Experimental Study on Dynamic Stiffness and Dynamic Damping of Actuators for Civil Aircraft Control Surfaces

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Abstract

Based on the airworthiness compliance requirements for the dynamic stiffness and dynamic damping of civil aircraft control surface actuators, the design requirements for the dynamic stiffness and dynamic damping of the control surface actuators of a large civil turboprop aircraft were studied from the perspective of meeting aircraft flutter stability requirements. The composition of the test device for verifying actuator dynamic stiffness and dynamic damping, as well as the principles for selecting test parameters, were discussed. Taking the aileron actuator of a large turboprop aircraft as an example, the test methods and results for the dynamic stiffness and dynamic damping of the aileron actuator were presented, and an extrapolation method for actuator dynamic damping test results was proposed to demonstrate that the actuator also meets airworthiness requirements under extremely severe failure conditions.

Full Text

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Abstract: Based on the airworthiness compliance requirements for the dynamic stiffness and dynamic damping of control-surface actuators of civil aircraft, and from the perspective of satisfying aircraft flutter-stability requirements, this study investigates the design requirements for the dynamic stiffness and dynamic damping of the control-surface actuators of a large civil turboprop aircraft. It discusses the composition of the verification test device for actuator dynamic stiffness and dynamic damping, as well as the principles for selecting test parameters during the experiment. Taking the aileron actuator of a large turboprop aircraft as an example, the study presents the test methods and results for the dynamic stiffness and dynamic damping of the aileron actuator, and proposes an extrapolation method for the actuator dynamic-damping test results, demonstrating that the actuator can still meet airworthiness requirements under extremely severe fault conditions.

Key words: dynamic stiffness; dynamic damping; control system; aeroelasticity; flutter

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Abstract: Based on the airworthiness compliance requirements for the control-surface actuator dynamic stiffness and dynamic damping of civil aircraft, and from the perspective of meeting aircraft flutter stability requirements, this study explores the design requirements for the dynamic stiffness and dynamic damping of control-surface actuators of a large civil turboprop aircraft. It discusses the composition of the actuator dynamic-stiffness and dynamic-damping verification test device, as well as the principles for selecting test parameters during the experiment. Taking the aileron actuator of a large turboprop aircraft as an example, the study discusses the methods and results of testing actuator dynamic stiffness and dynamic damping, and proposes a method for extrapolating actuator dynamic-damping test results, so as to demonstrate that the actuator meets airworthiness requirements even under extremely harsh fault conditions.

Key words: dynamic stiffness; dynamic damping; control system; aeroelasticity; flutter

As the key power devices that drive the deflection of aircraft control surfaces, control-surface actuators have dynamic mechanical characteristic parameters that are important inputs for structural dynamic modeling of control surfaces and for aeroelastic stability and vibration-response analyses

$$1-2$$

. In early aircraft, most primary control surfaces were operated through purely [[unclear: sentence continues on next page]].

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mass balancing to prevent flutter. For control surfaces operated manually or with power assistance, balance mass can prevent potentially catastrophic flutter during flight when the control surface is free or when the restraint stiffness is low[^3]. When the rotational free play of the control surface is too large, or when the stiffness of the control-system loop is insufficient, aeroelastic vibration is prone to occur; such vibration can be eliminated through mass balancing. Because balance mass usually causes a significant increase in the weight of the control surface, since 1980 aircraft manufacturers have begun using powered hydraulic actuators in new aircraft designs to provide restraint stiffness and/or damping to prevent flutter. At present, the control surfaces of most new civil aircraft are not mass-balanced; instead, they rely on independent, highly reliable control-surface restraint systems to prevent aeroelastic instability problems[^4–^6].

