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# A study of instability in a miniature flying-wing aircraft in high-speed taxi

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**Abstract** This study investigates an instability that was observed during high-speed taxi tests of an experimental flying-wing aircraft. In order to resolve the reason of instability and probable solution of it, the instability was reproduced in simulations. An analysis revealed the unique stability characteristics of this aircraft. This aircraft has a rigid connection between the nose wheel steering mechanism and an electric servo, which is different from aircraft with a conventional tricycle landing gear system. The analysis based on simulation results suggests that there are two reasons for the instability. The first reason is a reversal of the lateral velocity of the nose wheel. The second reason is that the moment about the center of gravity created by the lateral friction force from the nose wheel is larger than that from the lateral friction force from the main wheels. These problems were corrected by changing the ground pitch angle. Simulations show that reducing the ground pitch angle can eliminate the instability in high-speed taxi.



## 1. Introduction

Several next-generation civil transport aircraft and unmanned air vehicles (UAVs) are of flying-wing designs. Flying-wing aircraft have potential benefits over conventional configurations in aerodynamic and structural efficiency.[1] Many UAVs use the flying-wing configuration because it minimizes the observability of the aircraft while meeting flight performance requirements.[2] Over the last decade, flight tests have been conducted on flying-wing aircraft such as the X-45,[3–5] and the X-48B[6–8] from Boeing and the X-47B[2,9,10] from Northrop Grumman. Because flying-wing aircraft have no vertical tails, the lateral-directional dynamics and the directional control of these aircraft differ from those of conventional aircraft. These differences affect both the flying qualities and the stability of ground maneuvers.

A number of studies have been conducted to establish a mathematical model for aircraft runway dynamics.[11–17] In particular, several studies[11–13] considered the effects of the aerodynamic forces while taxiing. Abzug[11] replicated the 1935's demonstration of the tricycle landing gear arrangement effect on light aircraft directional stability in landing rollout by computer simulation. Zhang and Zhou[12] studied the takeoff run for a flying-wing aircraft and considered both the aerodynamic

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forces and the ground loads. Evans et al.[13] presented the development of a tricycle landing gear simulation model including several classes of system failures such as component degradation and jamming. Zhang and Nie[14] established a mathematical model of aircraft wheel braking and nose wheel steering, and studied landing gear strut loading during steering and braking control. Gu and Gao[15] established the dynamic model of landing gear shimmy, and analyzed directional stability during taxi by using this model. Ro[16] presented a descriptive modeling to study aircraft-runway dynamics, which is descriptive and structured in the sense that landing gear system is regarded as an assembly of suspension strut, tire, and wheel. Pi et al.[17] developed a generic aircraft ground operation simulation to predict the response of aircraft under various operating modes and surface conditions. In summary, although in many studies, mathematical model of aircraft ground dynamics has been established and the taxi maneuver has been simulates in several aspects, rare of them consider that aircraft design characters caused abnormal behavior study, and less of them concerns about taxing stability from the standpoint of aircraft design.

This study examines an instability phenomenon observed in a small experimental aircraft with a flying-wing configuration while taxiing at high speed. The cause of the problem is determined by examining the aerodynamic and structure mechanism of the experimental aircraft. Based on the results of the analysis, a mathematical model of instability is developed and the problem is reproduced in simulations. A solution to the problem is found by integrating the results from the analysis and the simulation. After validating the solution in the simulation, a flight test of the modified aircraft is performed and high-speed taxi stability is demonstrated.

## 2. Presentation of problem

This study examines the stability and control of a small experimental aircraft with a flying-wing configuration. Fig. 1 presents an overhead view of the aircraft, which has a takeoff weight of 34.3 N, a wing area of 1.13 m$^2$, a tip washout angle of $-3°$ and a wing loading of 3.1 kg/m$^2$. Propulsion is provided by an electric-powered ducted fan with a maximum takeoff thrust of 20 N. The engine thrust line passes through the center of gravity (C.G.) of the aircraft. The trailing edge control surfaces, from the tip to the root, are the split drag rudders, the elevons and the elevators. This aircraft does not have flaps

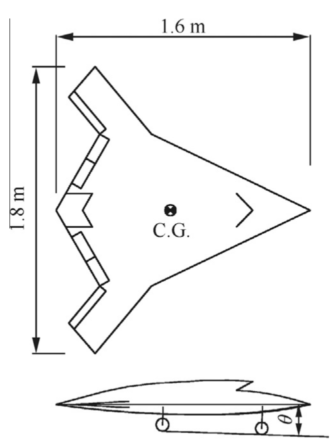


**Fig. 1** Planform and side views of aircraft.

or other high-lift devices. In the plane of symmetry, the center of gravity is 0.88 m from the nose and 7% MAC (mean aerodynamic chord, MAC = 0.93 m) in front of the aerodynamic center of the aircraft.

The landing gear configuration of the experimental aircraft resembles that of the large majority of small aircraft of similar weight and size. The landing gear struts are constructed from steel wire and the tires are polyurethane. To simplify the structure, the nose gear does not include a shimmy damper and the steering mechanism of the nose wheel is directly connected to an electric servo. The horizontal distance between the center of gravity and the main gear is 0.05 m and the distance to the nose gear is 0.58 m. The center of gravity is 0.15 m above the ground. There is no toe-in angle for the wheels on the main landing gear. This aircraft uses both nose wheel steering and split drag rudders to control the direction while taxiing and in takeoff runs. In order to reduce the takeoff run distance, the aircraft has a ground pitch angle of 4° (the angle between the chord line and the runway surface, shown in Fig. 1 as $\theta$).

When taxiing, all of the control surfaces initially remained neutral. When taxiing at low speed, the overall control of the aircraft was normal. However, in high-speed taxi trials a strange instability emerged. When the aircraft was disturbed even slightly in the yaw direction, such as by a side force on the nose wheel due to an uneven surface or a steering correction by the pilot, the aircraft performed a ground loop; i.e., the aircraft turned dramatically in the direction of the disturbance, leading to a heading change of greater than 180° over a short distance. Because this ground loop happened suddenly and the yaw rate increased rapidly, the pilot was unable to control it. Figs. 2(a)–(g) show sequential images of the instability, graphically shown in Fig. 2(h).

There are certain differences in the characteristics of ground loops with this aircraft and conventional taildragger aircraft. Taildragger aircraft are prone to ground loops while taxiing at low speed. As the taxi speed increases, the yawing moment from the vertical tail increases and improves directional stability. In contrast, the experimental aircraft was prone to ground loops while taxiing at high speed. A preliminary analysis eliminated the possibility that a structural asymmetry or pilot error caused the ground loop.

The ground loop problem also occurs in the aircraft shown in Fig. 3. The aircraft in Fig. 3 has a landing gear configuration similar to that of the aircraft in this study but is somewhat different in shape. The display of similar ground loop behavior indicates that the problem may be universal in small flying-wings.

A preliminary theoretical analysis indicates that the ground loop behavior is caused by the following two factors:

(1) The rigid connection between the nose wheel steering mechanism and an electric servo causes the load distribution to differ from that of a conventional tricycle landing gear configuration during takeoff run. Generally, ground loops are unlikely in aircraft with a tricycle landing gear configuration. The nose gear in aircraft with a typical tricycle landing gear layout usually features a shimmy damper. In these aircraft, the nose wheel can automatically turn in the direction of the velocity if the aircraft sideslips during takeoff run. The nose gear in many small aircraft with a tricycle landing gear layout resemble that of the aircraft in this study