Assessment of Mechanical Properties of Helicopter Cyclic Pitch Control Stick

Xu Fan
Chinese Flight Test Establishment, Xi'an 710000, Shaanxi, China
Corresponding author: Xu Fan (e-mail: douding20261227@163.com)

ABSTRACT The mechanical characteristics of a helicopter cyclic pitch control stick play a critical role in flight control performance and handling-quality evaluation. Existing assessment approaches mainly rely on force-gradient measurements and lack comprehensive characterization of control response behavior. This study proposes an integrated evaluation framework combining quantitative measurement and qualitative flight assessment for cyclic pitch control systems. Quantitative evaluation includes control-force and control-displacement characterization based on control-envelope modeling, highresolution force–displacement data acquisition, and dynamic response analysis. Qualitative evaluation incorporates pilot assessments of stick centering, jump behavior, and dynamic control characteristics under representative flight conditions. Experimental investigations conducted on a civilian light helicopter demonstrate that the measured controlforce gradients, operating strokes, trim-control displacement bands, and damping characteristics satisfy handlingquality requirements. The results further show that longitudinal and lateral control responses exhibit distinct forcedisplacement characteristics that support ergonomic operation and stable flight control. By establishing the relationship between control inputs, dynamic response behavior, and pilot perception, the proposed framework provides a systematic methodology for flight-control evaluation. The study offers an engineering-oriented approach for assessing human–machine interaction, control-signal responsiveness, and dynamic performance in helicopter flightcontrol systems.

INDEX TERMS flight control system, control signal response, dynamic characteristics, handling quality assessment

I. INTRODUCTION

CYCLIC pitch control stick mechanics assessment is an indispensable part of the overall helicopter handling quality assessment. Poor mechanics can mask otherwise good handling qualities and even render the helicopter unable to perform its mission. Taking stable level flight as an example, if the stick force is too high, preventing the pilot from making finetuning adjustments to the attitude, it increases the difficulty of maintaining speed and affects the accuracy of speed maintenance; if the stick force is too low, gusts can induce unintentional control inputs from the pilot, similarly increasing the difficulty of maintaining speed and affecting the stability of level flight. As part of the helicopter handling quality assessment, the mechanics assessment evaluates how the control system and its high-strength carbon fiber woven reinforcements interact to determine the extent to which these integrated components affect the helicopter's mission objectives. This analysis ensures that the mechanical precision of the flight controls and the structural integrity of the composite work in unison to meet rigorous performance standards.

II. EVALUATION METHODS

The mechanical characteristics assessment of helicopter cyclic stick includes both quantitative and qualitative aspects. Quantitative assessment includes control force and control travel. For irreversible control systems, control force and control travel can be tested and assessed on the ground; however, the cyclic stick of reversible control systems is subject to variable loads from the rotor cycle, which change with the flight state [1] . Since it is impossible to simulate aerodynamic feedback on the ground, the quantitative assessment of the mechanical characteristics of the control device must be carried out in the air, while characteristics unrelated to aerodynamic loads can be assessed on the ground, such as control travel.

The main content of qualitative evaluation is the test pilot's assessment of the impact of the cyclic pitch stick's mechanical characteristics on the performance of a specific mission. Whether it is an irreversible or reversible control system, qualitative evaluation must be conducted in flight. The test pilot's evaluation of the cyclic pitch stick's mechanical characteristics largely depends on the magnitude of the control amplitude and control force when performing a specific mission or maneuver, that is, the "feel" of operating the helicopter. Although this "feel" is difficult to quantify, it is closely related to the quantitative evaluation of system characteristics [2].

Deficiencies identified through quantitative ground assessments do not necessarily hinder helicopter performance during missions; qualitative assessments by test pilots are paramount. A comprehensive application of both quantitative and qualitative assessments, incorporating the structural analysis of highperformance technical materials used in component reinforcement, yields scientific and applicationoriented evaluations of the cyclic pitch control's mechanical properties. This integrated approach ensures that the interlaced fiber integrity and mechanical responsiveness are evaluated as a unified system to guarantee optimal flight performance.

