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The Results of Experimental Studies of Processes Occurring Within Combined Traction Levitation System

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Abstract: The given study presents the results of experimental studies of processes occurring within single point traction levitation system equipped with the model of traction levitation module for the combined traction levitation system based on the linear switched reluctance motor.

Key words: Traction levitation systems, combination of traction and suspension, linear switched reluctance machine, computer modeling, magnetic system

INTRODUCTION

The key constrain for the development of high speed transport systems equipped with the magnetic suspension is their high cost. At the present time the applied research is being conducted aimed at seeking technical solutions allowing us to reduce the cost for the development of systems due to their simplification.

The system simplification can be achieved by combining the functions of traction, levitation and heading hold within a single power component the traction levitation module. The simpler traction levitation system is possible to implement based on linear switched reluctance motor with transverse flux (Kireev *et al*., 2015; Biswas and Bannerjee, 2012). The configuration of the magnetic system of the electric machine is a set of U-core ferromagnetic elements mounted in series. The windings are supplied by unipolar current impulses coming from electronic converter. Ferromagnetic track elements are set discretely. It makes possible to develop a passive track structure with reduced materials consumption.

The influence research of the traction levitation module magnetic system configuration on the quality performance of traction levitation systems showed that in terms of energy efficiency of electromechanical energy conversion it is rational to apply a configuration of U-core ferromagnetic elements with a square tooth section. The developed mathematical model of the combined traction system and suspension as well as its computer implementation (Grebennikov *et al*., 2015; Chang *et al*., 2007) allowed us to perform simulation experiments on investigation the processes within the system and estimate system parameters and characteristics.

MATERIALS AND METHODS

In order to test the basic technical solutions the mock of the traction levitation module has been produced. The technical data of the mock is given in Table 1. The specific feature of the test object is the combination of levitation and traction functions. It highlights the task to study the characteristics of traction levitation module as a controlled object (Lenin and Arumugam, 2015). The test bench equipment (Fig. 1) has been produced to simulate partly the operating conditions for the traction levitation module. The traction levitation module 1 is connected with the angle sections of cross fastening 2 by threaded connection via pin stud 3 using the upper port of the arm. The second ends of the angle sections of cross fastening are connected together by threaded connection via pin stud 4. Stud ends are attached to the track structure 5 by roller supports 6. Platform 7 is installed and fixed on the angles of cross fastening. Weight 8 simulating the load is installed on the platform. The air gap is regulated by sensor 9.

Figure 2 presents the functional scheme of the traction levitation system. Windings L1-L3 of A1 module are supplied by half-bridge converters UZ1-UZ3. Currents i_a-i_c in the windings are measured by sensors OA1-OA3 and go through reversed feedback circuits to the input of comparison elements where the values are compared with the given current value i_{sv}, generated by the air gap controller. Unbalance signals Δi_a-Δi_c go to the input of current controllers which keep the given current value i_{sv} at a specified time interval. The time interval of power keys conductivity is determined by the traction control unit based on the signals coming from the

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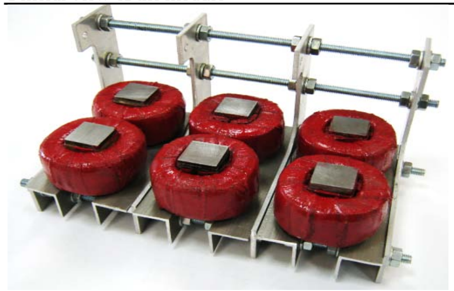
Table 1: Technical data of the traction levitation module

General view of the module	Magnetic system	U-core
	Standard size	PL20°20°40
	Electrical steel	3407
	Number of phases	3
	Passive stator	Iron
	Air gap (mm)	2.0
	Overall dimensions (mm)	220×120×100
	Weight (kg)	2.865
	Active phase resistance at 20°C (Ω)	3.622
	Supply voltage (V)	24
	Current density (A/mm^2)	5
	Rated phase current (RMS) (A)	2.5
	Type power converter	Half-bridge

