Towards Autonomous Driving: Design of Smart Damper – Energy Harvester

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Abstract: Majority of modern cars are equipped with standard suspension systems with hydraulic shock absorbers. They are reliable elements, but came to the limit of their possibilities to ensure reasonable level of vibration accelerations, when cars became lighter and diameters of the wheel rim and tires has big diameter. This paper provides possible solution for the modern car suspension systems with controlled damping and self-powering service and data transmission. Such dampers implements smart liquid and electrically realized damping force control. This paper focused on electrical properties of this type of shock absorbers. Provided experimental research use shock absorber – energy harvester of new design. All experiments performed on shock machine using produced by authors prototype of original design. Energy gaining performed using three similar prototypes with ferro-nanomagnetic liquid, permanent magnet core and ferromagnetic steel core. Obtained results provided in the graphical form as electric gain with open circuit and loaded by electric load.

Keywords: damping, vibration control, energy harvesting, mechatronic systems

1. Introduction

Recent development process of the automotive vehicles covers all areas of the technology – from powertrain to materials and body design. Decreasing weight of the car and increasing diameters of tires and wheel rims contradicts to requirement of vibration level diminishing in the car body due to worsening coefficient of weighted mass. Solution of these problems lays in increasing quality of suspension of the vehicle, which is related to the vibration damping process. Classical design of shock absorbers faces modernization, which includes all kind of damping force correction from vibration velocity and acceleration values. Usually such modernization leads to the increase of components, which makes these solutions expensive and increase failure probability. Mostly known modernization methods uses electrically or mechanically driven pass valves in the hydraulic system of shock absorber [1]. Number, position and design of these valves in hydraulic systems affects damping law and therefore continues to implement [2, 3]. Alternative efficient solutions in high comfort car are active damping systems [4], which ensures high comfort, but consumes external energy and causes frequent technological faults [5].

Development of suspension systems leaded by high number of scientific researches focused on improvements of damping characteristics, selection of used materials, creation of dampers with controllable damping characteristics [6] in real time and design of dampers with mechanical energy convert to electrical [7–10]. These entire improvements suit well for traditional cars but not sufficient for autonomous driving. In case of autonomous driving, not only to desire level of driving comfort has to be ensured but it also requires evaluation of some safety features, for example, vibration level when car moves on road surfaces with various roughness. Road surface roughness could be evaluated by implementing cameras or force/acceleration sensors in the vehicle suspension. The weakness of this approach covert by need of huge data processing power and remains dependent on road/weather conditions due to pollution of optical system of the cameras [11].

Another approach to solve this technical issue is to develop dampers, which can perform two functions simultaneously: a damper with controllable characteristics and road surface roughness sensor.

All roads can be characterized according ISO 8608 (Mechanical vibration – Road surface profiles – reporting of measured data), that categorize road roughness to classes from A to H. Road roughness define driving speed as well as comfort level inside vehicle, which requires to react suspension dampers by changing damping characteristics.

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This idea can be implemented using mechatronic damping system with ability to recognize road category and set required damping characteristics and to inform driving computer or human driver about velocity regime [12, 13]. Proposed damper – energy harvester with ferro-nanomagnetic fluid will have possibility to control its damping characteristics and at same time it will work as a sensor, which provides information about roughness off road surface. Moreover, this approach will allow to harvest electrical energy from vibrations and convert it to electrical energy. Mathematical evaluation of this approach and evaluation of mechanical energy which be harvested from suspension system is provided in our previous report [14].

This paper intended to present results of experimental research of our damper prototype focused on its energy harvesting.

2. Experimental research

2.1. Design of smart damper – energy harvester

New designed smart damper – energy harvester realizes three main functions: (a) controlling of damping ratio; (b) measuring of road surface roughness; (c) harvesting vibration energy.