A. QUANTITATIVE ASSESSMENT

1) Operating Stroke

The measurement of the cyclic pitch control stick's travel is completed on the ground. The helicopter does not require ground operation; it only needs to be connected to ground power and hydraulic systems to ensure their proper functioning [3].

With the collective pitch stick fully extended and the cyclic pitch stick and rudder pedals in a neutral position, engage the trim system and disengage the cyclic pitch stick friction lock. Establish two distinct reference points in the cockpit, parallel to the helicopter's longitudinal and lateral directions, respectively. Measure the distances between the cyclic pitch stick and these two reference points. Using a mathematical model, convert the measurement data to a Cartesian coordinate system and plot the control envelope. The cyclic pitch stick's movement includes two degrees of freedom: longitudinal and lateral. First, measure the position coordinates of the cyclic pitch stick's longitudinal limit travel, then measure the lateral limit travel coordinates at every 10% of the longitudinal position. Note that the pilot's leg interference with the cyclic pitch stick should also be included in the control envelope [4].

Taking the left-hand drive cycle pitch lever as an example, any lever position M (δ_{lat}, δ_{long}) can be transformed into a plane rectangular coordinate system with the neutral position as the origin through the mathematical model shown in Figure 1. When M is located in the first quadrant to the fourth quadrant, the analytical equations of the horizontal and vertical coordinates are shown in equations (1) to (4).

When M is in the first quadrant,

$$\begin{aligned} x &= \delta_{lat}\cos\angle MAO - |AO|, \quad y = \delta_{lat}\sin\angle MAO, \\ \angle MAO &= \angle BAO - \angle BAM \\ &= \arccos\frac{|AB|^2+|AO|^2-|BO|^2}{2|AB||AO|} - \arccos\frac{|AB|^2+\delta_{lat}^2-\delta_{long}^2}{2|AB|\delta_{lat}}. \end{aligned} \tag{1}$$

When M is located in the second quadrant,

$$\begin{aligned} x &= w - \delta_{lat}\cos\angle MAO, \quad y = \delta_{lat}\sin\angle MAO, \\ \angle MAO &= \angle BAO - \angle BAM \\ &= \arccos\frac{|AB|^2+|AO|^2-|BO|^2}{2|AB||AO|} - \arccos\frac{|AB|^2+\delta_{lat}^2-\delta_{long}^2}{2|AB|\delta_{lat}}. \end{aligned} \tag{2}$$

When M is located in the third quadrant,

$$\begin{aligned} x &= w - \delta_{lat}\cos\angle MAO, \quad y = -\delta_{lat}\sin\angle MAO, \\ \angle MAO &= \angle BAM - \angle BAO \\ &= \arccos\frac{|AB|^2+\delta_{lat}^2-\delta_{long}^2}{2|AB|\delta_{lat}} - \arccos\frac{|AB|^2+|AO|^2-|BO|^2}{2|AB||AO|}. \end{aligned} \tag{3}$$

When M is located in the fourth quadrant,

$$\begin{aligned} x &= \delta_{lat}\cos\angle MAO - |AO|, \quad y = -\delta_{lat}\sin\angle MAO, \\ \angle MAO &= \angle BAM - \angle BAO \\ &= \arccos\frac{|AB|^2+\delta_{lat}^2-\delta_{long}^2}{2|AB|\delta_{lat}} - \arccos\frac{|AB|^2+|AO|^2-|BO|^2}{2|AB||AO|}. \end{aligned} \tag{4}$$

2) Control Force

For irreversible control systems, the longitudinal and lateral mechanical properties of the cyclic stick can be measured from the ground. The helicopter does not require ground operation; only ground power and hydraulic connections are needed to ensure their proper functioning. With the collective pitch lever fully extended and the cyclic stick and foot pedals in a neutral position, the trim system is activated, and the friction lock on the cyclic stick is released. Using a handheld force gauge, the cyclic stick is slowly and uniformly pushed (or pulled) forward from its neutral position until it reaches its travel limit. Then, the lever is slowly and uniformly returned to the neutral position. To ensure data precision without interrupting the continuous motion, an integrated data acquisition system or high-speed video recording is employed to capture the realtime relationship between force and displacement, rather than manual point-by-point recording [5]. The same method is used to push (or pull) the cyclic stick backward, left, and right to complete the measurements. The entire process must be completed in one continuous motion at a steady, low velocity (approximately 1-2 cm/s). Any discontinuous or uneven movements will increase the error in lever force measurement due to breakout friction and inertia effects; therefore, any interruption necessitates re-measurement. The use of a digital force gauge with continuous peak-hold and data-logging capabilities is essential to maintain this uniformity while gathering high-resolution data points.

