ARCHIVES OF MECHANICAL TECHNOLOGY AND MATERIALS
Vol. 35 2015

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IDENTIFICATION OF THE PARAMETERS OF A BALL-SCREW MECHANISM MODEL

In this article a method for identification of the static properties of a ball-screw mechanism is shown. The nonlinearity of its deformation was shown experimentally. Then, a model of the mechanism was made and its parameters were identified. The experimental results were summarized and compared with calculations. Recommendations were made for the modeling of carrying units containing ball-screw mechanisms.

Key words: ball-screw, mechanism, identification, model, parameters

1. INTRODUCTION

Ball-screw mechanisms are now widely used in many technological devices, primarily to convert the rotary motion of a motor into the linear motion of the entire unit. These mechanisms are produced by specialized manufacturers offering a wide range of products to suit various needs [9]. Although information provided by manufacturers is sufficient for the selection of the mechanisms themselves, it is of little use in the design of entire technological devices. Requirements for these devices make it necessary to conduct computational analyses to predict their properties at the stage of design [6,7,8,16]; the analyses are usually performed with the use of the finite element method [10,17].

According to the publication [13] one can assume that a ball-screw mechanism is in a limited extent similar to a ball bearing. The main difference is that the racetrack is stretched along a helix. The rolling elements carry the load between the threads of screw and nut. Load of the balls depends on the axial force under the terms of Hertz contact theory. Using Hertz formulas one can obtain nonlinear equations defining the axial stiffness of the mechanism. The authors analyzed the

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impact of errors of balls on the stiffness of the mechanism, clearly stating that this effect is significant only at very low loads. In their work, they use a simplified model of the mechanism. It has a single nut and has no preload. A large number of publications [1,4,5,11,13,14,18,19,20] dealt with the problem of the angle at which rolling elements are positioned against its raceways. While determining its value which is a difficult issue, one can try to use Hertz contact theory. However, a detailed knowledge of mechanism geometry of both the contact zones and the racetracks is needed.

The structural complexity of modern technological equipment requires very detailed models [10], which greatly complicates the modeling of this type (Fig. 1). Often, due to a broad plan of analytical studies, with many variants of design, models have to be highly simplified, which brings about low reliability of the results. Maintaining a high level of details usually leads to the development of models characterized by low computational efficiency. In such situations, it is necessary to compromise between computational efficiency and the reliability of computations.

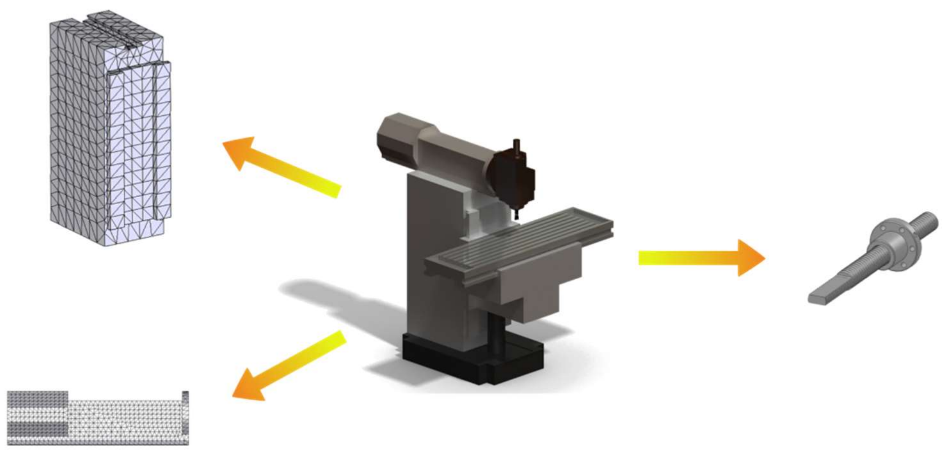

Fig. 1. The concept of modeling load-carrying systems in machines containing ball-screw mechanisms

In modeling the static properties of machines and technological equipment containing ball-screw mechanisms, one may perform simplifications with the use of discrete elements modeling the axial stiffness of these mechanisms [7] (Fig. 2). The substitute character of these elements requires the adoption of reliable parameters corresponding to the characteristics of the modeled properties. The values of the parameters may be obtained by their identification based on the experimental research performed on real objects.

