse properties: in the pre-resonance region, the system has a minimal appearance, but in the post-resonance, it is obviously inferior. Thus, the optimal level of damping in the classical passive suspension usually lies in the range from 0.2 to 0.4, which has a certain average value between the weak damping and the re-damped system. Then, take a look at car body mass acceleration response which is shown in Fig.2b. In the post-resonance region, there is a sharp increase in body acceleration, which occurs at the natural frequency of the wheel of the vehicle and as a consequence, a large force transmits to the car body, which deteriorates the smoothness of the car. Further as shown in Fig.3, this phenomenon affects the amplitude of car wheel as well and thus reduces the stability of its movement at high speeds.

![Figure 3. Amplitude frequency response of car wheel mass.](image)

Compared to passive suspension systems, active systems more effectively reduce the amplitude of the response at the resonant frequency of the sprung mass. However, at the resonant frequency of the unsprung mass, behave like passive suspensions. This is because the forces in the suspension need to control the movements of the bouncing wheels react to the sprung mass, and its acceleration of the sprung mass.

In addition to the fact that this phenomenon has a number of disadvantages, it can be considered as an opportunity to reveal additional energy in suspensions with regenerative functions, when using a dynamic absorber tuned to the natural frequency of vibration of the vehicle wheel. This approach will be described in the next section.

3. Tuned mass damper approach
The novelty of this particular idea is using a new type of construction with diaphragm springs and magnets, performing the function of tuned mass damper, which is able to oscillate in a magnet field from a solenoid, in this way allowing it to carry out two functions simultaneously: recovering the kinetic energy due to vibrations and damping the unsprung mass of the vehicle. In Fig.4 schematic view of construction and main parameters are shown. Where M is a sprung mass with stiffness K, m is an unsprung mass with stiffness k, X and Y are generalized coordinates, and η(t) is a kinematic exiting with amplitude η₀.
Figure 4. Schematic view of TMD structure.

Mass m is performing the function of tuned mass damper. As known, a tuned mass damper (TMD) is a mechanism applied in systems to suppress mechanical vibrations by kinetic energy [3]. In turn, the kinetic energy is expressed by (1):

\[ T = \frac{1}{2} m v^2 \]  

(1)

Where \( T \) is the kinetic energy, \( v \) is the velocity of mass \( m \). It is seen that, the kinetic energy is directly proportional to the mass of the damper and the square of its velocity. It follows that the key parameters in the tuning of the absorber is the choice of its mass and speed, which in turn depends on the characteristics of the oscillatory system, namely the spring stiffness and damping coefficient. Based on the above, there are two major types of TMD: with damping and without damping. TMD without damping is tuned to the frequency of the disturbing force. Such an absorber is called a narrow-band absorber, as it does not eliminate the threat of structural oscillations, when the frequency of vibration is out of tuned range. However, the insertion of damping allows it to significantly widen the bandwidth of effective operation of TMD. And it is important, that the energy dissipation in the dampers is carried with the use of dampers with viscous friction. For current research, the magnet (TMD) is oscillating while the wire (solenoid) stands still. Therefore, according to Faraday’s law, makes use of the magnetic flux \( \Delta \Phi \) through a hypothetical surface whose boundary is a wire loop. The electromotive force is given by the time derivative of the magnetic flux, described by (2):

\[ E = -\frac{\Delta \Phi}{\Delta t} \]  

(2)

Where \( E \) is the electromotive force (EMF) and \( \Delta \Phi \) is the magnetic flux. In this way the device is able to generate alternating current in the solenoid by suppress the energy of vibrations. Implementation of that kind of approach with classic passive car suspension will be considered in the next chapter.

4. Comparing classic car structure with and without TMD

Consider the classical car suspension system with tuned mass damper as shown in Fig.1b.

Where \( M_{PS} \) is a sprung mass (protected structure) with stiffness \( K_{PS} \) and damping coefficient \( C_{PS} \). \( M \) is an unsprung mass with stiffness \( K \) and damping coefficient \( C \). The TMD is represented by three
parameters: mass $m_1$, stiffness $k$ and damping coefficient $F_c$, $X$, $Y$ and $Z$ are their coordinates respectively, and $\eta(t)$ is a kinematic exiting with amplitude $\eta_{e}$.