For reversible control systems, stick force characteristics assessment can only be conducted in flight. In-flight assessment is performed with the cyclic pitch stick trim position as the reference point; deviations from the trim position cause changes in aerodynamic loads, therefore the stick displacement from the trim position cannot be too large. Factors such as atmospheric conditions, vibration levels, and flight safety make it difficult to accurately measure and record stick force data in flight. Based on the measurement data, the relative

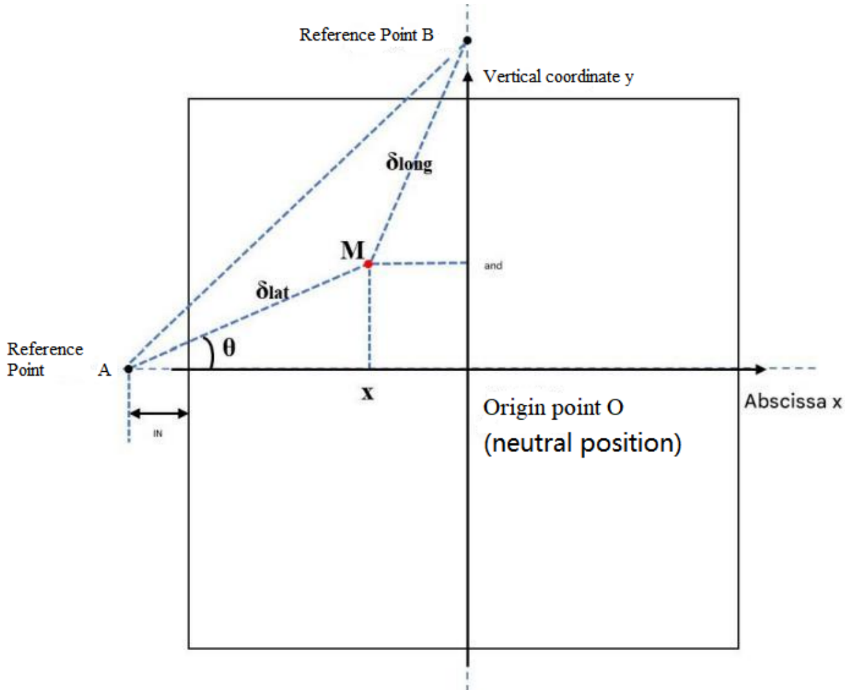


FIGURE 1. Mathematical model of left-hand drive cycle pitch position

relationship between stick force and stick displacement is analyzed, and test results for idle travel, starting force, and trim control displacement band are presented.

B. QUALITATIVE ASSESSMENT

The main items of the qualitative assessment include three aspects: Slack stick, jump pole, and dynamic characteristics. Each in-flight qualitative assessment requires recording the initial trim status data of the helicopter and control system.

1) Stick Loosening

Displace the cyclic pitch control stick from the trim position, then release the stick and observe whether it accurately returns to the initial trim position under the action of the trim spring. The specific operating procedure is as follows: Turn off the stability augmentation system, turn on the trim system, and release the cyclic pitch control stick friction lock. The helicopter should then fly stably at a typical speed at a safe altitude. Press and release the cyclic pitch control stick trim button, then push the stick forward a certain distance, observing and recording the trajectory of the cyclic pitch control stick and the helicopter's response. Use the same method to move the stick backward, left, and right respectively to complete the stick neutrality assessment in mid-air.

Qualitative assessment of the slack stick requires determining whether the cyclic stick returned to the neutral position, whether it was absolute centering or positive centering, and evaluating the centering characteristics. In this assessment flight, the control stick returned to positive centering due to spring preload and friction, approximately 2-3 cm from the operating trim position.

