Paweł KIELAN, Zbigniew PILCH

Politechnika Śląska, Wydział Elektryczny, Katedra Mechatroniki

doi:10.15199/48.2017.07.10

DSP Processor as part of a closed loop feedback in the system MR fluid clutch control maintaining a constant clutching torque

***Abstract**. The paper presents a research test stand developed in order to control the MR fluid clutch in a closed loop feedback. The individual elements of the stand with a focus on part containing the DSP processor that is used to record the signal voltage of the torque meter coupling are discussed. The influence of the temperature increase on the transmitted torque's value decrease is described. The waveforms of clutching torque without correction of power supply parameters (controlled in open-loop) as well as with the correction of power supply parameters i.e. the control in closed-loop feedback from DSP processor, are presented.*

***Streszczenie.** W artykule przedstawiono stanowisko badawcze do sterowania sprzęgłem magnetoreologicznym w zamkniętej pętli sprzężenia zwrotnego. Opisano poszczególne elementy stanowiska, z naciskiem na część zawierającą procesor sygnałowy DSP, który jest wykorzystywany do rejestracji sygnału napięciowego z czujnika momentu sprzęgającego. Scharakteryzowano wpływ wzrostu temperatury na spadek wartość przenoszonego momentu. Przedstawiono przebiegi momentu sprzęgającego bez korekcji parametrów zasilania (sterowanie w otwartej pętli) oraz z korekcją parametrów zasilania, czyli sterowanie w zamkniętej pętli sprzężenia zwrotnego od procesora sygnałowego DSP. (**Procesor DSP, jako część zamkniętej pętli sprzężenia zwrotnego w układzie sterowania sprzęgłem z cieczą magnetoreologiczną, utrzymujący stały moment sprzęgający**).*

Keywords: DSP processor, MR fluid clutch, close-loop feedback, clutching torque.
Słowa kluczowe: procesor sygnałowy DSP, sprzęgło z cieczą magnetoreologiczną, zamknięta pętla sprzężenia zwrotnego, sprzęgający moment obrotowy.

Introduction

Various viscosity fluids (magnetorheological, electrorheological) belong to one of the smart materials' groups. This type of fluid works, in magnetic field, in three different modes: valve (flow) mode [1-3], compressing mode [3], and shear (clutch) mode [4, 5]. In the presented case, the focus is placed on the flow-type clutch mode.

Magnetorheological fluid properties are determined by the shear stress τ [6] as a function of flux density B – curve in Fig.1.

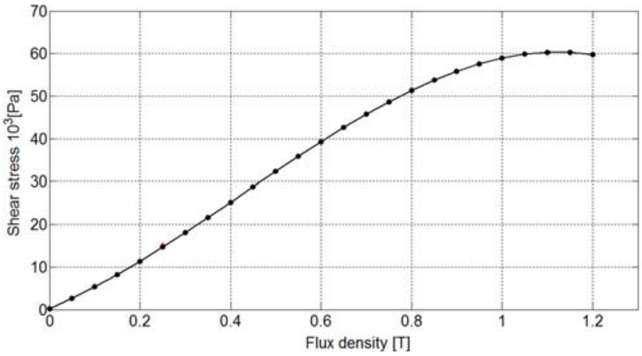

Fig. 1 The shear stress τ as a function of flux density B curve for MRF-140CG fluid

Other parameters of the liquid MRF-140CG [6]: density 3,54-3,74[g/cm^3], working temperature -40 to 130[°C], flash-point >150[°C].

According to the Bingham model, which describes the change in the tension of the magnetic fluid [7]:

$$\tau = \operatorname{sgn}\left(\frac{d\gamma}{dt}\right)\tau_0(B) + \mu\frac{d\gamma}{dt} \tag{1}$$

where: τ - shear stress in the liquid, $\tau_0(B)$ - limiting shear stress-dependent induction of B, μ - dynamic viscosity of a liquid (non-magnetic induction B), γ - shear deformation of the liquid.