For non-mass-balanced control surfaces, the stiffness and/or damping of the control system is relied upon to prevent flutter. For such control surfaces, safety analysis must show that the loss of the restraint measures for flutter suppression is extremely improbable, and the aircraft design features shall ensure adequate flutter margins under all possible control-system damage, failure, or fault conditions[^7]. The corresponding airworthiness compliance provisions include Article CCAR25.629 and Article CCAR25.1435 of Part 25 of the China Civil Aviation Regulations[^8]. For cases not explicitly specified in the airworthiness provisions, the aircraft model design organization, through technical communication with the airworthiness certification representative, prepares a control-surface flutter-prevention design airworthiness issue paper according to the design characteristics of the aircraft control-surface operating system[^9], specifying the design requirements and airworthiness verification methods for the dynamic stiffness and dynamic damping of the aircraft control-surface actuator.

To prevent flutter of control surfaces, extensive research has been conducted both in China and abroad on stiffness design methods for control-surface operating systems. For example, Cheng Fang et al.[^10] proposed a method for determining actuator dynamic-stiffness and dynamic-damping requirements from the perspective of aeroelastic stability; YANG et al.[^11] and SHIN et al.[^12] analyzed the influence of nonlinear dynamic stiffness of actuator systems on the flutter characteristics of control surfaces. As theoretical studies have continuously been verified and applied in engineering practice, the methods for designing actuator dynamic stiffness and dynamic damping for control-surface flutter prevention have become increasingly mature.

However, in the absence of sufficient engineering verification, actuator dynamic-stiffness and dynamic-damping verification tests remain necessary. When the dynamic-stiffness characteristics of a control-surface actuator cannot be determined through theoretical calculation, it is necessary to use actuator dynamic-stiffness tests to verify its dynamic-stiffness characteristics under normal conditions and under fault conditions[^13]. If an actuator operating in damping mode has flutter-suppression requirements, specific actuator dynamic-damping design requirements should be provided and verified through actuator dynamic-damping tests. Airworthiness verification of large civil aircraft in China started relatively late; actuator dynamic-stiffness and dynamic-damping verification tests have been carried out relatively rarely, and few documents provide detailed discussions of the tooling composition for such tests or the selection of test parameters.

From the perspective of design requirements for the dynamic stiffness and dynamic damping of flutter-prevention actuators for control surfaces, this study investigates the tooling composition, test methods, and principles for selecting parameters for dynamic-stiffness and dynamic-damping tests of control-surface actuators. Based on test cases, methods for analyzing test results are studied, demonstrating that control surfaces can satisfy airworthiness requirements even under extremely severe fault conditions, and providing a reference for the design and airworthiness verification of control-surface actuators for aircraft models.

1 Dynamic-Stiffness and Dynamic-Damping Design Requirements

For a certain large civil turbofan aircraft, the control surface is driven in pitch rotation by the piston rod of an electrohydraulic servo actuator installed at the trailing edge of the stabilizer, as shown in Fig. 1.

In-figure labels: stabilizer; control surface; actuator; heading.

Fig. 1 Control surface actuator connection

Neglecting the influence of rotational free play of the control surface, and according to the structural connection form of the control-surface system, the total stiffness K of the control surface consists of three parts: the support stiffness K_{R}, the connection stiffness K_{L}, and the actuator dynamic stiffness K_{PCU}, as shown in Fig. 2. In the figure, J is the moment of inertia, and K_{L} refers to the equivalent stiffness from the rear connection point of the control-surface actuator to the theoretical mass center of the control surface[^10].

Fig. 2 Composition of the dynamic stiffness of the control system

The expression for the total stiffness K of the control surface is shown in Eq. (1).

$$\frac{1}{K} = \frac{1}{K_{\mathrm{R}}} + \frac{1}{K_{\mathrm{L}}} + \frac{1}{K_{\mathrm{PCU}}} \tag{1}$$

The dynamic-stiffness requirement for the control-surface actuator may be determined by the following method.

1) Through variable-parameter flutter analysis of the control-surface rotational natural frequency, determine the minimum rotational natural-frequency value f of the control surface.

