Linear Motion Profile Generation using a Danaher Thomson Actuator with Ball Screw Drive

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Abstract: - A Danaher Thomson linear actuator with ball screw drive is used here to generate vibrations in the 1-3 Hz frequency range. More precisely, the linear motion profile corresponding to the vertical displacements induced under the driver seat by the car ride on some real random road profile was successfully generated using this Danaher Thomson actuator. Also was generated a simplified linear motion profile corresponding to the sum of three sinusoids: a first sinusoidal vibration with A_1=2cm amplitude and f_1=1 Hz frequency, a second sinusoid with A_2=1.5cm amplitude and f_2=1.5 Hz frequency and a third sinusoid with A_3=1cm amplitude and f_3=2 Hz. The actuator is commanded in position ("position mode"), but also in acceleration; for each elementary motion from one position to another, the user provides the limitations in velocity and acceleration/deceleration. The paper presents a simple method to automatically compute the uniform acceleration, maximum velocity and uniform deceleration needed for an elementary motion, taking into account the importance of increasing as much as possible this lifetime expectancy of the ball screw drive.

Keywords: - linear motion, Danaher Thomson electrical actuator, ball screw drive, vertical vibrations, control in position, acceleration/deceleration regime

1. INTRODUCTION

In order to reproduce in a dynamic car simulator the vertical displacements and accelerations of the driver seat, as a first case study we have simulated a real ride using CARSIM software [1]. Experimental measurements of the vertical vibrations under the driver seat during car rides can also be performed if necessary, without difficulty. For the considered real random road profile, the vertical vibrations corresponding to the driver seat can be characterized by: main frequencies below 10 Hz, vertical displacements not greater than 5 cm and maximum vertical accelerations about 3 m/s^2 = 300 cm/s^2 [2].

In order to generate such vertical linear vibrations, a ball screw drive electrical actuator has been chosen. Even if linear motion electrical actuators are not traditionally recommended as vibrations generators, we have preferred the electrical solution instead of hydraulic or pneumatic actuators for several reasons: simplicity of the electrical solution (which does not require additional components such as compressors, piping, filters, etc), its reasonable price, good accuracy, it is less noisy, "cleaner" [3]. The electrical actuator is easy to integrate with modern programmable controllers, being naturally well-suited for use in real-time systems, in conjunction with feedback control [4].

For electrical actuators with ball screw drives, a major issue is their life expectancy, more precisely the life expectancy of the ball screw drive, especially when used in vibratory environments. Recent researches focus on the increase of the performance of ball screw drives in correlation with the associated tribological and wear processes in linear rolling guidance systems [5]. Another application is the ball screw choice for machine tools feed drive with increasing cutting speed [6].

This technical paper shows how a linear motion profile corresponding to the vertical displacements induced under the driver seat by the car ride on some real random road profile can be successfully generated using a Danaher Thomson linear actuator with ball screw drive [7], taking into account its limitations in what concerns the maximum velocity, acceleration and deceleration.

As a second case study, we have generated a simplified linear motion profile corresponding to the sum of three sinusoids: a first sinusoidal vibration with A_1=2cm amplitude and f_1=1 Hz frequency, a second sinusoid with A_2=1.5cm amplitude and f_2=1.5 Hz frequency and a third sinusoid with A_3=1cm amplitude and f_3=2 Hz.

2. TECHNICAL CHARACTERISTICS OF THE DANAHER THOMSON ACTUATOR

The results presented in this paper are obtained using a Danaher Thomson servoactuator ECT09 B43R02PB 3220 0400 TN 02 with ball screw drive [7] shown in Figure 1, equipped with brushless AC servo motor in parallel configuration and with belt gear transmission. This servoactuator is controlled by a Danaher Motion Kollmorgen servodrive AKD-P00306-NBCN-E000 [8].

