JOURNAL OF AIRCRAFT
Vol. 46, No. 6, November–December 2009

Engineering Notes

Lateral Stability and Control of a Tailless Aircraft Configuration

Gloria Stenfelt* and Ulf Ringertz†
Royal Institute of Technology, 100 44 Stockholm, Sweden

DOI: 10.2514/1.41092

Introduction

A LOW radar signature is one of the goals when developing future generation military aircraft. The tail surfaces of the aircraft may be a significant contributor to radar signature [1] and a number of currently operational aircraft, such as the B-2, and demonstrators, such as the X-45, are flying wing designs without conventional tails. These flying wing configurations need to provide directional stability and control without the use of a fin and a rudder. On the B-2, directional control appears to be achieved using split ailerons that provide unsymmetric drag [2], thus generating a yawing moment. Another possibility is to use two trailing-edge control surfaces on one wing with one deflected up and the other down giving increased drag on that wing and consequently the desired yawing moment.

The flying wing concept has a long history. The German Horten brothers [3] developed a series of flying wing aircraft and also experimented with different approaches for achieving directional stability and control. The Horten designs were all equipped with mechanical control systems and there exist reports [3] that handling qualities were not always excellent due to the nonlinear response in the directional control devices used. More modern designs, such as the B-2, rely on digital control systems giving improved possibilities in artificially enhancing the handling qualities. Many of the difficulties involved in control of aircraft without a conventional tail is discussed by Colgren and Loschke [4].

The main difficulty associated with relying on creating differential drag for directional control is that the control response is likely to be very different in comparison to the use of a traditional fin with rudder. The rudder on a fin redirects the aerodynamic flow giving an almost immediate response that is well described using a simple linear model. A linear model for yawing moment as a function of rudder deflection greatly simplifies control system design. Differential drag, on the other hand, is inherently nonlinear and may also have zero slope at zero deflection making a quadratic dependence on control surface deflection a more accurate model.

The purpose of the present study is to investigate the aerodynamics of a generic aircraft configuration known as Swing with particular focus on lateral stability and control. The configuration used, see Fig. 1, has two trailing-edge flaps on each wing that are to be used for control around all three stability axes, namely pitch, roll, and yaw. In the present study, low-speed wind-tunnel testing is used to investigate the lateral stability and control properties of this configuration.

Received 18 September 2008; revision received 12 December 2008; accepted for publication 12 December 2008.

*Ph.D. Student, Division of Flight Dynamics; glorias@kth.se.
†Professor, Division of Flight Dynamics; rzu@kth.se. Member AIAA.

Experimental Setup

Tests are done in the low-speed wind tunnel L2000 at the Royal Institute of Technology (KTH). A freestream velocity of 30 m/s, corresponding to a Reynolds number of $6.9 \cdot 10^5$ is applied. The Swing model was designed using a CAD system and molds were cut using a computer controlled milling machine. The molds were then used to build the model with a carbon fiber epoxy composite material. A planform overview of the model is shown in Fig. 2 and additional geometrical data are listed in Table 1. Unlike a conventional aircraft, the wing tip is formed as a triangle with zero chord at the tip. A NACA-66009 airfoil is used for the wing, and the outer wing section is twisted up 5° around the leading-edge point of the wing. There are four trailing-edge control surfaces (flaps) that can be individually controlled using electrical servos. The flaps are used for control around all axes. All control surfaces are deflected with the same angle for pitch control. Asymmetric deflections with the same amplitude for both flaps on each wing is applied for roll control. Yaw control is achieved using a split flap deflection on one wing giving a yaw moment in the direction of the wing with deflected flaps. In this study, the focus is on the yaw response from a split flap deflection.

The fuselage of the wind-tunnel model is designed mainly to fit a balance that measures the aerodynamic forces and moments on the model, but also to resemble similar aircraft configurations in development. The balance is placed so that its reference point coincides with an expected neutral point at 0.44 m from the nose. The location of the neutral point was estimated using the potential flow method developed by Eller and Carlsson [5].

The deflection of the flaps is recorded with a motion capture system [6]. Here, infrared light is emitted from four cameras and reflective markers are put on the flaps. The light is reflected back to the cameras with a scan rate of 100 Hz and the system computes the distance to the markers. Hence, the marker positions can be put into a calibrated coordinate system. The distances between the markers and the rotation axis for the flaps are known, and the actual deflection angles can then be computed. Balance forces and wind-tunnel conditions are simultaneously measured in synchronization with the motion capture system.