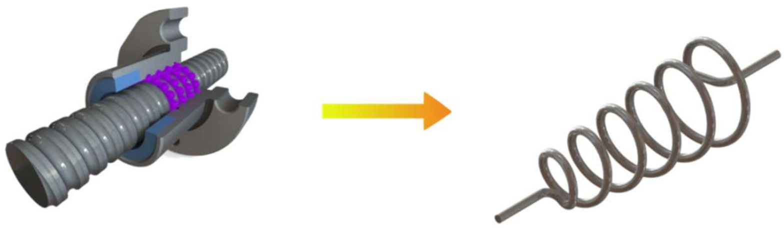

Fig. 2. Modeling ball-screw mechanism by replacing the mechanism with a spring element

The article describes the identification of parameters of modeled static properties of a ball-screw mechanism and provides an example of its application.

2. EXPERIMENTAL RESEARCH

The aim of the experimental research on a ball-screw mechanism was to obtain information about its static properties. In particular, the aim was to determine the characteristics of deformation in a screw-nut connection depending on the load on the mechanism in the direction of the screw axis. The study was conducted on a specially designed and built test bench (Fig. 3).

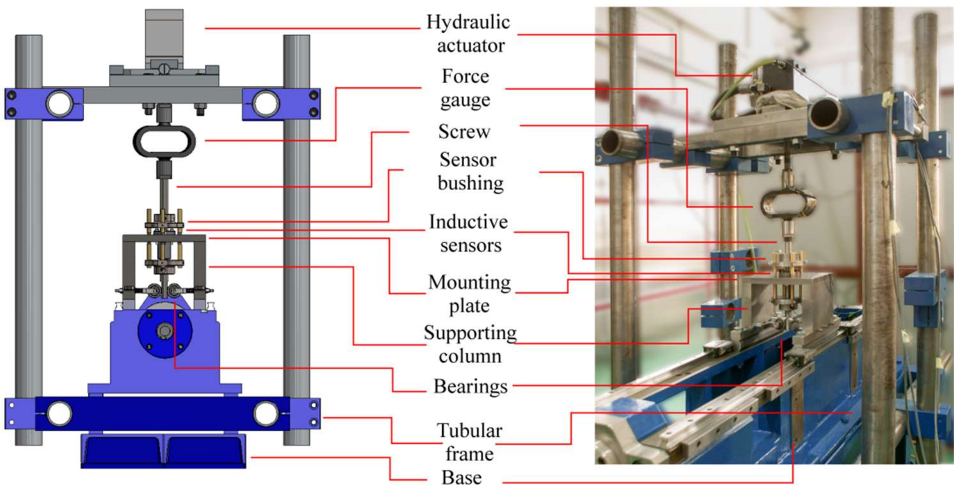

Fig. 3. The test bench for testing ball-screw mechanisms

At the test bench, hydraulic actuator was used to actuate the load. Measurement of forces was performed by the force gauge mounted directly to the test screw. The nut of the ball-screw mechanism was embedded in a special holder, which was attached to the base of the test bench. The hydraulic actuator was attached to the same base via a tubular frame.

The measurement of displacements was conducted by means of non-contact inductive sensors which use the differential system to measure the displacements of flanges mounted directly on the surface of the screw. During the displacement of the screw relative to the nut, the sensors move with the screw, recording the movement relative to the stationary mounting plate. In order to prevent unwanted rotation of the ball screw around its own axis, its end was immobilized by a pair of bearings. Cylindrical surfaces of the outer rings of these bearings were pressed to specially prepared flat surfaces at the end of the screw. This solution allowed the free movement of the screw along its axis (Fig. 4).