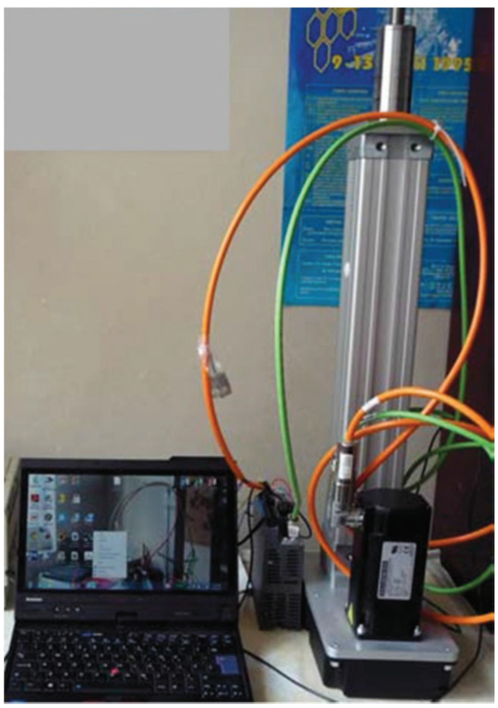


Figure 1. Danaher Thomson parallel B43 AC servoactuator [7] with AKD servodrive [8]

The main linear motion performances of the considered Danaher Thomson servoactuator with ball screw drive are [1]: maximum load = **1800 N**; maximum stroke (S_{max}) = **40 cm**; maximum velocity = **42 cm/s**; maximum acceleration/deceleration = **167 cm/s²**; repeatability = ± 0,05 mm.

The lifetime expectancy of such a ball screw drive device depends on several factors: load, speed, duty cycle, ambient temperature, screw type etc [7]. Thus, due to the dynamical charges/shocks induced in the ball screw assembly, the acceleration and deceleration regimes have a direct influence on the wear of the ball screw assembly and on its lifetime expectancy. In what concerns the acceleration profile used to command Danaher Thomson actuator, the trapezoidal acceleration profile has been chosen, consisting of rapidly reaching the desired constant acceleration/deceleration, followed by rapid/instant stopping. The Kollmorgen WorkBench software [8] offers also the alternative of using a OneToOne/S-Curve profile, but the trapezoidal acceleration profile is more rapid/reactive and thus more appropriate for our need to reproduce a vibratory (vertical) displacement.

The considered Danaher Thomson servoactuator with ball screw drive and controlled by AKD servodrive allows: **maximum velocity of 42 cm/s; maximum acceleration/deceleration of ±167 cm/s²**.

2.1. Simple method to compute acceleration, maximum velocity and deceleration needed for an elementary motion

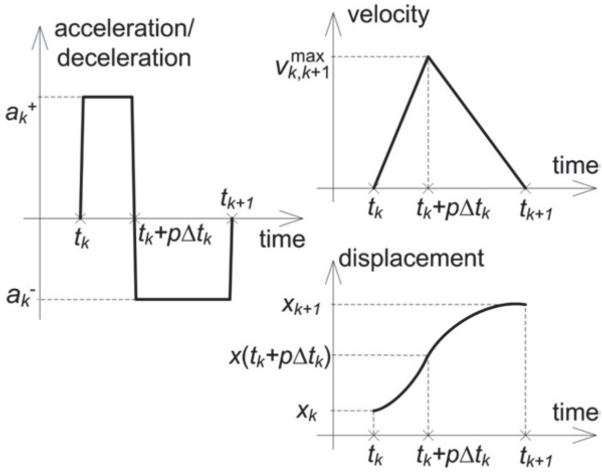
In order to increase as much as possible the ball screw drive lifetime expectancy, in the following we present a simple method to automatically compute the acceleration a_k^+, maximum velocity and deceleration a_k^- needed for an elementary motion between position x_k at time t_k and position x_{k+1} at time t_{k+1}. The idea is to find equalized $|a_k^+|=|a_k^-|$ in order to minimize $\max\left(|a_k^+|,|a_k^-|\right)$. Thus, the smaller maximum level of acceleration/deceleration $\max\left(|a_k^+|,|a_k^-|\right)$ we have, the smaller will be the dynamical charges/shocks on the ball screw drive, so the wear of the ball screw assembly will be smaller and the lifetime expectancy will increase.

As shown in Figures 2, the elementary motion between position x_k at time t_k and position x_{k+1} at time t_{k+1} is characterized by:

- uniform acceleration a_k^+ between t_k and the intermediate time $t_k + p\Delta t_k$, with $\Delta t_k = t_{k+1} - t_k$ and $p \in (0,1)$; if $p = \frac{1}{2}$, then the intermediate time corresponds to $\frac{t_k + t_{k+1}}{2}$;

- starting from null initial velocity $v_k = 0$, after this uniform acceleration a_k^+, the drive (end) attains its maximum velocity $v_{k,k+1}^{\max}$ at the intermediate time $t_k + p\Delta t_k$;

- uniform deceleration a_k^- between the intermediate time $t_k + p\Delta t_k$ and t_{k+1}; starting from the maximum velocity $v_{k,k+1}^{\max}$ at the intermediate time $t_k + p\Delta t_k$, after this uniform deceleration a_k^-, the drive ends with null velocity $v_{k+1} = 0$ at the final time t_{k+1}.