Test Results

Initially, longitudinal aerodynamic forces were measured to find interesting angles of attack for a detailed analysis of the lateral stability and control surface effectiveness. A sudden increase in pitch

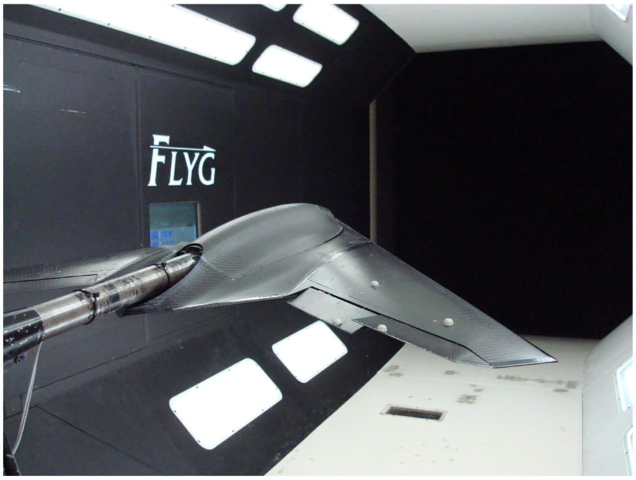

Fig. 1 Aircraft model in the low-speed wind tunnel.

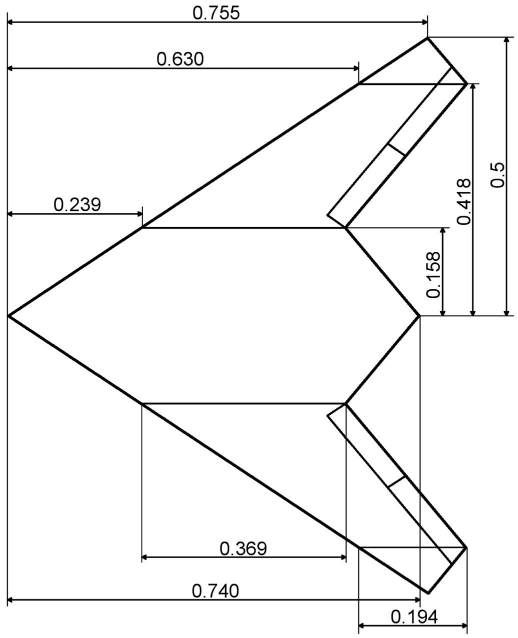

Fig. 2 Definition of the planform geometry (meters).

moment is observed at angles of attack above 10°. A visualization technique based on fluorescent oil [7] was used to investigate the flow on the upper wing surface. In Fig. 3, the flow is visualized at $\alpha = 5°$ to the left and at $\alpha = 11°$ to the right. At the low angle of attack, the boundary layer transitions to turbulent already at the leading edge and it stays attached until it reaches the trailing edge. No large three-dimensional effects can be seen. At 11° angle of attack, on the other hand, the flow pattern is significantly different. First, a separation line starting at the leading edge, and continuing over the wing toward the trailing-edge point of the wing tip, is apparent. Downstream of this line, a strong vortex causes high local velocities leading to large skin friction. The existence of the vortex was also verified using a tuft wand [7]. The strong variation in the flow pattern above 10° angle of attack is also apparent in the integrated forces and the control surface effectiveness, especially for the outer flap, as will be discussed further on.

Lateral Stability

Based on the pitch moment behavior, stability is investigated at low and high α with zero control surface deflection. The roll moment

Table 1 Dimensions of the wind-tunnel model

Entity	Notation	Value
Span	b	1.0 m
Mean chord	c	0.3373 m
Wing area	S	0.3373 m^2
Leading-edge sweep	Γ	56°
Trailing-edge flap chord	c_{TE}	0.04 m
Trailing-edge flap deflection interval	δ	±20°

C_l, side force C_S, and yaw moment C_n as well as their derivatives with respect to the sideslip angle β are determined. Positive β is defined as the nose going to the left, and stability in yaw is defined as $C_{n_\beta} = \partial C_n / \partial \beta > 0$. Hence, for positive β, the yawing moment should be positive to restore the airplane to symmetric flight [8]. Variations in β are performed for several angles of attack, and the yaw moment derivative, along with the roll moment and side force derivative, are shown in Fig. 4. Here, it is seen that Swing is not stable in yaw for low α, while the model is stable for the higher angles of attack. All coefficient derivatives are made nondimensional by performing the differentiation with respect to the variable in nondimensional form $\hat{\beta}$ with $\hat{\beta} = \beta / \beta_{\mathrm{ref}}$, where β_{ref} is 10°.