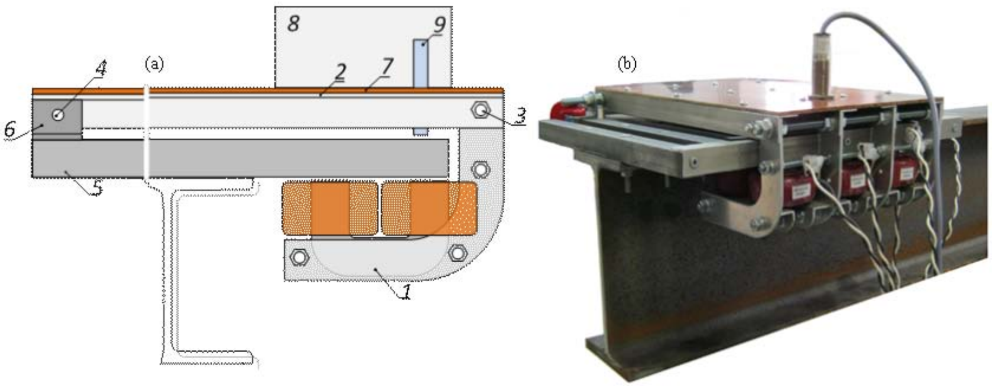


Fig. 1: a) The scheme of the test bench and b) its realization

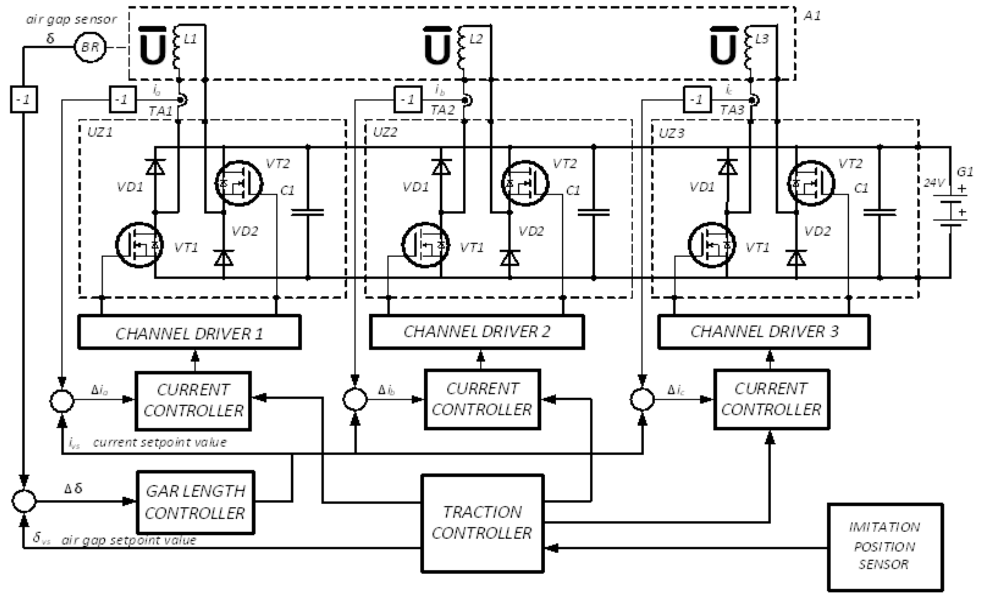


Fig. 2: Functional scheme of the traction levitation system model

position sensors simulator. The value of air gap δ is measured by the air gap sensor and then goes through reversed feedback circuits to the comparison element where it is compared with the given air gap value δ_{sv}, generated by the traction control unit. The unbalance signal Δδ goes to the input of the air gap controller which produces the general current signal for current phase controllers. During testing the current values i_a-i_c of the

