DETERMINING THE REQUIRED KINEMATIC CHARACTERISTICS OF AIRCRAFT GUN-MOUNT MOTION FOR ACTUATOR MOTOR SELECTION

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ABSTRACT

Based on the model of the GSh-301 gun mounted on a two-degree-of-freedom rotating gun mount on an aircraft, the loads acting on the mount are determined, including firing loads, aerodynamic loads, gravitational loads, inertial loads, and friction loads in the transmission components during firing. Given the specified combat mission, the minimum flight altitude and aircraft speed are identified as the basis for determining the required angular velocity and angular acceleration characteristics of the gun mount, which is designed to engage fixed ground targets. These required kinematic parameters provide the foundation for determining the dynamic characteristics of the actuator motors in the automatic weapon-control system.

Keywords: *GSh-301 gun; firing loads; aerodynamic loads; angular velocity; angular acceleration; actuator motors.*

1. INTRODUCTION

Aircraft-mounted automatic guns play a crucial role in modern airborne weapon systems, particularly in close air support and ground-attack missions that require high firing accuracy and rapid response. These weapons are typically integrated into automatic weapon-control systems, in which the gun mount serves as a key mechanical subsystem responsible for orienting the gun in both the vertical and horizontal planes. The dynamic performance of the gun mount directly affects the accuracy, responsiveness, and reliability of the entire weapon system.

During firing and target tracking, the gun mount is subjected to a combination of complex loads, including firing-induced loads, aerodynamic loads, gravitational loads, inertial loads, and frictional torques in the transmission mechanisms. Previous studies have demonstrated that these loads can significantly influence the dynamic behavior and stability of aircraft gun mounts, especially under high-speed flight conditions. Dynamic analyses of airborne gun installations indicate that aerodynamic torque and firing disturbances are dominant factors affecting mount motion at large deflection angles and high aircraft velocities [1, 2].

Most aircraft gun mounts are designed as two-degree-of-freedom rotational systems, driven by independent actuator motors in the azimuth and elevation axes. Accurate determination of the required angular velocity and angular acceleration of these axes is essential for ensuring effective target tracking. Kim et al. [3] developed a dynamic model of a two-axis gun turret and showed that actuator limitations in angular velocity and acceleration lead to degraded tracking performance. Similarly, Zhang and Wang [4] emphasized that the most demanding operating conditions for airborne gun mounts occur during rapid angular repositioning combined with high-speed flight, which imposes stringent requirements on the drive system.

In addition to inertial and firing-related effects, aerodynamic loads acting on externally mounted guns and their support structures contribute significantly to the total driving torque. Studies on aerodynamic torque acting on aircraft-mounted weapons have shown that these loads increase nonlinearly with aircraft velocity and exposed surface area, and therefore cannot be neglected in the design of high-speed airborne weapon systems [5].

Cook [6] further highlighted the strong coupling between flight dynamics and weapon dynamics, indicating that gun-mount kinematic requirements must be determined in conjunction with aircraft flight conditions.

From the perspective of actuator design, several researchers have proposed methodologies for sizing actuator motors based on dynamic and energy-related requirements rather than nominal static loads. Wang and Sun [7] introduced an actuator sizing approach for high-dynamic weapon positioning systems that accounts for angular velocity, angular acceleration, and power constraints. Gonzalez and Alvarez [8] demonstrated that energy-based motor selection provides better performance margins for fast-tracking systems. For military applications, Zhou and Wang [9] pointed out that actuator motors must be selected to withstand the most unfavorable operating conditions, rather than average mission profiles.

For aircraft engaging fixed ground targets, additional constraints arise from flight safety considerations. The minimum allowable flight altitude and corresponding aircraft velocity are limited by the danger of rebounding fragments, which directly affects the required motion of the gun mount during target tracking and disengagement maneuvers. However, existing studies often focus on structural strength or control algorithms, while the influence of mission-specific constraints on the required kinematic characteristics of the gun mount has received less attention.

