Experimental and numerical studies of magnetorheological damper control coil type RD–8040–3

Łukasz Jastrzębski
AGH University of Science and Technology
Department of Process Control
Cracow, Poland
lukasz.jastrzebski83@gmail.com

Marcin Węgrzynowski
AGH University of Science and Technology
Department of Process Control
Cracow, Poland
mweg@agh.edu.pl

Abstract — The paper presents the research of a linear magnetorheological damper (MR) coil type RD−8040 produced by Lord Corporation. The aim of the research was to determine electrical characteristics for AC voltage supplying the MR damper coil. Understanding of the dynamic characteristics of the control coil is necessary for the proper selection of the parameters for current controllers supplying MR dampers. In order to know the dynamic characteristics of the damper control coil laboratory tests and numerical calculations were carried out. The tests were performed for sinusoidal voltage with an amplitude of 1 V and frequency changed in the range of 0.1−100 Hz. The results of the experiments were compared with the results of the simulation by step responses, the characteristics of amplitude−frequency and phase-frequency. This work will be used to build a model of a self-powered vibration reduction system equipped with a conditioning system.

Keywords – MR damper; experiment; simulations

I. Introduction

The paper concerns the laboratory tests and numerical calculations of a magnetorheological (MR) damper control coil RD−8040 produced by Lord Corporation [1]. The control of MR dampers operating in semi-active systems for vibration reduction consists of giving a variable at the time of voltage u(t) in accordance with the implemented algorithm.

The force F_T generated by the damper depends both on the relative speed v of the movement of the piston rod relatively to the cylinder, as well as on the values of magnetic induction B generated by the current flowing through the coil. The objective of the paper is to understand the dynamic characteristics of the damper control coil, which enables to determine the relationship between the time−varying voltage $u(t)$ and the current intensity $i(t)$.

Understanding the dynamic characteristics of the coil is particularly important in case of construction of self−loading systems for vibration reduction described in the literature [2], [3]. This paper is an introduction to a broader study of dynamic phenomena that occur in an MR damper while controlled by time−varying voltage.

II. Laboratory setup

Laboratory tests were carried out on the laboratory stand shown in Fig. 1.

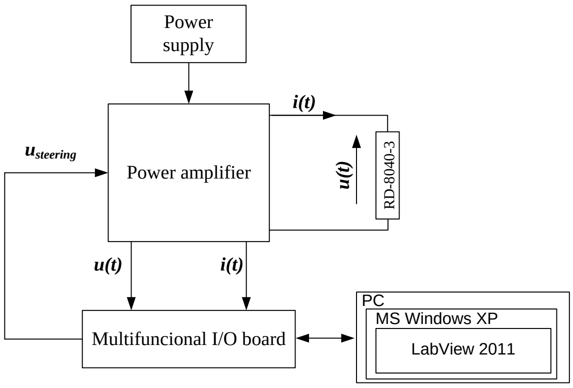

Fig. 1. Laboratory stand

The laboratory stand consists of a power amplifier, a generator RIGOL RG−DG1022, and a data acquisition system. The data acquisition system built is based on a modular system Compact−DAQ 9178 of National Instruments equipped with a module for measuring voltage NI−9205 and a computer running Windows XP with LabView 2011.

The RG−DG1022 generator produces a voltage $u_{we}(t)$, which is amplified by the power amplifier. It produces time−varying voltage $u(t)$ of sufficient current capacity, given to the MR damper control coil. The power controller has got transducers to measure the voltage $u(t)$ and current $i(t)$ flowing through the damper control coil.

All signals are converted to voltage signals ± 10V and sampled at a frequency of 50 kHz.

III. Results of experiment

The experiments were divided into two stages. In the first phase the flow of current $i(t)$ in the control coil was studied at step change in the voltage $u(t)$ (with an amplitude of 2V).

The step response of the current is shown in Fig. 2. The current reaches 90% of the determined value the time t_u = 55 ms. The value of current is determined to i_{const} = 0.37 A.

The performance shows that during the switching control (on−off type) the voltage should not be switched at a frequency greater than 5 Hz, due to the time to reach a fixed value of current.

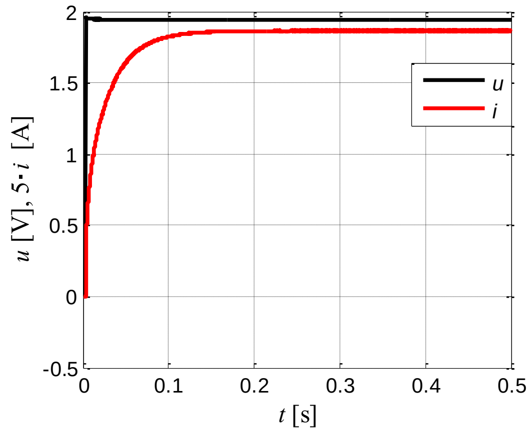

Fig. 2. Step response of current in the MR damper coil

In the second step the study was performed for a sinusoidal alternating voltage $u(t)$ at the control coil. This voltage had an amplitude of 1 V and the frequency was changed with in the range of 0.1 Hz to 100 Hz.

