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• LETTER •
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Taxiing stability verification and airworthiness certification for amphibious aircraft

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Dear editor,

Taxiing stability is an important issue in modern civil aircraft development and airworthiness certification. Incidents or abnormal problems consistently arise during aircraft taxiing, as a result of landing gear "walking", shimmying, and taxiing directional instability. The vibrations or instability associated with a landing gear system may affect the aircraft's normal directional control, shorten its service life, and even lead to runway excursion accidents. Therefore, taxiing stability verification has been an important concern for the development of a civil landing gear system. The taxiing stability of the landing gear is also one of the airworthiness requirements of the China Civil Aviation Regulations CCAR-25 (the Federal Aviation Administration of the United States has a regulation called 14CFR25). Section 25.233(c), "Directional stability and control", states the following: "The aircraft must have adequate directional control during taxiing. This may be shown during taxiing prior to takeoffs made in conjunction with other tests" [1]. An amphibious aircraft is usually installed with more unique and complex landing gear, and thus, an assessment of the taxiing stability of the landing gear is deemed more necessary. Previous studies on the overall layout and taxiing stability of amphibious aircraft landing gear are relatively rare. In [2–4], a numerical simulation is the main approach to taxiing stability.

In this study, we present a taxiing stability study on an amphibious aircraft. Simulation modeling and a stability assessment are overviewed in a step-by-step manner. The physical mechanism of the runway taxiing stability of the landing gear is interpreted. A multi-body dynamic model including the structural components of the nose and the main landing gears, fuselage, propellers, and main control surfaces is developed. The structural model is partially meshed into a rigid-flexible model. Restraints and loads are applied to establish proper kinetic relationships between the different components. Taxiing responses are derived for simulated runway flight-testing scenarios. Dynamic parameters including the compression stroke of the nose and the main landing gear, tire lateral load, total load, and aircraft yaw angle are analyzed. The effects of asymmetry disturbances on the aircraft taxiing stability are further investigated. The virtual simulation is then verified using laboratory dynamometer bench testing for the nose landing gear.

Theoretical interpretation. When tricycle aircraft are taxiing with sudden pedal control, or encounter external disturbances such as a crosswind or uneven ground, the aircraft will produce a sideslip angle, leading to a wheel deflection. As a result of the tire cornering, the lateral loads on both the nose wheels and the main wheels will generate torques toward the gravity of the aircraft. The restoring torque through lateral loads on the main wheels tends to provide stability in

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the aircraft's taxiing direction. Similarly, the lateral loads increase during a cornering of the nose wheels, which has an unstable effect on the aircraft's taxiing direction. If the nose wheels are completely free (or the steering system is inactive) and only a restoring torque of the main wheels occurs, the taxiing direction of the aircraft becomes stable. In contrast, when the damping of the nose wheels is too large, the aircraft becomes prone to losing its directional stability, as described in [3].

Modeling. For a taxiing stability analysis of a civil aircraft, a dynamic multi-body model is established, as shown in Figure 1(a). The restraints between the different landing gear components are applied according to the physical interfaces. The aerodynamic force, engine thrust, and loads on the shock absorbers of the nose landing gear (NLG) and the main landing gear (MLG) are defined. Simulation modeling of the landing gear is divided into three steps, namely, modeling of the landing gear structure, finite element meshing of the main components, and application of the motion constraints. A simplified three-dimensional model of the nose landing gear includes the outer cylinder, piston rod, torque arm, wheel hub, and tires. Based on the actual movement of the landing gear, motion constraints and assembly interfaces are defined between the structural components. A certain degree of freedom (DOF) in the axial translation and rotation occurs between the outer cylinder and piston rod, and thus, a cylindrical joint is used. A bracket joint is applied between the wheel hub and tires. Axial rotation occurs only between the piston rod and wheel hub, and a revolute joint is applied. The process of MLG modeling is similar to that of the nose landing gear. The loads acting on the landing gears include the air spring force and oleo-damping force of the shock absorber, the air spring force and damping force of the tire, and the lateral damper force, as described in [5]. A complex tire model based on the Smiley string contact theory is adopted. For the complex tire model, the main tire parameters include the tire radius, rolling damping, rolling radius, cornering stiffness, lateral stiffness, radial stiffness, and tire relaxation length. The corresponding force unit between the outer cylinder and the piston rod of the landing gear is directly applied. The loads on the landing gear are numerically extracted through spline force curves during the simulation.

Virtual simulation. For the virtual simulation model, the influence of the mass and inertia of the fuselage, as well as engine rotation, are considered. Four propellers are connected to the fuselage with the corresponding engine speed. A full-scale taxiing simulation model is assembled through bracket joints between the NLG, MLG, and fuselage. Virtual flight scenarios for the taxiing stability are developed under simulated runway conditions. Aerodynamic forces and four engine thrusts will act on the aircraft model. The aerodynamic force of the aircraft is a function of the flight speed, height, angle of attack, and sideslip angle. The engine thrust is calculated and applied according to the momentum conservation law. The dynamic responses during a symmetric taxiing state for the typical weight/center of gravity and design configurations of an aircraft are shown in Figure 1(b). During symmetric taxiing, there is no shift in the aircraft yaw angle. The lateral loads on the nose and main tires are relatively small and nearly equal to zero. The strut stroke and vertical loads of the tire are almost the same for the left and right wheels for each landing gear. This verifies that the aircraft has good taxiing stability in a symmetric state. During the aircraft taxiing simulation, a lateral disturbance (the external load is 10000 N) is applied for 2 s after 3 s of stable taxiing, the simulation results of which are illustrated in Figure 1(c). Based on the results, we can see that the aircraft's dynamic response is affected by the external disturbance. The yaw angle of the aircraft shows a short-term fluctuation. The NLG strut compression has little variation. In contrast, the strut compression stroke between the left and right MLG becomes inconsistent. The lateral loads on both the NLG and MLG tires change significantly as the aircraft begins to yaw. When the disturbance is withdrawn, the aircraft can quickly return to its neutral position, which indicates that the aircraft still has direction stabilization. The aircraft taxiing can automatically return to its original direction within 10 s after an external disturbance.