Figures 2. Elementary motion between position x_k at time t_k and position x_{k+1} at time t_{k+1}, for a trapezoidal acceleration profile

The elementary motion between position x_k at time t_k (with $v_k = 0$) and position x_{k+1} at time t_{k+1} (with $v_{k+1} = 0$), illustrated in Figures 2 and corresponding to a trapezoidal acceleration profiles, can be expressed using the following simple equations of motion:

$$\begin{aligned} x(t_k + p\Delta t_k) &= x_k + v_k \cdot p\Delta t_k + \frac{1}{2} a_k^+ (p\Delta t_k)^2 \\ &= x_k + 0 + \frac{1}{2} a_k^+ (p\Delta t_k)^2 \end{aligned} \quad (1)$$

$$v_{k,k+1}^{\max} = v_k + a_k^+ \cdot p\Delta t_k = a_k^+ \cdot p\Delta t_k \quad (2)$$

$$v_{k+1} = 0 = v_{k,k+1}^{\max} + a_k^- (1-p)\Delta t_k \quad (3)$$

$$\begin{aligned} x_{k+1} &= x(t_k + p\Delta t_k) + v_{k,k+1}^{\max}(1-p)\Delta t_k \\ &+ \frac{1}{2} a_k^- [(1-p)\Delta t_k]^2 \end{aligned} \quad (4)$$

By replacing $x(t_k + p\Delta t_k)$ given by (1) and $v_{k,k+1}^{\max}$ given by (2) into equation (4), it comes:

$$x_{k+1} = x_k + (\Delta t_k)^2 \left[a_k^+ \left(p - \frac{p^2}{2} \right) + a_k^- \frac{(1-p)^2}{2} \right]. \quad (5)$$

From (2) and (3), the following relation between a_k^+ and a_k^- is obtained:

$$(1-p)\, a_k^- = -p \cdot a_k^+ . \quad (6)$$

By replacing a_k^- obtained from (6) into (5), one obtains the expression of a_k^+:

$$a_k^+ = \frac{2(x_{k+1} - x_k)}{p(\Delta t_k)^2}, \quad (7)$$

then:

$$a_k^- = -\frac{2(x_{k+1} - x_k)}{(1-p)(\Delta t_k)^2}. \quad (8)$$

From (7) and (8), it is clear that $\max\left(|a_k^+|, |a_k^-|\right)$ is minimized for $p = \frac{1}{2}$, i.e., when the intermediate time corresponds to $\frac{t_k + t_{k+1}}{2}$, in this case we have:

$$a_k^+ = \frac{4(x_{k+1} - x_k)}{(\Delta t_k)^2} = -a_k^- , \quad (9)$$

$$x(t_k + \frac{\Delta t_k}{2}) = x_{k+\frac{1}{2}} = \frac{x_k + x_{k+1}}{2}, \quad (10)$$

$$v_{k,k+1}^{\max} = \frac{2(x_{k+1} - x_k)}{\Delta t_k}. \quad (11)$$

So, for the elementary motion defined by (9)-(11), it corresponds a smaller maximum level of acceleration/deceleration $\max\left(|a_k^+|, |a_k^-|\right)$, which brings an infinitely small but very important contribution to increasing the life expectancy of the ball screw drive.

Of course, the computed velocity $v_{k,k+1}^{\max}$ (11), uniform acceleration a_k^+ and uniform deceleration a_k^- given by (9) are bounded by the aforementioned maximum values: 42 cm/s maximum velocity and ±167 cm/s^2 maximum acceleration/deceleration. Due to these limitations, the considered Danaher Thomson servoactuator with ball screw drive and with AKD servodrive will not be able to perform the elementary motions which are too rapid for its performances.

In the "Motion Tasks" table of the Kollmorgen WorkBench software [8], the following information must be provided when commanding an elementary motion between position x_k at time t_k and position x_{k+1} at time t_{k+1}: • position x_{k+1} to be attained from the current position (which is x_k); • uniform acceleration a_k^+ and uniform deceleration a_k^-

computed by (9) and bounded, if necessary, by ±167 cm/s^2; • maximum velocity $v_{k,k+1}^{\max}$ given by (11).

