Application of the Lift Loading Method in Landing Gear Drop-Test Performance Analysis

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Abstract

Landing gear lift-simulation drop test is a method that applies equivalent lift directly to the landing gear rather than reducing equivalent mass, which considers the influence of lift on landing gear drop performance and more realistically simulates the landing/ship-landing process of the landing gear. This study takes a certain type of carrier-based aircraft main landing gear as the research object. Based on different lift loading methods (theoretical lift-simulation and drop-test lift-simulation), firstly, a dynamic model for landing gear lift-simulation drop test is established; secondly, numerical simulation calculations for landing gear lift-simulation drop test are performed using ALTLAS software; finally, experimental verification is conducted on a drop test bench equipped with a lift-simulation dynamic simulation device. Through verification and comparison of results under different sink speeds, the correctness and effectiveness of the lift loading method in landing gear lift-simulation drop test are validated; the drop-test lift-simulation method, through theoretical modeling of the landing gear lift-simulation drop test system, achieves equivalent lift loading for landing gear, and serves as an analytical approach that can effectively assist in landing gear buffer system design and buffer performance verification.

Full Text

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Abstract: In simulated landing-gear drop tests with lift, an equivalent lift is applied directly to the landing gear rather than reducing the equivalent mass, thereby accounting for the influence of lift on the landing-gear drop-test performance and more realistically simulating the touchdown/landing process of the landing gear. Taking the main landing gear of a certain type of aircraft as the research object, and based on different lift loading methods (theoretical simulated lift and drop-test simulated lift), this study first establishes a dynamic model for simulated landing-gear drop tests with lift; then uses ALTLAS software to perform numerical simulation calculations for simulated landing-gear drop tests with lift; finally, tests are carried out and verified on a drop-test bench equipped with a lift simulation device. Through verification and comparison of the results at different sink speeds, the correctness and effectiveness of applying the lift loading method in simulated landing-gear drop tests are validated. By theoretically modeling the simulated landing-gear drop-test system, the drop-test lift simulation method realizes the loading of the landing gear with an equivalent lift; it is an analytical approach that can effectively assist the design of landing-gear buffer systems and the verification of buffer performance.

Keywords: landing gear; lift loading method; numerical simulation; drop test; wing lift simulation

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Application of the lift loading method in the analysis of landing gear drop shock performance

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Abstract: The landing gear drop shock featured with wing lift directly applies the equivalent lift to the landing gear instead of reducing the equivalent mass, and the effect of wing lift on the landing performance of landing gear is considered. The landing process of the landing gear can be simulated more truly with the aid of the landing gear drop test featured with wing lift. This paper takes a certain type of strut-type main landing gear as the research object. Based on different lift loading methods (i.e., theoretical lift simulation and drop test lift simulation), first, the dynamic model of landing gear drop shock featured with wing lift is established. Then, the numerical simulation of landing gear drop shock featured with wing lift is carried out by using ALTLAS software. Finally, the landing gear drop test is carried out on the drop test bench with the wing lift simulation device. By the verification and comparison of the results under different sinking speeds, the correctness and effectiveness of the application of lift loading method in the landing gear drop test featured with wing lift are verified. Drop test lift simulation realizes the loading of the equivalent lift on

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the landing gear via the theoretical modeling of the system of landing gear drop test featured with wing lift. The drop test lift simulation can effectively assist

the development of the landing gear buffer system and the verification of the buffer performance.

Key words: landing gear; lift loading method; numerical simulation; drop test; wing lift simulation

Landing gear is a device specifically provided for an aircraft to take off, land/ditch, taxi, move on the ground, and park. During landing/ditching and taxiing, the aircraft impacts the ground to varying degrees; the landing gear bears and attenuates this impact, thereby reducing the aircraft' s landing/ditching overload. In addition, the landing gear plays a very important role in improving aircraft structural fatigue life, ground maneuverability, and passenger comfort. Therefore, the rationality of the landing-gear layout and structure, as well as the optimal design of its buffering performance, directly affect the aircraft' s takeoff/landing and taxiing characteristics[^1].