2) According to the relationship between rotational frequency and rotational stiffness[^14], determine the minimum rotational stiffness K of the control surface.

$$K = \left(\frac{2\pi f}{b}\right)^2 \cdot J \tag{2}$$

where f is the frequency; b is the effective length of the rocker arm; and J is the moment of inertia.

3) Through detailed-model static-strength calculation, determine the actuator support stiffness K_{R}.

4) Establish a finite-element model of the control surface. Assuming that the support stiffness K_{R} and the actuator dynamic stiffness K_{PCU} are infinitely large, obtain the rotational frequency f of the control surface through modal analysis, and determine the connection stiffness K_{L} using the same calculation method as in Eq. (2).

5) Finally, determine the minimum actuator dynamic-stiffness requirement K_{PCU} from Eq. (1).

Under small-deformation conditions, the linear stiffness components of the control system in Eq. (1), multiplied by the square of the effective length of the control-surface horn arm, can be converted into the rotational stiffness of the control surface. Taking the aileron control system of a large turboprop aircraft as an example, the actuator is an electro-hydraulic servo actuator, which converts hydraulic energy from the hydraulic source into mechanical energy by executing commands from the main controller, thereby driving the deflection motion of the control surface. To meet the anti-flutter design requirements, the dynamic-stiffness design requirements for the aileron control system are shown in Table 1.

Table 1 Dynamic stiffness requirements of the aileron control system

Parameter	Numerical requirement
f/Hz	≥ 24.000
$K/(\mathrm{Nm} \cdot \mathrm{rad}^{-1})$	$\geq 2.889 \times 10^5$
$K_{\mathrm{R}}/(\mathrm{Nm} \cdot \mathrm{rad}^{-1})$	$\geq 5.344 \times 10^6$
$K_{\mathrm{L}}/(\mathrm{Nm} \cdot \mathrm{rad}^{-1})$	$\geq 2.453 \times 10^6$
$K_{\mathrm{PCU}}/(\mathrm{Nm} \cdot \mathrm{rad}^{-1})$	$\geq 3.488 \times 10^5$

A torsional damping element is used to simulate the actuator's dynamic damping characteristics. Through variable-parameter flutter analysis with respect to the rotational frequency of the control surface, the minimum actuator damping value that satisfies the flutter design requirements over the range from 0 Hz to the required minimum rotational natural frequency f is taken as the dynamic-damping design requirement for the control-surface actuator.

Again taking the aileron control system of a large turboprop aircraft as an example, each aileron has two actuators connected in a "primary–backup" configuration. According to the calculation and analysis of the failure state, under the condition that one actuator on a single aileron is connected and operating in the damping state while the other actuator is disconnected, the minimum rotational dynamic-damping requirement for the aileron is 300 Nms/rad.

2 Test Case

2.1 Test Method and Installation

The dynamic-stiffness and dynamic-damping tests of primary control-surface actuators are part of the review of the fly-by-wire flight control system. They are used to demonstrate that the qualification-test results for actuator dynamic stiffness and dynamic damping satisfy the design requirements, and to characterize the product' s compliance with CCAR25.629, CCAR25.1435, and the relevant airworthiness issue papers.

Because the stiffness characteristics of the actuator differ to some extent under tension and compression, the actuator dynamic-stiffness test should include both tensile dynamic-stiffness tests and compressive dynamic-stiffness tests. The test is carried out by a frequency-sweep loading method. Before the test, a preload is applied to the actuator so that the actuator piston rod undergoes compressive or tensile deformation. A load-biased sinusoidal frequency-sweep test is then conducted using the applied preload as the mean load. The applied load and the deformation displacement of the actuator piston rod are measured, and the stiffness characteristics of the actuator are obtained from the relationship between load and displacement.

