NASA/CR—2000-210561

# An Evaluation of an Analytical Simulation of an Airplane With Tailplane Icing by Comparison to Flight Data

Dale W. Hiltner
Ohio State University Research Foundation, Columbus, Ohio

December 2000

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National Aeronautics and
Space Administration

Glenn Research Center

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## Acknowledgments

I would like to thank the NASA Glenn Research Center Icing Branch for providing funding to support this effort through a grant to The Ohio State University. I also wish to thank the Tailplane Icing Program lead engineer and technical monitor, Tom Ratvasky, for his ongoing support and guidance. Dr. Richard Freuler provided support and encouragement during my employment at The Ohio State University Aeronautical and Astronautical Research Laboratory, increasing my understanding of the university research system. Special thanks go to Dr. James Riley of the FAA William J. Hughes Technical Center, whose continued interest in the Tailplane Icing Program ensured its completion.



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$C_T$ thrust coefficient

$F_{ye}$ column (or stick) force, positive pull, lbs.

G acceleration of gravity

$n_c$ commanded load factor

$n_z$ normal acceleration, z-direction

t time

V airspeed

$\alpha$ angle-of-attack of aircraft reference line

$\alpha$ tailplane angle-of-attack

$\delta$ flap deflection angle

## Executive Summary

This report presents the assessment of an analytical tool developed as part of the NASA/FAA Tailplane Icing Program. The analytical tool is a specialized simulation program called TAILSIM which was developed to model the effects of tailplane icing on the flight dynamics of the NASA Glenn Research Center DHC-6 Twin Otter *Icing Research Aircraft*. This report compares the responses of the TAILSIM program directly to flight test data. The comparisons should be useful to potential users of TAILSIM.

The comparisons show that the TAILSIM program qualitatively duplicates the flight test aircraft response during maneuvers with ice on the tailplane. TAILSIM is shown to be quantitatively "in the ballpark" in predicting when Ice Contaminated Tailplane Stall will occur during pushover and thrust transition maneuvers. As such, TAILSIM proved its usefulness to the flight test program by providing a general indication of the aircraft configuration and flight conditions of concern.

The aircraft dynamics are shown to be modeled correctly by the equations of motion used in TAILSIM. However, the general accuracy of the TAILSIM responses is shown to be less than desired primarily due to inaccuracies in the aircraft database. The high sensitivity of the TAILSIM program responses to small changes in load factor command input is also shown to be a factor in the accuracy of the responses. A pilot model is shown to allow TAILSIM to produce more accurate responses and contribute significantly to the usefulness of the program. Suggestions to improve the accuracy of the TAILSIM responses are to further refine the database representation of the aircraft aerodynamics and tailplane flowfield and to explore a more realistic definition of the pilot model.

# 1.0 Introduction and Background

## 1.1 The Tailplane Icing Program

Icing is one of the most insidious problems of aircraft operations. Ice contamination of aircraft surfaces can have a dramatic impact on an aircraft's flight characteristics. Typically, when discussing icing the wing is most often considered. Historically pilots have checked for ice on the wings as the most critical indication of icing conditions. This is understandable, since changes in wing characteristics have the greatest impact on the performance of an aircraft.

However, there is another serious icing scenario: ice contamination of the tailplane, with or without ice contamination of the wing. Tailplane icing may result in an Ice Contaminated Tailplane Stall (ICTS) event, which occurs when the local angle-of-attack (AOA) at the tailplane exceeds the stalling angle-of-attack. It most commonly occurs when an aircraft is on approach and has flaps extended. The result can be an uncontrollable nose down pitching motion and accompanying dive from which the aircraft may be too low to recover. An ICTS event is often accompanied by nose down elevator lock, a condition in which the differential pressure on the elevator of the stalled tailplane may cause the elevator to be forced into a nose down position. The resulting elevator hinge moment may be strong enough to pull the yoke from the pilot's hands, and prevent recovery to a nose up control position. Examples of ICTS accidents and incidents are reported in References 1 to 3.

