Modelling of Mechatronic Devices Supported by 3D Engineering Software

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Abstract:

Modelling is considered to be an inherent part of design process of mechatronic devices and systems, in particular when solving problems of dynamics and accuracy of actuators and sensors. Mathematical software packages such as Matlab/Simulink are commonly used for this purpose. Engineers and designers who integrate mechanical components of devices under design, usually employ special computer software known as 3D CAD for creating three dimensional images. Typically it is used to generate technical drawings and layouts but its usability is more extensive. The paper presents ability of such software to support simulation where a linear stepping actuator is an example of a device under design.

Keywords: *mechatronic drive, linear actuator, modelling*

1. Introduction

Modelling is recognized as one of characteristic features of mechatronic systems and devices designing. However the term "modelling" is a general one and it covers various techniques referring to various domains and parts of a system under design. The authors attempt to address those techniques to particular phases of design process as they were previously defined. The analysis has shown that the following phases of the design process could be identified [7]:

- developing of a system structure,
- identifying sensors and actuators,
- designing of sensors and actuators,
- designing of subsystems: electromechanical, electronic and software,
- supervising of making a prototype,
- trials with modifications of a system in any layer.

Mathematical models used in design process (Fig.1) usually are expressed in either balance, constitutive or phenomenological equations. Their complexity depends upon the described phenomena, the goal of experiments, available data as well as simulation software capability.

2. Determination of user's needs and analysis of a main function of the system

Designing should be started from the definition of client's requirements. It has to consists of following parts [7]:

– *system functions*, commonly presented as operating algorithms or lists of operations that device has to do with numerically defined characteristics,
– *description of a system structure* including mechanical, electronic and software subsystems,
– *description of system environment* with physical and legal conditions, also possible presence of other systems and user.

In this phase, when user's needs are reviewed, 2D or 3D geometrical models of the device under design can be generated in order to obtain the client's approval for either its look or layout (Fig. 2). It can be extended by modelling some activities when using the device or system – sometimes technical models are used. When analysing a main function of a system, time relations between particular operations are crucial.

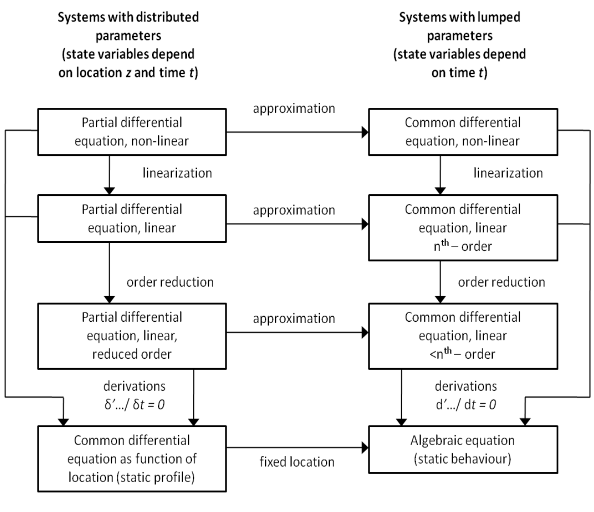

Fig. 1. Classification of models with respect to type of state variables by [1]

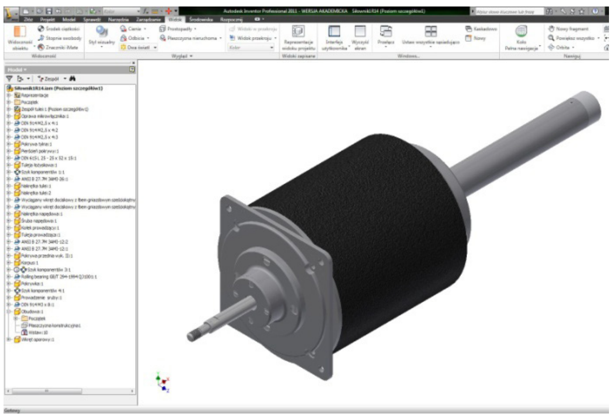

Fig. 2. Virtual three dimensional model of an actuator developed with Autodesk Inventor. Use of such a model allows presenting desired dimensions, movement ranges or displacement of mounting holes

At the phase of main function analysis, the functional concept of a device is being developed. Upon this concept a list of necessary actuators and sensors is formulated. User's requirements are translated into technical requirements for each unit, either actuating or measuring. 3D software is not useful for this stage of project. Block diagrams are the most common form to illustrate these works.