The amplitude of the frequency-sweep load applied in the dynamic-stiffness test should be considered according to the flutter mode shape and control-surface deflection. In general, the flutter mode is a coupling of stabilizer bending–torsion and control-surface rotation; the actuator vibration load can be calculated from the flutter frequency and the rotational inertia of the control surface, and a conservative consideration can be made by superposing the aerodynamic load generated by control-surface deflection. However, if the actuator displacement caused by the above loads during the test is too small and leads to large measurement errors, the amplitude of the frequency-sweep load should be appropriately increased. Through variable-load frequency-sweep tests, the influence of the test frequency-sweep load on the test results is evaluated, and the final frequency-sweep loading amplitude is determined. According to the analysis results of the aircraft flutter characteristics, the frequency-sweep range of the actuator dynamic-stiffness test should cover the main modal frequencies that affect the aircraft flutter characteristics.

The magnitude of damping is strongly related to motion velocity. During the dynamic-damping test, the actuator is in a damping state, and the same frequency-sweep loading method is used. The damping magnitude is directly related to motion velocity; during the test, the frequency-sweep frequency and the frequency-sweep displacement amplitude directly affect the motion velocity of the actuator piston rod and thus have a certain influence on the test results. Therefore, in the dynamic-damping test, the influence of actuator motion velocity should be fully considered, and tests with variable frequency-sweep displacement amplitudes should be conducted.

According to the design characteristics of electro-hydraulic servo actuators[1], during aircraft service, wear of the sealing rubber ring of the actuator piston may lead to hydraulic leakage. Hydraulic leakage has a certain influence on the dynamic stiffness and dynamic damping of the actuator, and this failure mode should be considered during testing.

The dynamic-stiffness and dynamic-damping test bench is shown in Fig. 3. The test bench includes a fixed support, a test loading machine, remote servo-actuator system integrated verification equipment, and a hydraulic oil source that supplies pressure to the actuator.

In-figure labels: test machine; actuator; hydraulic oil source; remote servo-actuator system integrated verification equipment.

Fig. 3 Schematic diagram of test installation

The actuator is installed on the test machine through tooling fixtures, and the actuator test equipment controls the actuator so that it remains at the required position. During the dynamic-stiffness test, the test machine provides the specified load sweep. During the dynamic-damping test, the test machine provides the specified displacement sweep.

2.2 Test Methods and Results

2.2.1 Actuator Dynamic-Stiffness Test

Taking the dynamic-stiffness test of the aileron actuator of a civil large turboprop aircraft as an example, before the test, flutter characteristics of the whole aircraft were analyzed, and the aircraft flutter mode was determined to be an antisymmetric wing bending–torsion coupled flutter mode. Through modal contribution calculation and parameter sensitivity analysis, the main related modes were determined to include the wing symmetric first bending mode (2.521 Hz), the wing antisymmetric first bending mode (3.796 Hz), the fuselage horizontal first bending mode (5.431 Hz), the engine antisymmetric pitch mode (4.122 Hz), the wing antisymmetric first torsion mode (9.085 Hz), and aileron rotation (24.819 Hz).

[1] 15

Therefore, for the actuator tensile dynamic-stiffness test, the loading tensile force was set, the starting frequency of the sine sweep was 1 Hz, the ending frequency was 30 Hz, and the sweep step was 1 Hz. For the actuator compression dynamic-stiffness test, the same loading parameters were set. For the test condition in which the actuator piston sealing rubber ring was removed to simulate hydraulic leakage of the actuator, "leakage" was indicated in both the dynamic-stiffness and dynamic-damping test conditions for distinction. Table 2 gives partial results of the aileron actuator dynamic-stiffness test.