The structure of the smart damper presented in the Figure 1. This prototype is designed to operate in environment, where vibrations are relative and there are two bodies with relative displacements. It consists from frame 1, which is made of magnetic-neutral material and can be attached to the moving body by a fixing eye 6. Frame 1 is a tube which acts as cylinder and contains ferromagnetic liquid 5. Piston stem 3 is attached to the piston 4. Piston stem 3 can move along its axis and therefore can be attached to car body similar as traditional shock absorber. In order to keep proper liquid position within piston, in the other end of cylinder there are installed piston 8 and compensating spring 7. Two magnetic sources attached to the top and bottom of piston 4 could be realized as permanent magnets or electromagnets. These magnets create magnetic field media, which shaped by magnetic liquid placed in the gaps of the piston 4. When force applied to the piston stem 3, piston 4 moves along frame 1 and thus alternate magnetic field passes through the solenoid coils 2, where electric current generated.

Behavior of ferro-nanomagnetic fluid as magnetic core in the linear generator, by our best knowledge, not researched widely; therefore, we build three prototypes of such shock absorber with different inner piston materials as core of generator. There were used as test core: i) permanent magnets with known magnetic flux value; ii) magnetically soft steel core with negative pattern of metal/gaps, in order to model used liquid configuration; iii) liquid core with ferro-nanomagnetic fluid. In all cases piston was designed as cylinder from parallel plastic cylinders with different material inserts between them. In case when permanent magnets were used, fluctuations of magnetic field were caused by oscillations of permanent magnets in respect of stationary coils. In case when magnetic steel, only two permanent magnets were used, they were placed on the top and bottom of piston and inserts of steel were used to transmit electromagnetic flux. Piston with ferromagnetic fluid had same configuration but instead of steel, fluid was used as media to transmit magnetic flux. These different designs allow us to create different distributions and concentrations of magnetic flux in respect of stationary mounted coils.

These three prototypes let us decide about efficiency of our prototypes for energy harvesting and determine liquid magnetic properties in the range of implemented frequencies. These results further will be used for magnetic chain optimization of the damper – energy harvester.

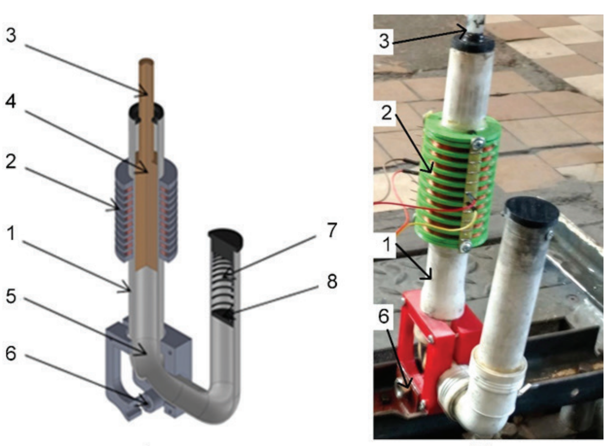

Fig. 1. Structure of shock absorber: a) 3D model cross-section view, b) view of produced prototype: 1 – frame; 2 – solenoid coil; 3 – piston stem for force application; 4 – piston; 5 – Ferro-nanomagnetic fluid; 6 – fixing eye; 7 – compensating spring; 8 – air piston

Rys. 1. Struktura amortyzatora: a) widok przekroju modelu 3D, b) widok wyprodukowanego prototypu: 1 – rama; 2 – cewka elektromagnesu; 3 – trzon tłoka do przyłożenia siły; 4 – tłok; 5 – płyn ferro-nanomagnetyczny; 6 – mocowanie oka; 7 – sprężyna kompensacyjna; 8 – tłok pneumatyczny

2.2. Experimental setup

Experimental research built in the laboratory of Department of Mechatronics, robotics and digital manufacturing and tested in the laboratory of Automotive transport, using our produced test rig, which is shown in Fig. 2.