Analysis of landing/ditching characteristics of landing gear[^2-4] plays a vital role in the development of aircraft landing-gear systems, and the effects of multiple factors must be taken into account. Among them, wing lift is one of the most critical influencing factors. Wing lift is a distributed load acting on the airframe and is directly related to factors such as the aircraft wing planform, flight angle of attack, and speed; therefore, certain simplifications must be made in computational analysis. Assuming that a lift force equal to one times the weight is applied at the aircraft center of gravity and remains constant during aircraft landing/ditching is a common method for simulating and loading wing lift[^5-6], namely the theoretical lift-simulation method. In addition, the equivalent lift decomposed to the front and main landing-gear pivot axes is called the landing-gear equivalent lift. In the design phase of the landing-gear buffer system, designers use the theoretical lift-simulation method to determine the internal structural parameters of the shock absorber and theoretically obtain the most desirable buffering performance of the landing gear. However, the calculation results obtained from theoretical lift simulation ultimately need to be verified through parameter-selection tests by means of drop tests, so as to assist in correcting the sensitive parameters of the landing-gear buffering performance.

In the test verification stage for landing-gear buffering performance, in order to simulate the landing/ditching characteristics of the landing gear realistically and effectively in a laboratory environment, there are currently two internationally used landing-gear drop-test methods: the "reduced-mass method" [^7] and the "lift loading method" [^8]. The "reduced-mass method" is based on energy equivalence, in which the work done by lift is equivalent to a reduction in the dropped mass for the landing-gear drop test. It is a free-fall drop-test method without lift action, and the dropped mass at this time is not equal to the equivalent mass of the landing gear. The "lift loading method" is a drop test with lift action. Considering the influence of wing lift during aircraft landing/ditching, the dropped mass at this time is equal to the equivalent mass of the landing gear. For a laboratory landing-gear simulated-lift drop test, a special lift-simulation device capable of providing simulated lift power is added to the drop-test rig.

In general, a simulated-lift actuating cylinder (pneumatic cylinder) or a highly elastic rubber rope is used to apply a vertically upward load to the hanging basket, thereby simulating the aircraft wing lift. However, the output load of the rubber rope changes considerably due to its elastic deformation, making lift simulation unstable; moreover, the output load is relatively small and cannot satisfy the requirement for approximately constant lift simulation. Therefore, lift simulation in landing-gear simulated-lift drop tests generally uses a lift-simulation actuating cylinder fixed to the drop-test rig.

By considering the action of wing lift, researchers have carried out drop tests and simulations for landing-gear buffering performance based on the lift loading method. Qi Buhe et al.[^8], in combination with a drop-test task for a certain type of aircraft landing gear, developed a drop-test system capable of simulating aircraft wing lift and successfully applied it to a landing-gear simulated-lift drop test. Dou Qingbo et al.[^9], based on a full-aircraft drop test of a carrier-based aircraft, studied methods for simulating wing lift, proposed a lift-loading method suitable for full-aircraft drop tests, and successfully applied it to a full-aircraft drop test of a certain type of carrier-based aircraft. Shen Qiang et al.[^10] carried out simulated-lift drop-test simulation of landing gear in the ADMAS/Aircraft software environment based on the lift loading method, and analyzed the application of the lift loading method in research on landing-gear buffering performance. Fang Jianyi et al.[^11], based on a landing-gear landing dynamics model and in combination with the external-field use conditions of the main landing gear of a certain type of helicopter, analyzed the landing characteristics of the main landing gear under a small lift coefficient, and also provided an optimization scheme for the shock absorber.

It is worth noting that, at present, the method commonly used in theoretical research on landing-gear simulated-lift drop tests is the theoretical lift-simulation method, which can only serve the initial design stage of the landing-gear buffer system and cannot be applied to the test verification stage. In order to effectively guide the design of landing-gear simulated-lift drop tests, shorten the test verification cycle, and promote the development process of landing gear, this study proposes for the first time the drop-test simulated-lift method. The drop-test simulated-lift method establishes a dynamic model of the dropped-body system and the lift-simulation system in a landing-gear simulated-lift drop test, in which the landing-gear equivalent lift is provided by a lift-simulation cylinder, thereby theoretically simulating the lift action during the landing-gear drop process. This study takes the main landing gear of a certain type of carrier-based aircraft as the research object. First, a landing-gear simulated-lift drop dynamic model is established based on the lift loading method; then, numerical simulation of the landing-gear simulated-lift drop is performed based on ALTLAS software; finally, through comparison with simulated-lift drop-test data, the correctness and validity of the landing-gear simulated-lift drop theoretical model are verified. The drop-test simulated-lift method proposed in this study can effectively simulate landing-gear simulated-lift drop tests, verify the calculation results obtained based on theoretical lift simulation, and provide an important

Fig. 1 Two-mass model of landing gear

Figure 1: Fig. 1 Two-mass model of landing gear

basis for the design of the carrier-based aircraft landing-gear buffer system.

