Experimental Study of Dynamic Characteristics of the Electromagnet Actuators with Linear Movement

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***Abstract*—**An approach for experimental measurement of the dynamic characteristics of linear electromagnet actuators is presented. It uses accelerometer sensor to register the armature acceleration. The velocity and displacement of the moving parts can be obtained by integration of the acceleration results. The armature movement of permanent magnet linear actuator is acquired using this technique. The results are analyzed and the performance of the supposed approach is compared with the most commonly used experimental setup where the displacement of the armature vs. time is measured instead of its acceleration.

***Keywords*—**Dynamic characteristics, dynamic simulation, linear actuators.

I. INTRODUCTION

WHEN an electromagnetic actuator is studied its static characteristics are most widely used. The actuator actually never works in static regime. The dynamic characteristics describe completely the behavior of the actuator taking into account all physical phenomena associated with it. Therefore building and verifying those characteristics is important especially when novel constructions of actuators are studied.

The study of dynamic behavior is coupled problem and it implies combined examination of three types of problems:

- electrical circuit,
- electromagnetic field,
- mechanical movement,

The mechanical movement of the armature and processes in the electric circuit are described with ordinary differential equations and electromagnetic field with second order partial differential equations. The heating of the actuator during its operation can be also taken into account in some applications where the parameters of the system change significantly with the rise of temperature.

The main problem appears to be the coupling of the processes in the field, circuit and the mechanical movement.

There are two general approaches to solve such kind of tasks:

- Coupled and
- Decoupled

In the coupled approach, the equations describing electrical circuit and movement are embedded in the finite element method. Thus a new task is solved in any time step [2]-[4].

The second approach [5], [7] presumes decoupled analysis of the processes, i.e. the electromagnetic field problem is solved prior to circuit and movement equations. First magnetic field distribution is found out for a big number of certain current and displacement values. The electromagnetic force and inductance are obtained in each case. After that a circuit and movement equations are solved based on these values.

In any case the computational model can be fastidious against some parameters like material properties, geometrical interpretation – especially small dimensions, etc. There are coefficients that are hard to be estimated a priori. For example those are the friction and damping coefficients appearing in the balance of forces acting to the armature.

Therefore an experimental study of the dynamic characteristics for verifying and tuning the computational model is always necessary. The variety of the constructions and parameters of the actuators makes practically impossible the use of a unified, standard measurement setup and the obtaining of the dynamic characteristics can engage significant efforts.

An easy to implement low cost approach for experimental measurement is presented in the paper. It makes possible the obtaining of the dynamic parameters of the linearly moving armature of the actuator with minimum efforts and ensures acceptable accuracy and high level of unification.

The set of dynamic parameters discussed here includes:

- the armature displacement – x, mm,
- the armature velocity – v, m/s,
- the armature acceleration – a, m/ s^2,
- the current trough the coil of the actuator – I, A,

all measured versus time - t in seconds.

II. APPROACHES FOR EXPERIMENTAL MEASUREMENTS OF THE DYNAMIC CHARACTERISTICS

The displacement of the armature versus time is commonly acquired in the standard approach used fort the dynamic characteristics measurement. A diagram showing the main

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blocks of a typical setup is presented in Fig. 1.