Motivated by these considerations, this paper proposes a method for determining the required kinematic characteristics of an aircraft gun mount based on comprehensive load analysis and realistic combat-mission constraints. Using the GSh-301 aircraft gun mounted on a two-degree-of-freedom rotating gun mount as a representative example, the acting loads are evaluated and the required angular velocities and angular accelerations are determined for the most unfavorable operating conditions. The obtained kinematic requirements provide a practical basis for preliminary actuator motor selection in automatic aircraft weapon-control systems.

2. METHOD FOR CALCULATING LOADS AND DETERMINING THE REQUIRED KINEMATIC CHARACTERISTICS OF THE GUN MOUNT

2.1. Computational model

The gun mount is typically designed to allow the cannon to rotate with two degrees of freedom: in the vertical plane and in the horizontal plane, driven by two corresponding actuator mechanisms. Figure 1 shows the gun-mount model designed for installation on an aircraft to engage ground targets.
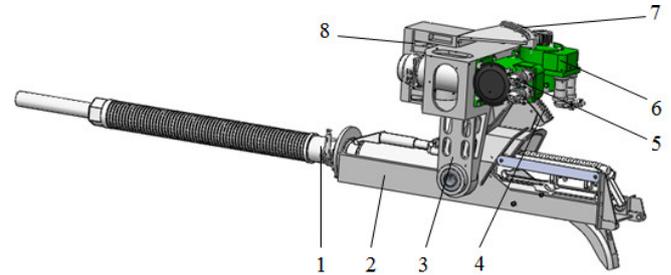

Figure 1. Gun-mount model installed on an aircraft

1 - Cannon; 2 - Gun mount; 3 - Rotating base; 4 - Elevation gear arc; 4 - Elevation drive mechanism; 5 - Azimuth drive mechanism; 6 - Azimuth gear arc; 6 - Fixed base

2.2. Calculation of loads acting on the gun mount

The loads acting on the gun mount include the firing load M_{fl}, the aerodynamic load M_{al}, the gravitational load of the gun M_q, the inertial load M_{il}, and the friction load in the transmission components M_{fl}. The firing load M_{fl} may be neglected in the calculations because, during the gun-mount design, the offset between the gun bore axis and the rotation axes is typically assumed to be zero. The inertial load M_{il} is significantly smaller than the other loads and can therefore be omitted from the total load.

The aerodynamic load M_{al} is a distributed load. However, it can be replaced by an equivalent force applied at the center of pressure of the airflow acting on the "exposed" part of the system in the airstream. Figure 2 shows the computational diagram for determining the aerodynamic load acting on a bar of area F, with the principal axis (Y-axis) and the dynamic axis (Z-axis).
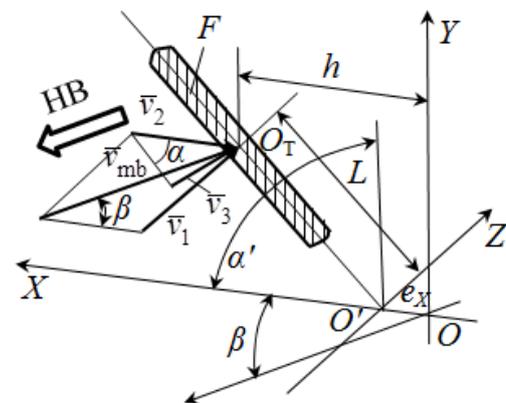