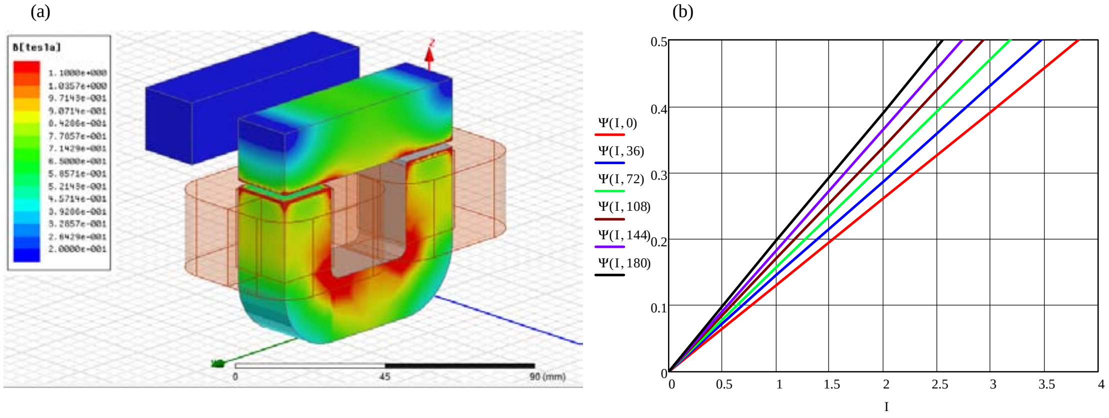


Fig. 3: a) The solid model of the power element and b) simulation results for the ψ (I, x)

air gap δ and phase voltage values were recorded by measuring and computing complex MIC-036. Therefore, the test bench equipment makes it possible to research the module characteristics under the single-point suspension system and simulation of linear moving at the cyclic current switching in the phase windings.

Traction characteristics of the model can be estimated based on the test method with models application. The tests with models include the calculation carried out on the mathematical models of the object, when the full-scale test data requires as initial one for simulation (test with modelling). Thus, for the evaluation of the traction characteristics of the traction levitation module mock it is necessary to get the characteristics of the power element magnetic system and calculate the traction force using the computer model.

RESULTS AND DISCUSSION

To compare the performance of magnetic suspension systems, designed by separate and combined levitation and traction schemes, the parameters of the power element in the levitation mode were estimated. In this regard the poles of the middle power element were installed in line with the track element. Converter UZ2 fed winding L2 with direct current, the value of which was specified by the air gap controller. During the experiment we were estimating the system operation mode with the actual current value 2.5A. This was done by varying the gap value in the range from 2-3 mm and load weight in the range from 90-130 N. The stable operation mode of the traction levitation system was ensured by adjustment of the air gap controller. Table 2 shows the technical data of the power element in the levitation mode. We determined the parameters of the traction levitation module combining the functions of levitation and traction. For this purpose, windings L1-L3 of module A1 were fed from converters UZ1-UZ3 by currents i_a-i_c , the values of which were set by the air gap controller. During experiment the load was selected which ensured the stable levitation mode under the same gap and current values indicated in the previous experiment. Table 3 presents the parameters of the module in the stable operation mode of the system under the switching frequency of phase currents equal to f = 50 Hz. The comparison shows that at the equal gap and current values in the windings, the levitation quality coefficient of the combined traction levitation system decreases 1.76 times in comparison with the conventional electromagnetic suspension system due to periodic changes of phase currents.

For the evaluation of the traction characteristics of the traction levitation module mock we calculated the dependency family of flux linkage of power element winding Ψ(I, x) from current I and axis of motion x. The solid model of the power element was used for calculation in Maxwell 3D (Fig. 3a). The calculation was performed on the computer model described in (Grebennikov *et al*., 2015; Chang *et al*., 2007). Simulation results for data in Table 3 are presented in Table 4.

To investigate the relation between levitation and traction processes, the periodic signal with an amplitude corresponding to air gap changes in the range from 1-3.5 mm are sent to the air gap set point value (Fig. 2) of the gap length controller. Figure 4 shows the oscillograms of processes which prove that the current controllers complete the input, commands for the gap, simulating the amplitude of phase currents i_a-i_c synchronously with the gap changes.

