Conceptual Design of Electromechanical Systems Using Ferrofluids

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Abstract — **This paper presents an overview of a new conceptual design of electromechanical systems using ferromagnetic liquids. Idea of the new concept is explained, advantages and disadvantages of such systems are discussed and three illustrative examples are presented. Numerical simulations and experiments on real devices are employed to study properties of these systems.**

Keywords — Air gap, ferrofluid, ferromagnetic liquids, electromechanical systems, magnetic forces, static characteristics, dynamic characteristics, numerical simulation, experimental verification.

I. Introduction

Ferromagnetic liquids present new intelligent material. Magnetorheological liquids with ferromagnetic particles sized in µm, able to change their viscosity and even state of matter with applied magnetic field, are nowadays more and more often used in technical applications such as controlled dampers, brakes, clutches and seals [see e.g. 1]. Unlike of magnetorheological fluids, ferromagnetic liquids with particles sized in nm, called ferrofluids, present a liquid ferromagnetic material with viscosity not dependant (or with very low, negligible dependence) on magnetic field [2]. Nanotechnologies present rather stable liquid ferromagnetic matter that remains liquid even at high values of magnetic field. This brings us to an idea to fill the air gap of an electromechanical system with magnetically conductive matter that still allows movement. This technology has not been fully investigated yet, very few relevant sources can be found [3, 4].

Fig. 1. Ferrofluid EFH-1 without and with applied magnetic field.

It is necessary to say, that authors of this paper work in the field of the theory of electrical engineering and are not professional designers of electric machines. This paper should not be understood as an instruction how to design electromechanical systems; it just presents an idea of an innovative approach. If this idea will be used in future designs, or not, it remains to be seen and must still be investigated and decided.

II. Physical Principle

A simple electromechanical system presented in Fig. 2 will be used to demonstrate the physical principle of the idea.

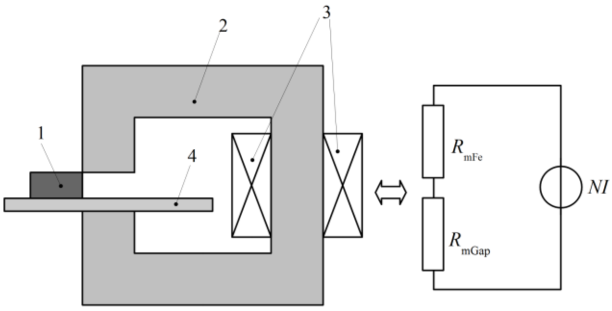

Fig. 2. Simple electromechanical actuator and its equivalent magnetic circuit; 1 – movable part, 2 – magnetic circuit, 3 – winding, 4 – air gap between movable and static part.

If the winding is powered, the movable part of the actuator is attracted between the poles of the magnetic circuit. With acceptable simplification (neglecting of leakage magnetic flux), the theory of magnetic circuit can be used to model this device. The total magnetic flux Φ enclosing trough the actuator can be counted as

$$\Phi = \frac{N I}{R_{m}} = \frac{N I}{R_{m\,Fe} + R_{mGap}} = \frac{N I}{\dfrac{l_{Fe}}{\mu_{Fe} S} + \dfrac{l_{Gap}}{\mu_{Gap} S}} \quad , \qquad (1)$$

where R_m stands for magnetic reluctance and μ_{Fe}, μ_{Gap} for magnetic permeabilities of the used materials. It is clearly visible that as higher is the magnetic permeability of the material in the air gap, the higher is the generated magnetic flux. Force acting on the movable body can be counted e.g. from the energy of the magnetic field as

$$F_x = \frac{dW_m}{dx} = \frac{d(\Phi I)}{dx} \quad . \qquad (2)$$

When the air gap of an electromechanical system is filled with ferrofluid, higher magnetic forces are generated using the same powering current. This effect is accompanied with several other phenomena that need a further study.

With the decrease of the total magnetic reluctance, the total inductance of the electromechanical system rises. This is a welcomed effect, however, with a higher induction, the total time response of the electric circuit increases. A time constant of a simple *RL* transient is given as $\tau = L/R$.

Cooling properties of the ferrofluids are well known [5]. The presence of the ferrofluid may provide additional cooling for the device, among other decreasing the total resistance and electric circuit time constant. The cooling can be achieved by different means than ferrofluid as well, but this phenomenon is positive.