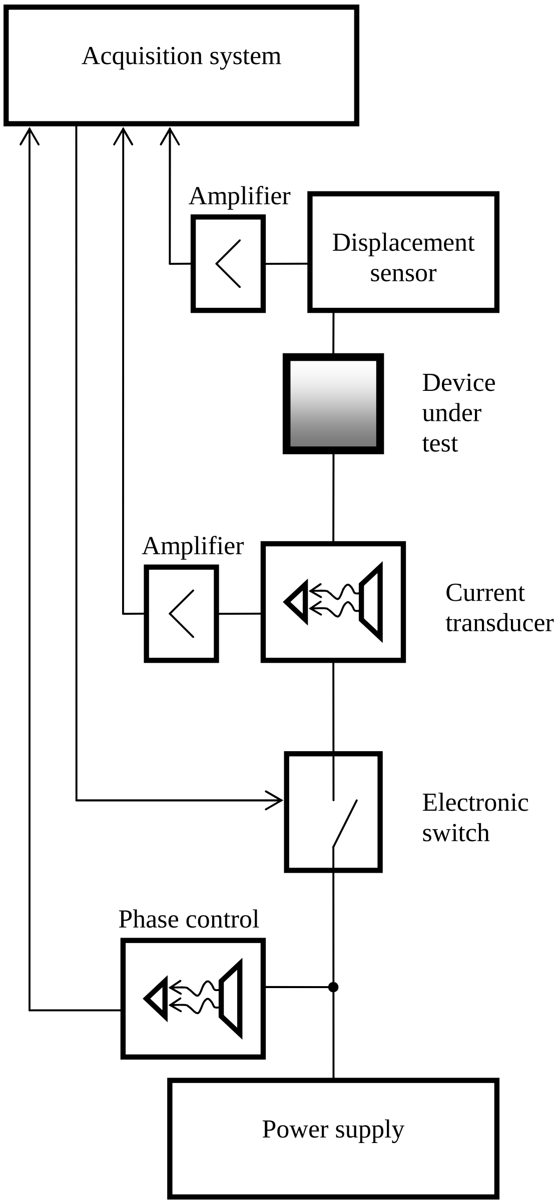

Fig. 1 The common setup for dynamic characteristics measurement. The current I and the armature displacement x can be directly obtained.

The parameters that can be directly measured are the current I and the armature displacement x versus time. The precision of the results is determined by the sensors used. There is a big variety of optical and magnetic displacement sensors with analog or digital interface. Some of them offer quite high sensitivity and sufficient range of measurement.

Sometimes it can be difficult to fix the sensor to the armature. The additional inertia added to the armature should be carefully considered especially when it is very light.

A typical results [8] obtained by using optical displacement sensor are shown in Fig. 2.

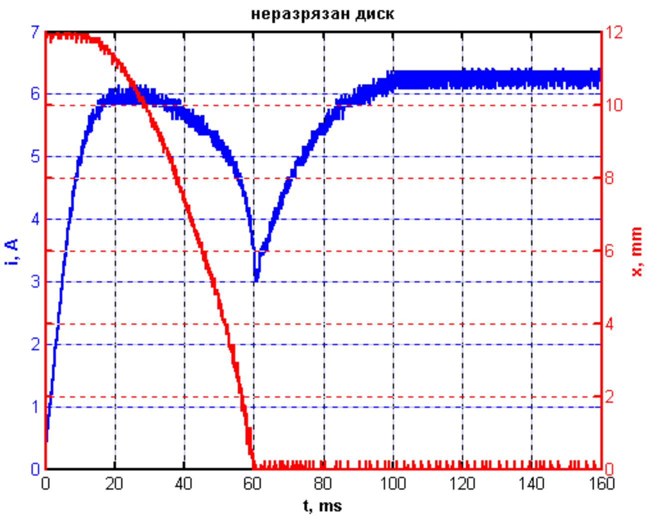

Fig. 2 Displacement x in mm (right axe) and current I in A, obtained by using an optical displacement sensor and measurement setup according to Fig. 1

In Fig.2. a relatively long armature movement is acquired. The results for the displacement x are with satisfying precision but they contain noise due to the way of measurement. That noise can not be easily filtered because the phase of the results must stay unchanged.

If only the armature displacement versus time need to be analyzed the presence of noise is not a significant issue but if the velocity or the acceleration has to be obtained the noise can make it really tricky.

The presence of data describing the variation of the displacement x vs. time makes possible the derivation of the velocity - v and acceleration - a at least theoretically. After that by the help of Newton’s principle:

$$F = ma \tag{1}$$

the electromagnetic force can be calculated.

The first derivative of the displacement is approximated by the final increments:

$$v(t) = \dot{x}(t) \approx \frac{\Delta x}{\Delta t} \tag{2}$$

The loss of precision is inevitable when (2) is used and it increases with each subsequent derivation. For the digital differentiation it is proven that the imprecision can be estimated by:

$$\varepsilon \le \frac{c_k(x)h}{2} = O\left(h^k\right), \tag{3}$$

where c_k is the relevant scaling factor for calculating x at the point t, h is the step of increment of t (sample time) and k is the order of derivation.

The practical implementation of the above approach is constrained not only by the inherent loss of precision after numerical differentiation but also by its noise susceptibility.

Fig. 3 shows the derivation results obtained by applying equation (2) to the containing noise data for the displacement shown in Fig. 2.