The experiments allowed us to assume that modulation of phase currents induced by gap fluctuation due to the interference can impact on the traction characteristics of the module creating traction force

Table 2: Technical data of the power element in the levitation mode

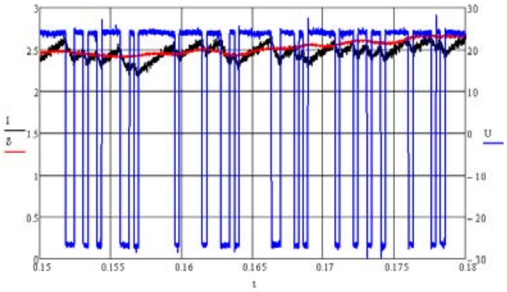
General view of the module	Parameter name	U-core
	Supply voltage (V)	24.1250
	The coil current (RMS) (A)	2.3980
	Air gap average value (mm)	2.4340
	Deviation of air gap from the average value (%)	+9.2-9.8
	The active winding resistance (Ω)	4.3420
	Power consumed by the power element (W)	25.3540
	Active power losses in winding (W)	24.9590
	Consumption current (A)	1.0510
	Lift force (N)	129.0000
	The coefficient voltage forcing	2.3050
	Energy levitation quality factor	0.9840
	Coefficient levitation quality	15.2000

Table 3: Technical data of the traction levitation module in the levitation mode

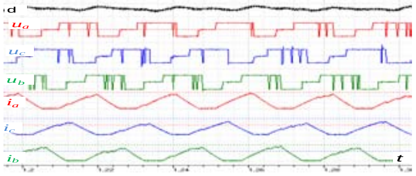
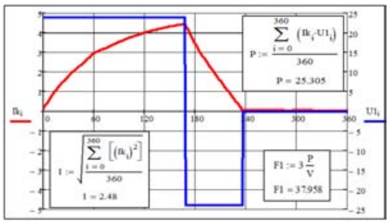
Oscillograms processes	Parameter name	Values
	Supply voltage (V)	24.000
	The coil current (RMS) (A)	2.480
	The coil current (amplitude) (A)	4.450
	The active winding resistance (O)	4.342
	Air gap average value (mm)	2.430
	Lift force (N)	220.000
	Current frequency (Hz)	50.000
	Coefficient levitation quality	8.640

Table 4: Simulation results for the traction levitation module in traction mode

Oscillograms processes	Parameter name	Value
	Supply voltage (V)	24.000
	The coil current (RMS) (A)	2.480
	Air gap average value (mm)	2.430
	The active winding resistance (O)	4.342
	Active power force element (W)	25.305
	Power consumed by the module (W)	75.915
	Traction force (N)	37.958
	Traction force/normal force	0.170
	Current frequency (Hz)	50.000
	Speed (m/s)	2.000

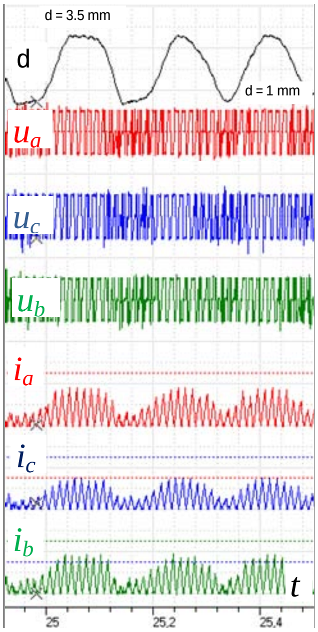


Fig. 4: Waveforms of phase voltage u_a-u_c, phase current i_a-i_c and air gap δ

pulsation. At the steady operation mode (under δ_{vs} = const) the gap pulse induced by the phase currentz pulsation was recorded. Thus, Fig. 5a shows the phase voltage Ua, phase current Ia and air gap δ under the traction mode simulation. It proves that two adjoining current periods significantly differ from each other in terms of the shape. It can be seen the gap pulsation with the period equal to the period of the current change. Figure 5b presents the oscillograms of total phase current Io and air gap δ proved that the maximum gap value coincides with the maximum total current values Io.

We have studied the processes occurring within the system at the switching of operation modes. Figure 6 shows the oscillograms of the processes under the simulation of switching from “run out” mode to “traction” mode. It is assumed that at these modes the vehicle after reaching the specified speed switches to the inertial mode. At this mode in order to keep the object in levitation state, the direct current, regulated in terms of the value, goes simultaneous to all windings. The current switching in the windings occurs at the transition to the traction mode.