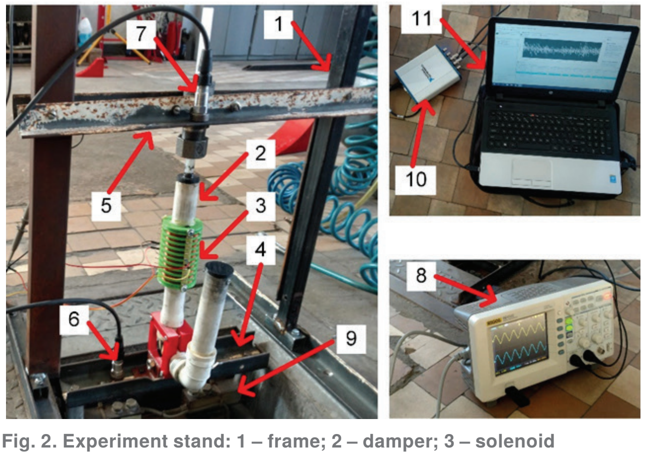

Fig. 2. Experiment stand: 1 – frame; 2 – damper; 3 – solenoid coil; 4 – down transverse beam; 5 – top transverse beam; 6 and 7 – accelerometers; 8 – oscilloscope; 9 – shaker of automotive suspension; 10 – data storage device; 11 – computer

Rys. 2. Stanowisko eksperymentalne: 1 – ramka; 2 – przepustnica; 3 – cewka elektromagnesu; 4 – belka poprzeczna skierowana w dół; 5 – górna belka poprzeczna; 6 i 7 – akcelerometry; 8 – oscyloskop; 9 – wytrząsarka zawieszenia samochodowego; 10 – urządzenie do przechowywania danych; 11 – komputer

Test rig consist of the frame (1) which was tightly attached to the firm ground. Prototype of the damper – energy harvester (2) was fixed to the upper (4) and lower (5) traverse beams. Upper beam (5) tightly attached to the frame (1), lower beam (4) installed on the shaker of automotive suspension (9). When shaker is activated, lower transverse beam to which damper is attached performs reciprocating movement. Same movement is transmitted to the piston which together with ferro-nanomagnetic fluid passes through the coils (3) where electric power is generated. Output terminals of the coils are connected to the oscilloscope (8), which provides measurements of generated voltage. A hydraulic shaker was used as generator of oscillations, which can generate oscillations with stroke up to 6 mm under the frequency 24 Hz and payload up to 800 kg. Vibration level of lower and upper transverse beams measured by two accelerometers (6, 7) Ini 603C01 (PCB Piezotronics, Depew, USA). Signals from accelerometers registered using data acquisition system USB-4432 (10) (National instruments, Austin, USA) and personal computer (11). All data analysis performed using NI software LabVIEW.

Using described setup, the possibilities of energy harvesting and road roughness sensing were evaluated, using all three prototypes of smart dampers.

2.3. Research methodology

Experimental research performed measuring voltage generated by the prototype then lower transverse beam (Fig. 2) oscillates with 6 mm stroke on the frequency of 24 Hz simulating harmonic kinematic excitation from the road roughness.
Firstly, the efficiency of separate coils of all three prototypes were evaluated. For this purpose, induced voltage on open circuit conditions in each coil was measured using multimeter DT30B.

Secondly, on the same excitation conditions time – voltage dependencies were registered when 100 Ω electrical load is applied to the circuit. These dependencies allowed to evaluate amount of harvested energy and at the same time shows possibilities to use damper – energy harvester as a road roughness sensor.

Final experiments were performed using prototype with ferro-nanomagnetic fluid. In this case were performed voltage measurements on the open circuit and on the circuit with 10 Ω electrical load. Simultaneously vibration level was measured on the input (piston stem Fig. 1) and output (fixing eye Fig. 1) of the damper. All obtained and processed results presented in the following part of the report.

2.4. Results and discussion

In the beginning, induced voltage on the coil measured on open circuit conditions. This measure shows RMS of the voltage on the separate coils (Fig. 3).

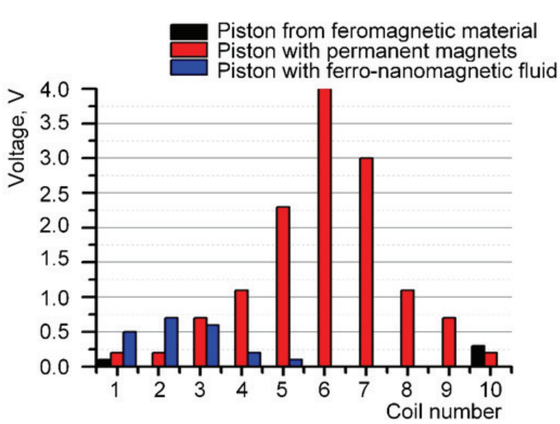

Fig. 3. Generated voltage on the coil (open circuit) with three prototypes
Rys. 3. Generowane napięcie na cewce (obwód otwarty) z trzema prototypami

From (Fig. 3) it is seen that on open circuit conditions highest voltage is generated using permanent magnets, but damper with ferro-nanomagnetic fluid also shows sufficient results to use damper as road roughness sensor.