Table 2 Results of dynamic-stiffness test of aileron actuator

Tab. 2 Results of dynamic stiffness test of aileron actuator

Frequency/Hz	Tensile dynamic stiffness/($\mathrm{N\,m\cdot rad^{-1}}$), normal	Tensile dynamic stiffness/($\mathrm{N\,m\cdot rad^{-1}}$), leakage	Compressive dynamic stiffness/($\mathrm{N\,m\cdot rad^{-1}}$), normal	Compressive dynamic stiffness/($\mathrm{N\,m\cdot rad^{-1}}$), leakage
1	1.18×10^6	1.36×10^6	1.18×10^6	1.18×10^6
2	8.46×10^5	9.31×10^5	8.87×10^5	1.00×10^6
3	7.68×10^5	7.90×10^5	8.78×10^5	8.83×10^5
4	7.39×10^5	7.67×10^5	8.36×10^5	8.54×10^5
5	7.18×10^5	7.48×10^5	8.31×10^5	8.46×10^5
6	7.20×10^5	7.36×10^5	8.30×10^5	8.44×10^5
7	7.18×10^5	7.30×10^5	8.32×10^5	8.42×10^5
8	7.25×10^5	7.36×10^5	8.40×10^5	8.41×10^5
9	7.15×10^5	7.25×10^5	8.29×10^5	8.41×10^5
10	7.19×10^5	7.29×10^5	8.36×10^5	8.41×10^5
15	7.22×10^5	7.31×10^5	8.40×10^5	8.49×10^5
21	7.35×10^5	7.39×10^5	8.48×10^5	8.66×10^5
25	7.41×10^5	7.49×10^5	8.56×10^5	8.70×10^5
30	7.53×10^5	7.55×10^5	8.71×10^5	8.83×10^5

A comparative analysis of the test results in Table 2 and the required dynamic-stiffness values for the aileron actuator is shown in Fig. 4. The results indicate that the flutter-prevention design requirements for the aileron actuator are satisfied. From the above test results, it can also be seen that:

1) The actuator dynamic stiffness decreases rapidly at first as frequency increases, and then changes slowly.

2) The hydraulic-leakage fault state of the actuator piston sealing rubber ring has little effect on the actuator dynamic stiffness.

Fig. 4 plot labels: horizontal axis, frequency/Hz; vertical axis, rotational stiffness/(10^5 $\mathrm{N\,m\cdot rad^{-1}}$). *Legend: tensile test result; tensile test result (leakage);*

compression test result; compression test result (leakage); required rotational stiffness value.

Figure 4 Curves of aileron actuator dynamic-stiffness test results

Fig. 4 Curves of aileron actuator dynamic stiffness test results

2.2.2 Actuator Dynamic-Damping Test

Before the actuator dynamic-damping test, considering that the magnitude of damping is strongly related to the motion speed, numerical simulation analysis was used to determine the maximum deflection rate that the control surface could reach during flight.

The aeroelastic dynamic response analysis module (SOL146) of the commercial software MSC NASTRAN was used to analyze the dynamic response characteristics when the aileron, after reaching the limit deflection, suddenly enters the damping mode. A structural-dynamics finite-element model of the aircraft right wing was established. The wing fixed surface and the aileron were modeled with a single-beam model to simulate their stiffness characteristics, and the sectional stiffness parameters of the beam elements were obtained by calculation from the sectional stiffness of the aircraft right wing. The mass characteristics of the wing were simulated by distributed mass-point elements. Beam elements with equivalent stiffness were used to simulate the suspension connection between the aileron and the wing, as well as the connection between the engine and the wing. The spring element CELAS2 was used to simulate the rotational stiffness of the aileron [16 − 17]. The structural-dynamics finite-element model of the right wing is shown in Fig. 5.

Fig. 5 diagram label: aileron.

Figure 5 Finite-element model of right-wing dynamics

Fig. 5 Finite element model of aileron frequency response analysis

When establishing the aerodynamic model, according to the aerodynamic shape of the right wing, ···

The planar aerodynamic grid of the stabilizing surface and aileron of the right wing is shown in Fig. 6.

Fig. 6 Aerodynamic model for aeroelastic calculation of the right wing

When simulating the dynamic response of the aileron damping state, the time history of the aileron deflection response is simulated for the case in which, at the cruise speed V_c, the aileron actuator fails at the limiting-deflection position and enters the damping mode, as shown in Fig. 7.