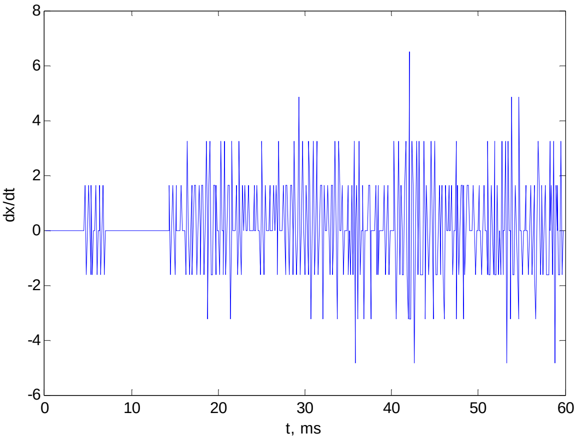

Fig. 3 Results after attempt to apply directly equation (2) to the noisy displacement data shown in Fig. 2

It is obvious that the data have to be smoothed before numerical differentiation. Even if this is done the way of smoothing has so big influence on the results that they can not be considered to be correct without additional check up.

III. DIRECT ACCELERATION MEASUREMENT

When it is important to have the accurate experimental results for armature acceleration and velocity the former quantity can be directly measured.

The measurement of acceleration of the armature instead its displacement offers the advantage that the other quantities (velocity and displacement) can be obtained by numerical integration. The integration as an opposite to the differentiation is not susceptible to the noise introduced to the signal.

The low cost acceleration measurement can be easily implemented by the use of semiconductor acceleration sensors.

IV. ACCELERATION SENSOR

The semiconductor acceleration sensors consist of a surface micromachined capacitive sensing cell (g-cell) and a CMOS signal conditioner contained in a single integrated circuit package. The g-cell is a mechanical structure formed from semiconductor materials. It can be modeled as a set of beams attached to a movable central mass that moves between fixed beams. The movable beams can be deflected from their rest position by subjecting the system to acceleration (Fig. 4).

When the beams attached to the center mass move, the distance from them to the fixed beams on one side will increase by the same amount that the distance to the fixed beams on the other side decreases. The change in distance is a measure of acceleration.

The g-cell beams form two back-to-back capacitors (Fig. 4). As the center plate moves with acceleration, the distance between the beams change and each capacitor's value will change.

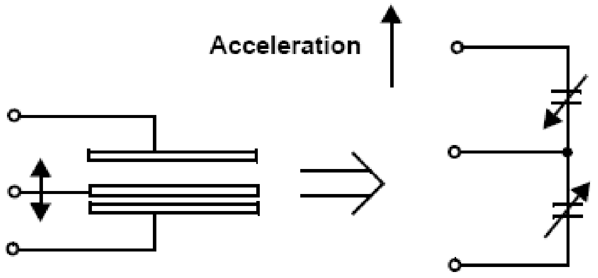

Fig. 4 Acceleration transducer physical model and its corresponding equivalent circuit model.

V. EXPERIMENTAL RESULTS

The Freescale MMA2202KEG accelerometer [6] was used to measure the acceleration of the armature of the electromagnetic actuator. The sketch of the construction of the actuator [1] is shown in Fig. 5 and its main dimensions are given in Table I. The coil is supplied with 36 V DC.

The output of the sensor is connected to the one channel of the storage oscilloscope. The other channel is fed with the current signal obtained by the mean of shunt resistor. The oscilloscope is triggered from the current signal.

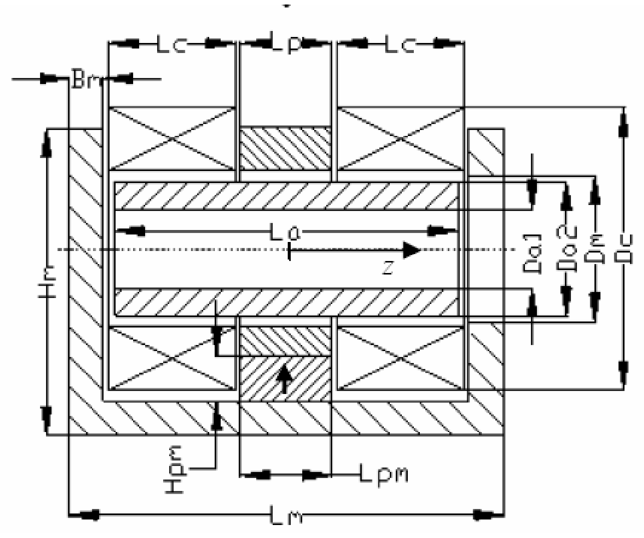

Fig. 5 Actuator construction.

