Development of a small-sized electromechanical steering gear unit by simulation modeling

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Abstract. In this paper the results of the development of an electromechanical steering gear based on waveform reductor that provides rotary motion of the working surfaces of small-sized aerial munition are presented. Calculations of the design parameters of the components of the steering gear, the formation of the desired dynamic properties of the product are implemented by the method of simulation modeling in the Matlab Simulink environment. The model is fully parametrized. The Simulink-model contains blocks that implement signal conversion in accordance with the physical model of real equipment. The article presents the results of laboratory and flight tests of a prototype of steering gear confirming the success of the adopted circuitry solutions and the adequacy of the developed simulation model. The developed simulation model can be used as universal design tool for electromechanical steering gears.

1. Introduction

Nowadays one of the most perspective aspect of development in aerial drive equipment is power electromechanical steering gear within the concept of aircraft ‘complete electrification’ [1]. At that, demands issued upon compact aerial munitions are constantly increasing, hence, demands on actuator mechanism specifications – steering gears - are increasing, respectively.

Constructive and technical problems arising for specialists at the stage of development of electromechanical steering drives can be successfully solved by methods of simulation modeling [2,3].

Analysis of scientific articles by Russian [4-6] and foreign authors [7,8] showed a wide coverage of this issue. But at the same time, only a few scientific publications [9,10] contain the results of approbation of the developed models, as well as a comparision of the simulation results of field tests of prototypes.

Overview of steering gear designs of domestic and foreign manufacture showed that nowadays compact aerial munitions widely comprise drives based on ballscrew gear [4,11,12]; drives based on roller gears [13]; waveform gears [14-16]; waveform gears with intermediate rolling elements.

The search for ways to solve the development of a small-sized steering gear eventually led to the decision to use waveform reductor. The advantages of a mechanical gearbox based on waveform reducer are described by the authors in the works [13,17,18]. Besides, choosing a waveform reductor, it is possible to choose the design of a ‘power mini-gear’ as a circuit solution, which allows to minimize the dimensions of the steering gear [19].
The purpose of this article is to develop electromechanical steering gear unit based on a waveform reductor using a simulation modeling method for a small-sized aerial munitions and to assess the adequacy of the model based on the results of field tests.

2. Methods and materials
Electromechanical steering gear operational principle, regardless of the type of mechanical gearbox, is explained with the functional scheme (figure 1).

Figure 1. Functional scheme of steering gear: inertial control system (ICS), steering gear control unit (SGCU), power amplifier (PA), erection device (ED), AM – actuating motor, mechanical reductor (MR), feedback angle transducer (FAT), object of control (Steer), $\delta_{ICS}$ – angle assigned from ICS, $U_{SGCU}$ – voltage of SGCU, $M_m$ – torque moment on the motor shaft, $M_h$ – friction moment, $M_{fr}$ – hinge moment (external moment of load) on the steer, $\delta_s$ – turning angle of the steer, $\delta_{FAT}$ – angle of FAT.

Steering gear mathematical model is represented in the form of differential equations (1-3) and analytical expressions (4 – 10), which describe physical processes in the electrical drive [3,16,20]:

$$u_m(t) = C_e \cdot \frac{d\delta_m(t)}{dr} + R_m \cdot i_m(t) + L_m \cdot \frac{di_m(t)}{dr},$$  \hspace{1cm} (1)

$$J_t \cdot \frac{d^2\delta_s(t)}{dr^2} = M_{t,m}(t) - M_{fr,red}(t) - M_h(t),$$  \hspace{1cm} (2)

$$M_{t,m}(t) = q_{red} \cdot \left(M_m(t) - M_{fr,m}(t)\right),$$  \hspace{1cm} (3)

$$M_m(t) = C_m \cdot i_m(t)$$  \hspace{1cm} (4)

$$\delta_s(t) = \frac{\delta_m(t)}{q_{red}}$$  \hspace{1cm} (5)

$$M_h(t) = K_h \cdot \delta_s$$  \hspace{1cm} (6)