Yaw Control Using Differential Flaps

For yaw control investigations, differential flap deflections from 0 to ±20° are applied. A positive deflection of $\delta_s = 20°$ is defined as inner flap down 20° and outer flap up 20° on one wing only. Both flaps are deflected with the same amplitude δ_s, because the secondary effect of the differential flap deflection on the roll moment is very small.

The yaw efficiency of a positive differential flap deflection versus a negative one for 0 and 15° angle of attack is shown in Fig. 5. For low α, a positive deflection is more efficient, while for higher α, a negative deflection is more efficient in generating a large yaw moment. Evaluating the amount of yaw moment that is produced at different sideslip angles, using the sideslip derivatives shown in Fig. 4, one can conclude that control surface efficiency is enough to control the model up to $\beta = 10°$.

The experimental data are more scattered for 15° angle of attack and positive differential flap deflections. This is probably due to how the flow is separated near the tip on the upper surface, as shown with oil flow visualization in Fig. 3. The outer flap, that is deflected up, is assumed to be more influenced by this separated flow and the yaw moment is thus reduced.

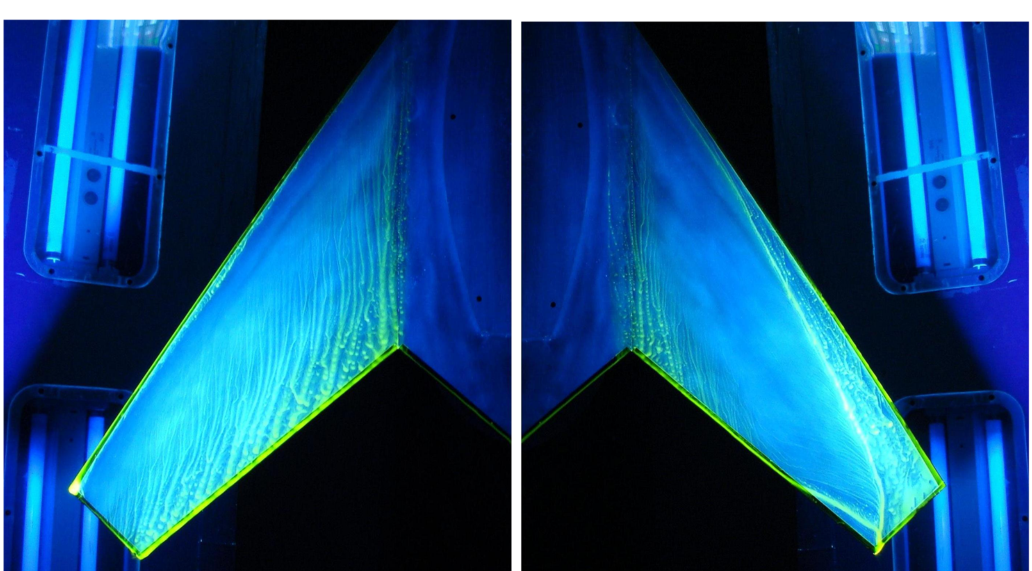

Fig. 3 Oil flow visualization at $\alpha = 5°$ to the left and $\alpha = 11°$ to the right.

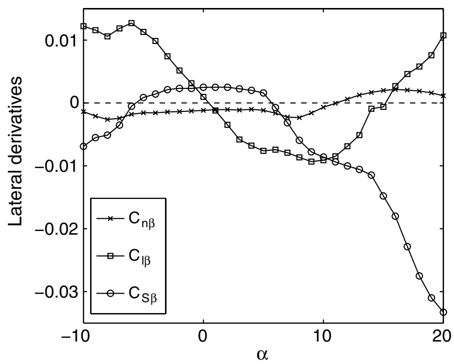

Fig. 4 Lateral derivatives for zero control surface deflection.

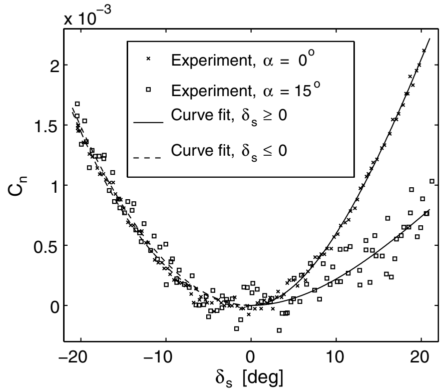

Fig. 5 Yaw moment vs differential flap deflection for $\alpha = 0$ and 15°.