The output of the accelerometer MMA2202KE is internally offset to the half of the supply voltage when no acceleration is registered. That is useful because positive and negative accelerations can be measured with a single supply to the chip and explains the oscilloscope screenshot shown in Fig. 6.

TABLE I
MAIN ACTUATOR DIMENSIONS (IN MILLIMETERS)

dimension	Symbol	value
Core length		
Core height		
Core width		
Core thickness		
Length of the armature		
Outer diameter of the armature		
Inner diameter of the armature		
Axial length of the coils		
Outer diameter of the coil		
Length of the permanent magnet		
Height of the permanent magnet		
Length of the permanent magnet pole		

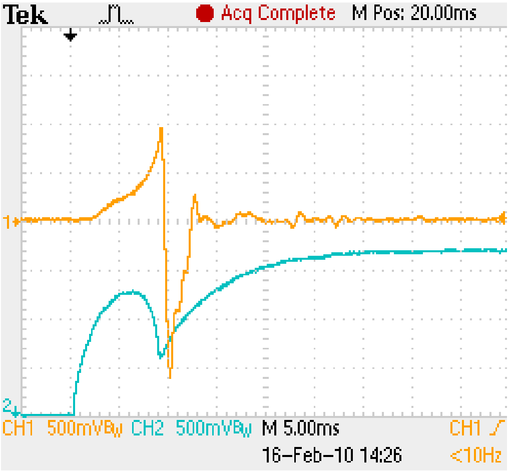

Fig. 6 Oscilloscope screenshot (Ch1 – acceleration 40 mV/g, Ch2 – current signal with 1 Ω shunt resistor)

The end of the movement and the moment of stroke of the armature to the actuator stop is clearly seen.

The explicit Runge-Kutta integration is applied to the acceleration signal after its scaling. The period of integration is controlled by the current variation. The process starts (time t=0) when the current starts to increase and it is over at the time corresponding to the local minimum in the curve of the current. It is exactly the moment when the armature hits the stop of the actuator.

The scaled measurements together with the computed results are shown on Fig. 7 and Fig. 8. Those figures represent the dynamics when armature moves in opposite directions. In Fig. 7 it moves in conventionally negative direction or closes while in Fig. 8 it opens.

The mechanical and electrical transients in both cases differ because the construction of the actuator is magnetically non symmetric. The electromagnetic force in positive direction (opening) is much higher because the magnetic flux exited by the coil and those of the permanent magnet act together. For the movement in the negative direction the polarity of the coil voltage is reversed and the coil flux has to overcome the flux of the permanent magnet.