2) Stick Jump

Move the periodic pitch lever away from the balancing position by a certain distance, then press the balancing release button and observe the movement trajectory of the periodic pitch lever and the final balancing position. The specific operating method is as follows:

With the stability augmentation system off, the trim system on, and the cyclic pitch control stick friction lock released, the helicopter maintains stable level flight at a safe altitude and typical speed. Press the trim button while simultaneously pushing the stick forward a certain distance; release the trim button after stabilization [6]. Then return the stick to the initial trim position, press and release the trim button again, and observe and record the trajectory of the cyclic pitch control stick and the helicopter's response. Use the same method to move the stick backward, left, and right respectively to complete the in-flight assessment of the jump control. Qualitative evaluation of the jump stick requires providing the overshoot of the control stick after strong control and pressing the trim button again. Excessive overshoot causes the helicopter to produce unexpected control responses. In this flight test, strong control stick control of 2cm forward and backward resulted in an overshoot of 2-3cm after pressing the trim button, while strong control stick control of 2cm to the left and right resulted in an overshoot of approximately 1-2cm. The helicopter's in-flight response was as expected, and no major adverse reactions occurred.

3) Dynamic Characteristics

Simulate step-input excitations of varying amplitudes by applying a calibrated displacement to the cyclic stick and releasing it instantaneously to observe the free-oscillation decay trajectory . The specific operating procedure is as follows: Turn off the stability augmentation system, turn on the trim system, and release the cyclic stick friction lock. After the helicopter reaches a steady flight state, the pilot applies a specific displacement pulse; the resulting oscillations are recorded via onboard sensors to calculate the logarithmic decrement and damping ratio. Another pilot should observe the helicopter's response and be prepared to intervene to prevent any divergent helicopter response. Move the lever forward, backward, left, and right respectively, evaluating the magnitude of the lever force and the ease of operation.

Quantitative and qualitative evaluation of dynamic response characteristics includes assessing the frequency and decay envelope of the helicopter control stick after excitation 6. This involves checking the damping ratio ($\varsigma\varsigma$) of the control stick to ensure it is sufficiently damped to prevent pilot-induced oscillations (PIO). To conform to ergonomic design, the mechanical impedance and restoration forces are analyzed to ensure that longitudinal resistance gradients are higher than lateral gradients for equivalent displacements, providing the pilot with distinct directional feedback. In this test, sensor data confirmed that the control stick exhibited significant dynamic damping (approaching a deadbeat response). No repeated oscillations exceeding oneand-a-half cycles were observed, and the calculated damping ratios remained within the Level 1 handling quality range . Consequently, the mechanical characteristics of the control stick quantifiably conformed to ergonomic design standards by providing stable centering and predictable resistance.

C. SAFETY PRECAUTIONS

1) Ground Test Evaluation

All procedures and restrictions related to the operation of ground power (electrical) and hydraulic equipment, as well as the auxiliary power unit (APU), must be followed. Before testing, all equipment used for mechanical characteristic testing and evaluation must be inventoried and checked one by one. After testing, a final check confirms that all equipment has been removed from the cockpit. Ground tests involving rotor rotation must be conducted with extreme caution. The aircraft should be parked in a level, open area (e.g., an apron); ground support and testing personnel must have a full understanding of the test procedures and remain away from the rotor. During testing, handle the aircraft with care, and never exceed the limits for control displacement and control rate.

2) Aerial Test Evaluation

All aerial mechanical property tests and evaluations must be conducted at a sufficient safe altitude, away from the ground and obstacles. Testing must follow a systematic build-up approach with a progressive increase in applied force, rate, and displacement. Crucially, high-amplitude tests, such as stick-jump or pulse excitation at limit displacements, shall only be performed after the helicopter's structural envelope clearance has been confirmed for the specific flight condition. One test pilot is responsible for the specific operation of the test, while another test pilot is responsible for data recording and safety monitoring. In the event of any unexpected response from the aircraft, the pilot must immediately recover and ensure sufficient time and space to avoid collision with the terrain [7]. The test plan must explicitly verify that the intended control displacements do not exceed the cleared structural or aerodynamic limits of the airframe before execution.