The value of torque transmitted through the clutch depends on the shear stress τ. The full expression for the torque transmitted by the clutch, that takes into account the velocity shear in the liquid, is given by the following form:

$$T = \frac{4\pi}{3}\cdot i_{tcz}\cdot\left(R_2^3 - R_1^3\right)\cdot\left(\tau_0(B) + \mu\frac{d\gamma}{dt}\right) \tag{2}$$

where: i_{tcz} - number of clutch discs; R_2, R_1 - outer and the inner radius of clutch discs.

During operation, the coupling heat is produced as the result of mechanical losses. Losses are generated by slipping between the clutch discs in the liquid [8, 9]. They are also due to friction in the bearings [9]. These losses are converted into heat that causes the temperature increase of the liquid and all components of the coupling.

The test stand for control of the MR fluid clutch in a closed loop feedback

In the field of technology, there are many instances when it is extremely important to maintain the constant parameters of mechanical power (rotation speed and torque).

The latest research carried out by the authors allowed them to develop a prototype of MR fluid clutch [4]. The number of studies completed, enabled them to draw the conclusion that the fluid changes its physical parameters under the influence of heat, what consequently leads to the alterations in the mechanical parameters of the clutch [9], [10]. It was decided that this research would focus on recording the clutching torque during the operation of the clutch while applying two alternative approaches. The first approach applies fixed supply parameters while the other applies the clutching torque correction by changing the parameters of the power supply. For this purpose the test stand was developed, which enabled the authors to proceed with the outlined tests.

Figure 2 presents general concept of the measuring system in which the feedback loop was constructed with the use of the following components:

1 - a source of torque and rotational speed of the hydraulic motor in the form of MP 80,
2 - prototype of MR fluid clutch,
3 - torque meter KTR DATAFLEX 22/20,
4 - powder brake FUMO VER-30H-20-6,
5 - thermovision camera FLIR A325,
6 - programmable laboratory power supply 3-channel

PPS3205T-3S ATTEN with the possibility of external control via a USB port for controlling the values of the current and voltage coupling (Ic, Uc) and the brake (I_B, U_B),
7 - computer data acquisition and control system with the possibility of control by changing power supply settings.
8 - digital signal processor (DSP).

The digital signal processor and the Control_MRCluch program are the principal components of the measuring system. In the present study, the digital signal processor has been used for the sole purpose of recording, in real time, the voltage value of torque meter. The voltage of output signal of torque meter was connected to the input of the analog-to-digital converter on the processor card DS1104.

By developing a part of the test stand that includes a digital signal processor DSP the implementation of simulation using the Hardware-in-the-loop (HiL) technique is possible. The subsequent studies will aim at presenting the usage of the discussed test stand for rapid prototyping of devices with magnetorheological fluid.

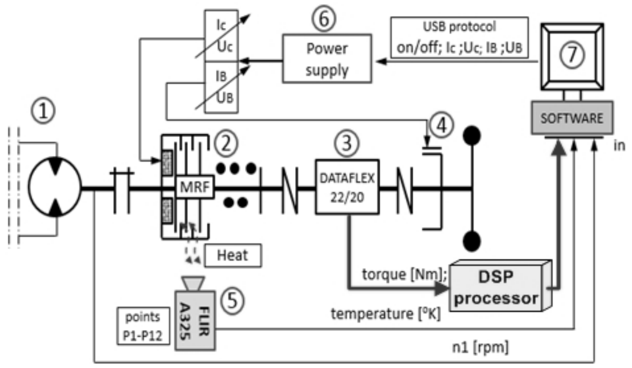

Fig. 2 Schematic diagram of MR fluid clutch control system in a closed-loop feedback

Software applied in the test stand

The test stand was developed basing on three types of software, due to their functions (Fig.3):

1. The program **ThermoVision camera FLIR** provides temperature measurement at selected points on the surface of the MR fluid clutch and records the measured values in a text file.
2. The program **Matlab/Simulink** was used to develop an algorithm that captures signals from the torque meter. Additionally, the program enables the implementation of the source code of the algorithm on the digital signal processor.
3. The program **Control_MRCluch** provides the possibility of changing the power supply parameters for the individual elements of the test stand, based on the data recorded by the program ThermoVision camera FLIR and data recorded by the digital signal processor.