Experiment validation. The landing gear simulation model was validated based on the actual static pressure to deformation curve of the shock absorber and tires. Dynamometer testing for the nose landing gear has been completed through a large flywheel test bench at the AVIC Aircraft Strength Research Institute. The test cases include four different inflatable pressure combinations for the left and right tires, five types of vertical loads on the landing gear, and ten taxiing speed conditions. Under all testing conditions, the nose landing gear did not demonstrate any unstable phenomenon with or without an external excitation, which verifies the simulation data described in this letter. However, dynamometer testing may not properly consider the factors of the fuselage flexibility or real runway situation. A full-scale

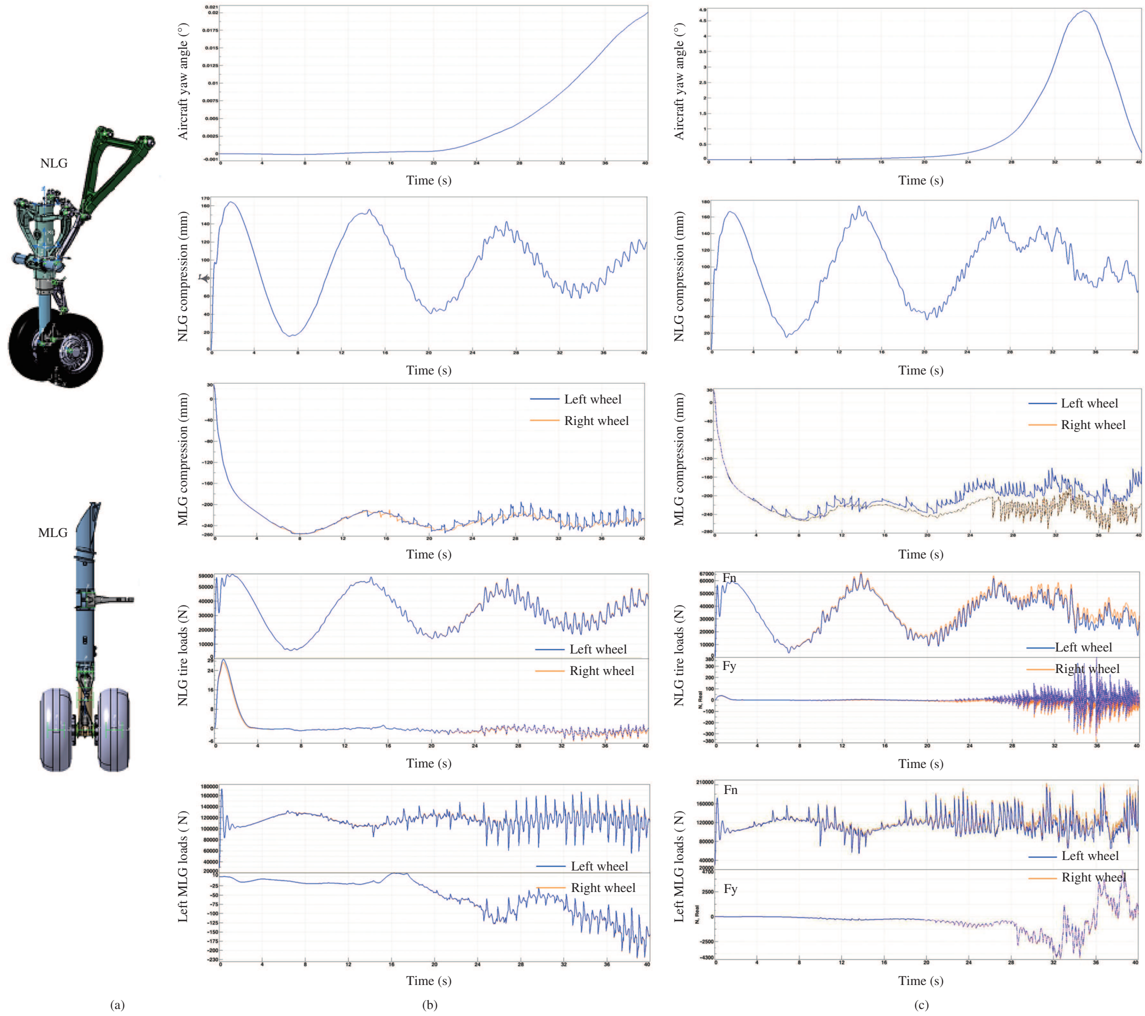

Figure 1 (Color online) Taxiing stability simulation results. (a) Simulation model of NLG and MLG; (b) taxiing in symmetric scenario; (c) taxiing with lateral disturbance.

virtual prototype simulation cannot be replaced completely by the dynamometer testing (ground laboratory testing). A virtual simulation can be used to evaluate the effects of different landing gear configurations, and pre-test more flight scenarios.

Conclusion. Through a virtual simulation of the taxiing stability, dynamic 6-DOF equations were implicitly applied in a simulation model. A preview of the aircraft runway taxiing dynamics was obtained. An amphibious aircraft has good directional stability for both a symmetric taxiing state and during disturbances. Dynamometer bench testing shows that the taxiing stability simulation achieves consistent results. A virtual verification technique is expected to become one of the prospective means of compliance for civil aircraft certification, and will help prevent the occurrence of taxiing instability.

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