3. DANAHER THOMSON ACTUATOR USED TO GENERATE THE VERTICAL MOTION IN A DYNAMIC CAR SIMULATOR

The considered Danaher Thomson servoactuator with AKD servodrive was able to retrieve the vertical displacements of the driver seat during a real ride (result already announced in [9]). So far, the actuator was controlled offline and without charge.

The vertical displacements to be retrieved were in fact obtained by CARSIM simulations, considering a car ride on the real random road profile shown in Figure 3, using the same road profile for the left and right wheels simultaneously ("bicycle" car model). The amplitude spectral density of the considered road profile is given in Figure 4 [2]. As for the geometrical and inertial characteristics of the simulated car, details can be found in [2].

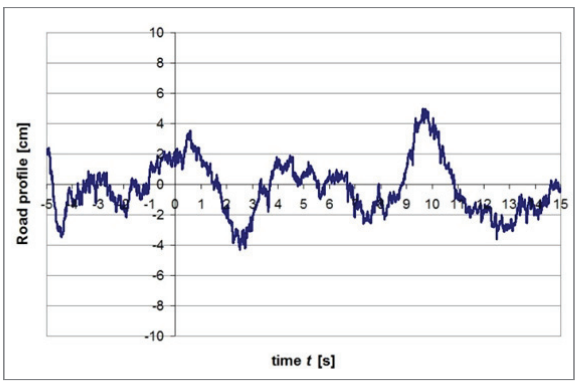


Figure 3. Real random road profile considered to simulate a real ride using CARSIM software [2]

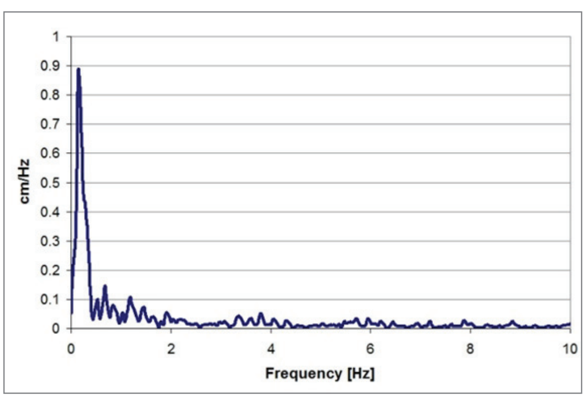


Figure 4. Amplitude spectral density of the considered real random road profile [2]

Figure 5 shows how the vertical displacement of the driver seat during a real ride on the road profile presented in Figures 3 and 4 (in blue), was successfully retrieved using the considered Danaher Thomson servoactuator with ball screw drive and with AKD servodrive (in red).

Figure 6 shows in red the uniform accelerations and decelerations computed as in §2.1 and corresponding to the retrieved motion profile from Figure 5, while in blue are shown the same accelerations and decelerations measured using an independent accelerometer (for verification). More precisely, a Brüel&Kjær accelerometer type 4368 has been used and the obtained signal has been amplified using a Brüel&Kjær amplifier type 2635 and acquired using a Velleman oscilloscope type PCSU1000 [9]. The good agreement in Figure 6, between the accelerations commanded by the AKD servodrive and the real accelerations measured using a Brüel&Kjær accelerometer, proves the good performance and reliability of the Danaher Thomson servoactuator with ball screw drive and with AKD servodrive. This good performance and reliability will be illustrated in the next section on a second case study, i.e., a motion profile corresponding to the sum of three sinusoids with frequencies between 1 and 2 Hz.

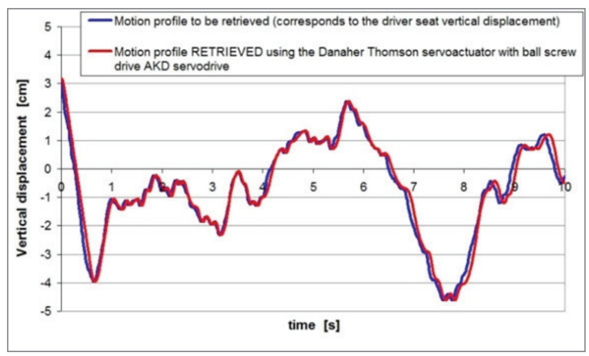


Figure 5. Retrieval of a motion profile corresponding to the vertical vibrations of the driver seat during a real ride, using the Danaher Thomson servoactuator with ball screw drive and with AKD servodrive