3. Developing of actuators and sensors

A result of this stage of a design should be a proposal of technical solutions of particular actuators and sensors identified at previous stage. In this phase typical modelling and simulation of dynamical systems is performed in order to obtain time responses, which supports decisions upon technical solutions of actuators and sensors [7].

3.1. Modelling with CAD 3D software

This stage of design can be aided to some extent by 3D CAD software. The software gives engineers an opportunity to create in virtual reality various versions of mechanical parts of sensors and actuators in order to test them at very low cost. Definition of physical parameters of 3D models such as material properties, factor of friction, stiffness or elasticity are so close to reality, that in majority of cases the models are very reliable.

Simulations of object dynamics can be carried on final model of an assembly or on demonstrative, draft one. In the second option parts will be made in simplified way to illustrate only their main functions, essential for results of simulation (Fig. 3). Simplified models allow to proceed more tests and simulations with bigger number of possible configurations. This leads up to choosing optimal solution.

The following example presents ability of 3D CAD software to perform such simulation. Autodesk Inventor

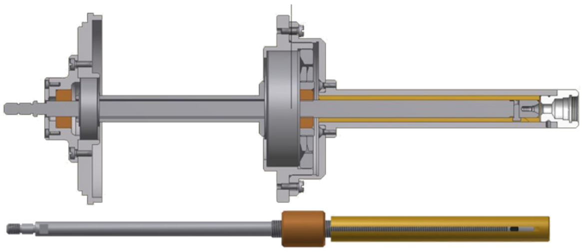

Fig. 3. Screw gear – virtual model prepared for preliminary simulation

software package was used for experiments upon screw gear (Fig.4) used in linear actuator driven by stepping motor.

When mechanical properties of the gear are declared, actuating forces and loads can be applied to the model. Results of such simulation showing time series of pusher travel and velocity are presented in Fig. 5.

Due to some limitations of the program the motor torque which drives the nut was modelled as a step function. Though it differs much from real form of torque of stepping motor, experiments generated time responses of pusher position and velocity being a basement for some practical conclusion. When loading force is opposite to the pusher movement (0 – 1 s) then velocity grows slowly, with acceleration 19,5 mm/s2. When motor torque drops

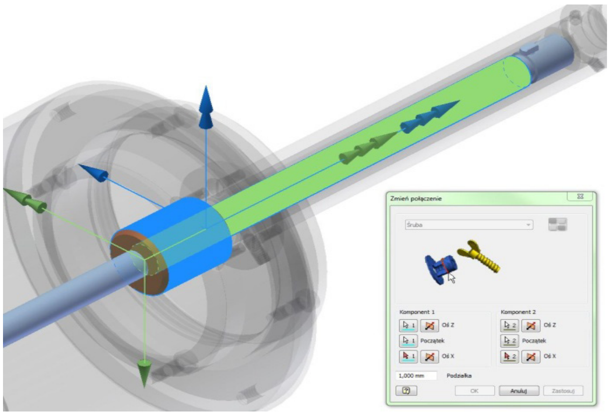

Fig. 4. Selection of components of screw gear

to 0 (1 – 2 s) the pusher stops after 0,16 s. As the screw gear used in actuator is self-locking one, no movement occurs under axial force applied to the pusher. When motor torque acts in consistency to the loading force vector (2 – 3 s) acceleration is more than twice bigger (43 mm/s2) and the pusher travel is also bigger, so it overcomes the starting position. Repeating of the same operation cycle makes position of the pusher even more distant from the starting point. It proves the essential effect of load upon performance of the actuator. In fact when stepping motor is applied, positioning is controlled by the number of timing pulses.

The 3D software used for simulation described above has many limitations referring to shape of input signals applied to the model. Therefore other tools should be used in order to obtain more reliable results.