At the same time, the drop-test-based lift simulation method can guide the design of the landing-gear lift-simulated drop-test system, improve test accuracy, assist in verifying the cushioning performance of the landing gear, and thereby promote the development process of the landing gear.

1 Dynamic Model of Landing Gear in Lift-Simulated Drop Test

1.1 Differential Equations of Theoretical Lift-Simulation Motion

When performing theoretical analysis of the cushioning performance of landing gear, for the convenience of establishing the dynamic equations, a two-mass spring-damper model is generally adopted

$$12-13$$

, as shown in Fig. 1. According to the motion characteristics of the landing gear system, the equivalent mass of the landing gear is divided into two concentrated masses: the elastic supported mass above the air spring, including the fuselage (in the drop test, referring to the hanging basket, fixtures, and ballast), the outer cylinder of the shock absorber, etc.; and the non-elastic supported mass below the air spring, including the inner cylinder, wheel assembly, and brake device, etc.

图 1 起落架二质量弹簧-阻尼模型

Fig. 1 Two-mass model of landing gear

The equations of motion for the above parts can be written as

$$\begin{cases} M_1\ddot{x}_1 = -F_a - F_h - L + M_1 g - F_f - F_l \\ M_2\ddot{x}_2 = -F_t + F_h + F_a + M_2 g - F_f + F_l \end{cases} \tag{1}$$

where M_1 and M_2 denote the elastic supported mass and the non-elastic supported mass, respectively; x_1 and x_2 denote the vertical displacements corresponding to the elastic supported mass and the non-elastic supported mass, respectively; F_a is the air-spring force; F_h is the hydraulic damping force; F_f is the friction force between the piston rod and the shock-absorber strut; F_t is the ground reaction force acting on the tire; F_l is the structural limiting force of the shock absorber; and F_a is expressed as

Fig. 2 Tire static pressure curve

Figure 2: Fig. 2 Tire static pressure curve

$$F_a = A_a \left[\frac{P_{a0}}{(1 - A_a S/V_0)^n} - P_{\text{atm}} \right] \tag{2}$$

where A_a is the effective pressurized area of the shock-absorber air chamber; S is the shock-absorber stroke; V_0 is the initial air volume; n is the polytropic exponent of compression of the air chamber; P_{a0} is the initial pressure of the air chamber; and P_{atm} is the standard atmospheric pressure. F_h is expressed as

$$\begin{cases} F_h = \dfrac{\rho A_h^3 \dot{S}^2}{2C_d^2 A_d^2} \operatorname{Sng}(\dot{S}) + \dfrac{\rho A_h^3 \dot{S}^2}{2C_{ds}^2 A_{ds}^2} \operatorname{Sng}(\dot{S}) \\ \operatorname{Sng}(\dot{S}) = \begin{cases} 1, & \dot{S} > 0 \\ 1, & \dot{S} < 0 \end{cases} \end{cases} \tag{3}$$

where ρ is the hydraulic-fluid density; A_h is the effective oil-pressure area of the main oil chamber; A_d is the effective flow area of the main oil orifice; C_d is the flow coefficient of the main oil orifice; A_{ds} is the effective flow area of the return oil orifice; C_{ds} is the flow coefficient of the return oil orifice. F_f is expressed as

$$F_f = F_{fp} + F_{fc} \tag{4}$$

where F_{fp} is the friction force at the shock-absorber leather cup; and F_{fc} is the bending friction force of the shock-absorber strut. F_t is expressed as

$$F_t = n_t (1 + C_T \dot{\delta}) f(\delta) \tag{5}$$

where n_t is the number of wheels on a single landing gear; C_T is the vertical vibration damping coefficient of the tire (C_T is generally taken as 0.04 s/m); and $f(\delta)$ is the tire static pressure curve (Fig. 2). F_l is expressed as

$$F_l = \begin{cases} K_l S, & S < 0 \\ 0, & 0 \le S \le S_{\max} \\ K_l (S - S_{\max}), & S > S_{\max} \end{cases} \tag{6}$$

where $S_{\max}$ is the maximum stroke of the shock absorber; and K_l is the axial stiffness of the shock absorber.