The key aerodynamic parameters that describe the conditions of an ICTS event are illustrated in Figure 1. This figure shows a cruise condition and an approach condition. At cruise, the higher airspeed requires a low angle-of-attack, $\alpha$, and a low wing lift coefficient and circulation. The low wing circulation causes a small downwash angle resulting in a small, but typically negative, tailplane angle-of-attack, $\alpha_t$. At approach airspeed with approach flaps extended, the angle-of-attack may be similar, but, due to the lower airspeed and flap deflection, the wing lift coefficient and circulation are larger. This larger circulation causes a larger downwash angle resulting in a much more negative tailplane angle-of-attack. The additional effect of a negative, or nose down, pitch rate about the aircraft center-of-gravity causes the tailplane angle-of-attack to become more negative simply by the airflow induced at the tailplane moment arm location.

Over the past 18 years, ICTS has been responsible or is suspected in 16 accidents with 139 fatalities (Ref. 4). Due to their flight at lower altitudes where icing is more common and their simple reversible control systems, commuter class aircraft are most commonly affected. In response to this problem, the Federal Aviation Administration (FAA) has conducted workshops on the ICTS phenomenon and conducted a study to identify aircraft susceptible to ICTS. As a result of this effort, more knowledge of ICTS has been presented to the pilot community (Refs. 1 to 3, and 5 to 7) and a greater understanding of ICTS is developing.

The tailplane icing phenomenon has been studied using the methods of flight tests (Refs. 1 and 8), wind tunnel tests of typical tailplane airfoils (Refs. 5 and 6), and analysis of aircraft dynamics (Refs. 7 and 9). Most of the previous efforts attempted to define the effects of tailplane icing on local tailplane airfoil characteristics or overall aircraft dynamic characteristics. Reference 7 included nonlinear tailplane data in a simplified longitudinal flight path simulation analysis. Reference 9 attempted to quantify tailplane lift requirements during dynamic pushover maneuvers.

Currently, a pushover to zero load factor, or the Zero-G maneuver, and steady heading sideslips are the only practiced flight test methods to indicate susceptibility to ICTS (Ref. 10). The effect of the Zero-G maneuver is to increase the negative angle-of-attack at the tailplane. The intent is to create larger negative tailplane AOA than would normally occur during a typical flight. As defined in Reference 10, the maneuver is expected to be performed over a complete range of flap deflections and airspeeds, with representative tailplane ice shapes attached to the tail. If tailplane stall occurs, as indicated by a stick force reversal, the aircraft is considered to be susceptible to ICTS.

The Zero-G maneuver analysis of Reference 9 shows a good correlation with known aircraft susceptibility. However, no attempt at comparing such analysis to flight test data has been made. Additionally, Reference 7 shows effects of tailplane icing on aircraft responses, but these results are considered to be qualitative. Clearly, there is a need to quantify more completely the aerodynamic and dynamic phenomenon of pushover maneuvers.

To meet this need for more accurate, quantified knowledge of the aerodynamics and flight dynamics of the ICTS phenomenon, NASA Glenn Research Center (GRC), the FAA William J. Hughes Technical Center, and The Ohio State University, instituted a project to more fully investigate the ICTS phenomenon. The Tailplane Icing Program (TIP) was a four-year research program that utilized the NASA GRC Icing Research Tunnel (IRT), The Ohio State University (OSU) Low Speed Wind Tunnel, NASA GRC's DeHavilland DHC-6 Twin Otter Icing Research Aircraft, and analytical tools.

Flight testing of the DHC-6 Twin Otter was the culmination of all other TIP efforts, and provided the most important results for the TIP project (Ref. 11). This effort will be briefly discussed in the next section. An aircraft simulation program that incorporated the effects of tailplane icing was developed specifically for the TIP project to generate analytical results. This nonlinear simulation program of the DHC-6 Twin Otter (named TAILSIM) was used to provide insight into potential ICTS areas of the flight envelope prior to flight testing, and to support the flight test results. The effectiveness of TAILSIM in this role and as a predictive analytical tool provides the subject of this report.