Time vs. induced voltage dependence on one coil using all prototypes provided in the Fig. 4. From time vs. voltage curves, it is seen that highest amount of energy is generated using piston with permanent magnets; prototype with ferro-nanomagnetic fluid generates approximately 30% less power.

Further the results of vibration level and induced voltage measured in adjacent coils at open circuit conditions is provided (Fig 5).

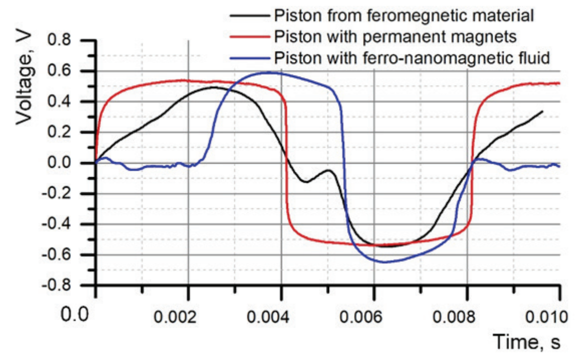

Fig. 4. Induced voltage on the coil with different material in the piston under electric load
Rys. 4. Napięcie indukowane na cewce z różnym materiałem w tłoku pod obciążeniem elektrycznym

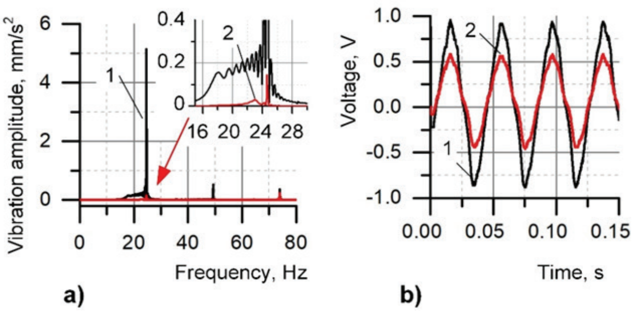

Fig. 5. Characteristics of prototype of smart damper – energy harvester: a) Amplitude-frequency characteristics measured on damper holder's (Fig. 2) at open electrical circuit. 1) vibrations on down transverse beam; 2) vibrations on top transverse beam, b) The voltage generated by the damper at an open electrical circuit in adjacent coils (Fig. 3), 1) second coil 2) third coil
Rys. 5. Charakterystyka prototypu inteligentnego tłumika: a) Charakterystyka amplituda-częstotliwość zmierzona na uchwycie amortyzatora (rys. 2) przy otwartym obwodzie elektrycznym. 1) drgania dolnej belki poprzecznej; 2) drgania górnej belki poprzecznej. b) Napięcie wytwarzane przez przepustnicę w otwartym obwodzie elektrycznym w sąsiednich cewkach (rys. 3), 1) druga cewka 2) trzecia cewka

The results of measuring vibration level and induced voltage in adjacent coils then electric circuit is loaded by 10 Ω electrical load is provided in Fig. 6.