The ferrofluids are considered to be used as advanced insulation materials, e.g. in power transformers [6]. Presence of the ferrofluid in an electromechanical system may provide additional insulation.

The viscous losses caused by the movement of the device movable body in the liquid are the main problem of the ferrofluid presence in the air gap. These losses depend on viscosity of the used fluid and on the speed of the device. These losses can exceed all gains.

Additional problems are related to the construction requirements on the ferrofluid filled devices. The system must be properly sealed to prevent leakage of the fluid, moreover, the ferrofluids have tendency to slowly degrade when exposed to open air.

Next problem is the high cost of the presently available ferrofluids, in hundreds of Euro per litre. This cost significantly depends on the amount purchased and may be lowered with mass production in future.

III. Examples of Electromechanical Systems with Ferrofluid Filled Gap

Operation of several electromechanical systems with ferrofluid filled gap was observed at our department using numerical simulations and experimentally in order to familiarize with their behavior and to predict possible applicability of this technology.

Ferrofluid EFH-1 from the Ferrotec company was used in these applications. The relative magnetic permeability in the linear part of the magnetization characteristics of this fluid was determined as μ_r = 1.789. (Method for determination of magnetic properties of liquids presented by authors in [7] was used.)

A. Electromechanical Actuator with Ferrofluid Filled Gap

A simple electromechanical actuator as possible (Fig. 3) was designed with stress on eliminating as much additional physical phenomena as possible in order to study the ferrofluid effect on the device properties.

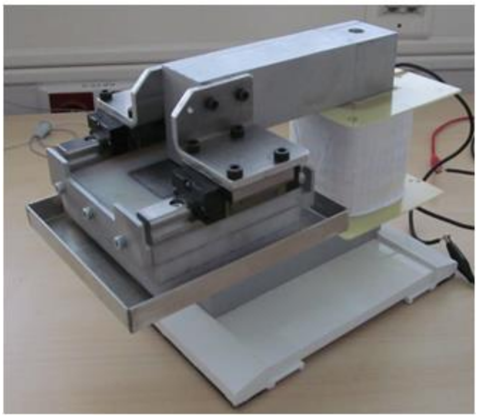

Fig. 3. Designed simple electromechanical actuator.

Dimensions of the device can be seen in Fig. 4.

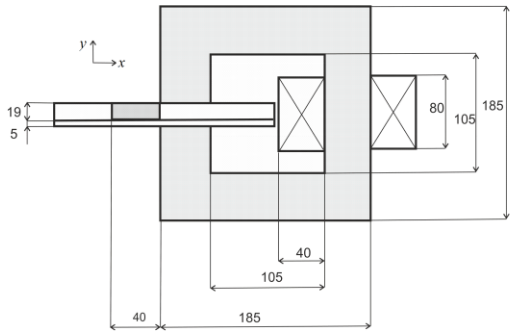

Fig. 4. Dimensions of the designed simple electromechanical actuator and its mathematical model.

Due to its simple construction, the actuator is easy to model in 2D. FEM solver Agros2D [8] was used to simulate the generated static forces in dependence on the permeability of the used ferrofluid. The used mesh can be seen in Fig. 5.

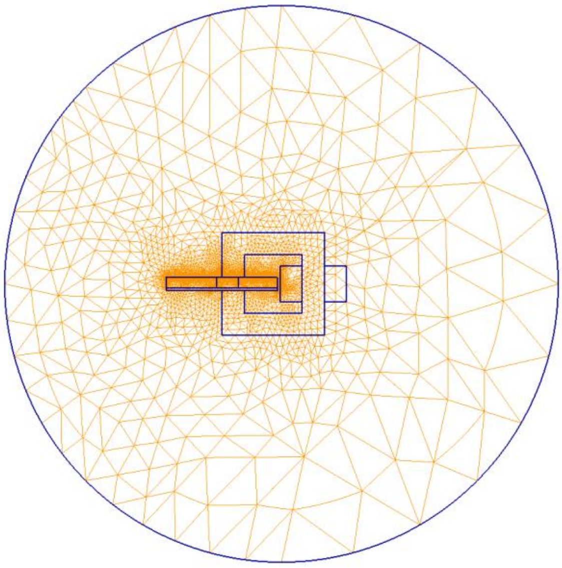

Fig. 5. Used mesh for the 2D simulation of the actuator, Agros2D.