The program *Control_MRCluch* is one of the basic components of the test stand. The aforementioned program enables reading (from a text file) the temperature values recorded by the program *ThermoVision camera FLIR*, as well as reading the value from the memory cell of the digital signal processor, which contains the current registered torque coupling. Additionally, the program provides the means necessary for changing parameters for the individual elements of the test stand, according to the selected mode of operation of the program, eg. correction mode of torque coupling.

Computer program *Control_MRCluch* was written in C# by the authors. It is an extended version of the program *CP&CiCL* [10], with additional algorithm that reads the data from the memory of the digital signal processor and the additionally implemented correction mode of power supply parameters on the basis of the measured torque coupling.

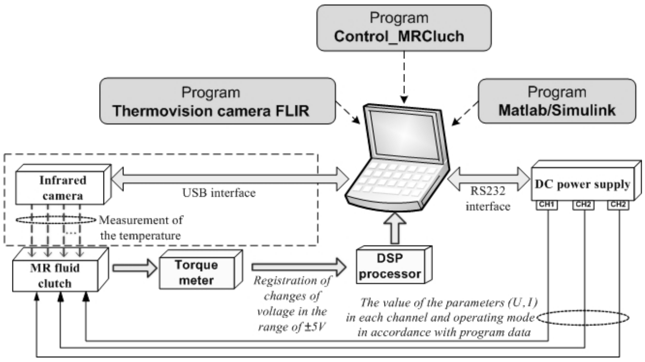

Fig. 3 Software applied in the test stand

Process of creating a program for DSP processor

The digital signal processor DSP on the test stand provides the possibility of measuring the clutching torque in real time. This measurement is carried out on the basis of the value of voltage from the torque meter. In order to measuring and converting the value of voltage in real time, the program has been developed on the DSP processor.

Figure 4 presents the block diagram representing the implementation in the DSP processor of the signal recording program.

The program implemented in a DSP processor has been developed as a model in Matlab/Simulink, which is provided with a library RTI (Real-Time Interface). Additionally, the program Matlab/Simulink is equipped with the Real-Time Workshop toolbox, which executes the process of generating C code based on the block diagram (model) from Simulink.

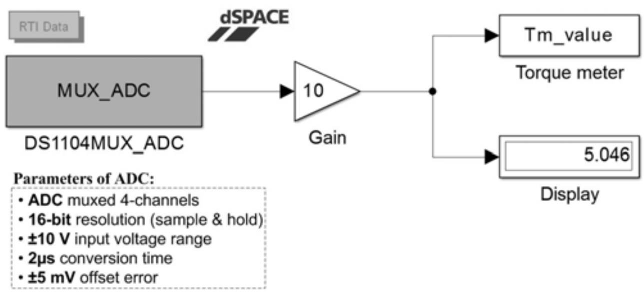

Fig. 4 Block diagram representing the implementation in the DSP processor of the signal recording program from the torque meter

Analogue - digital converter is used as an input of digital signal processor card DS1104. Toolbox MUX_ADC is a 4-multiplexed, 16-bit channel of converter. The signal from the torque meter is connected to the channel.

Figure 5 presents the process of creating a program for DSP processor.

The entering of the appropriate parameters of the simulation is followed by compiling the block diagram (model) from Simulink at the code in C. The source code of the program as well as the additional files, necessary for the proper operation of the digital signal processor are generated during the compilation. The aforementioned source code and files are then implemented on the platform of digital signal processor.