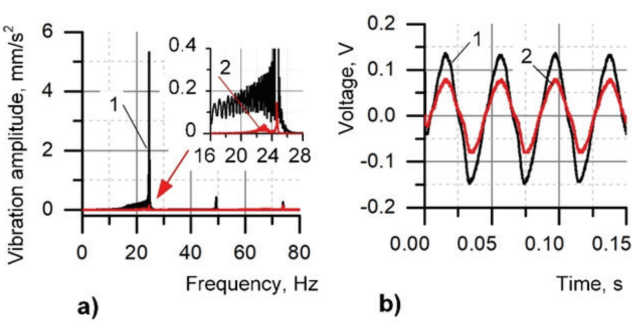

Fig. 6.Characteristics of prototype of smart damper – energy harvester when electric circuit loaded by 10 Ω electric load: a) Amplitude-frequency characteristics measured on damper holder's (Fig. 2) at open electrical circuit. 1) vibrations on down transverse beam; 2) vibrations on top transverse beam. b) The voltage generated by the damper at an open electrical circuit in adjacent coils (Fig. 3). 1) second coil 2); third coil
Rys. 6. Charakterystyka prototypu inteligentnego amortyzatora przy obciążeniu elektrycznym 10 Ω: a) Charakterystyka amplituda-częstotliwość zmierzona na uchwycie przepustnicy (rys. 2) przy otwartym obwodzie elektrycznym: 1) drgania dolnej belki poprzecznej; 2) drgania górnej belki poprzecznej; b) Napięcie generowane przez przepustnicę w otwartym obwodzie elektrycznym w sąsiednich cewkach (rys. 3). 1) druga cewka 2); trzecia cewka

Comparing Fig. 5 and Fig 6 it is noticeable that damping characteristics depends on the load of electric circuit. In case then circuit was loaded (Fig. 6.a), damping force was increased and more power of vibrations were transmitted from lower transverse beam to the upper one (Fig. 2). Also, from figures 5 and 6 it is seen that curve shape of measured voltage corresponds to the parameters of the harmonic excitation. Even taking into account that in this case generated voltages were quite low (1V on open circuit, 0.15 V on 10 Ω loaded circuit) obtained results confirms the initial idea that damper with ferro-nanomagnetic fluid can operate as damper-energy harvester and road roughness sensor simultaneously.

3. Conclusions

Performed experimental research of prototypes evidently showed possibility to use ferro-nanomagnetic fluid as magnetic core of the shock absorber – energy harvester with lower efficiency than permanent magnets, but higher than magnetically soft steel. Loss of efficiency of fluid system due to material change using 6 mm stroke and 24 Hz frequency was about 20% comparing to the case with permanent magnets. Even if testing program is ongoing, optimization of magnetic circuit is possible.

Damping force for this prototype is far not enough for real damping due to not sufficient electric efficiency, but force is noticeable even now and decrease of 0.1 mm/s^2 is recorded at 20 Hz mode. This design of prototype [15] is suitable to use in hydraulic damping, it means that it is possible to use this prototype inside shock absorber in the low frequency ranges even with inefficient electric power generation and therefore low damping efficiency from power harvesting.

Acknowledgment

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W kierunku jazdy autonomicznej: konstrukcja inteligentnego amortyzatora

Streszczenie: Większość nowoczesnych samochodów jest wyposażona w standardowe układy zawieszenia z hydraulicznymi amortyzatorami. Aktualnie stosowane amortyzatory są niezawodne, jednak nie umożliwiają dalszego rozwoju w odniesieniu do znacznych wartości przyśpieszeń drgań w lekkich samochodach o dużych średnicach felg i opon. Artykuł przedstawia nowe możliwości rozwiązań w nowoczesnych układach zawieszenia z kontrolowanym tłumieniem, autonomicznym zasilaniem oraz monitoringiem. Zaproponowane tłumiki zapewniają inteligentne, elektrycznie sterowaną siłę tłumienia. W pracy skupiono się na właściwościach elektrycznych zaproponowanych amortyzatorów cieczowych. Do badań eksperymentalnych wykorzystano opracowany przez autorów prototyp amortyzatora, a eksperymenty przeprowadzono na maszynie uderzeniowej. Pozyskiwanie energii z amortyzatora zrealizowano przy użyciu trzech podobnych prototypów z cieczą z nanocząstkami magnetycznymi na bazie żelaza, rdzeniem z magnesem trwałym i rdzeniem ze stali ferromagnetycznej. Uzyskane wyniki przedstawiono jako uzyskaną energię elektryczną zarówno w układzie z otwartym obwodem, jak i obciążeniem elektrycznym.

Słowa kluczowe: tłumienie, kontrola wibracji, pozyskiwanie energii, systemy mechatroniczne, amortyzator

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