Figure 2. Diagram for calculating aerodynamic load

Based on dividing the gun barrel into sectional areas with corresponding moment arms, the aerodynamic

force formula is used to determine the moments acting on the "exposed" part of the barrel relative to the principal axis Y (M_{alY}) and the dynamic axis Z (M_{alZ}), depending on the deviation angles α and β [1]:

$$M_{alY} = c_{X1} \frac{\rho v_{mb}^2}{2} \left[\sum_i F_i(e_X + L_i \cos\alpha) \right] \sin^2\beta \qquad (1)$$

$$M_{alZ} = c_{X3} \frac{\rho v_{mb}^2}{2} (\sum_i F_i L_i) \cos^2\beta \sin^2\alpha \qquad (2)$$

where c_{X1} and c_{X3} are the frontal drag coefficients of the barrel in the airflow; ρ is the air density; v_{mb} is the aircraft velocity; F_i is the sectional area of each longitudinal segment of the gun barrel; L_i are the corresponding moment arms; β and α are the deviation angles of the gun in the horizontal and vertical planes, respectively.

The gravitational load M_q is calculated as the sum of the component loads acting on each element of the system. For the configuration in which the gun mount is installed on an aircraft to engage ground targets, the moment M_{qZ} with respect to the dynamic axis is determined using the following formula:

$$M_{qZ} = \eta \sum_{i=1} [G_i l_i \cos(\alpha - \alpha_i^0)] \qquad (3)$$

where η is the aircraft overload factor; l_i is the distance from the center of mass of element i to the dynamic axis of the gun mount; α is the deviation angle of the gun from the neutral position; φ_i is the angular position of the center of mass of element i when $\alpha = 0$.

The friction-load moment M_{fl} in the system's kinematic joints and in the drive mechanism generally has a relatively small magnitude:

$$M_{fl} = 0.1 M_\Sigma = 0.1(M_{al} + M_q) \qquad (4)$$

2.3. Determination of the minimum altitude Hmin and aircraft velocity vmb in the calculation mode
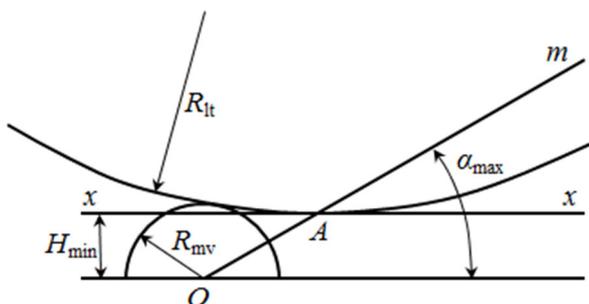

Figure 3. Diagram for calculating H_{min} and v_{mb} the calculation mode

When an aircraft engages ground targets, it is necessary to ensure the aircraft's safety from fragments that may rebound upward. Assuming the gun is depressed to its maximum angle α_{max}, then for each minimum altitude H_{min}, the aircraft must maintain a certain velocity v_{mb} to escape the hazardous area. Figure 3 illustrates the geometric method used to determine the minimum altitude H_{min} and the required aircraft velocity v_{mb}.

The fragment rebound zone is modeled as a hemisphere with center O and radius R_{mv}. From point O, a line Om is drawn, forming the angle α_{max} with the horizontal plane. For each minimum altitude H_{min}, a line xx parallel to the horizontal plane is drawn, intersecting the inclined line Om at point A. A circle of radius R_{lt} is then drawn so that it is tangent to both the circle centered at O and the line xx at point A. The required aircraft velocity at that condition is: $v_{mb} = R_{lt}\eta g$.

By analyzing various values of H_{min} and v_{mb}, the most critical case can be determined, thereby establishing the maximum required angular velocity and angular acceleration about the dynamic axis of the gun mount.

2.4. Calculation of the required kinematic parameters of the gun mount

The required angular velocities about the principal axis and the dynamic axis are determined as follows [10]:

$$\dot{\beta}_{max} = \frac{v_{mb\,max}}{p_{Y\,max}} \sin^2 \beta_{max};$$
$$\dot{\alpha}_{max} = \frac{v_{mb\,max}}{H_{min}} \sin^2 \alpha_{max} \qquad (5)$$

where p_Y is the distance between the relative motion trajectory of the target and the dynamic axis Y, determined with consideration of the fragment rebound zone.