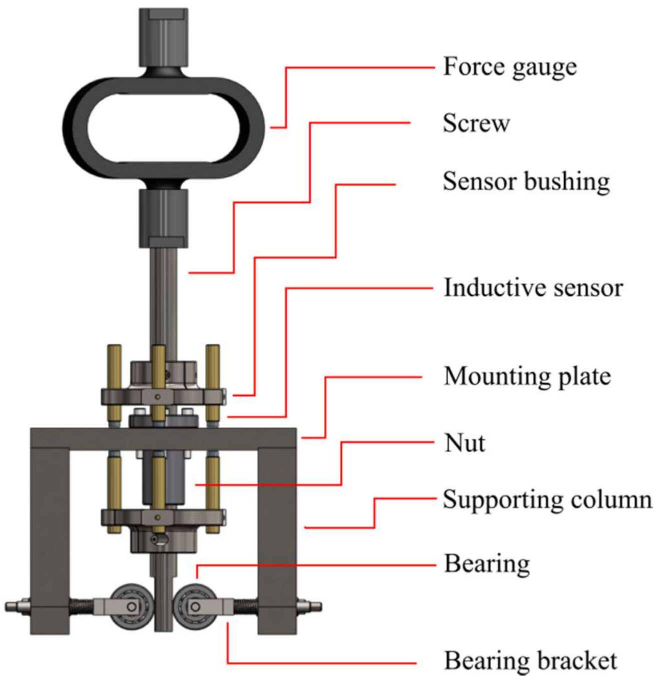

Fig. 3. Diagram of the test bench used to study the ball-screw mechanism

The research plan included the determination of response to quasi-static load in three variants, according to the diagram shown in Figure 5. In the first variant (A) tensile force was applied. In the second variant (B) the unit was loaded alternately by compressive and tensile forces. In the third variant (C) only compressive force was applied.

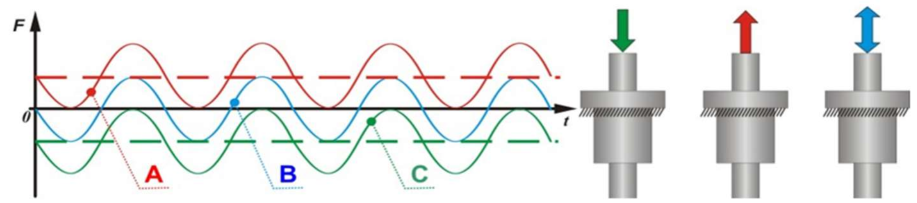

Fig. 4. A diagram of three variants of load on the ball-screw mechanism during the experiment

The signals of measuring flange displacements were obtained for each load variant, and after the processing of these signals [16] the characteristics of axial displacement relative to the nut were obtained. Sample results of these studies, compared with the results of calculations, are shown in Figure 7.

3. PARAMETERS OF THE MODEL

In practice, computational analysis of load-carrying systems in technological machines often includes the modeling of ball-screw mechanisms with the use of translational discrete components. In the analyses of the static properties, these elements have bilateral axial elasticity characteristics. Figure 6 schematically shows the modeling of a ball-screw mechanism as adopted in the applied process of identification.