Figure 3 shows the amplitude-frequency characteristic of the admittance $Y(f)$ expressed by the formula:

$$Y(f) = 20\log\frac{I(f)}{U(f)} \tag{1}$$

$$U(f) = \sqrt{\frac{1}{T}\int_0^T u^2(t)dt}\ ;\ I(f) = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \tag{2}$$

Where: $U(f)$, $I(f)$ – root mean square value of the voltage $u(t)$ and current $i(t)$ flowing in the control coil, depending on the frequency f.

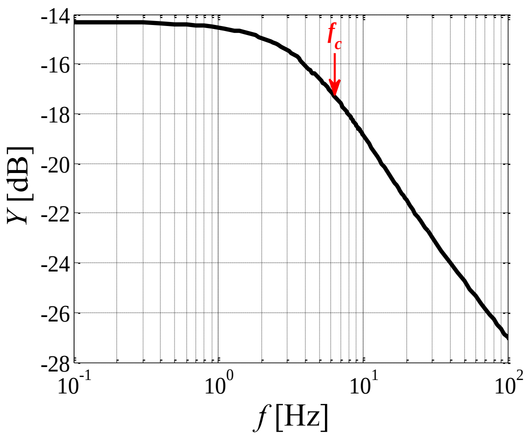

Fig. 3. Amplitude–frequency response of the MR damper coil

From the frequency characteristic it was possible to read the value of the cutoff frequency f_c=6.3 Hz, defined as a reduction of the signal by 3 dB. The cutoff frequency f_c corresponds to a phase shift $\varphi = -28$ ° shown in Fig. 4.

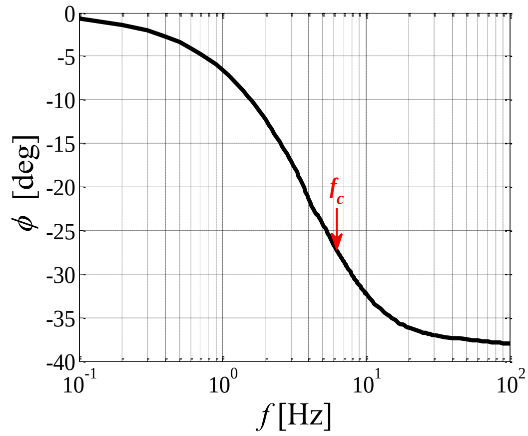

Fig. 4. Phase–frequency response of the MR damper coil

Figure 5 presents the frequency characteristics of the real power P, reactive power Q and apparent power S. The graph shows twice the decline of real power P at the cutoff frequency f_c. At this frequency, the maximum value of reactive power Q was observed in the control coil circuit.

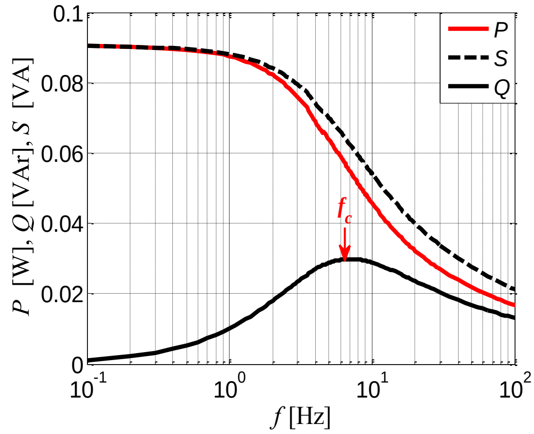

Fig. 5. Real power, reactive power and apparent power.

Figures 6÷8 show the time patterns of the voltage $u(t)$, the current $i(t)$ and the instantaneous power $p(t)$ at the frequency of 0.5 Hz, 6 Hz and 100 Hz. With the increase of the frequency f, an increased phase shift between the current $i(t)$ and the voltage $u(t)$ was observed, which at a frequency of 100Hz reached a value of $\varphi = -38°$. For the frequency shown, the current amplitude value was: 0.18 A, 0.12 A, and 0.05 A.