The required angular acceleration is determined from the following formula [10]:

$$\ddot{\beta}_{max} = (\frac{v_{mb\,max}}{p_{Y\,max}})^2 \sin^2 \beta_{max} \sin 2\beta_{max};$$
$$\ddot{\alpha}_{max} = (\frac{v_{mb\,max}}{H_{min}})^2 \sin^2 \alpha_{max} \sin 2\alpha_{max} \qquad (6)$$

3. CALCULATION OF THE REQUIRED PARAMETERS AND SELECTION OF THE ACTUATOR MOTOR

An actuator motor is considered suitable when its dynamic characteristics match the corresponding required characteristics [11, 12]:

$$N = N_{req}; \quad P = P_{req}; \quad M = M_{req} \qquad (7)$$

where N is the motor power; P is the motor thrust; M is the torque.

The dynamic characteristics in the first two equations are those of the motor itself and do not depend on the choice of gearbox. Therefore, they are used for preliminary motor selection. The dynamic characteristic in the third equation is determined not only by the motor parameters but also by the gearbox. Here, only the problem of motor selection based on energy-related characteristics is considered.

Required dynamic characteristics of the drive mechanism [11, 12]:

$$N_{req\max}^{OY} = M_{req\max}^{OY}\dot{\beta}_{\max} \; ; \quad P_{req\max}^{OY} = M_{req\max}^{OY}\ddot{\beta}_{\max} \; ; \quad (8)$$

$$N_{req\max}^{OZ} = M_{req\max}^{OZ}\dot{\alpha}_{\max} \; ; \quad P_{req\max}^{OZ} = M_{req\max}^{OZ}\ddot{\alpha}_{\max} \; . \quad (9)$$

When selecting a motor for both drive mechanisms, the required values are taken as the maximum values for each characteristic:

$$N_{req\max} = \max(N_{req\max}^{OZ}, N_{req\max}^{OY}) \; ;$$
$$P_{req\max} = \max(P_{req\max}^{OZ}, P_{req\max}^{OY}) \; . \quad (10)$$

Using the maximum values $N_{req\max}$ and $P_{req\max}$ obtained from expression (10), a preliminary selection of an actuator motor that satisfies the energy-related requirements can be made. To accurately determine the suitability of the selected motor, verification calculations must be performed to ensure it meets the torque-related requirements.

4. CALCULATION EXAMPLE

In the SolidWorks environment, a model of the gun mount made of 35ХГСЛ steel with a density of 7800kg/m³ was constructed and equipped with the gun ГШ-301. The gun mount features a maximum elevation angle of $\alpha = 30°$ in the vertical plane, a corresponding traverse angle in the horizontal plane $\beta = \pm 15°$ and an axial misalignment of $e_X = 10$cm. The mount is installed on the SU-27 attack aircraft, which operates at a maximum flight velocity of $v_{mb\max} = 300$m/s.

The geometric dimensions of the airflow-exposed "protruding" sections of the system are as follows: $F_1 = 0.07$m², $F_2 = 0.07$m², $F_3 = 0.05$m², $L_1 = 1.402$m, $L_2 = 0.845$m, and $L_3 = 0.205$m. The overload factor η is assumed to be 1 under conditions of target tracking, horizontal-flight attack maneuvers, and disengagement from the combat loop.

