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Design of a Servo Mechanism for Controlling Missile Fins in Pitch and Yaw Planes

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This paper explores the design and implementation of a servo mechanism utilizing DC electromotors for control of missile fin position. This research is focused on the analysis and optimization of DC electromotors to enhance the performance of servo systems in terms of speed, torque, accuracy and efficiency. Combination of theoretical approaches and experimental test were performed to validate the proposed mechanical construction of a servo mechanism.

Key words: **mechanical design, servo mechanism, brushed DC motor, missile fin control surfaces.**

Introduction

THE missile control servo system plays a crucial role in the guidance, navigation, and stabilization of missiles. It is responsible for precisely directing the missile towards its target, compensating for external factors like wind, and ensuring the missile maintains its intended trajectory.

Missile control systems vary significantly depending on the type of missile (air-to-ground, ground-to-air, anti-ship, etc.) and the level of sophistication required for the mission. They integrate sensors, algorithms, actuators, and communication systems to ensure the missile reaches its target accurately and efficiently.

Air-to-ground missile control systems play a key role in ensuring precise delivery of the missile to its intended ground target. The choice of actuator technology within servo systems significantly impacts missile performance and overall efficiency.

The choice of actuator technology depends on factors such as missile size, intended mission, performance requirements, weight constraints, and cost. Advances in materials discovery and highly sophisticated engineering are increasingly influencing the development of new actuator technologies that provide improved performance characteristics for air-to-ground missile servo systems.

In summary, electromechanical actuators (EMA) are devices that convert electrical energy into mechanical movement. They play a significant role in various applications including aviation, robotics, automotive systems, and industrial mechanics. In the context of air-to-ground missile servo systems, EMAs are used to control missile flight surfaces such as ailerons or canards to achieve precise maneuvering and guidance.

EMAs consist of an electric motor that generates torque, gearbox (if necessary), and a mechanical linkage system that may involve a combination of gears, levers, and other mechanical components in that way to translate the motor's rotational movement into linear or rotational movement of the control surface.

Dc motor selection

For a successful selection of the motor, it is necessary to meet the technical requirements, which will be presented in the Tab. 1

Table 1. Technical requirements

Maximal angular velocity of canards	$\dot{\theta}_{max} = 3\ \text{rad}/s$
Maximal torque	$M_{hmax} = 15\ \text{Nm}$
Maximal deflection angle	$\theta_{max} = \pm 25^{\circ}$

Following the above mentioned requirements and operating conditions in terms of supply voltage and nominal current, it is decided to use Maxon assembly with number 715337 where is included: 1) brushed dc motor (268214), 2) ball bearing screw drive (363970) with reduction 1:1, maximal feed force continuous 386 N, maximal feed velocity 133 mm/s and 3) Encoder MR, Type L, 256 CPT, 3 channels, with line driver.

Main characteristics of the dc motor (268214) are: Nominal voltage 24V, Nominal current 3.47 A, Nominal speed 8050 rpm, Nominal torque 0.856 Nm, Stall torque 1.02Nm.

Eq.1 and Eq.2 represent the gear ratios under the conditions of achieving maximum torque on the steering shaft and achieving maximum angular deflection speed, respectively.

$$i_{Mmax} \geq \frac{M_{hmax}}{\eta_G M_{mmax}} = \frac{15}{0.94 * 1.02} = 15.64 \tag{1}$$

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$$i_{\omega max} \leq \frac{\omega_{mmax}}{\theta_{max}} = \frac{843}{3} = 281 \qquad (2)$$

Demanded total load torque (including static and dynamic load) for our application is 15 Nm. Distance between axis of rotation and axis of motor in our case is 40 mm, so maximal axial force is 375 N, given in Eq. (3).

$$F = \frac{M}{r} = \frac{15}{0.04} = 375N \qquad (3)$$

Eq.4 and Eq.5 represent the torque on the steering shaft and torque of the motor in arbitrary position, respectively

$$M_h = Fr \qquad (4)$$

$$M_m = \frac{Fp\eta}{2\pi} \qquad (5)$$

Torque ratio in arbitrary position is given by Eq.6.

$$i_M = \frac{M_h}{M_m} = \frac{2\pi Fr}{Fp\eta} = \frac{2\pi r}{p\eta} = 136 \qquad (6)$$

where p = 2 mm is thread pitch and $\eta = 94\%$ is maximum efficiency of screw drive.

From Eq.6 can be concluded that condition (1) is satisfied.