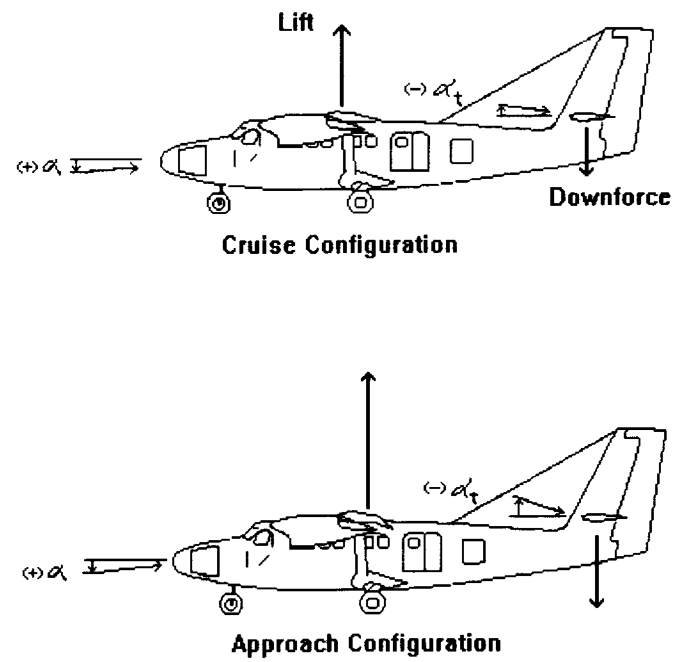


Figure 1. Effect of Configuration on Wing and Tailplane Angle-of-Attack

## 1.2 TIP Flight Testing

Extensive flight testing of the NASA GRC DHC-6 Twin Otter Icing Research Aircraft was the major effort of the TIP project. The DHC-6 Twin Otter was chosen for this testing because of its availability and known susceptibility to tailplane stall. Another advantage was that prior flight-testing had been accomplished to produce a coefficient database using parameter estimation methods (Ref. 8).

Forty-two research flights were conducted in the two-phase flight test program. Flight test maneuvers with three different ice shapes and a clean tailplane included 1g wings level and steady-state sideslip test conditions, pushovers to varying G levels, elevator doublets, thrust transitions, and wind up turns. This testing is fully described in the test report, Reference 11, and associated papers (Refs. 12 to 14).

The first phase of TIP flight-testing performed initial evaluation of the DHC-6 Twin Otter with a clean tailplane and was accomplished in September-October, 1995. This testing accomplished maneuvers at a full range of flight conditions and aircraft configurations. It provided valuable experience and baseline knowledge and insight into the aircraft's dynamics and tailplane flow characteristics. Analysis of this testing resulted in the re-calibration of the tailplane 5-hole flow probes to a larger angle-of-attack range and re-working of the downwash calculations for TAILSIM. These results helped to improve the accuracy of TAILSIM so that TAILSIM responses could be used in the test preparation and safety oversight process for the next phase of flight testing with ice shapes on the tailplane. TAILSIM provided insight into the tailplane stall envelope and helped define potentially limiting aircraft configurations and maneuvers for the NASA Twin Otter.

The primary purpose of the second phase of flight-testing was to perform pushover and additional maneuvers to evaluate the tailplane stall characteristics of the aircraft with ice shapes on the tailplane. This testing was accomplished in July-October 1997. Ice shapes tested included a double-horn, glaze ice shape called the S&C ice shape (Figure 2), an Inter-cycle ice accretion from IRT testing (Figure 3), and a Failed-Boot ice accretion from IRT testing (Figure 4). Testing was accomplished with all three ice shapes and repeatability testing was accomplished with the baseline clean (uniced) tailplane.

As in the first phase testing, full ranges of flight conditions and aircraft configurations were tested. The pushover maneuver and a thrust transition maneuver resulted in the most negative tailplane angle-of-attack. During the testing control force reversals were experienced during pushovers to Zero-G at $\delta_f = 20°$ flap deflection with both the Failed Boot and S&C ice shapes. A full tailplane stall occurred during a thrust transition maneuver at V = 85 KIAS with $\delta_f = 40°$ and the Failed Boot ice shape on the tailplane.