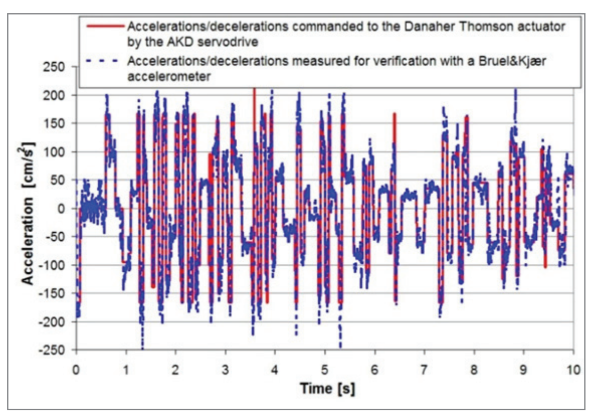


Figure 6. Accelerations/decelerations associated to the motion profile in Figure 5, corresponding to the vertical vibrations of the driver seat during a real ride

4. DANAHER THOMSON ACTUATOR USED TO GENERATE A MOTION PROFILE CORRESPONDING TO THE SUM OF THREE SINUSOIDS

A second case study of profile motion generation using the Danaher Thomson servoactuator with ball screw drive and with AKD servodrive concerned a displacement equal to the sum of three sinusoids: a first sinusoidal vibration with A_1=2cm amplitude and f_1=1 Hz frequency, a second sinusoid with A_2=1.5cm amplitude and f_2=1.5 Hz frequency and a third sinusoid with A_3=1cm amplitude and f_3=2 Hz.

Figures 7-9 show the displacements, velocities and accelerations for this sum of three sinusoids motion profile, in three variants: 1) corresponding to the theoretical sum of three sinusoids (curves to be retrieved); 2) what provides the AKD servodrive (position feedback PL.FB, velocity feedback VL.FB, acceleration command IL.CMDACC); 3) the acceleration measurement provided by an independent Brüel&Kjær accelerometer (from this measured acceleration are integrated analogically firstly the velocity then the displacement).

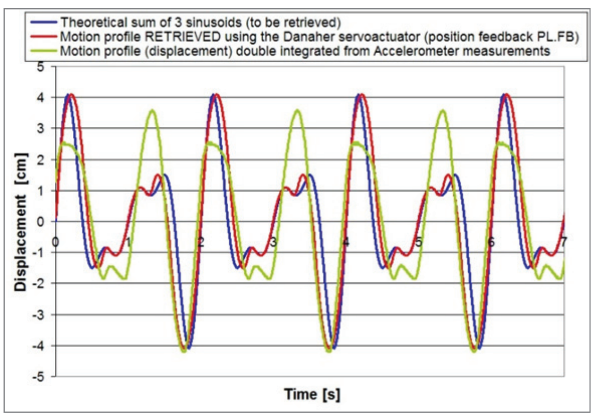


Figure 7. Retrieval of a motion profile (displacement) corresponding to the sum of three sinusoids between 1 and 2 Hz, using the Danaher Thomson servoactuator with ball screw drive and with AKD servodrive

A very good agreement between commanded and measured accelerations can be observed in Figure 9, which is quite normal since the Danaher Thomson servoactuator with ball screw drive is commanded in acceleration by the AKD servodrive (trapezoidal acceleration profile). Of course, it is commanded in acceleration, by computing the uniform acceleration and uniform deceleration for an elementary motion as in §2.1 (formulas (9)), so that to obtain/retrieve the desired motion profile. So, it is more correct to say that the Danaher Thomson servoactuator is commanded in acceleration, but also in position (the motion profile is retrieved).

The less but still good agreement between the displacements feedback provided by the Danaher Thomson servoactuator with ball screw drive and the displacement obtained by double integration of the independent accelerometer measurements, can be explained by the lack of precision of the double integration performed analogically by the measurement chain.

In what concerns the velocities (Figure 8), the agreement is better than for the displacements, since a single integration performed analogically by the measurement chain is obviously more precise than the double integration (which follows after the single integration, being a supplementary analogical operation/computation).