III. EVALUATION RESULTS

A cyclic pitch stick mechanical characteristic test and evaluation was conducted on a civilian single-engine dual-control system light multi-purpose helicopter. The evaluation included two main parts: quantitative evaluation and qualitative evaluation. The quantitative evaluation included the control travel and mechanical characteristics of the cyclic pitch stick; the qualitative evaluation included the control dynamics characteristics such as stick neutrality and stick jump.

A. QUANTITATIVE ASSESSMENT RESULTS

1) Operating Stroke

The cyclic pitch control stick's travel distance is shown in Figure 2. The straight lines in the lower left and lower right corners represent the interference of the pilot's legs on the cyclic pitch control stick's travel distance, while the dashed line on the outside represents the cyclic pitch control stick's control envelope. As shown in Figure 2, the overall cyclic pitch control stick measurement for the helicopter is accurate, with only slight deviations at the left and right front limits. This is because the cyclic pitch stick was not pushed to its limit position during the test, but this does not affect the overall envelope range. The longitudinal cyclic pitch control stick range of the test helicopter is 0-33.3 cm (where 0 cm corresponds to 0% and 33.3 cm corresponds to 100% of the longitudinal travel), and the lateral cyclic pitch control stick displacement is 28.6 cm (totaling a 100% lateral span). The red line represents the pilot's leg position limitation; by mapping the physical displacement to these percentage values, the force gradient data in subsequent sections can be directly correlated to the physical stick position in the cockpit; these limitations vary slightly among different pilots, requiring a large amount of data for statistical analysis [8].

2) Controlling Force

The test results of the operating force of the cyclic stick are shown in Figure 3. The longitudinal force characteristics of the control lever are shown in Figure 3. The x-axis represents both the physical displacement in centimeters and the relative percentage of the total 33.3 cm travel. Starting from the neutral reference point (identified as 0 cm or approximately 47% of the total longitudinal travel), the force gauge pushes the control lever forward; the starting

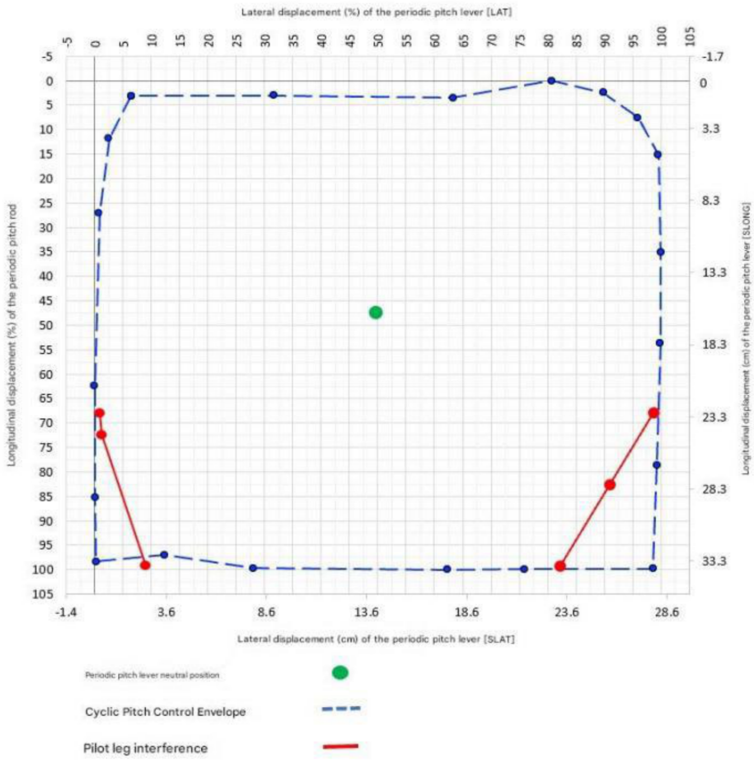
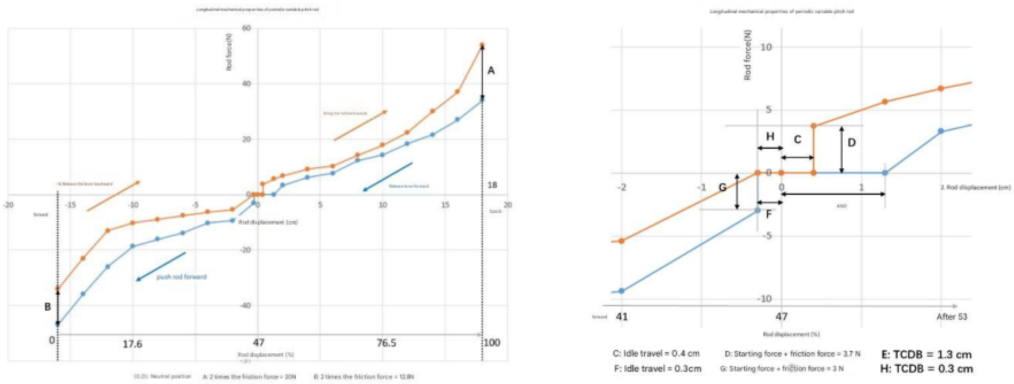