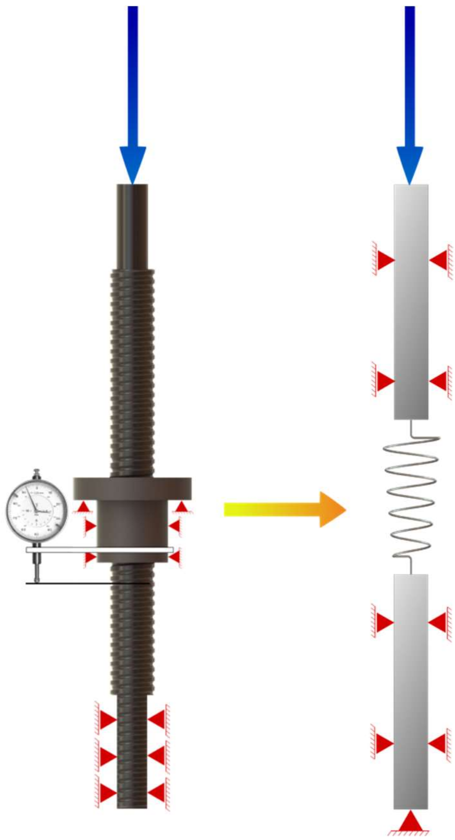

Fig. 5. Diagram of ball-screw mechanism modeling adopted in the identification process

Based on the evaluation of results of experimental studies non-linear characteristics describing the modelled properties of the ball-screw in the following formula were adopted:

$$u = CF^{m} \tag{1}$$

where:
u – linear deformation of the ball-screw mechanism (change in distance between the points on the nut and screw measured along the axis of the mechanism), [μm],
F – axial loading force applied on the mechanism [N],
C, m – parameters of the function.

As part of the identification process, parameters *C* and *m* were sought. This process was carried out separately for tension and compression. The least-squares method served as an identification criterion:

$$K(X) = \sum_{i=1}^{n} (u_{di} - u_{ai})^2 \tag{2}$$

where:
udi – deformation recorded in the i-th point of experimentally determined static characteristics,
uai – deformation recorded in the i-th point of the analytically determined static characteristics in the process of modeling and identification calculations
n – number of pairs of points in which the force has the same value in both experiment and computational model.

After the determination of characteristics describing the model on the basis of an experiment, one needs to identify parameters describing these characteristics. The very process of identification is a form of iterative optimization process, where the objective function is to reduce the difference between the characteristics obtained using a computational model and the experimental characteristics of the mechanism.

The identification process of function (1) parameters was carried out in MATLAB [2], the authors developed a program which with the use of the Optimization toolbox ran special computational FEM program – Helicon [7,8]. The model was solved in Helicon and the results of these computations – the uai (2) values were used for calculation of K (2)

Figure 7 presents a summary of the computational and experimental characteristics.

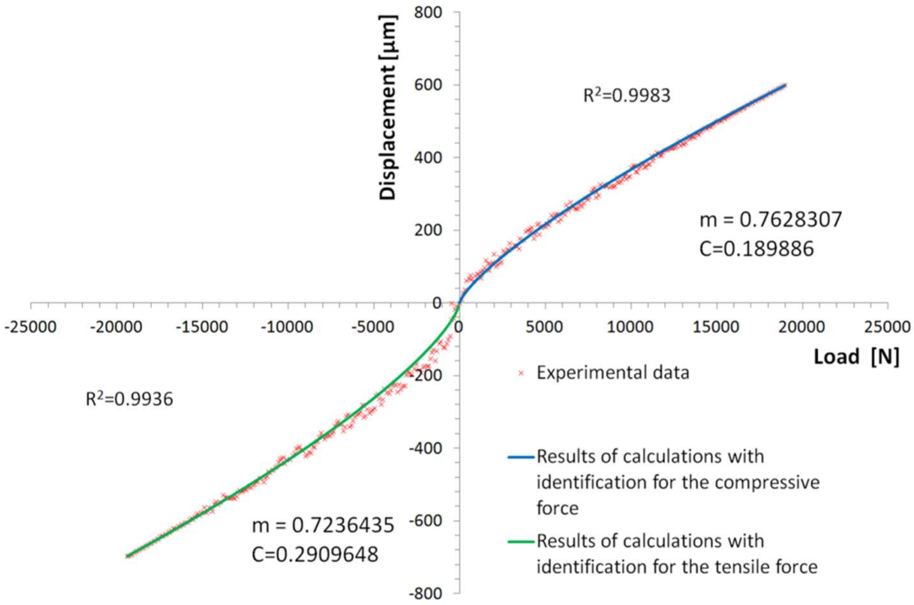

Fig. 6. Summary of computational and experimental characteristics and the identified parameters

In view of the different course of characteristics in the area of compression and tension forces, the best results were obtained for two separate sets of parameters that describe the characteristics. The values of these parameters are visualized in Figure 7. The calculations were performed using Matlab [2,12].