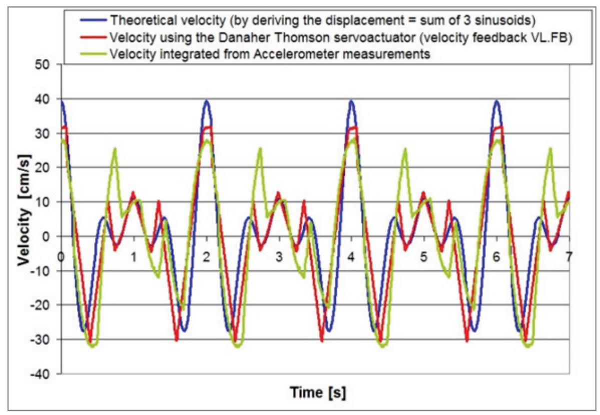


Figure 8. Velocities associated to the motion profile (displacements) in Figure 7, corresponding to the sum of three sinusoids between 1 and 2 Hz

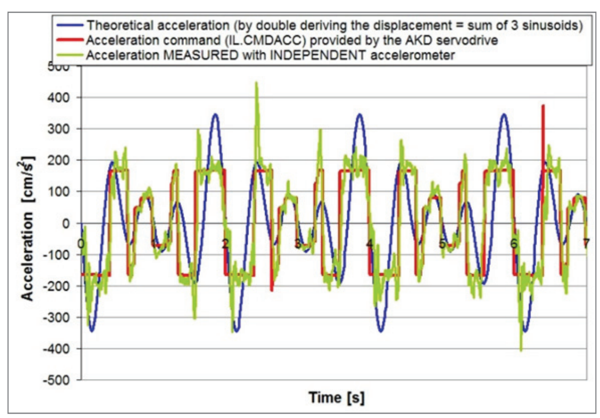


Figure 9. Accelerations/decelerations associated to the motion profile (displacements) in Figure 7, corresponding to the sum of three sinusoids between 1 and 2 Hz

5. CONCLUSIONS

The considered Danaher Thomson servoactuator with ball screw drive and with AKD servodrive was able to successfully generate vibrational displacements in the 1-3 Hz frequency range. Two case studies are exemplified: the generation of the vertical vibration of a driver seat during a real ride, respectively the generation of a displacement given by the sum of three sinusoids with frequencies between 1 and 2 Hz. The Danaher Thomson device was reliable and precise in performing these tasks.

We have also presented a method to minimize, during an elementary motion, the maximum level of uniform acceleration/ uniform deceleration. This practical minimization brings an infinitely small but very important contribution to increasing the life expectancy of the ball screw drive.

Further technological use of the Danaher Thomson device will bring new data concerning the life expectancy of the ball screw drive system, especially when working under charge, as it will be the case when the Danaher Thomson servoactuator with ball screw drive will be implemented in a dynamic car simulator, with the goal of generating appropriate vertical vibrations. A real time control of the Danaher Thomson device will also be developed.

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REFERENCES

[1] MECHANICAL SIMULATION CORPORATION, *CARSIM software*, http://www.carsim.com/

[2] O. Melinte, D.N. Dumitriu, *CARSIM software simulations of half-car vertical 2D dynamics and vehicle suspension behavior*, Proceedings of the the Annual Symposium of the Institute of Solid Mechanics and Session of the Commission of Acoustics (XXIVth SISOM 2013), Bucharest, May 21-22, 2013, pp. 148-153, ISSN 1843-5459.

[3] P. Zhang, *Industrial Control Technology – A Handbook for Engineers and Researchers*, William Andrew Inc., 2008.

[4] A. Kamalzadeh, *Precision control of high speed ball screw drives*, PhD thesis, University of Waterloo, Ontario, Canada, 2008.

[5] G.C. Puiu, *Contribuţii privind creşterea performanţelor şuruburilor cu bile în corelaţie cu procesele tribologice*, PhD thesis, "Gheorghe Asachi" Technical University of Iaşi, Romania, 2012.

[6] J.Z. Sobolewski, Investigation of ball screws for feed drive, Journal of Machine Engineering, vol. 13, no. 4, pp. 86-95, 2013.

[7] http://www.thomsonlinear.com/downloads/actuators/Precision_Linear_Actuators_cten.pdf, *Precision Linear Actuators* (catalog), 84 pages, Thomson™.

[8] *Kollmorgen WorkBench* – Version 1.10.0.39534 (software), http://www.kollmorgen.com/, Copyright © Kollmorgen 2009.

[9] D.N. Dumitriu, C. Lala, D. Baldovin, *On the acceleration regimes of a Thomson linear motion actuator used as vibrations generator in the 1-3 Hz range*, The Annual Symposium of the Institute of Solid Mechanics (SISOM 2014), Bucharest, May 22-23, 2014.