FIGURE 2. Cyclic Pitch Shifter Control Envelope

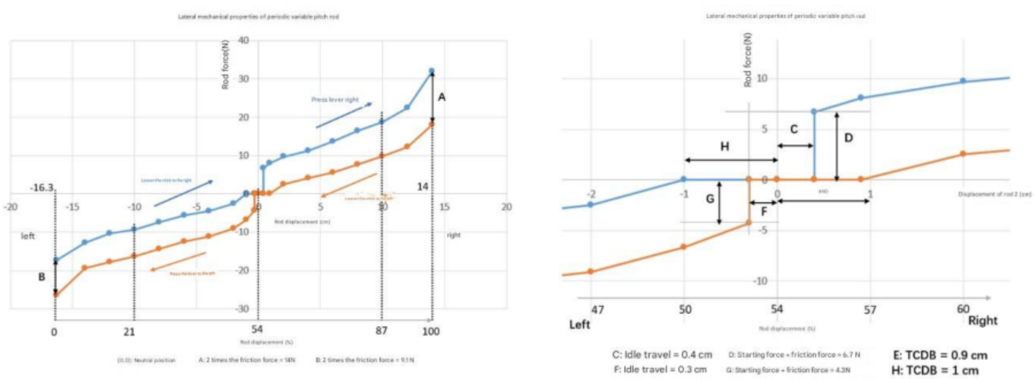
force for the forward push is 3N, and the starting force for the rear pull is 3.7N, with the longitudinal starting forces being basically the same. The maximum control lever force at the front limit is 45N, and the maximum control lever force at the rear limit is 55N. Analysis of the data shows that the force characteristics of the control lever differ in the forward and backward directions, with the maximum force at the rear limit slightly greater than the maximum force at the front limit, which meets the design requirements for ergonomics. The idle travel of the trim control system is approximately 0.3cm in the forward push direction and approximately 0.4cm in the backward pull direction. As illustrated in Figure 3(b), these physical measurements correspond to the narrow percentage bands (e.g.,the ‘ H ’ and ‘ C ’ TCDB regions) surrounding the 47 % neutral mark. These values are both within acceptable ranges (GJB). According to the relevant provisions of 902B-2017 Military Helicopter Flight Quality Specification, the flight travel during each operation should be coordinated with the flight quality level required by the helicopter [9].

The lateral force characteristics of the control stick are shown in Figure 4. Starting from the reference point, the force gauge presses the control stick to the left and right. The starting force of the left press is 4.3N, and the starting force of the right press is 6.7N. The lateral starting force is larger than the longitudinal force, but it still meets the requirement of the national military standard level one starting force of 2 ~ 7N. The maximum control stick force at the left press limit is about 27N, and the maximum control stick force at the right press limit is 31N. Through data analysis, it can be concluded that the lateral control force of the control stick is less than the longitudinal control stick control force, which meets the design requirements of human-machine efficiency. The idle travel of the trim control system is about 0.3cm in the left press direction and about 0.4cm in the right press direction, both of which are within the acceptable range. According to the relevant provisions of the national military standard “Military Helicopter Flight Quality Specification” GJB902B-2017, the idle travel in each control should be coordinated with the flight quality level required by the helicopter [10].