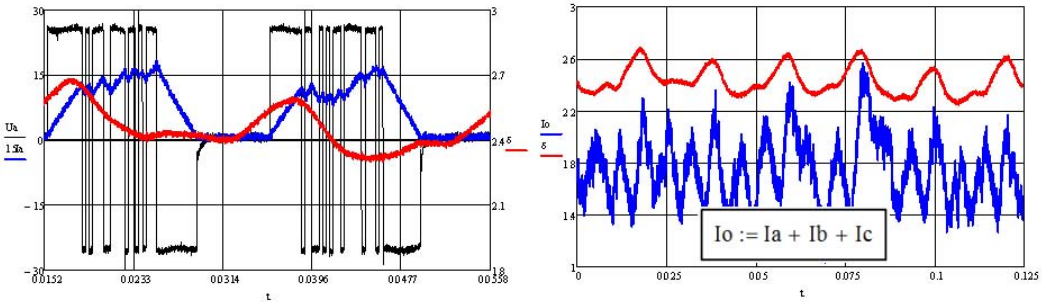


Fig. 5: a) Waveforms of phase voltage U_α, phase current Ia and air gap d and b) the sum of the phase currents Io and air gap δ

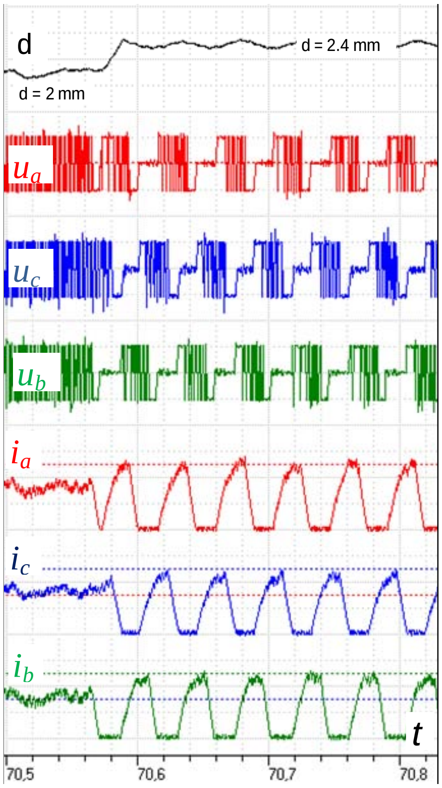


Fig. 6: The transition from inertial motion to traction mode

The peculiarity of the given process is the fact that at the switching of the operation mode the system seeks the new stability increasing the value of air gap $\Delta\delta = 0.4$ mm under current amplitude rising on average in 1.4 times.

The development of the combined traction levitation system based on the linear switched reluctance motor for the vehicle equipped with magnetic suspension is performed by stages. Previously we had performed the theoretical studies of electromechanical processes occurring within the traction levitation system. It made possible to formulate the main technical solutions and control algorithms. It is extremely difficult to perform the experimental verification of agreed technical solutions on the full-functional physical model of the object, due to the fact that along with the attitude control of the vehicle via the only power channel, there are problems with a mutual influence of power channels in the multipoint combined traction levitation system.

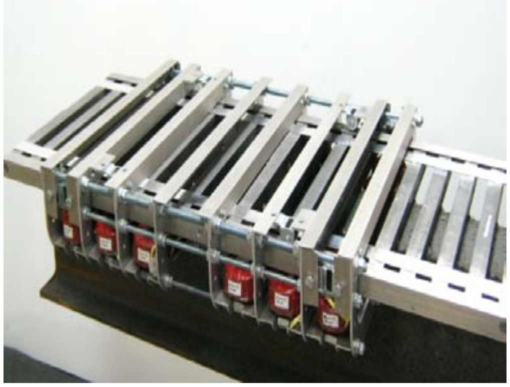


Fig. 7: Transports platform layout with magnetic suspension

Therefore, from the methodological view the experimental verification of agreed technical solutions is reasonable to perform in two stages: at the first stage, the characteristics of traction levitation module are studied based on the simplified scheme of the single-point suspension; at the second stage it is supposed to test the full-functional traction levitation system. The basic of this system is the mock of the transport platform equipped with four traction levitation modules (Fig. 7).

CONCLUSION

As the result of the researches conducted we have attained the empirical data containing the information about electromechanical processes necessary for designing of the traction levitation system. The parameters and characteristics of the traction levitation module mock have been estimated. We demonstrated the performance of the traction levitation module as a part of the traction levitation system.

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