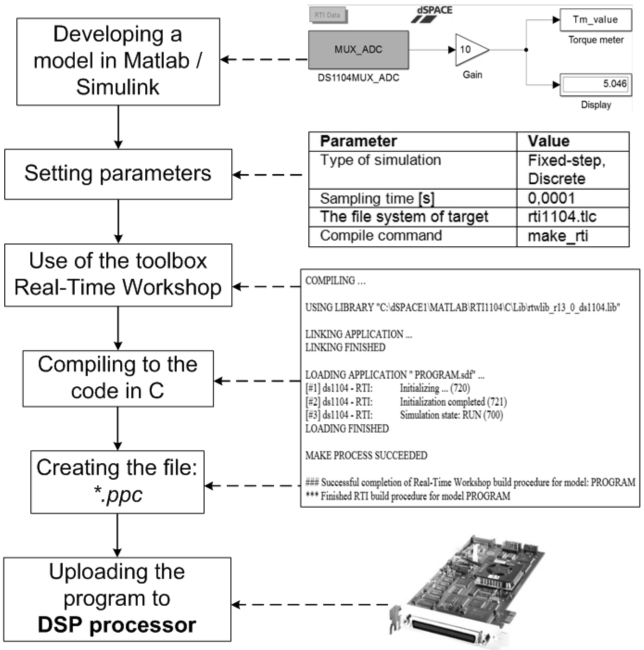

Fig. 5 The process of creating a program for DSP processor

Result of measurement

The studies were conducted in three stages. In the first stage the infrared camera and one of the modes of operation of the program *Control_MRClutch* were used. In this mode, the power supply of the coil was turned off when the previously set value of temperature has been reached [10]. Developing an automated mode, which turned off the power supply of the coil clutch, was crucial due to the long waiting time necessary for reaching a certain temperature value. For example in order to reach the temperature T_p = 343K (70°C) for the current I_c = 0.5A time taken was 52 minutes.

Figure 6 presents the set of characteristics of the temperature increase on the external surface of the clutch (measured with infrared camera FLIR A325) for different values of currents (I = 0.3, 0.4, 0.45, 0.5, 0.6A). The rotational speed of the active member was set on $n1$ = 110 rev/min and for passive member $n2$ = 0 rev/min (slip s = 1). Measurements were carried out until the clutch reached a temperature equal to 343K.

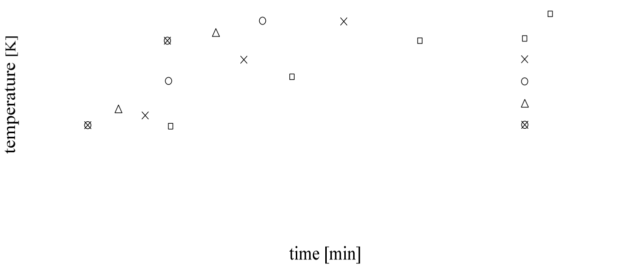

Fig. 6 Time characteristics of heating of clutch for different values of currents supply of coil

The collated results show unequivocally that the increase in the power supplied to the clutch significantly affects the heating time of clutch. Figure 7 presents the heating times of clutch for different values of currents supply of coil.

In the figure 7, a continuous line indicates a graph of measurement data whereas the dashed line indicates the approximation function of these data. The expression for the approximation function is: $t = 719 \cdot I^2 - 838 \cdot I + 271$.

The approximation function allows to determine the time of heating to the temperature 343K for currents for which measurements have not been carried out.

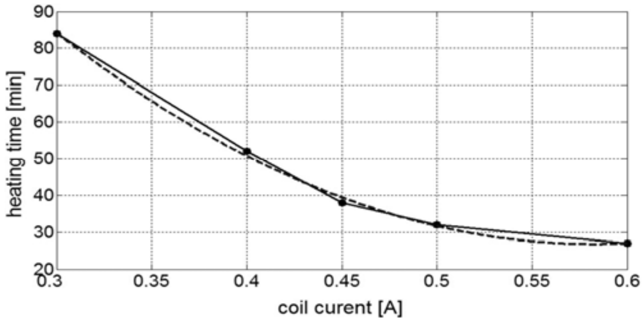

Fig. 7 The heating times of clutch for different values of currents supply of coil

The temperature increase causes:

- the increase of the resistance of the power supply circuit clutch coil (using a constant voltage source - decline in current),
- the decline in the value of current to decrease the magnetic induction in the magnetic circuit coupling,
- the decrease of the viscosity of the MR fluid [11] which affects the component of stress (or torque) in a state of slip.