图 2 轮胎静压曲线

Fig. 2 Tire static pressure curve

Fig. 3 The drop test model of landing gear with wing lift

Figure 3: Fig. 3 The drop test model of landing gear with wing lift

When the lift force L is assumed to act at the aircraft center of gravity, its magnitude is equal to the equivalent mass of the aircraft. Before equivalent decomposition to the lift at the rotating shaft of the main landing gear, the calculation method in which the lift is equal to the equivalent load is, for the main landing gear, expressed as

$$L = \frac{G_{zl}}{2} = G_{dl} \tag{7}$$

where G_{zl} is the landing weight of the aircraft; and G_{dl} is the main-landing-gear equivalent load.

1.2 Differential Equations of Motion for the Drop-Test Model with Simulated Lift

The landing-gear drop-test model with simulated lift is shown in Fig. 3. In this model, the equivalent lift required by the landing gear is provided by the simulated-lift actuator. The aircraft weight represented by the landing gear is consistent with the weight of the falling-mass system (including the basket, airframe simulator, and landing gear). The free-fall method is adopted, and the aircraft sink velocity is determined by the release height h of the falling-mass system.

图 3　起落架落震仿升模型

Fig. 3　The drop test model of landing gear with wing lift

The basket falls from the specified release height and simultaneously strikes the force-measurement platform and the top cap of the simulated-lift actuator. When the basket is in good contact with both the force-measurement platform and the top cap of the simulated-lift actuator, this instant is taken as the zero point of the drop test, i.e., the vertical displacement of the basket centroid is $y_{\mathrm{C}} = 0$; the piston-rod displacement of the simulated-lift actuator is $y_{\mathrm{L}} = 0$; the vertical displacement of the wheel axle is $y_{\mathrm{U}} = 0$; and the distance from the lower edge of the wheel to the upper plane of the drop-test platform is $L_0 = 0$. The simulated lift is the impact contact force F_{L} between the basket and the simulated-lift actuator, namely

$$F_{\mathrm{L}} = \begin{cases} K_{\mathrm{L}}\left(y_{\mathrm{C}} - y_{\mathrm{L}}\right) + C_{\mathrm{L}}\left(\dot{y}_{\mathrm{C}} - \dot{y}_{\mathrm{L}}\right), & y_{\mathrm{C}} \geq 0 \\ 0, & y_{\mathrm{C}} < 0 \end{cases} \tag{8}$$

where K_{L} is the stiffness coefficient of the pad, and C_{L} is the damping coefficient of the pad.

Based on the motion characteristics of the landing-gear drop-test system with simulated lift under laboratory conditions, the dynamic equations of the drop-test model with simulated lift can be expressed as

$$\begin{cases} M_{\mathrm{L}}\ddot{y}_{\mathrm{L}} = F_{\mathrm{L}} - F_{\mathrm{a}} \\ M_{\mathrm{C}}\ddot{y}_{\mathrm{C}} = -F_{\mathrm{L}} - F_y + M_{\mathrm{C}}g \\ M_{\mathrm{U}}\ddot{x}_{\mathrm{U}} = F_x - D \\ M_{\mathrm{U}}\ddot{y}_{\mathrm{U}} = F_y - V_{\mathrm{T}} + M_{\mathrm{U}}g \\ I_{\mathrm{U}}\dot{\omega} = D\left(R - \delta/3\right) \end{cases} \tag{9}$$

where M_{L} is the mass of the piston rod of the simulated-lift actuator; M_{C} is the elastic support mass of the landing gear; M_{U} is the non-elastically supported mass of the landing gear; I_{U} is the wheel rotational inertia; F_x is the horizontal force exerted by the landing gear on the basket; F_y is the vertical force exerted by the landing gear on the basket; V_{T} is the vertical force exerted by the drop-test platform on the wheel; D is the longitudinal friction force exerted by the drop-test platform on the wheel; R is the initial wheel radius; ω is the wheel rotational speed; F_{a} is the air-spring force of the simulated-lift actuator, which is constant during the drop test, as given in Eq. (10); and δ is the tire compression, as given in Eq. (11).