The distribution of the magnetic vector potential in the solved area can be determined from the equation

$$\mathrm{curl}\left(\frac{1}{\mu}\mathrm{curl}\boldsymbol{A}\right)=\boldsymbol{J} \quad . \qquad (3)$$

The magnetic induction can be determined from its definition, the magnetic force $\boldsymbol{F}_m$ acting on the movable body can be determined form the change of the total magnetic energy.

$$\boldsymbol{B}=\mathrm{curl}\boldsymbol{A},\quad W_m=\int_V\left(\int_0^B \boldsymbol{H}\mathrm{d}\boldsymbol{B}\right)\mathrm{d}V,\quad \boldsymbol{F}_{mx}=\frac{\mathrm{d}W_m}{\mathrm{d}x} \quad . \qquad (4)$$

Convergence of the solution in dependence on the dimensions of the used model, number of elements of the mesh, polynomial order of elements and used adaptability was observed. Simulated dynamic characteristics as the magnitude of acting magnetic forces in dependence on the actual position of the movable core can be seen in Fig. 6. The ferrofluid with different magnetic permeabilities was used in the model to observe the influence. Magnetic permeability of the ferrofluid was considered in the model linear, real forces are expected to lie lower due to magnetic saturation of the fluid.

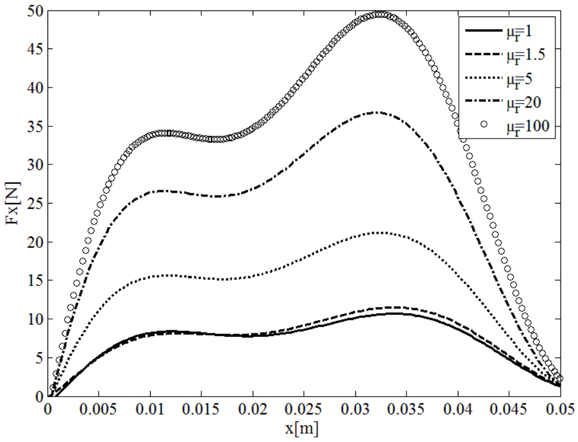

Fig. 6. Example of the simulated static characteristics for different permeabilities of the used ferrofluid, the current density of the winding $\boldsymbol{J} = 5{\cdot}10^6$ A/m^2, magnetic induction in the fluid $B = 0.6$ T, Agros2D.

The precondition of the generated magnetic forces increase depending on the permeability of the medium used in the gap was fulfilled. Nowadays available ferrofluids have quite weak ferromagnetic properties, in the range of $\mu_r = 1$~5, higher relative permeabilities were considered in the model for a better illustration of the effect.

The dynamics of the device with and without ferrofluid was simulated using the mathematical model based on a set of ordinary differential equations built with the use of the classical Newtonian dynamics. The model was implemented and solved in Matlab.

$$\frac{\mathrm{d}i(t)}{\mathrm{d}t} = \frac{u_0(t) - Ri(t)}{L(x)}$$

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{F_{\mathrm{mag}\,x}(i,x) - \frac{k_\mathrm{v}}{r}(F_{\mathrm{mag}\,y}(i,x) + F_\mathrm{g}) - 6\pi\eta r v}{m} \qquad (5)$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = v$$

A nonlinear coil $L(x)$ was considered in the model, acting forces were determined with the use of FEM simulation, $\frac{k_\mathrm{v}}{r}$ represents bearings losses, $6\pi\eta r v$ represents viscous losses in the fluid, where η stands for the fluid viscosity.

Series of dynamic simulations for different physical properties of the used fluid were performed. Results show that the viscosity increase of the used fluid negatively affects the overall dynamics as considered. Moreover, because the viscous losses depend on the speed of the device, when higher forces and then speeds are achieved, these losses grow. This problem should be approached using optimization techniques in the future. Examples of the simulations can be seen in Fig. 7 and Fig. 8.