These aspects prove that, during the operation of the clutch, as the temperature increases [9] value of the transmitted torque decreases.

Therefore in the second stage, changes in clutching torque as a function of time without the correction of power supply parameters (control in open loop) were recorded.

Figure 8 presents an example of such measurement results for the prototype of the clutch, supplying the coil current I = 0,6A and for $n1$ = 110 rev/min, and $n2$ = 0 rev/min (slip s = 1).

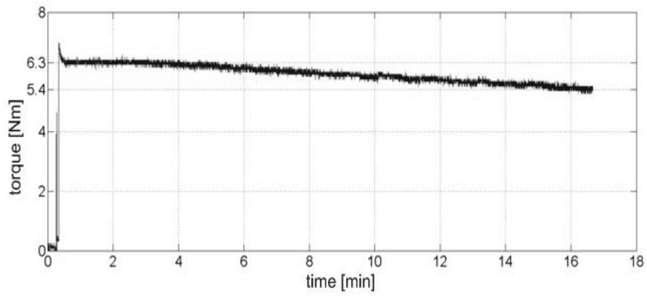

Fig. 8 Changing the clutching torque in a function of time - control in open-loop

Recording time of waveforms of torque depends on the maximum recording time of the oscilloscope (Tektronix MDO3012), which was 100s/div. For maximum time 1000s it gives 16,7min.

By adopting a linear decrease of torque as a function of time, it can be assumed that during 1 min of operation of the clutch in slip s = 1, clutching torque decreases by the value that is equal to 0,056Nm. Referring this value to the characteristics of the temperature increase as a function of current (Fig. 6), the value of the decrease of the torque corresponding to the temperature increase of value equal to 10K can also be specified.

For the current equal to 0.6A at the time of 16 minutes the temperature of the clutch increases by 30K and the torque decreases by 0,9Nm.

In the third stage of the study the digital signal processor necessary to capture the voltage signal from the torque meter was used. The measurement was carried out in real time, and data containing the value of torque was read by the program *Control_MRClutcg* in the period equal to 400ms.

Based on the stored value of torque, the algorithm of the program (correction mode of clutching torque) changed the value of the coil supply (voltage and current). The initial values of the coil supply were set in the same way as in the second stage.

Figure 9 presents the waveform of changing the clutching torque of MR fluid clutch in a function of time, which is controlled in closed-loop feedback from the digital signal processor (DSP).

Supplying the coil current I = 0,6A and for $n1$ = 110 rev/min, and $n2$ = 0 rev/min (slip s = 1).

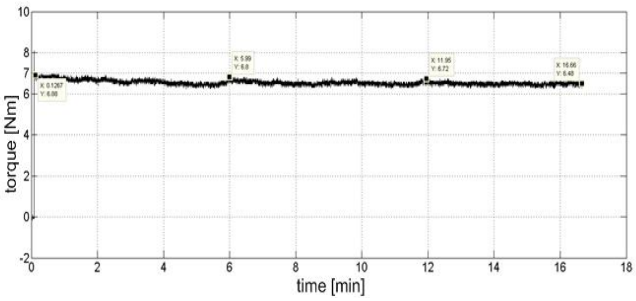

Fig. 9 Changing the clutching torque in a function of time - control in closed-loop feedback from the DSP processor

According to the assumptions, the use of the clutch control in a closed loop feedback from the digital signal processor significantly influences the correction of the clutching torque of the clutch.