$$F_{\mathrm{a}} = N\left(M_{\mathrm{C}} + M_{\mathrm{U}}\right)g \tag{10}$$

where N is the lift-simulation coefficient, and $N \leq 1.0$.

$$\delta = \begin{cases} y_{\mathrm{U}} - L_0, & y_{\mathrm{U}} > L_0 \\ 0, & y_{\mathrm{U}} \leq L_0 \end{cases} \tag{11}$$

The initial conditions for Eq. (9) are

$$\begin{cases} y_{\mathrm{L}}\big|_{t=0} = 0,\ \dot{y}_{\mathrm{L}}\big|_{t=0} = 0 \\ y_{\mathrm{C}}\big|_{t=0} = 0,\ \dot{y}_{\mathrm{C}}\big|_{t=0} = V_{\mathrm{S}} \\ x_{\mathrm{U}}\big|_{t=0} = 0,\ \dot{x}_{\mathrm{U}}\big|_{t=0} = 0 \\ y_{\mathrm{U}}\big|_{t=0} = 0,\ \dot{y}_{\mathrm{U}}\big|_{t=0} = V_{\mathrm{S}} \\ \omega\big|_{t=0} = V_{\mathrm{L}}/R \end{cases} \tag{12}$$

where V_{L} is the aircraft horizontal velocity, and V_{S} is the aircraft sink velocity.

Fig. 4 Dynamic model of landing gear

Figure 4: Fig. 4 Dynamic model of landing gear

1.3 ALTLAS Landing-Gear Dynamic Simulation

In this study, the ALTLAS software is used to perform simulation calculations for landing-gear drop tests with simulated lift. ALTLAS is an engineering system software package developed by the China Aircraft Strength Research Institute on the basis of many years of combined experimental and theoretical research. It is mainly used for analyses of landing-gear shock-absorption performance, taxiing loads, and shock-absorber orifice-parameter optimization. The ALTLAS software mainly includes three modules: parametric modeling, numerical calculation, and post-processing. The post-processing module can implement functions such as data display, curve plotting, and display of typical calculation results [14].

For the aerodynamic modeling problem of a single landing-gear system with aircraft weight represented, it is assumed here that the non-elastically supported mass is simplified to the wheel-axle center point, and that the landing-gear shock strut is simplified to a massless elastic rod. Therefore, the simplified dynamic model of the main landing gear in this paper is shown in Fig. 4.

The non-elastically supported mass block of the landing gear has a total of four degrees of freedom of motion $(x_\mathrm{u}, y_\mathrm{u}, z_\mathrm{u}, \omega_\mathrm{T})$, including three translational degrees of freedom $(x_\mathrm{u}, y_\mathrm{u}, z_\mathrm{u})$ in the $o_\mathrm{u} - x_\mathrm{u} y_\mathrm{u} z_\mathrm{u}$ coordinate system, and one rotational degree of freedom (ω_T) about the wheel-axle center C. Its dynamic equations are

$$\begin{cases} \ddot{x}_\mathrm{u} = \left(D_\mathrm{T}^x - F_x\right)/M_\mathrm{u} \\ \ddot{y}_\mathrm{u} = \left(V_\mathrm{T} - F_y\right)/M_\mathrm{u} - g \\ \ddot{z}_\mathrm{u} = \left(D_\mathrm{T}^z - F_z\right)/M_\mathrm{u} \\ \dot{\omega}_\mathrm{T} = -\left[D_\mathrm{T}^x(R-\delta) + M_\mathrm{T}\right]/I_\mathrm{u} \end{cases} \tag{13}$$

where $\{F_x, F_y, F_z\}$ are the components, in the $o_\mathrm{u} - x_\mathrm{u} y_\mathrm{u} z_\mathrm{u}$ coordinate system, of the forces exerted by the landing gear on the body connection point A; D_T^x is the tire longitudinal horizontal force (in the $-ox_\mathrm{u}$ direction); D_T^z is the tire lateral horizontal force (in the $-ox_z$ direction); and M_T is the wheel braking torque.