Newton's law applies to that system given by (3).

\[
\begin{align*}
M_p \dddot{Z} + C_p \dddot{Z} - C_p \dddot{X} + K_p \dddot{Z} - K_p \dddot{X} &= 0 \\
M \dddot{X} + C \dddot{X} - C_0(t)X + KX - K_0(t) - C_p \dddot{Z} + C_p \dddot{X} - K_p \dddot{Z} &= 0
\end{align*}
\]

Then, using the Laplace transformation, amplitude of car body, wheel and TMD can be derived. Substituting the initial conditions into derived equations we are able to plot and analyze main dependencies of such a structure. The initial conditions were obtained according to TMD optimization process Kopylov et al [4]. Applying TMD on the wheel does not affect performance of the car body in the whole range of operating frequency, as clearly shown in Fig.5a.

![Figure 5. a) Amplitude frequency response of car body. b) Acceleration frequency response of car body.](image)

However as seen in Fig.5b, a TMD significantly reduces the peak of amplitude in the range near the natural frequency of car wheel, thus improving the comfort performance of the car. And as expected, the TMD also reduces amplitude response of car wheel as shown in Fig.6a. This in turn, improves the driving and handling performance of the vehicle.

If considering the TMD as an actuator of regenerative system, the key parameter which can affect regenerative ability is velocity of oscillation. According to a familiar modern solution in the field of regenerative car suspensions, the typical actuator has a relative velocity of about 0.2-0.4 m/s which in turn is able to harvest 16-64W of energy [5]. The TMD approach allows it to reach peak velocity by suppressing vibration energy at 0.8 m/s and at the same time providing the car with better handling performance and comfortability as shown in Fig.6b.

These results undoubtedly confirm the feasibility for such methods of regeneration and damping for car suspensions, but only for implementation as a structure parallel to passive suspension.
5. Conclusion

In this paper, the idea of using a tuned mass damper as a part of classic car suspension was introduced, for such a system, the car body, wheel amplitude, and acceleration response were obtained.

With the coefficient of damping $\zeta=0.4$ for protected structure and initial excitation with amplitude 0.02m, the system with TMD showed better properties of performance. Particularly, acceleration response of the car body mass at the peak of resonance at the wheel natural frequency reduced from 0.22 to 0.18m/s$^2$, a reduction of 19%. This led to the improved comfort of driving in the post-resonance region. Further, the amplitude response of wheel reduced from 0.029 to 0.023m, a reduction of 21%, improving driving operating performance. In addition, compared to familiar modern constructions of regenerative suspensions, the current method allows actuators to reach a velocity of 0.8m/s, which is double the value of familiar modern constructions. Thus this method causes an increase in the production of electrical energy. These results undoubtedly confirm the feasibility of such methods of regeneration and damping using in classical car suspension systems.

The aims of the further research are: to develop optimized design and methods of control, with the particular value of the power of regeneration for such systems, and to analyze the system with a TMD as a part of active car suspension.

References

[1] Chew Kuew Wai, "Electric Vehicle Energy Harvesting System", 2013 IEEE Conference on Sustainable Utilization and Development in Engineering and Technology, pp.7-10, November 2013.

[2] Zoran Stevic, "New Generation of Electric Vehicles", (pp58). Croatia: InTech, 2012.

[3] J. Mondal, B. Azzam, and M. Abuhalaiqa,"Active Tuned Mass Damper", Control and Automation (MED), 2015 23th Mediterranean Conference, pp.1192-1197, July 2015.

[4] S.Kopylov, C.Z.Bo, "Electromagnetic Tuned Mass Damper Approach for Regenerative Suspension", International Journal of Aerospace and Mechanical Engineering, Vol:12, №2, pp.59-63, 2018.

[5] L.Zuo, B.Scully, J.Shestani and Y.Zhou, "Design and characterization of an electromagnetic energy harvester for vehicle suspensions", Smart Materials and Structures, 19, pp.1-10, 2010.