(a) (b)

FIGURE 3. Longitudinal mechanical properties of the periodic variable pitch rod



(a) (b)

FIGURE 4. Lateral mechanical properties of the periodic variable pitch rod

IV. CONCLUSION

To address the evaluation of the mechanical properties of helicopter cyclic pitch control sticks, a mathematical model of the control envelope was established that incorporates the interlaced structural dynamics of the composite fiber textiles used in the stick's reinforcement. This model ensures that the mechanical response of the control system is analyzed in tandem with the anisotropic tension and weave density of the highperformance fabrics to guarantee structural precision. The relative relationship between stick force and stick displacement was analyzed, and key characteristic parameters such as idle travel, starting force, and trim control displacement band were derived. Combined with the qualitative evaluation content of test pilots in the air, scientific and application-oriented evaluation results of the mechanical properties of cyclic pitch control sticks can be provided, offering a new approach and method for the comprehensive evaluation of the mechanical properties of helicopter cyclic pitch control sticks in the future.

AUTHOR CONTRIBUTIONS

XU Fan designed, collected and analyzed the data, and drafted the manuscript. XU Fan conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. XU Fan participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

FUNDING

This research received no external funding.

ACKNOWLEDGEMENTS

Not applicable.

REFERENCES

[1] M. Ni and H. Wu, "Design of robust stable controller for linear uncertain systems," Acta Automatica Sinica, vol. 18, no. 5, pp. 585-589, 1992.

[2] Y. Han, R. Li, and Y. Zhang, "An Optimal Control Method for Trajectory Tracking and Swing Suppression in Helicopter-Slung Load System," International Journal of Aeronautical and Space Sciences, prepublish, 2025,doi : 10.1007/S42405-025-01063-W.

[3] L. Wang, R. Chen, P. Li, X. Meng, and Y. Zhao, "Pilot-helicopter-slung-load coupled dynamics and fuzzy gain scheduled adaptive anti-swing strategy," Aerospace Science and Technology, vol. 168, Art. no. 110974, 2026, doi: 10.1016/J.AST.2025.110974.

[4] X. Ma, Y. Li, J. Zhang, Y. Cao, and M. Zhou, "Sensitivity analysis of a forward nonlinear biodynamic muscle-soft tissue-seat system for helicopter occupants under vibration and impact loads in airworthiness certification," Aerospace Science and Technology, vol. 168, Art. no. 110819, 2026, doi: 10.1016/J.AST.2025.110819.

[5] K. Zhang, Q. Miao, and B. Jiang, "Learning-Based Fault-Tolerant Optimal Formation Control of Helicopters: An Incremental Fully Actuated System Approach," IEEE Transactions on Cybernetics, vol. 56, no. 1, pp. 81-93, 2026, doi: 10.1109/TCYB.2025.3610020.

[6] T. Liu, J. Ding, J. Xu, D. Zhao, and X. Qiu , Design and dynamics analysis of three-degree-of-freedom kinematic mechanism for helicopter attitude simulation, "Scientific Reports," 2025; 15(1):7463, doi: 10.1038/S41598-025-89278-5.

[7] A. Chaudhary, R. Pillai, S. Upadhyaya, and G. Kaushik, "Stabilizing a nonlinear helicopter model: Advanced hybrid optimization technique for controlled rotor dynamics and vibration minimization under external disturbances," Journal of Vibration Engineering & Technologies, vol. 13, no. 3, pp. 199, 2025, doi: 10.1007/S42417-025-01759-Z.

[8] J. Hu, Y. Yang, N. Hu, and X. Lin, "Dynamic modeling and characteristic analysis of a helicopter main reducer for tooth crack diagnosis," Measurement, vol. 247, Art. no. 116823, 2025, doi: 10.1016/J.MEASUREMENT.2025.116823.

[9] Equipment Development Department of the Central Military Commission, "GJB 902B-2017, Flight Quality Specifications for Military Helicopters," Beijing, China: National Military Standards Publishing and Distribution Department, 2017.

[10] J. Zhang, J. Yang, and P. Xia, "Aeromechanical stability of rotor/fuselage coupling system in helicopter ground taxiing," Aerospace, vol. 12,no. 11, 2025, doi: 10.3390/AEROSPACE12110989.