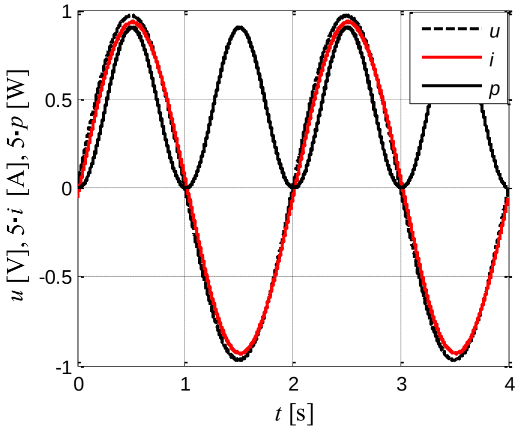

Fig. 6. Time pattern of voltage $u(t)$, current $i(t)$ and power $p(t)$ in the MR damper coil for $f = 0.5$ Hz.

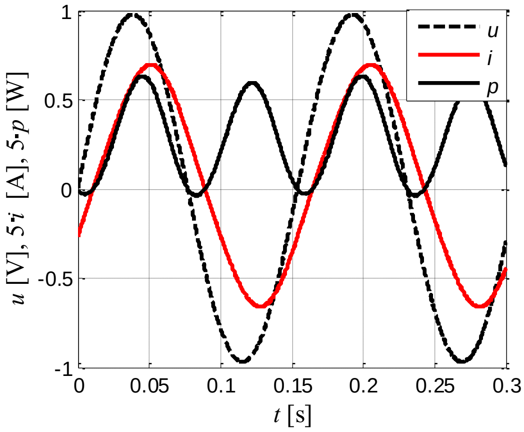

Fig. 7. Time pattern of voltage $u(t)$, current $i(t)$ and power $p(t)$ in the MR damper coil for $f = 6.5$ Hz.

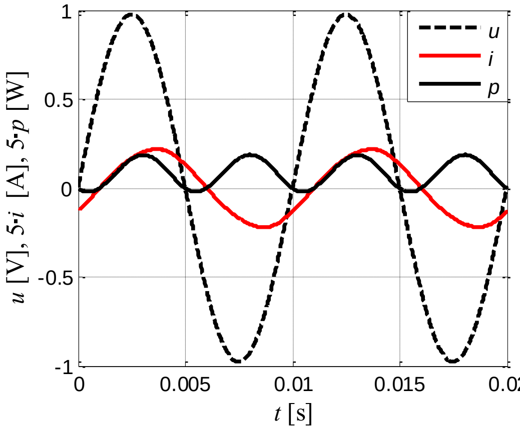

Fig. 8. Time pattern of voltage $u(t)$, current $i(t)$ and power $p(t)$ in the MR damper coil for $f = 100$ Hz.

IV. Numerical Calculations

To identify the parameters of the MR damper coil numerical calculations were performed. In each conductor which is located in an alternating magnetic field eddy currents are formed. The model of the control coil adopted for the calculation (Fig. 9) [4] takes into account the phenomenon of eddy currents.

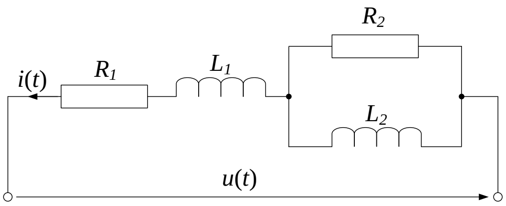

Fig. 9. Equivalent circuit model of the magnetic circuit: second order system

To identify the parameters (resistances R_1, R_2 and inductances L_1 I L_2) of the control coil model, its transfer function $G(s)$ was set:

$$G(s) = \frac{I(s)}{U(s)} = \frac{\alpha_1 s + \alpha_2}{\alpha_3 s^2 + \alpha_4 s + \alpha_5} \tag{3}$$

Where: $I(s)$ − Laplace transform of the output signal, $U(s)$ − Laplace transform of the input signal, $\alpha_1=L_2$, $\alpha_2=R_2$, $\alpha_3= L_1 \cdot L_2$, $\alpha_4=R_1 \cdot L_2+R_2 \cdot L_1+L_2$, $\alpha_5=R_1 \cdot R_2$.

The aim of the identification was to determine the values of the transfer function $G(s)$ parameters. In the process of identifying the coefficients α_1, α_2, α_3, α_4, α_5, a procedure of searching for the values within the determined range of variation was applied. For each set of parameters, the comparison of the transmittance response y_{nc} to stroke unit (voltage with an amplitude of 2V) was carried out, with the response recorded during the laboratory studies y_{lt}. The criterion adopted was the minimum mean square error:

$$\min_{\alpha_1,\alpha_2,\alpha_3,\alpha_4,\alpha_5} \left[\sum_{t=0}^{\infty} \left[\left(y_{nc}\left(\alpha_1,\alpha_2,\alpha_3,\alpha_4,\alpha_5\right) - y_{lt} \right) \right]^2 \right] \tag{4}$$

The identified transfer function $G(s)$ takes the form:

$$G(s) = \frac{0.0031s + 0.1865}{0.0002263s^2 + 0.0383s + 1} \tag{5}$$

Knowing the values of the parameters α_1, α_2, α_3, α_4, α_5 the values of the electrical parameters of the control coil circuit were determined (R_1=5.36 Ω, L_1=73 mH, R_2=0.1865 Ω, L_2=3.1 mH). For the transfer function described, an amplitude-frequency characteristic (Fig. 10) and phase-frequency characteristic (Fig. 11) were set.
It results from the waveforms that the cutoff frequency amounts to f_c=6.76 Hz, and the phase shift between the current

intensity i(t) and the voltage on the control coil $u(t)$ is approximately φ = 34º.