Modeling Lateral Aerodynamics

Close examination of the experimental results suggest that a linear model is adequate for modeling the effect of sideslip on yaw moment, roll moment, and the side force. The secondary effect on the roll moment caused by a differential flap deflection on one wing is so small that it can safely be neglected. The influence of an aileron deflection or a split flap deflection on the side force can also be neglected.

For the influence of a split flap command on the yaw moment shown in Fig. 5, a nonlinear model is clearly required. It appears that it is sufficient to model the yaw moment as a third-order polynomial with different coefficients for positive and negative split flap deflections δ_s. Examining the results presented in Fig. 5 reveals some interesting features of this configuration in terms of yaw control. There is, in most cases, two different deflections that generate the same yaw moment. It may be beneficial to choose the smallest deflection generating the desired yaw moment. Unfortunately, the yaw control efficiency is significantly affected by the angle of attack. For low angles of attack, δ_s should be positive, that is, the outboard flap should be deflected up and the inner flap down. For higher angles of attack, the efficiency is much reduced for positive δ_s, whereas the efficiency is almost unaffected by the angle of attack for negative δ_s.

Conclusions

Not surprisingly, the results presented in this study confirm that control of a reduced radar signature aircraft may be quite challenging. The focus here was placed on yaw control using differential flaps, but one should remember that the four flaps on this aircraft are also needed for pitch and roll control. An interesting feature of using the differential flaps for yaw control is that there are two very different flap settings that give the same yaw moment, one better at low angle of attack and the other better at high angle of attack. On top of that, pitch and roll control must be maintained, giving a most challenging control system design task. Particular difficulties will arise in low-speed flight on approach and takeoff where control surface authority is very limited. Control in low-speed flight is also difficult because of a lower wing loading in comparison to more traditional fighter aircraft configurations. The wing loading must be moderate for the present configuration because the maximum angle of attack can not be much larger than 10° due to the rapid increase in nose-up pitch moment for higher angles of attack. The lower wing loading will make the aircraft more sensitive to gusts and crosswind at takeoff and landing.

The yaw moment as function of flap deflection is well represented using fairly simple nonlinear functions. However, linearization of the expression makes little sense because there is no response in a linear model if the linearization is performed at $\delta_s = 0$. Consequently, most of the standard control system design methods [9] that rely on the accuracy of a linear state space model are not of much use.

Acknowledgments

This project is financially supported by the Swedish Defence Materiel Administration project number 297794-LB747451 monitored by Curt Eidefeldt. The authors also wishes to thank David Eller and Marianne Jacobsen for their support when performing this study.

References

[1] Jenn, D., *Radar and Laser Cross Section Engineering*, AIAA Education Series, AIAA, Reston, VA, 2005.

[2] Nickel, K., and Wohlfahrt, M., *Tailless Aircraft in Theory and Practice*, AIAA Education Series, AIAA, Washington, D.C., 1994.

[3] Myhra, D., *The Horten Brothers and Their All-Wing Aircraft*, Schiffer Military/Aviation History, Schiffer Publ., Atglen, PA, 1998.

[4] Colgren, R., and Loschke, R., "Effective Design of Highly Maneuverable Tailless Aircraft," *Journal of Aircraft*, Vol. 45, No. 4, 2008, pp. 1441–1449. doi:10.2514/1.32083

[5] Eller, D., and Carlsson, M., "An Efficient Aerodynamic Boundary Element Method and Its Experimental Validation," *Aerospace Science and Technology*, Vol. 7, No. 7, Nov. 2003, pp. 532–539. doi:10.1016/S1270-9638(03)00056-7

[6] Kuttenkeuler, J., "Optical Measurements of Flutter Mode Shapes," *Journal of Aircraft*, Vol. 37, No. 5, 2000, pp. 846–849. doi:10.2514/2.2679

[7] Barlow, J. B., Rae, W. H., and Pope, A., *Low Speed Wind Tunnel Testing*, Wiley-Interscience, New York, 1999.

[8] Etkin, B., and Reid, L. D., *Dynamics of Flight, Stability and Control*, Wiley, New York, 1996.

[9] Stevens, B. L., and Lewis, F. L., *Aircraft Control and Simulation*, 2nd ed., Wiley, New York, 2003.