The nonlinearity of the experimental characteristic is related to the contact of the rolling elements with nut and screw raceways. In addition, when the load is applied the angle under which the balls contact with raceways is changning. Preload used in the mechanism beyond eliminating axial play has a positive effect on linearization of the load characteristic. Due to the need of ensuring a long life of a ball-screw mechanism the use of a large preload is not possible. As a result of lower preload one can observe a nonlinearity in the abovementioned graph (fig. 7.). Therefore it seems to be reasonable to adopt an exponential form of the model to describe a ball-screw mechanism.

4. SUMMARY

The article presents the results of experimental studies and identification calculations concerning a single ball-screw mechanism – a mechanism with a single nut (R1512 210 13, 25x5Rx3-4). On the basis of experimental studies of structurally similar mechanisms [3], one can expect analogous variability of characteristics in response to compression and tension. This makes it possible to formulate recommendations concerning the application of models of ball-screw mechanisms in the computational analyses of machines containing load-carrying systems, and take into account the variability of their deformations. Undoubtedly, this complicates the modeling of such objects but should improve the reliability of the results of analyses.

5. DISCUSSION

One of the most important conclusions of this work is that there is a need for using different parameters for a model of a ball-screw mechanism in cases of tensile and compressive forces. The graph (fig. 7.) clearly shows the differences in behavior of the mechanism in the case of positive and negative forces. We belive that this behavior has its basis in the construction of the transmission. The application of preload, that reduces the axial clearance is here realized by the combination of two separate nuts. When the load is small which is until it exceeds preload only one of the two nuts works. It is relevant which of the nuts is the active one. One of the nuts is closer to the flange while the other is fixed to the first one with a spacer. Due to the finite stiffness of the spacer the load characteristic is different for tensile and comprehensive forces.

The fit of computational characteristic in the terms of positive load is very good (R^2=0.9983). In terms of the negative loads the experimental characteristic due to the construction of the mechanism is so nonlinear that the adopted exponential model cannot be adjusted in such an accurate way as for the positive loads. The incompatibility for negative loads suggests that the adopted model was too simplified. It does not consider the impact of the spacer between the two nuts. This statement requires further research involving the development of more complicated models. On the other hand, the main goal of the work was to build a simple model of a ball-screw mechanism. Presented model, despite its flaws can be successfully used for the calculation of the entire machine tool systems. The divergence of computational and experimental characteristics can be seen only when applied forces are small and negative. The authors predict that there is no significant effect on the quality of calculation results of entire machine tools with the use of described model.

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IDENTYFIKACJA PARAMETRÓW MODELU MECHANIZMU ŚRUBOWO-TOCZNEGO

S t r e s z c z e n i e

W artykule przedstawiono przykład identyfikacji mechanizmu śrubowo-tocznego w zakresie jego właściwości statycznych. Opisano badania doświadczalne tego mechanizmu wykazując nieliniowy charakter jego odkształceń. Opracowano adekwatny model mechanizmu i przeprowadzono proces identyfikacji jego parametrów. Zestawiono i porównano wyniki badań doświadczalnych z wynikami obliczeń. Sformułowano zalecenie dotyczące modelowania układów nośnych maszyn technologicznych zawierających w swojej konstrukcji mechanizmy śrubowo-toczne.

Słowa kluczowe: mechanizm śrubowo-toczny, identyfikacja, parametry, model