Fig. 7 Time history of aileron deflection rate simulation

From Fig. 7, the instantaneous maximum aileron deflection angular velocity is 1.94 rad/s, which is far greater than the corresponding maximum aileron deflection angular velocity that can be reached on the test bench during the dynamic damping test. Since, during the dynamic damping test on the test bench, the sweep speed cannot cover the maximum deflection angular velocity that the aileron may actually reach, a dynamic damping test with variable sweep amplitudes was adopted to study the relationship between the aileron actuator dynamic damping and the sweep amplitude and frequency. Extrapolation analysis of the test data was used to demonstrate compliance with the airworthiness requirements.

During the actuator dynamic damping test, when the piston sealing rubber ring was intact, the sweep amplitude was 0.3 mm; when the piston sealing rubber ring was removed, the sweep amplitudes were 0.3, 0.5, 0.7, 1.0, and 1.2 mm, respectively. Based on the preliminary test of the maximum sweep-frequency capability of the test bench before the test, the sweep starting frequency was determined to be 1 Hz, the ending frequency 15 Hz, and the sweep step 1 Hz. Table 3 gives the dynamic damping test results of the aileron actuator. Through comparative analysis of the test results, after the actuator piston sealing rubber ring was removed (simulating leakage), the dynamic damping value was smaller than that in the no-leakage case. The test mainly verifies that the minimum dynamic damping value of the actuator meets the anti-flutter design requirements of the aileron; therefore, the variable-sweep-amplitude dynamic damping test mainly targets the leakage condition when the actuator piston sealing rubber ring is removed.

Table 3 Aileron actuator dynamic damping test results
Tab. 3 Aileron actuator dynamic damping test results

Frequency / Hz	Rotational dynamic damping / (Nms · rad^{-1}), Result 1	Rotational dynamic damping / (Nms · rad^{-1}), Result 2	Rotational dynamic damping / (Nms · rad^{-1}), Result 3	Rotational dynamic damping / (Nms · rad^{-1}), Result 4	Rotational dynamic damping / (Nms · rad^{-1}), Result 5	Rotational dynamic damping / (Nms · rad^{-1}), Result 6
1	3 290	2 140	2 410	3 080	4 070	4 410
3	3 160	2 040	3 650	2 970	2 200	1 800
5	2 960	1 880	2 490	1 830	1 460	1 260
7	2 340	1 450	1 880	1 500	1 190	998
10	1 960	1 040	1 440	1 200	981	933
13	1 570	966	1 210	1 000	912	881
15	1 380	1 040	1 070	915	873	841

Figure 8 is the trend plot of the aileron actuator dynamic damping test results versus sweep frequency. After removing individual irregular test points that may have been caused by measurement errors, the relationships among actuator dynamic damping, sweep amplitude, frequency, and actuator fault condition are as follows.

1) Overall, the actuator dynamic damping value decreases as the sweep frequency and amplitude increase.
2) Under the actuator leakage fault state, its dynamic damping value is reduced to a certain extent compared with the no-leakage condition.

Fig. 8 Curves of aileron actuator dynamic damping test results

The above dynamic damping test results show that there is a certain relationship between the dynamic damping value of the aileron actuator and the sweep amplitude and frequency. Suppose that, during the dynamic damping test, the sweep displacement amplitude is a, and the rocker-arm length of the control surface is b. Then the relationship between the control-surface deflection angle, the sweep amplitude, and the rocker arm is

$$\theta \approx (a/b)\sin(\omega t) \tag{3}$$

If the control-surface deflection amplitude is $\bar{\delta}$, then $\bar{\delta} = a/b$. Differentiating the above expression gives the angular velocity of the control surface as