The load diagrams acting on the gun mount are presented in Figure 4. The minimum altitude is $H_{\min} = 180$m at $v_{mb} = 300$m/s. The maximum values of the required kinematic characteristics of the gun mount were obtained as follows:

$$\dot{\beta}_{\max} = 0.45 \text{ rad/s}; \; \ddot{\beta}_{\max} = 1.5 \text{ rad/s}^2;$$

$$\dot{\alpha}_{\max} = 0.42 \text{ rad/s}; \; \ddot{\alpha}_{\max} = 0.6 \text{ rad/s}^2.$$

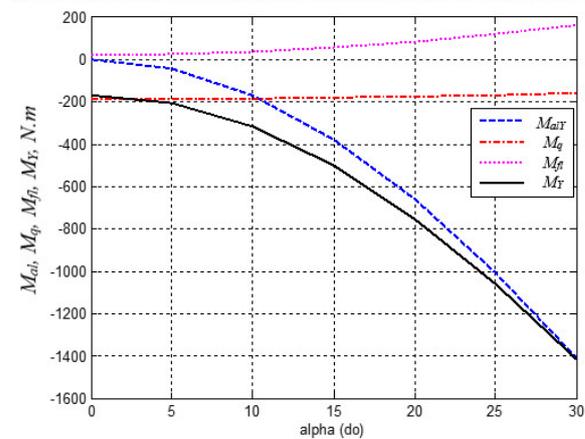The maximum required torque of the drive mechanism, reached at $\alpha = 30°$:

$$M_{req\max}^{OZ} = 1420 \text{ N.m}; \; M_{req\max}^{OY} = 393 \text{ N.m}.$$

The maximum required motor power and the maximum power slew-rate are:

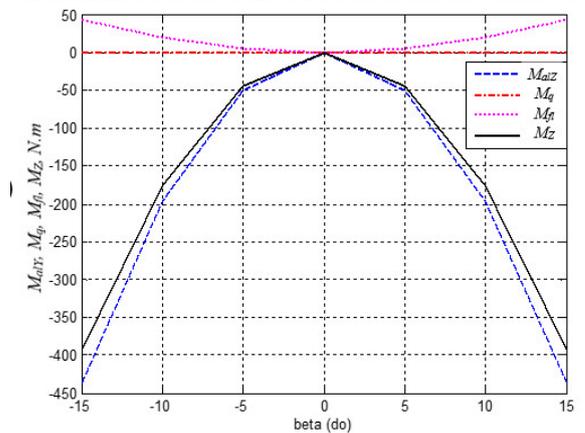$$N_{req\max} = \max(N_{req\max}^{OZ}, N_{req\max}^{OY}) = 596 \text{ W};$$

$$P_{req\max} = \max(P_{req\max}^{OZ}, P_{req\max}^{OY}) = 851 \text{ W/s}.$$

a)

b)

Figure 4. Loads acting on the drive mechanism in the vertical plane (a) and in the horizontal plane (b)

With the calculated results, selecting the МУ-550ТУ motor with its rated characteristics of $N_{motor} = 1840$W and $P_{motor} = 3200$W/s would fully ensure the ability to rotate the gun and track the target for engagement even under the most demanding operating conditions.

5. CONCLUSION

This study has presented a systematic approach for determining the required kinematic characteristics of an aircraft gun mount intended for engaging fixed ground targets under realistic combat conditions. Based on a comprehensive load analysis of a two-degree-of-freedom gun mount equipped with the GSh-301 aircraft gun, the main load components acting on the mount - including aerodynamic loads, gravitational loads, and frictional loads - were identified and quantitatively evaluated. The analysis shows that, under high-speed flight conditions, aerodynamic and gravitational moments dominate the total load acting on the drive mechanisms and therefore must be explicitly considered in the design process.

By incorporating mission-specific constraints such as the minimum allowable flight altitude and corresponding aircraft velocity required to ensure safety from fragment rebound, the most unfavorable operating conditions of the gun mount were identified. On this basis, the maximum required angular velocities and angular accelerations about both the elevation and azimuth axes were determined. These kinematic requirements provide a direct and practical foundation for evaluating the energy-related characteristics of the actuator motors, including required power and power slew-rate.

The proposed approach can be applied at the early design stage of aircraft weapon-control systems to support rational actuator selection and improve overall system performance. Future work will focus on extending the model to include firing-induced disturbances and control-system dynamics, as well as experimental validation of the proposed method under representative operating conditions.

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