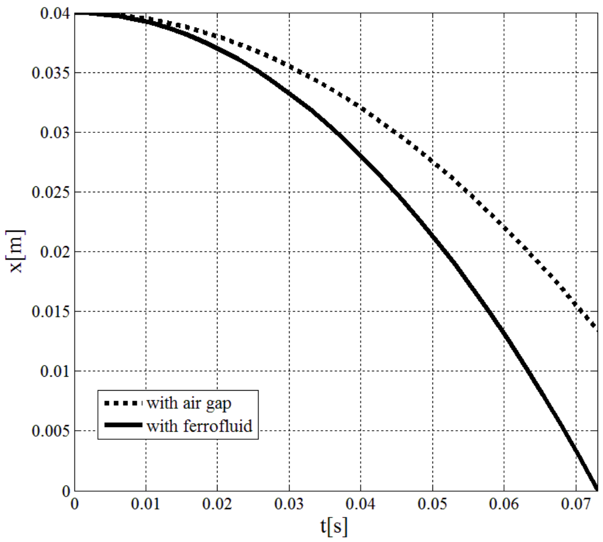

Fig. 7. Example of the simulated dynamic characteristics as the position of the movable part of the actuator in time; low viscous ferrofluid.

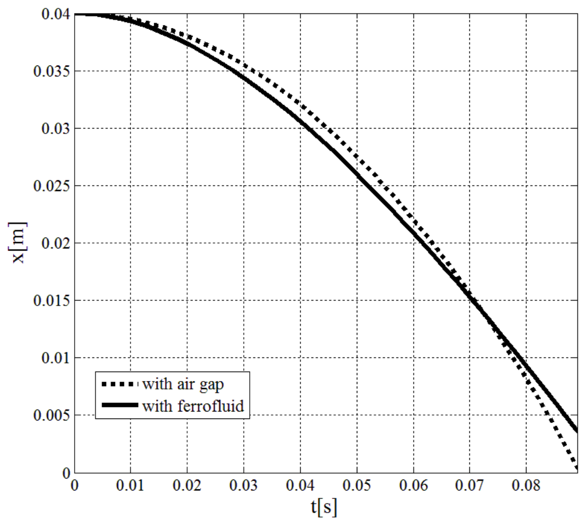

Fig. 8. Example of the simulated dynamic characteristics as the position of the movable part of the actuator in time; high viscous ferrofluid.

To evaluate results gained by the numerical simulation, static characteristics were measured as the magnitude of forces generated by the device for different fixed positions of its core using a dynamometer.

Fig. 9. Apparatus for measuring the static force characteristics of the actuator.

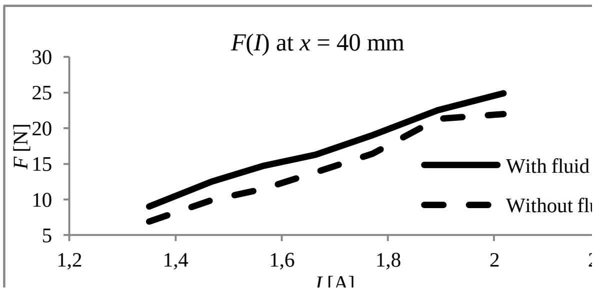

Fig. 10. Measured horizontal static forces with and without ferrofluid filled air gap at x = 40 mm position (maximal shift) of the movable body of the actuator.

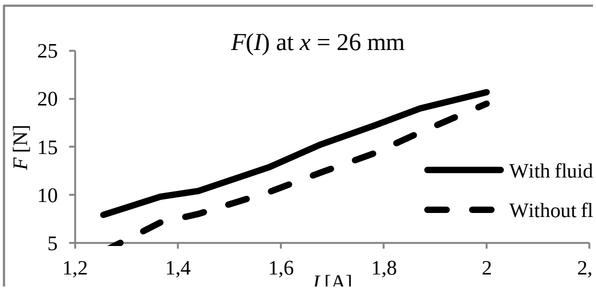

Fig. 11. Measured horizontal static forces with and without ferrofluid filled air gap at x = 26 mm position of the movable body of the actuator.

Finally, dynamics of the device as the position of the movable core in time was measured using high speed camera.

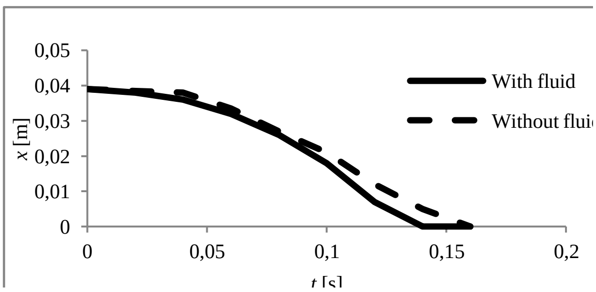

Fig. 12. Example of the measured dynamical characteristics of the experimental linear electromechanical actuator; winding powered by DC I = 1.5A (current in the steady state).