$$J_t = J_s + q_{red} \cdot J_{m+red}$$  \hspace{1cm} (7)

$$T_m = \frac{L_m}{R_m}$$  \hspace{1cm} (8)

$$M_{fr,m}(t) = \left|M_{fr,m}(t)\right| \cdot \text{sign} \left(\frac{d\delta_m(t)}{dr}\right)$$  \hspace{1cm} (9)
\begin{equation}
M_{\text{fr.red}}(t) = \left| M_{\text{fr.red}}(t) \right| \cdot \text{sign} \left( \frac{d\delta_s(t)}{dt} \right)
\end{equation}

where \( u_m(t), i_m(t) \) – voltage on the motor armature winding and current in it, \( \delta_m(t) \) – turning angle of motor shaft, \( C_e \) – motor counter-EMF coefficient, \( R_m \) – motor rotor winding resistance, \( L_m \) – armature inductance, \( M_m(t) \) – torque moment on the motor shaft, \( M_h(t) \) – hinge moment (external moment of load) on the steer, \( M_{\text{fr.m}}(t), M_{\text{fr.red}}(t) \) – friction moment in the motor and redactor, \( M'_{\text{t,m}}(t) \) – motor torque moment to the steer, \( J'_1 \) – total inertia moment to the steer, \( q_{\text{red}} \) – gear ratio, \( C_m \) – motor moment coefficient, \( \delta_s(t) \) – turning angle of the steer, \( T_m \) – motor time constant, \( K_h \) – proportional coefficient between hinge moment \( M_h(t) \) and turning angle of the steer \( \delta_s(t) \), \( J_s \) – steer inertia moment, \( J_{m+\text{red}} \) – inertia moment of the drive rotating parts consisting of motor rotor inertia moment \( J_m \) and wave reductor inertia moment \( J_{\text{red}} \).

Based on functional scheme (figure 1) and equations (1–10), simulation discrete parametric model of steering gear has been formed in Matlab program and its packet Simulink (figures 2-4) [21-23]. It accounts for possible non-linearities of the system.
Figure 4. “Microcontroller” subsystem.

Developed simulation model is a set of function sequence, combined into control program in Matlab language as well as set of blocks from Simulink library. In the developed model the system parameters are set as variables, it allows to unify the model and realize dependent parameter automatic recalculation in the control program. Simulation model of the steering gear allows to reveal variable interdependency, their time behavior, as well as to predict object behavior. Possibility of parameter prediction of erection device is realized in the control program. According to electrical scheme of the steering gear control unit, negative current feedback is realized which allows to stabilize the motor resistance variation due to temperature. Simulation model is transformed to physical model of real equipment: continuous subsystem blocks (blocks of transfer functions) are transformed to discrete, discrete transformation of signals is performed, as well as blocks for ADC realization are included.

Using the developed simulation model, steering gear characteristics are investigated. Based on obtained scientific-practical results the following strategy of steering gear parameter synthesis has been developed: required mechanical power is calculated and possible version of electrical motor is chosen on the basis of steering gear preset characteristics; optimal value of load transfer unit reduction is determined and necessary reductor is chosen; steering gear simulation model is realized; erection device is calculated in order to provide the required dynamic features of the system; dynamic and statistic characteristics of the system are estimated, its parameters are specified; preferred motor type and reductor type is chosen according to obtained results.

3. Results and discussion
Steering gear is developed using the system parameters, calculated with abovementioned strategy. It is proposed to consider reductor based on waveform gear as an actuator mechanism, which allows to realize the system required parameters in given dimensions [8-11]. Operation principle of the waveform gear is based on gearwheels – rigid and flexible (figure 5) – interaction (catching). Flexible gearwheel, which is in the form of a ring or thin-shell structure, is deformed with the wave former.