图 4 起落架动力学模型

Fig. 4 Dynamic model of landing gear

The initial conditions for solving Eq. (13) are:

Fig. 5 Schematic diagram of landing gear drop test system

Figure 5: Fig. 5 Schematic diagram of landing gear drop test system

$$\begin{cases} \{x_{\mathrm{u}}, y_{\mathrm{u}}, z_{\mathrm{u}}\}^{\mathrm{T}}\big|_{t=0} = B\{x^t_{C0}, y^t_{C0}, z^t_{C0}\}^{\mathrm{T}} \\ \omega_{\mathrm{T}}\big|_{t=0} = \begin{cases} 0 & \text{(actual landing)} \\ V_{\mathrm{L}}/R & \text{(actual rolling)} \\ -V_{\mathrm{L}}/R & \text{(drop test)} \end{cases} \\ \{\dot{x}_{\mathrm{u}}, \dot{y}_{\mathrm{u}}, \dot{z}_{\mathrm{u}}\}^{\mathrm{T}}\big|_{t=0} = \{V_{\mathrm{L}}, -V_{\mathrm{s}}, 0\}^{\mathrm{T}} \end{cases} \tag{14}$$

where $\{x^t_{C0}, y^t_{C0}, z^t_{C0}\}^{\mathrm{T}}$ are the initial coordinates of point C, the center of the landing-gear wheel axle; and B is the coordinate transformation matrix, which can be written as

$$B = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{15}$$

2 Landing-Gear Simulated Lift Drop Test

2.1 Test System Composition and Principle

The test rig is a column-type free-drop test system. The test system mainly includes a lift system (including the lifting actuator, electromagnetic lock, and other subsystems), a mechanical system (including the guide lock frame, basket, fixtures, and other subsystems), a simulated lift aerodynamic system (including pneumatic actuators and other subsystems), and a test subsystem (including sensors and a data acquisition system), among others. A schematic diagram of the landing-gear simulated lift drop test is shown in Fig. 5.

图 5 落震试验台示意图

Fig. 5 Schematic diagram of landing gear drop test system

2.2 Test Method

The landing-gear drop test [15 − 17] is conducted using a free-falling mass. The equivalent mass of the landing gear is simulated by the mass of the entire drop-body system (including the basket, fixtures, counterweights, and landing gear). In the drop test based on the lift loading method, the equivalent mass of the landing gear is equal to the mass of the entire drop-body system. The aircraft landing attitude angle (i.e., the included angle between the landing-gear strut and the forward direction) is ensured by the landing-gear mounting fixture, and the aircraft touchdown sink velocity is ensured by the release height of the drop-body system.

Before the test, the test article is first inspected after assembly and inflation, and the drop-body system is weighed. Counterweights are adjusted so that the mass of the drop-body system reaches the equivalent mass required for the test. The simulated lift system is then pressurized; after the pressure of the simulated lift system reaches the specified value, the test begins. During the test, the lifting system of the test rig first raises the drop-body system to the specified release height and locks it, and then zeroing operations are performed on the force-measuring platform and the relevant test sensors. After all preparations are completed, the control system opens the electromagnetic lock at the upper part of the drop-body system, allowing the drop-body system to fall freely along the upright guide rails and strike the ground force-measuring platform. At the same time, the simulated lift actuator applies to the drop-body system an upward lift force perpendicular to the opposing surface and equal in magnitude to the landing-gear equivalent mass. Before the landing gear contacts the force-measuring platform, the data acquisition system is triggered, and the test data collected by the sensors before landing-gear contact and after contact with the force-measuring platform are obtained. The procedure for the landing-gear simulated lift drop test is shown in Fig. 6.

[Flowchart of landing gear drop test process]

Flowchart text:

Start → Check the filling parameters of the test article → Weigh the drop-test system → Determine the "zero point" of the drop-test system → Low-height drop, $H = (100 \pm 20)\,\mathrm{mm}$ → Confirm the operating status of each system → Record the system operating conditions → Raise the drop-test system, with height error within 1% → Unlock and drop → Is the measurement-force error $\leq 3\%$?

If N: Check the sensitivity of the test-system sensors and eliminate line interference → return.

If Y: Analyze the on-site results → Is the energy error $\leq 3\%$?

If N: Adjust the air pressure of the lift-simulation actuator → return to on-site result analysis.

If Y: End.