Based on the created models, it was experimentally verified that both static and dynamic characteristics of an electromechanical system can be improved using the ferrofluid in its gap. However, as simulations showed, the success of this improvement is dependent on the material properties of the used ferrofluid and speeds of the electromechanical system.

B. Electrically Controlled Switcher Working in a Ferrofluid Bath

Electrically controlled switcher with classical construction (see Fig. 13) placed in a ferrofluid bath was observed in its operation.

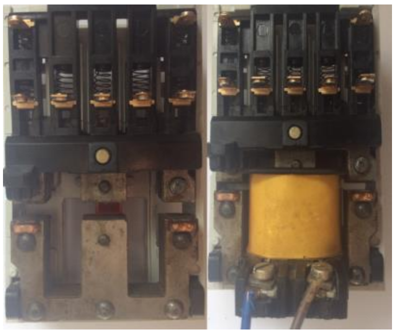

Fig. 13. Used electrically controlled switch.

An oscilloscope was connected to the switcher contacts to measure its time response for different values of the powering voltage and different positions of the switcher movable core. The ferrofluids effect to cool the devices was observed as well.

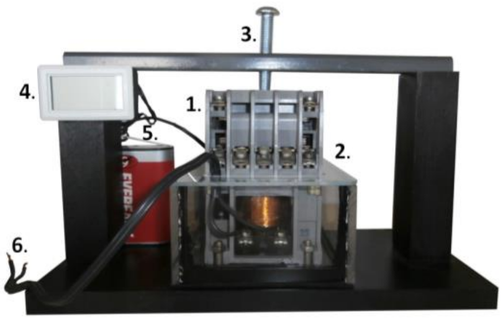

Fig. 14. Experimental setup: 1 – switcher; 2 – ferrofluid container; 3 – regulation of thickness of air gap; 4 – temperature display; 5 – source for LCD display; 6 – contacts of switcher.

Following graphs and table show the experimental results. To study changes of the static characteristics of the ferrofluid filled switcher, its inductance was measured for different positions of the movable body. Measured results were compared with the FEM simulation of the devices in Agros2D.

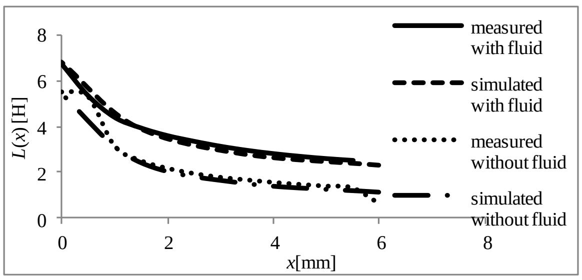

Fig. 15. Inductance L of the switch with and without ferrofluid filled gap, comparison of the measured and simulation results, measured with *RLC* meter with a very low measuring current $i \to 0$, simulated with a very low current density in the powering coil J = 1 A/m^2.

The switcher was then DC powered with different voltage levels, current needed to operate the switcher for different starting positions of the movable body was measured.

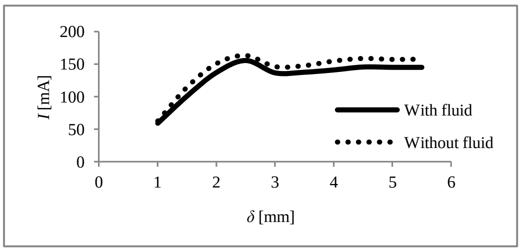

Fig. 16. Minimum current needed to operate the switch for different positions of the movable body.

Because the coil heats during the operation, the total resistance of the circuit was observed in time to find out the cooling properties of the ferrofluid.

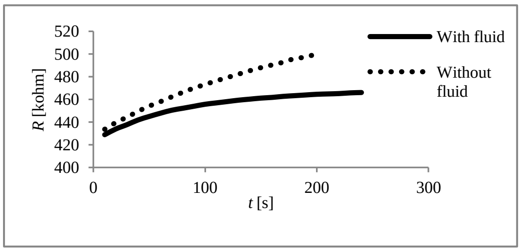

Fig. 17. Total resistance of the electric circuit of the switch, powered by U = 80 V, in time.

Finally, dynamics of the switcher on the time to operate were measured with oscilloscope.