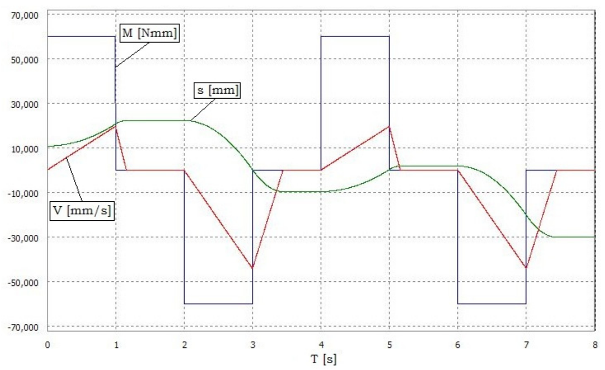

Fig. 5. Simulation of a helical joint dynamic with applied load of 30 N; actuating torque M, rod velocity V, rod position s

3.2. Modelling with software for multidomain simulation of dynamic systems

When modelling actuators, the procedure starts with either rotational or linear movement model, depending upon the kind of movement realised by a drive used. If rotational movement takes place, then the classical equation of torque equilibrium makes the model

$$(J_m + J_l)\frac{d^2\gamma}{dt^2} + K_D\frac{d\gamma}{dt} + M_f\ \mathrm{sgn}\left\{\frac{d\gamma}{dt}\right\} + M_l = M_m \qquad (1)$$

where: J_l – moment of inertia of rotating elements reduced to the motor shaft [kg/m²], J_m – moment of inertia of motor rotor [kg/m²], K_D. – coefficient of viscous damping [Nm/rad/s], M_m – motor torque [Nm], M_l – active load torque reduced to the motor shaft [Nm], M_{lf} – frictional load torque reduced to the motor shaft [Nm], γ – angle of rotation of rotor [rad]. It is a base for the whole model, which is created by developing models of all components included into the above equation.

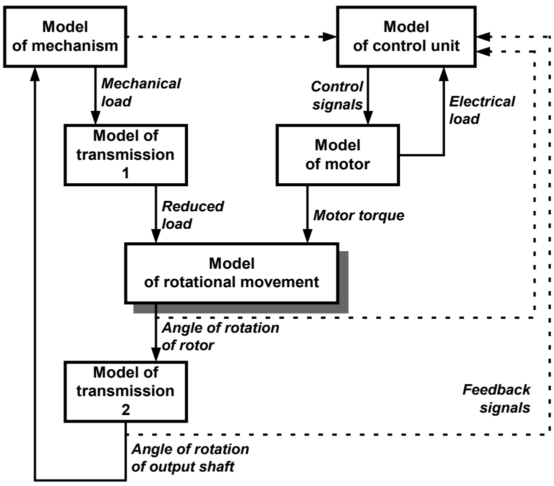

Fig. 6. Concept of modelling

Modelling of driving motor

The driving motor is represented in the model as its torque M_m as well as mass moment of inertia of rotor Jm. Torque M_m is an electromagnetic torque M_e [Nm] diminished by internal losses of motor

$$M_m = M_e - \sum_i M_s \tag{2}$$

where M_s denotes torque of losses inside the motor [Nm]. Electromagnetic torque is a function of control voltage or voltages. In case of direct current motor it is given by simple linear relation [5]

$$M_e = K_T \cdot i \tag{3}$$

where: K_T – torque constant [Nm/A], i – motor current [A]. Motor current is determined using voltage equilibrium equation [5]

$$u = R_t \cdot i + K_E \cdot \omega + L \frac{\mathrm{d}i}{\mathrm{d}t} \tag{4}$$

in which: u – control voltage [V], R_t – terminal resistance [Ω], L – winding inductance [H], K_E – back EMF constant [V•s/rad], ω – angular velocity of rotor [rad/s].

In case of stepping motor the so called "idealized" model is usually used. Its electromagnetic torque is a function of discrepancy angle between magnetic axis of rotor and stator and is given by the equation.

$$M_e = -M_{max} \sin(\delta) - D_m \frac{\mathrm{d}\gamma}{\mathrm{d}t} \tag{5}$$

where: M_{max} – maximum torque of motor [Nm], D_m – coefficient of electromagnetic damping [Nm•s/rad], δ – discrepancy angle of position of the rotor in relation to the axis of electromagnetic field of stator [rad]. In hybrid stepping motors the discrepancy angle is calculated as

$$\delta = Z_r [\gamma - \gamma_u(t)] \tag{6}$$

where: γ – angle of rotation of rotor [rad], γ_u – instantaneous stable balance position of rotor [rad], Z_r – number of teeth of rotor.

Application of the selected motor model is dependent not only upon its credibility but also upon availability of its coefficients. An example of difficulties of such kind utilizing of the "idealized" stepping motor model is. Even renown manufacturers in their catalogues do not refer to this simplest model – do not publish values of coefficient of electromagnetic damping D_m, necessary for proper simulation.