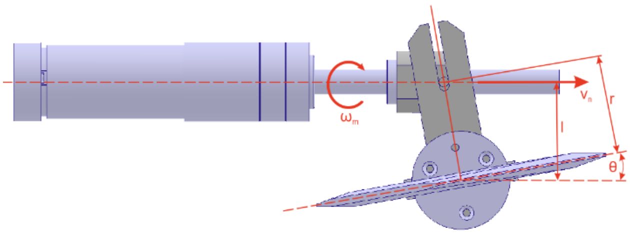

Figure 1. DC motor with its linkage system

Second demand is that system must satisfy angular velocity of 3rad/s.

Pitch thread is denoted as p, axial velocity of nut is V_n, mean thread diameter $2r_n$.

Therefore

$$\frac{V_n}{r_n \omega_m} = tan\alpha = \frac{p}{2\pi r_n} \qquad (7)$$

$$V_n = \frac{p\omega_m}{2\pi} \qquad (8)$$

From Fig.1 it can be seen

$$V_n cos\theta = r\dot{\theta} \qquad (9)$$

$$\frac{p\omega_m}{2\pi} cos\theta = r\dot{\theta} \qquad (10)$$

$$\dot{\theta} = \frac{pcos\theta}{2\pi r}\omega_m \qquad (11)$$

$$\frac{\omega_{canard}}{\omega_m} = \frac{\dot{\theta}}{\omega_m} \qquad (12)$$

$$i_\omega = \frac{\omega_{canard}}{\omega_m} = \frac{pcos\theta}{2\pi r} = 125 \qquad (13)$$

Eq.13 represents the angular velocity ratio in arbitrary position where can be seen that condition (2) is also satisfied.

Servo system design and analysis

For the development of an air-to-ground guided missile, a servo system was developed for steering the missile along the pitch and yaw channels.

The simplified explanation of the servo mechanism's operation shown on Fig.1 involves a DC motor delivering torque through the rotation of a threaded spindle. This causes linear motion of the nut, which is transmitted through a system of levers to rotate the shaft to which the control surface, in our case the rudder, is attached. The Fig.2 to Fig.5 will illustrate the initial and final positions of the servo mechanism for a 25° angle in the positive direction.

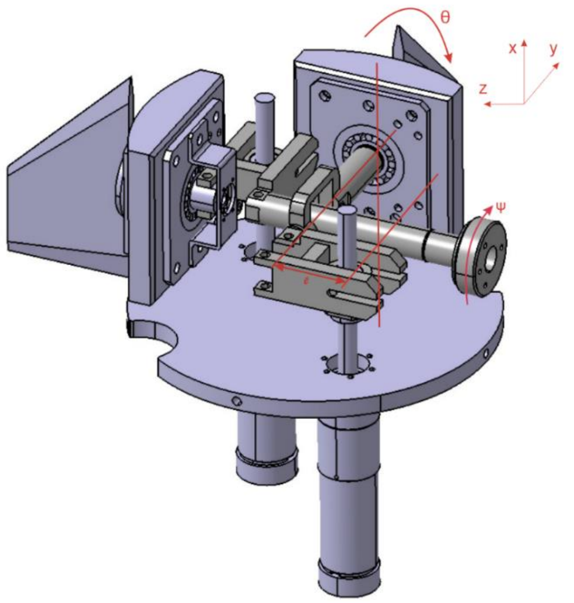

Figure 2. Air-to Surface missile Servo

For the displayed position of the servo mechanism in the image, we will adopt a coordinate system where the x-axis is along the direction of missile movement, the y-axis is the axis around which pitching occurs, and the z-axis is for yawing. Positive directions for rotations around these axes will follow the right-hand rule convention. Both direct current motors with threaded spindles and nuts drive both axes and are positioned along the x-axis, corresponding to the missile's direction of travel. The initial or zero position of the servo mechanism is depicted in the image, where all angles and linear displacements are zero.

The servo analysis is divided into two parts for easier explanation.

Kinematics

Missile servo system kinematics involves the study of motion and geometry concerning the control surfaces of a missile. It analyzes how actuators, often driven by DC motors and threaded spindles, translate rotational motion into linear movement of control surfaces like fins or canards. By understanding this kinematics, engineers ensure precise adjustments of the missile's trajectory for accurate targeting and maneuverability during flight, enhancing overall operational effectiveness and mission success rates.