Conclusions

On the basis of studies that have been carried out on the developed test stand, the following conclusions were drawn:

- Increase of the temperature of the MR fluid during operation (the coils supply) causes a decrease in the value of clutching torque.
- Decrease in the value of the supply current of coil, caused by increased resistance of the coil windings as well as changing the parameters of the fluid due to temperature increase, has an impact on the decrease in clutching torque.
- In order to maintain a constant torque of the coupling during operation of the clutch, the clutch should operate in a closed loop feedback.
- The clutching torque can be adjusted by increasing the supply current in proportion to changes in the value of the clutching torque (measured using the torque meter).
- Thanks to the digital signal processor DSP, the developed test stand can be used for rapid prototyping devices in which power is transported between moving parts through the magnetorheological fluid. In this case, the torque is kept at a constant level.

***Authors**: dr inż. Paweł Kielan, Politechnika Śląska, Wydział Elektryczny, Katedra Mechatroniki, ul. Akademicka 10a, 44-100 Gliwice, E-mail: pawel.kielan@polsl.pl; dr inż. Zbigniew Pilch, Politechnika Śląska, Wydział Elektryczny, Katedra Mechatroniki, ul. Akademicka 10a, 44-100 Gliwice, E-mail: zbigniew.pilch@polsl.pl.*

REFERENCES

[1] McLaughlin G., Hu W., Wereley N. M., Advanced magnetorheological damper with a spiral channel bypass valve. Journal of Applied Physics 115, 17B532 (2014); doi: 10.1063/1.4869278
[2] Wang D. H., Ai H. X., Liao W. H., A magnetorheological valve with both annular and radial fluid flow resistance gaps., Smart materials and structures. 18 (2009)115001 (16pp), doi:10.1088/0964-1726/18/11/115001
[3] Vishal N. Sulakhe, Chandrakant Y. Thakare, Pavan V. Aute., Review - MR Fluid and Its Application., International Journal of Research in Aeronautical and Mechanical Engineering, Vol.1 Issue.7,(November 2013). pp: 125-133
[4] Kielan P., Kowol P., Pilch Z.: Conception of the electronic controlled magnetorheological clutch., Przegląd Elektrotechniczny (Electrical Review), ISSN 0033-2097, R. 87 NR 3/2011, s.93-95
[5] Szeląg W.: Electromagnetic converters with magnetorheological fluid (in polish), Publishing House of Poznan University of Technology, Poznań, (2010)
[6] Information materials LORD Corporation: www.rheonetic.com
[7] Claracq J., Sarrazin J., Montfort J.p.: Viscoelastic properties of magnetorheological fluids. Rheol Acta (2004) 43: 38–49 DOI 10.1007/s00397-003-0318-7
[8] Hou You Fu, Tian Zu Zhi, Wang Nan Nan: The Steady-state and Transient Temperature Field of a Magnetorheological Fluid Transmission Device, International Conference on Computer, Mechatronics, Control and Electronic Engineering (CMCE), (2010), pp. 149-153
[9] Pilch Z.: Analysis of Established Thermal Conditions for Magnetorheological Clutch for Different Loading Conditions, ISBN-13: Analysis and Simulation of Electrical and Computer Systems. Springer International Publishing. (2015), 197-213, ISBN-13: 978-3-319-11247-3
[10] Pilch Z., Kielan P.: Infrared camera as part of a feedback loop in the MR fluid coupling research, 16th International Conference on Research and Education in Mechatronics. REM2015, Bochum, Germany, November 18-20, Proceedings. Ed. Rolf Biesenbach and Albrecht Weinert. Bochum : Deutsche Gesellschaft fur Mechatronik, (2015), s. 283-287, DOI: 10.1109/REM.2015.7380408
[11] Potoczny M.: Ciśnienie krytyczne i opory ruchu w uszczelnieniach z cieczą magnetoreologiczną. Rozprawa doktorska. Akademia Górniczo-Hutnicza, Kraków (2012)