Figure 5. Three-dimension model of the steering gear.
Steering gear unit consists of three basic units: four steering gears (figure 6); electronic unit of gear control; power part power source. Steering gear unit is a four-channel servo-system which provides transformation of independent electrical control inputs along each channel according to commands output by inertial control system to rotation motion of output component, kinematically coupled to axis (shaft) of the corresponding steer of the device.

Figure 6. Steering gear prototype model.

Figure 7. Steering gear unit on the hinge-moment simulation table.

To estimate effectiveness of the developed simulation model and developed strategy, series of experimental investigations were conducted. Theoretical calculation correctness and simulation model validity were tested with experimental methods on the steering gear prototype models as well as during flight testing of the compact aircraft munition.

Developed model validity was estimated according to compliance to steering gear unit main parameters (readjustment, time and speed of bringing the steer to the preset angle, static error in bringing the steer, etc.), obtained as a result of simulation and experiment.

Climatic and mechanical testing of steering gear unit prototype model based on waveform reductor showed operability of the device in specified operational conditions.

Load (in the form of hinge moment) testing of steering gear unit prototype model was conducted on the hinge-moment simulation table (figure 7). Hinge-moment simulation table actuator mechanism consists of the following parts: four load-electrodrives; four angle transducers; four torque transducers; supports and brackets for installation, positioning and adjustment of both steering gear unit and hinge-moment simulation table elements.

During load testing of the steering gear unit the following dependencies were determined (figure 8): maximum drive speed from load $V_{\text{max}} = f(M_h)$; time of bringing the control object to preset angle from load $t_{\text{br}} = f(M_h)$; error of bringing to the preset angle from load $\delta_{\text{br}} = f(M_h)$.

Figure 8. Experimental results of the steering gear unit testing on hinge-moment simulation table. Maximum drive speed from load $V_{\text{max}} = f(M_h)$ (a); time of bringing the control object to preset angle from load $t_{\text{br}} = f(M_h)$ (b); error of bringing to the preset angle from load $\delta_{\text{br}} = f(M_h)$ (c).
Experimental results (figure 8) on the hinge-moment simulation table showed that the steering gear unit reproduces required characteristics.

The results of steering gear flight mission, generated by the ICS from the upper deck simulator during test launching of the compact aircraft munition on the testing field are represented in figure 9.

![Figure 9](image)

**Figure 9.** Comparison of simulation and flight test results. The compact aircraft munition is on the firing pad of the upper deck simulator, motors are ON, it induces the compact aircraft munition vibration (1); lift-off the firing pad of the upper deck simulator, ICS stabilization (2); the compact aircraft munition flight training (3).

High-frequency vibrations on the flight training area are caused by residual vibrations in the stabilization loop.

Based on the results (figure 9) of the experimental launching of the compact aircraft munition, it can be concluded that steering gear with waveform reductor successfully provides the transformation of input electrical control signals, according to commands output by inertial system, to rotational movement of output element.

Except natural experiment result analysis for the estimation of the developed model validity to real prototype of steering gear, a real flight mission was trained in the simulation model. Simulation modeling results are also represented in the figure 9. The figure 9 shows good compliance of the simulation modeling results and experimental results. Insignificant difference during training of flight mission in experiment and model may be caused by difference in specifications of the motor prototype model of the steering gear and nominal specifications of the model.

4. Conclusion

Simulation modeling is currently one of the most powerful analysis tools used by specialists responsible for the development and operation of complex processes and systems. Strategy of steering gear parameter synthesis using the simulation model, generated in Simulink with differential equations of electrical gear movement, and supplemented with control program wherein parametric modeling is realized, is proposed within the scope of work. Testing results of the proposed strategy showed the potential realization of the model which can output recommended parameters of the steering gear elements in semi-automatic mode. Simulation model in the development of electromechanical steering gear allows to save time and total cost of the device by means of possible problems and errors detection at the beginning of the project, reducing working effort of the development. The developed simulation model can be used as universal design tool for electromechanical steering gears.

Model prototype of the steering gear unit was developed using parameters, calculated with the abovementioned strategy; laboratory and natural experiment results confirmed its operability.
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