Modelling of control unit and feedback loops

A typical way of modelling control units is developing adequate functions of control voltage or voltages being responsible for generating of electromagnetic torque. In the simplest case it can be an undisguised function of time

$$u = u(t). \tag{7}$$

Drive systems of mechatronic devices usually operate with closed feedback loops either of position or velocity type depending upon main function of analysed assembly. Usually it is then sufficient to apply surrogate models of control units available in various publications e.g. [4] and frequently expressed as transmittances. It also has to be emphasised that modern controllers for stepping motors operate with very sophisticated procedures, usually not sufficiently described and therefore it is far difficult to prepare a credible model of such device.

Modelling of transmission

From the point of view of modelling transmission system plays two separate functions:
- reduction of mechanical loads related to the driven mechanism to the motor shaft,
- reduction of velocity of motor shaft to mechanism.

Reduction of torques and reduction of moments of inertia is performed using classical relations

$$M_l = \frac{M_{mech}}{\eta_p \, i_p}, \quad J_l = \frac{J_{mech}}{i_p^2}, \tag{10}$$

in which: M_{mech} – load torque resulting from mechanism [Nm], i_p – gear ratio, J_{mech} – moment of inertia of rotating parts of mechanism [kgm2], η_p – efficiency of a gear.

Reduction of velocity is given by formula coming straight from definition of gear ratio

$$\omega_{mech} = \frac{\omega}{i_p}, \tag{11}$$

where ω_{mech} denotes angular velocity of output shaft of a gear [rad/s].

Depending upon type and quality of gear its ratio as well as efficiency may vary, particularly cyclically in function of angle of rotation. In this case it is justified to use models created by expansion into Fourier series experimentally registered relations between torque as well as kinematic accuracy and angle of rotation [4].

Modelling of a mechanism

Because of adopted concept of modelling the driven mechanism is represented by torques and moment of inertia, which can be functions of time, angle of rotation, velocity or other quantities

$$M_{mech} = f(t,\gamma,\omega,...)\,, J_{mech} = g(t,\gamma,\omega,...)\,. \quad (12)$$

In Fig. 7 simulation model of the actuator developed in Matlab-Simulink software environment is presented.

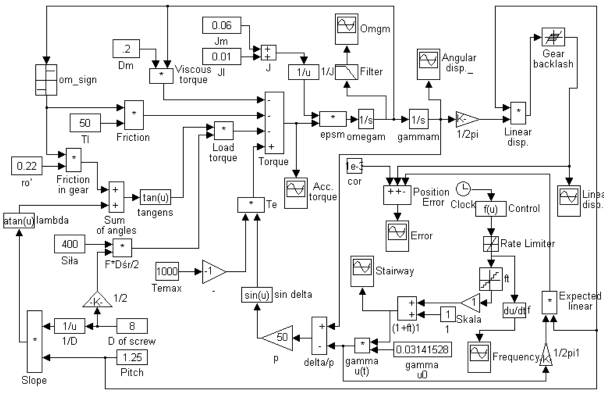

Fig. 7. Simulation model of the actuator driven by a hybrid stepping motor

The role of CAD 3D programs can be quite extensive at this stage for it is a source of reliable mechanical data to be included in the model, such as: masses, moments of inertia, location of gravity centres and geometrical parameters. Special modules of 3D software are used for this purpose (Fig. 8).

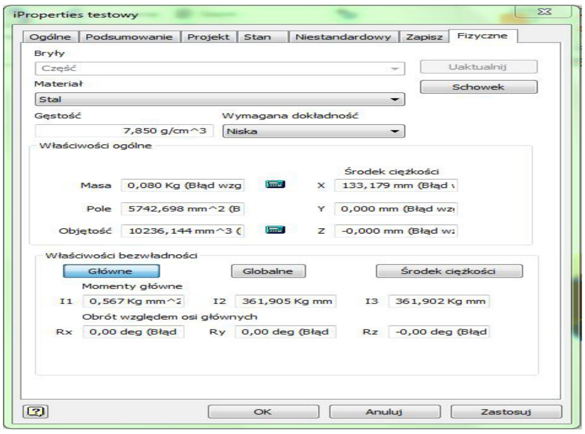

Fig. 8. Dialog window of part properties. In physical properties tab one can describe material the part will be made of. On this basis parameters such as mass, gravity centre, mass moment of inertia are calculated

Typical software for simulation of dynamic systems produces time responses of the system output quantities as well as quantities that are not visible or not measurable in a real device, for instance discrepancy angle in a stepping motor (Fig. 9).