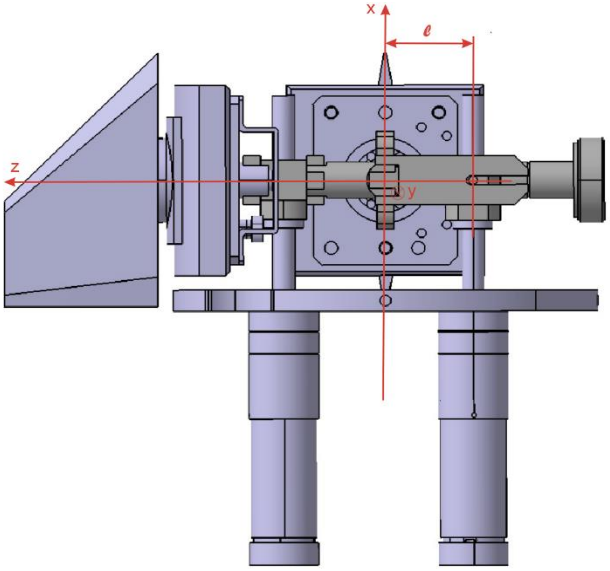

Figure 3. Servo initial position

The first fundamental kinematic equation of motion for a servo - mechanism shown on Fig.3 is:

$$x = ltg\theta \tag{14}$$

The Eq.14 describes the relationship between the vertical linear displacement of the nut, marked in Fig.3 as x, and the rotational angle of the shaft with the fin, denoted as θ.

$$x = ltg\theta \; / * \frac{d}{dt} \tag{15}$$

$$\frac{dx}{dt} = l\frac{d(tg\theta)}{dt}\frac{d\theta}{d\theta} \tag{16}$$

$$x = l\frac{d(tg\theta)}{d\theta}\frac{d\theta}{dt} \tag{17}$$

$$x = l\frac{1}{cos^2\theta}\dot{\theta} \tag{18}$$

$$\dot{\theta} = \frac{cos^2\theta}{l}\dot{x} \tag{19}$$

By finding the first derivative of the previous equation, it is obtained the expression that gives us the dependence of the angular velocity $\dot{\theta}$ of the shaft on the linear velocity of the nut $\dot{x}$.

The dependence between the angular velocity $\dot{\theta}$ and the linear velocity $\dot{x}$ is indeed nonlinear. This nonlinearity arises because $\dot{\theta}$ depends on the cosine squared of the angle θ, which varies with the position of the nut x. As θ changes, the relationship between $\dot{\theta}$ and $\dot{x}$ is not a simple linear proportionality but rather a function that involves trigonometric terms and the mechanical linkage geometry.

In practical terms, this means that changes in the linear velocity $\dot{x}$ do not result in directly proportional changes in the angular velocity $\dot{\theta}$. The exact relationship depends on the specific geometry and kinematics of the servo mechanism, including factors such as the length l and the angle θ at any given time.

Using the equation, we obtained earlier:

$$\dot{\theta} = \frac{cos^2\theta\dot{x}}{l} \tag{20}$$

Where $l = 40$ mm and $\dot{x} = 133\ mm/s$, for the given range from -25° to $+25^{\circ}$, the angular velocity $\dot{\theta}$ will be approximately 2.7 rad/s in both cases, with different signs due to the opposite direction of the angle θ, and for 0 degree the value of angular velocity will be around 3.3 rad/s.

The second fundamental kinematic equation of motion is Eq.21, where r represents the shortest distance from the point where the force acts to the axis of rotation of the shaft. In this context, r represents the lever arm of the force.

$$r = \frac{l}{cos\theta} \tag{21}$$

By taking the first derivative with respect to time, we obtain the following expression:

$$\frac{dr}{dt} = \frac{d}{dt}\left(\frac{l}{cos\theta}\right) \tag{22}$$

$$\frac{dr}{dt} = l\frac{d}{dt}\left(\frac{1}{cos\theta}\right) \tag{23}$$

$$\frac{dr}{dt} = l\left(\frac{0 * cos\theta - 1 * (-sin\theta)}{cos^2\theta}\right) \tag{24}$$

$$\frac{dr}{dt} = l\frac{sin^2\theta}{cos^2\theta}\frac{d\theta}{dt} \tag{25}$$

$$\dot{r} = l\frac{sin\theta}{cos^2\theta}\dot{\theta} \tag{26}$$

which Eq.26 represents the relative velocity of the crank-shaft along the fork groove.

$$\Delta r = l\frac{1 - cos\theta}{cos\theta} \tag{27}$$

Eq.27 represents distance of crankshaft from initial position to new position depended of angle θ along the fork groove.