TABLE I.
TIME TO SWITCH CONTACTS WITH AND WITHOUT FERROFLUID FOR DIFFERENT POWERING VOLTAGES

powering voltage U [V]	with ferrofluid time to switch		without ferrofluid time to switch	
	1st contact t_{1f}[ms]	2nd contact t_{2f}[ms]	1st contact t_1 [ms]	2nd contact t_2[ms]
80	40,26	42,53	46,67	50,66
90	27,26	28,87	27,4	29,27
100	22,87	24,27	22,7	23,6
110	20,13	21,13	19,27	20,4
120	18,47	19,47	17,8	18,6

The experimental results show that using the ferrofluid, the induction increases, minimum current needed to operate decreases because of the increase of the generated magnetic forces and the ferrofluid provides additional cooling to the electric circuit. However, the overall time response of the switcher improves only at lower powering voltages. This is caused by increasing viscous losses caused by the movement in the fluid; these losses are dependent on the device speed. Higher velocities are achieved with higher generated forces. Positive effect of the ferrofluid on the time response of the switcher is highlighted by blue and the negative effect by red in Table 1.

C. Ferrofluid Filled Rotating Electric Machine

A universal serial motor CG06 (Fig. 18) was injected with EFH-1 ferrofluid and its operation was observed. During the motor operation, centrifugal forces act on the ferrofluid placed between its rotor and stator. It has been experimentally verified that the magnetic forces acting on the ferrofluid exceed these forces and the ferrofluid does not spurt out of the air gap. When the motor is off, magnetic forces generated by the residual magnetization of the stator material are strong enough to keep the ferrofluid in its position.

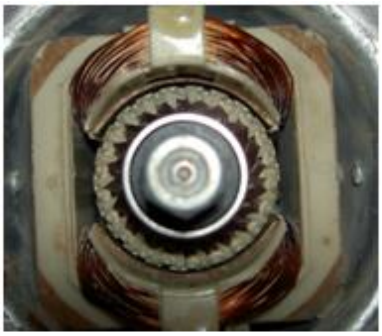

Fig. 18. Used universal serial electric machine CG06 1600W.

Static characteristics of the motor were investigated (Fig. 19). The rotor was fixed in a static position and forces acting on the rotor for different power were measured. As expected, forces are increased because of the improvement of the motor magnetic circuit.

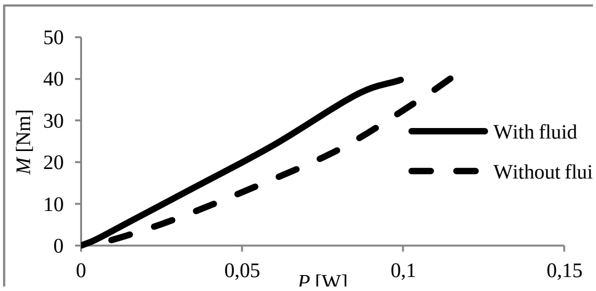

Fig. 19. Influence of the ferrofluid on the motor torque in dependence on supported electric power, measured while fixed rotor.

Speed of the unloaded rotor at different levels of powering voltage was investigated to reflect viscous losses caused by the ferrofluid. Example of such characteristics can be seen in Fig. 20.

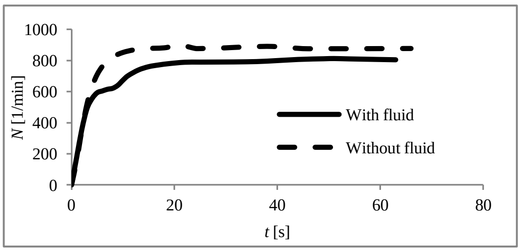

Fig. 20. Influence of the ferrofluid filled gap on speed of the unloaded motor, U = 9 V.

It is clear from the figure, that the ferrofluid affects the speed negatively at higher speed. This was expected because of the increase of the viscous losses depending on the speed of the movable body. Fig. 21 shows the beginning of the characteristics presented in Fig. 20, start of the unloaded motor.

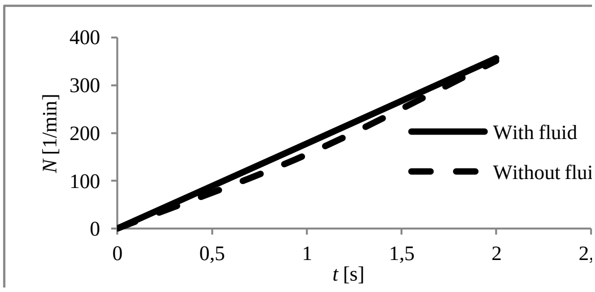

Fig. 21. Influence of the ferrofluid filled gap on the start of the unloaded motor.