图 6 起落架落震试验流程

Fig. 6 Landing gear drop test process

2.3 Lift Loading Criteria

This landing-gear lift-simulation drop test simulates, in the laboratory, the landing environment of the landing gear. For the simulation of lift during landing-gear touchdown, the main considerations are the magnitude of the lift, its duration of action, and its influence on the attitude of the landing gear. The following requirements should be met: during the drop-test process, the applied lift on the landing gear should remain constant; the applied lift should not affect the vertical impact velocity of the landing gear at the instant it contacts the force-measuring platform; and the applied lift should not affect the landing attitude of the landing gear during the drop-test process.

2.4 Principle of Lift Loading

To satisfy the requirements for applying landing lift to the landing gear, lift-simulation actuators are used throughout the drop-test process. They apply, respectively, constant loads equal to one quarter of the landing-gear landing mass to four locations on the bottom of the basket of the drop-test system, as shown in Fig. 7. At the instant when the landing gear contacts the force-measuring platform, the lift-simulation actuators act on locations , , , and at the bottom of the basket; location is the center of gravity of the drop-test system. In addition, the landing-gear lift-simulation device is installed perpendicular to the ground. This lift-loading method can ensure that the landing gear maintains its landing attitude without change during the drop-test process.

Compared with other dynamic loading devices such as hydraulic actuators, when pneumatic actuators are used as the device for simulating aircraft lift, their load-output response time is short. At the instant when the landing gear contacts the force-measuring platform, the lift-simulation actuators can rapidly apply lift to the drop-test system, simulating the action of aircraft lift, and they do not change the magnitude of the drop-impact velocity of the landing gear.

[Action points of wing lift simulation actuators]

图 7 仿升作动筒作用点

Fig. 7 The action points of wing lift simulation actuators

In the landing-gear lift-simulation drop test, the lift-simulation actuator and a large-capacity pressure-stabilizing storage tank are used to realize simulation of wing lift. The magnitude of the output lift is determined by the contact area between the internal piston of the lift-simulation actuator and the compressed air, as well as by the internal air pressure. At any moment, the magnitude of the lift output by the lift-simulation device is

$$T = np\pi R^2 \tag{16}$$

where T is the lift output by the lift-simulation actuator at any moment; n is the number of lift-simulation actuators; p is the internal pressure of the lift-simulation actuator; and R is the radius of the internal piston rod of the lift-simulation actuator.

[Variation of air pressure inside the lift simulation actuator during the drop test]

图 8　落震试验过程中仿升作动筒内部气压变化

Fig. 8　Variation of air pressure inside the lift simulation actuator during the drop test

The measured air pressure on the piston working area inside the lift-simulation actuator in this lift-simulation drop test is shown in Fig. 8. It can be seen from the figure that throughout the landing-gear drop-test process, the internal air pressure of the lift-simulation actuator remains essentially unchanged. This indicates that, at any moment during the test process, the lift output by the lift-simulation system remains unchanged, thereby effectively ensuring the accuracy and effectiveness of the simulation of landing lift for the landing gear over the entire test process.

When the internal piston area of the pneumatic actuator is fixed, the magnitude of the load output has a linear relationship with the internal air pressure. This is beneficial for adjusting the internal air pressure of the lift-simulation actuator according to the specific test content, so as to control the mean value of the simulated lift and ensure that the lift is consistent with the wing lift corresponding to the landing mass of the landing gear ($T = L$), thereby accurately controlling the power absorbed by the lift-simulation system···

quantity, ensuring the accuracy of the simulated drop test.

3 Results Analysis

In this study, the main landing gear of a certain type of shipborne aircraft is taken as an example. The main state parameters of the landing gear are shown in Table 1.

Table 1 Landing gear technical parameters

Tab. 1 Landing gear technical parameters

No.	State parameter	Unit	Value
1	Piston-rod diameter	mm	144
2	Shock absorber structural stroke	mm	480
3	Shock absorber operating stroke	mm	432
4	Wheel diameter	mm	412
5	Strut inflation pressure	MPa	1.04
6	Main oil-orifice diameter	mm	12.4

The sink velocities are selected as 4, 5, 6, and 7 m/s; the drop-test conditions are shown in Table 2.

The comparison of the main parameter results is given in Tables 3–4, and the power plots from the simulation and test results are shown in Figures 9–12.