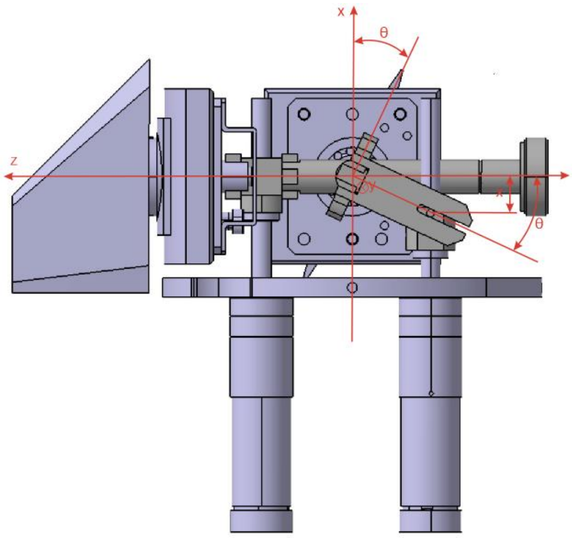

Figure 4. Angles and displacements on servo with aileron deflection of 25°

Dynamics

Missile servo system dynamics examines the complex interactions between forces, motion, and control inputs within the system. It focuses on how the servo actuators respond to external commands, environmental factors, and the missile's own aerodynamic forces during flight. Engineers analyze these dynamics to optimize responsiveness, stability, and accuracy of the missile's control surfaces, ensuring effective navigation and targeting capabilities in varying operational conditions.

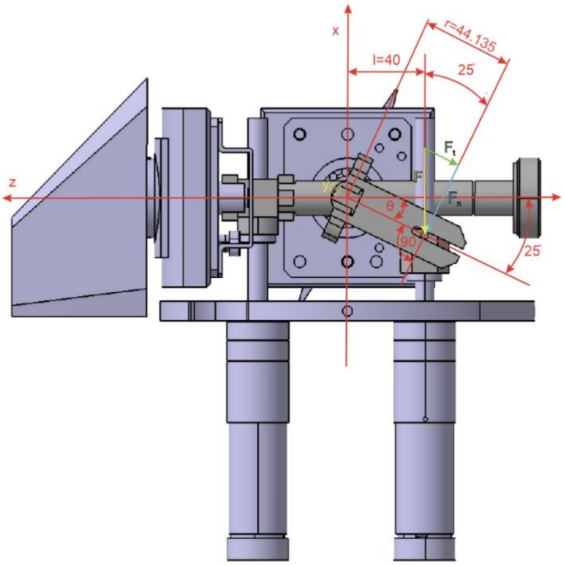

Figure 5. Forces applied on servo with aileron deflection of 25°

In the initial position, the torque equation can be written in the form of

$$M = Fl \tag{28}$$

It is interesting to notice that the torque remains the same regardless of the position of the mechanism, which is also expressed by the equation

$$M = F_N r = F\cos\theta \frac{l}{\cos\theta} = Fl \tag{29}$$

Conclusion

This study has investigated the design and implementation of a servo mechanism utilizing DC electromotors for the precise control of missile fin positions. Through a combination of theoretical analysis and experimental validation, we have demonstrated significant advancements in optimizing DC electromotors to achieve enhanced performance metrics such as speed, torque, accuracy, and efficiency. The findings underscore the effectiveness of our mechanical design in improving servo system capabilities, particularly in critical applications like missile fin control surfaces. Future research could explore further refinements in motor design and control algorithms to continually advance the performance and reliability of servo mechanisms in demanding operational environments.

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Dizajn servo mehanizma za upravljanje krilima rakete u ravni propinjanja i skretanja

Ovaj rad istražuje dizajn i implementaciju servo mehanizma koji koristi DC elektromotore za kontrolu položaja krila rakete. Ovo istraživanje je fokusirano na analizu i optimizaciju DC elektromotora za poboljšanje performansi servo sistema u smislu brzine, obrtnog momenta, tačnosti i efikasnosti. Za validaciju predložene mehaničke konstrukcije servo mehanizma izvršena je kombinacija teorijskih pristupa i eksperimentalnog ispitivanja.

Ključne reči: **mehanički dizajn, servo mehanizam, jednosmerni motor sa četkicama, upravljačke površine krila rakete.**