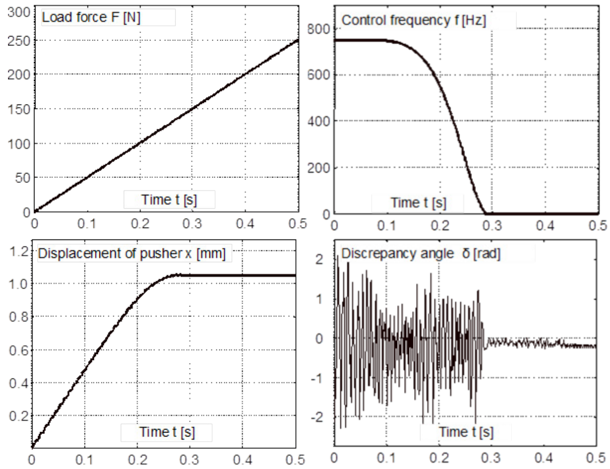

Fig. 9. Results of simulation of a linear actuator driven by stepping motor

4. Designing of mechanical subsystem

When designing mechanical subsystem, it becomes a common practice to develop its 3D model aimed at avoiding geometrical collisions between parts and used for calculation of distribution of various space dependent quantities such as: temperature, stress or strength (Fig. 10).

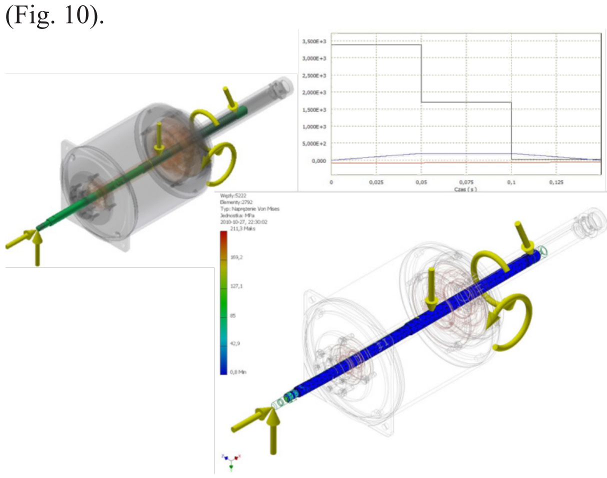

Fig. 10. FEM strength analysis can be based on forces calculated during dynamic simulations

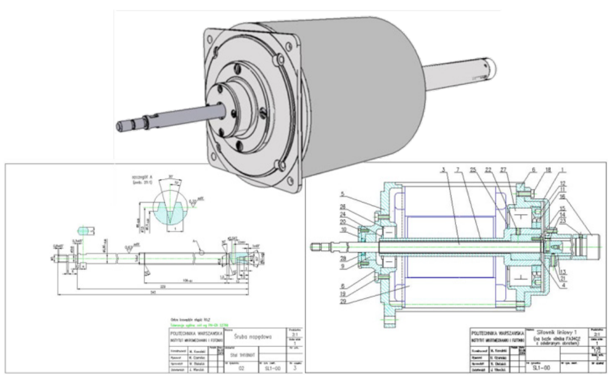

Fig. 11. Three dimensional models of parts and assemblies are used to create technical drawings

Design process has to be ended with technical drawings of the whole device. When 3D CAD software is used virtual prototype of the device is being created. This prototype represents geometry, material and physical properties that real device will have. It assures elimination of mechanical collisions between parts and is a base for developing set of standard 2D drawings (Fig.11).

5. Summary and conclusions

The software for various kinds of modelling becomes still more and more compatible, giving opportunities to exchange data between different packages. Analysis of conducted modelling and simulations allows authors to end with some conclusion upon reliable use of such tools in order to keep engineers conscious of actual role of modelling.

First of all, it is worthful that possibility of data exchange between engineers software constantly spreads. That makes modelling easier and simulation results more accurate.

During designing mechanical subsystems of mechatronic devices, significant role plays three dimensional modelling bounded both with geometry of assemblies under design and with other quantities related to their location in space.

Development of actuators and sensors requires in most cases time domain simulations. Models of lumped parameters described by ordinary differential equations are commonly used.

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