Table 2 Landing gear drop simulation parameters

Tab. 2 Landing gear drop simulation parameters

No.	Landing gear parameter	Unit	Value
1	Aircraft landing attitude	–	Level
5	Lift ratio	–	1
6	Sprung mass	kg	9 200
7	Unsprung mass	kg	200
8	Parking load	kN	88

It can be seen from the power plots of the landing-gear shock-absorbing system at different sink velocities that the results obtained based on numerical simulation and drop-test verification agree well. Comparing the test verification data in Tables 3–4 with the numerical calculation results shows that the maximum relative error between the test results and the numerical calculation results is 3.97%, and the minimum can reach 0.05%, satisfying engineering requirements.

Table 3 Comparison between the calculated and measured results ($V_s = 5$ m/s)

Tab. 3 Comparison between the calculated and measured results ($V_s = 5$ m/s)

Condition	Maximum vertical displacement of center of gravity / mm	Maximum shock-absorber stroke / mm	Maximum tire vertical force / kN	Shock-absorbing system energy / J	Shock absorber energy / J
Theoretical simulation	488.24	423.36	247.28	119 859.44	107 519.28
Drop simulation	495.92	427.84	236.48	116 721.68	103 828.96
Drop test	489.36	423.60	240.88	116 029.52	–
$\frac{\mid - \mid}{} \times 100\%$	0.22%	0.05%	2.65%	3.30%	–
$\frac{\mid - \mid}{} \times 100\%$	1.34%	1.00%	1.82%	0.59%	–

Fig. 9 Buffer system power diagram ($V_s = 4$ m/s)

Figure 6: Fig. 9 Buffer system power diagram ($V_s = 4$ m/s)

Fig. 10 Buffer system power diagram ($V_s = 5$ m/s)

Figure 7: Fig. 10 Buffer system power diagram ($V_s = 5$ m/s)

Table 4 Comparison between the calculated and measured results ($V_s = 6$ m/s)

Tab. 4 Comparison between the calculated and measured results ($V_s = 6$ m/s)

Condition	Maximum vertical displacement of center of gravity / mm	Maximum shock-absorber stroke / mm	Maximum tire vertical force / kN	Shock-absorbing system energy / J	Shock absorber energy / J
Theoretical simulation	531.36	445.92	323.60	172 514.56	151 383.28
Drop simulation	530.40	445.44	316.80	161 567.52	141 260.24
Drop test	532.56	444.40	315.04	165 915.92	–
$\frac{\mid - \mid}{} \times$ 100%	0.22%	0.34%	2.71%	3.97%	–
$\frac{\mid - \mid}{} \times$ 100%	0.40%	0.23%	0.55%	2.62%	–

Fig. 9 Buffer system power diagram ($V_s = 4$ m/s)

Fig. 10 Buffer system power diagram ($V_s = 5$ m/s)

Fig. 11 Buffer system power diagram ($V_s = 6$ m/s)

Fig. 12 Buffer system power diagram ($V_s = 7$ m/s)

Fig. 11 Buffer system power diagram ($V_s = 6$ m/s)

Figure 8: Fig. 11 Buffer system power diagram ($V_s = 6$ m/s)

Fig. 12 Buffer system power diagram ($V_s = 7$ m/s)

Figure 9: Fig. 12 Buffer system power diagram ($V_s = 7$ m/s)

4 Conclusion

Taking the main landing gear of a certain carrier-based aircraft as the research object, this study first establishes a landing-gear simulated drop-shock dynamics model based on the lift loading method (theoretical simulated lift and drop-shock simulated lift). Then, according to the structural parameters and the internal filling parameters of the shock absorber, numerical simulation calculations are carried out in the ALTLAS software, and the results are compared with validated test results, verifying the correctness and effectiveness of the simulated drop-shock dynamics model for the landing gear developed in this study. Numerical simulation of landing-gear drop shock based on the lift loading method does not require a complex iterative process, and thus can improve the efficiency of theoretical analysis of landing-gear cushioning performance. In addition, by establishing a dynamics model of the landing-gear simulated drop-shock test system through the drop-shock simulated-lift method, the landing-gear simulated drop-shock test can be effectively and realistically simulated, guiding the design of the landing-gear simulated drop-shock test system, improving test accuracy, and providing an important auxiliary means for the design of carrier-based aircraft landing-gear buffer systems and the verification of cushioning performance.

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