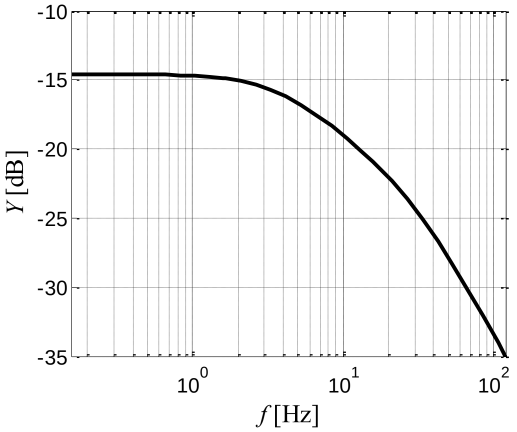

Fig. 10. Amplitude–frequency response of the MR damper coil

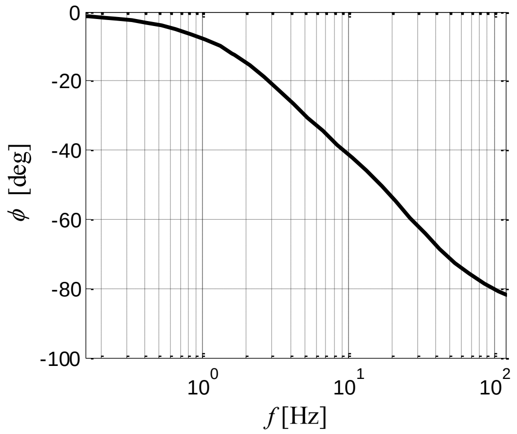

Fig. 11. Phase–frequency response of the MR damper coil

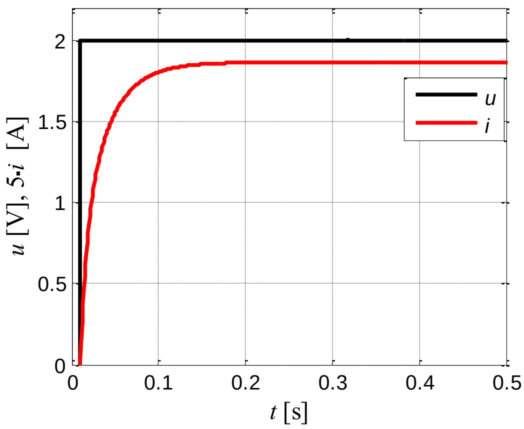

Fig. 12. Step response of current in the MR damper coil

The step response of the current is shown in Fig. 12. The current reaches 90% of the determined value the time t_u = 55 ms. The value of current is has the same as in the experimental test case.

V. Summary

The paper presented the experimental tests and the results of numerical calculation of a damper control coil RD-8040. The aim of this study was to understand the dynamic properties of the MR damper control coil. The knowledge of these is required to build semi−active vibration reduction systems as well as systems of energy recovery. In these systems, the power supply voltage of the coil is variable over time.

To determine the value of the current flowing through the coil the admittance Y is to be determined, which depends on the frequency of excitation. An equally important issue is the knowledge of the phase shift between the current intensity $i(t)$ and the voltage $u(t)$. It can significantly affect the mechanical characteristics of the vibration reduction systems where MR dampers are used.

The laboratory tests conducted and the numerical calculations showed that:

- the cutoff frequency for the damper control coil is 6.3 Hz,
- the time after which the current value reaches 90% of the determined value is 55 ms,
- the phase shift for the frequency f_c is −28º,
- the phase shift for the maximum test frequency f=100 Hz is −38º,
- the differences between the results obtained from computer simulations and the laboratory tests result from the model of the damper coil.

Observed difference in the frequency and phase response between results of experimental tests and computer simulations, assumed that control coil model require modification of the structure and re-identification parameters.

Further research will include determination of mechanical characteristics of MR damper with variable supply voltage and comparison with the characteristics developed for the fixed value of the supply voltage. The dynamic properties to be known will allow to select the appropriate control algorithms for the damper RD−8040. It is also possible to build an electromagnetic transducer dedicated as a power source for damper in a self−supplying vibration reduction system. Knowledge of the dynamic properties of the control coil will allow impedance matching of the coil circuit to the MR damper coil.

Acknowledgment

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