$$\dot{\theta} \approx (\bar{\delta}\omega)\cos(\omega t) \tag{4}$$

It can be seen that, provided the rocker-arm length of the control surface is determined, the rotational velocity of the control surface is proportional to the product $\bar{\delta}\omega$ of the sweep amplitude and sweep frequency of the control surface during the test. According to the correspondence between actuator displacement and control-surface deflection angle

relationship; during the leakage-condition tests, the aileron deflection-angle amplitudes were 0.1°, 0.2°, 0.3°, 0.4°, and 0.5°, respectively. The test-condition data in the sweep-frequency range of $3 \sim 15$ Hz, where the linear segment was relatively good, were selected to analyze the relationship between damping and the aileron deflection angular velocity.

Taking the reciprocal of the maximum aileron rotational angular velocity, $1/(\omega\bar{\delta})$ (motion frequency ω, rad/s; motion amplitude $\bar{\delta}$, rad), as the abscissa, and actuator dynamic damping as the ordinate, a two-dimensional plot was made, as shown in Fig. 9. It can be seen that the dynamic damping and $1/(\omega\bar{\delta})$ are essentially in a linear relationship.

Fig. 9 Linear extrapolation of aileron actuator damping test results
Visible plot annotation: $y = 217x + 509.95$. The vertical axis is rotational damping / $(\mathrm{Nms}\cdot\mathrm{rad}^{-1})$, and the horizontal axis is $1/\omega\bar{\delta}$.

The relationship between the actuator dynamic damping and the aileron deflection frequency and amplitude is fitted as

$$c = \frac{217}{\omega\bar{\delta}} + 509.95 \tag{5}$$

This relationship reflects the following characteristics of the actuator damping:

1) The actuator dynamic damping decreases as the aileron-surface deflection angular velocity increases, and the relationship is basically linear.

2) The relationship indicates that there is a minimum damping value. For the aileron actuator, the minimum value is 509.95 Nms/rad.

According to the linear extrapolation of dynamic damping in Eq. (5), when the instantaneous maximum deflection angular velocity of the aileron is 1.94 rad/s, the dynamic damping is 621.75 Nms/rad. From the linear extrapolation result, the dynamic damping value of the aileron actuator satisfies the anti-flutter design requirements.

3 Conclusions

Through the study of the design method for actuator dynamic stiffness and dynamic damping in aircraft control-surface actuation systems, and taking the aileron actuator of a large civil turboprop aircraft as an example, the anti-flutter design requirements for the dynamic stiffness and dynamic damping of the aileron actuator were given. The test methods and fixtures for verification tests of actuator dynamic stiffness and dynamic damping were discussed.

To verify that the actuator dynamic stiffness and dynamic damping meet airworthiness requirements, the tests must consider that the actuator still satisfies the design requirements under the most severe conditions. The following factors should be considered in the design of the test fixture.

1) The principal modal frequencies affecting the aircraft flutter characteristics should be used as the basis for determining the maximum sweep frequency in the actuator dynamic stiffness test.

2) The sweep-load magnitude of the test bench should be determined with reference to flutter vibration loads and control-surface-deflection aerodynamic loads, and according to the actual excitation displacement generated by the actuator piston rod, so as to reduce displacement-measurement errors.

3) The maximum motion speed that the actuator piston rod may reach during the dynamic damping test should be considered. Because the motion speed is strongly correlated with the dynamic damping value, the sweep amplitude and frequency of the test fixture should have a relatively large adjustment range.

Through the variable-sweep-frequency dynamic stiffness test of the actuator, the test results can directly demonstrate that the airworthiness compliance requirements are met. However, the actuator dynamic damping test is limited by the loading speed of the test bench, making it difficult to simulate the actuator motion under extreme conditions. The extrapolation method for actuator dynamic damping and control-surface deflection angular velocity proposed in this study can compensate for the influence of the sweep-amplitude and frequency limitations of the test fixture, and provides a reference for demonstrating that the dynamic damping test results of civil-aircraft actuators satisfy anti-flutter design requirements.

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