Viscous losses are lower at lower speed and the ferrofluid filled gap has positive effect on behaviour of the device. However, this gain is cancelled at higher speed.

To investigate the characteristics of the motor at physically real conditions, the motor was loaded and its start was investigated with and without ferrofluid filled gap (Fig. 22). During the start of the motor, at low speed, the ferrofluid once again has positive effect on the behaviour of the motor. Characteristics of the loaded motor confirm the expectation for this technology to be advantageous in slow running electromechanical devices.

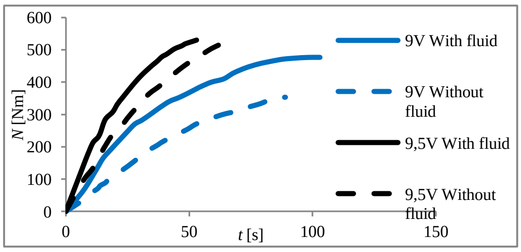

Fig. 22. Influence of the ferrofluid filled gap on the start of the loaded motor, different powering voltages.

It has been experimentally confirmed that the ferrofluid present in the air gap of the examined rotating electric machine has positive effect on its behaviour at low speed. For experimentally studied electric machine CG06, efficiency increase by 5.9 % was calculated under 300 rpm. At higher speed, viscous losses in the fluid exceed the gain in magnetic forces.

Conclusion

The presence of up to date available ferrofluid in the air gap of an electromechanical system is not generally advantageous. It improves the magnetic conductivity of the magnetic circuit, its magnetic induction and generated static forces, it may provide additional insulation or cooling, but at higher velocities, the viscous losses caused by the movement in the fluid exceed gains. Although new types of the ferrofluids with lower viscosities and/or better magnetic properties can be expected to be manufactured in a near future due to the intensive boom in the field of nanotechnologies nowadays, this technology does not seem to be generally applicable in electromechanical systems. It may find its use in special, low velocity applications, or in devices that work in a start-stop regime.

Moreover, higher construction requirements to seal up the liquid and high costs of the nanofluids present additional problems to introduce investigated technology in practice.

However, according to our opinion, any technology able to improve the efficiency of an electromechanical system is worth of further research.

Acknowledgment

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References

[1] M. Kubík, I. Mazůrek, J. Roupec, J., Z. Strecker, O. Macháček, "Design of Semi-active Magnetorheological Valve with Non-magnetic Bypass," *Transactions on Electrical Engineering*, no. 1, 2015. ISSN 1805-3386. [Online]. Available: http://www.transoneleng.org, [Accessed: 30. Sep. 2015].

[2] S. Odenbach. "Magnetoviscous effects in ferrofluids," Berlin: Springer, 2002, 151 s. *Lecture notes in physics*. Monographs. ISBN 3-540-43068-7; ISSN 0940-7677.

[3] S. Engelmann, A. Nethe, T. Scholtz , H. Stahlmann, 2004. "Experiments with a ferrofluid-supported linear electric motor," *Applied Organo metallic Chemistry*, **18**(10), pp. 529-531.

[4] A. Judge, "Air gap elimination in permanent magnet machines." Disertation Thesis, 2012, Worcester Polytechnic Institute. 157 p.

[5] S. Odenbach. "Ferrofluids—magnetically controlled suspensions," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2003, 217.1, pp. 171-178.

[6] P. Kopčanský, L. Tomčo, K. Marton, M. Koneracká, M. Timko, I. Potočová. "The DC dielectric breakdown strength of magnetic fluids based on transformer oil," *Journal of Magnetism and Magnetic Materials*. 2005, č. 289, s. 415-418. ISSN 0304-8853.

[7] D. Mayer, P. Polcar. "A novel approach to measurement of permeability of magnetic fluids," *Przeglad Elektrotechniczny*, 88(7 B), 2012, pp. 229-231. ISSN 0033-2097.

[8] P. Karban, F. Mach, P. Kůs, D. Pánek, I. Doležel, I.: "Numerical solution of coupled problems using code Agros2D," *Computing*, 2013, Volume 95, Issue 1 Supplement, pp 381-408, DOI 10.1007/s00607-013-0294-4.