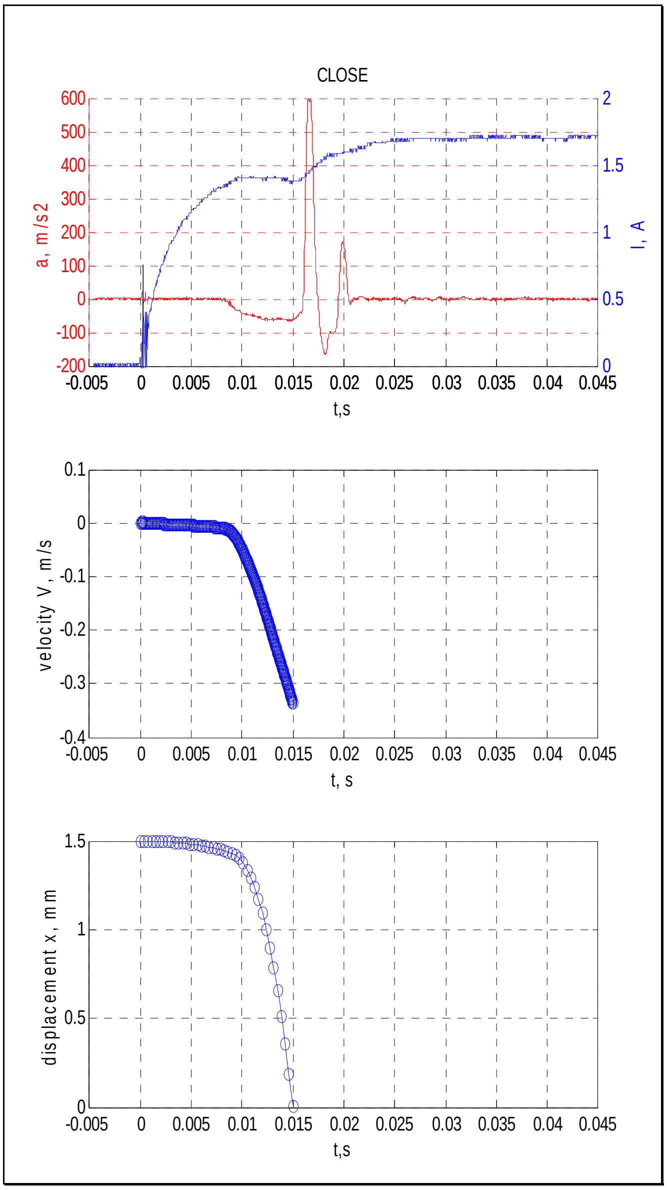

Fig. 7 The measured – acceleration and current and the computed – velocity and displacement for the closing armature (movement in conventionally negative direction)

The main drawback of this way of measurement of the dynamic characteristics is the delay introduced by the sensor.

The accelerometer output is internally smoothed with a 4-pole switched capacitor filter that introduces delay. There is another source of delay – electrical saturation recovery time. It appears when the measurement limit is achieved and internal amplifiers are saturated.

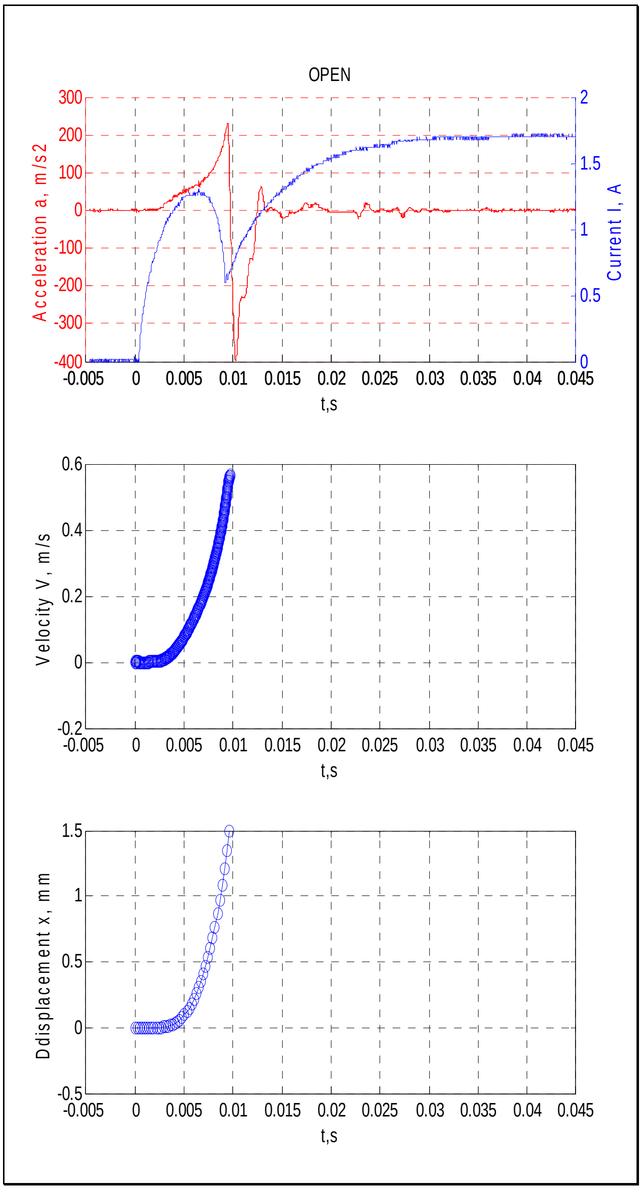

Fig. 8 The measured – acceleration and current and the computed – velocity and displacement for the opening armature (movement in conventionally positive direction)

VI. CONCLUSION

Accelerometer sensors can be easily adapted for experimental verification of the simulated dynamic characteristics. The use of this low cost measurement approach offers flexibility and lack of noise susceptibility.

The internal sensor delay adds a level of uncertainty when the displacement of the armature is derived from its acceleration. In case of electromagnet actuator this can be overcome by using the current curve to determine the end of the movement.

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