Other maneuvers were flown to provide further insight and data for further analysis. The results of these flight tests clearly showed the limits on the ability of the flow to remain attached to the tailplane. Conditions of high thrust setting, low airspeed, large flap deflections, and aggressive nose down maneuvering resulted in degraded control and aircraft stability. A key result of this flight testing, in addition to defining these problem areas, was to note the sometimes subtle differences between a tailplane stall and a wing stall. This was important information, as the recovery for a wing stall is the opposite of a recovery for a tailplane stall, and was documented in an educational video tape for pilots (Ref. 15).

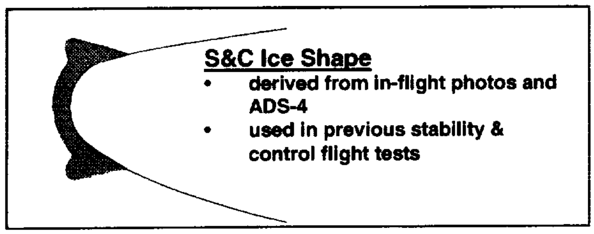


Figure 2. S&C ice shape

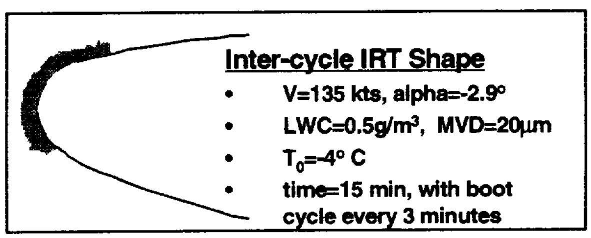


Figure 3. Inter-cycle ice shape

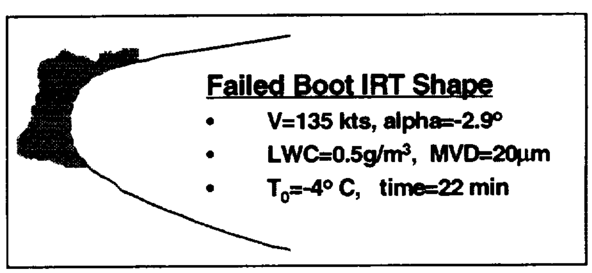


Figure 4. Failed-Boot ice shape

1.3 TAILSIM Development

A key element of the TIP project was to use this flight test data to support the development of analytical tools. A goal was to provide an analytical capability that could discriminate tailplane sensitivity to icing, and match the response of the aircraft in flight. The wealth of data available for the DHC-6 Twin Otter provided an excellent source of information for the development of this analytical tool, the flight path simulation program TAILSIM, so named because of its emphasis on the effects of tailplane aerodynamics. This report does not attempt to provide detailed information on TAILSIM, but only to assess its performance using flight test data from the DHC-6. A full description of the analytical models embodied in TAILSIM, and of the experimental database used by TAILSIM in simulating flight test data from the DHC-6, can be found in Reference 18.

The ICTS phenomenon is highly nonlinear, so the analytical tool chosen for the TIP was a nonlinear simulation program. The TAILSIM program provided the desired fidelity in describing these nonlinear tailplane stall aerodynamics and aircraft dynamics. A requirement of the analytical tool included the ability to output aircraft parameters and local tailplane parameters during a time history maneuver to support the flight testing. Due to these specific requirements and the desire to maintain flexibility in program development, an in-house program was created.

Nonlinear simulations typically consist of aircraft coefficients contained in tables that are used to determine the forces and moments acting on an aircraft. These forces and moments are then used in the nonlinear aircraft equations-of-motion to determine the accelerations on the aircraft. These accelerations are then integrated to determine the aircraft's motion. A benefit of this analysis method is that the tables can be used to describe any parameter to a high level of fidelity. Another advantage is that different characteristics can be implemented readily by changing the data in the tables and the build-up equations describing the forces and moments.

The implementation of TAILSIM was relatively straightforward using a 4th order Runge-Kutta method to integrate the standard aircraft equations-of-motion. A database was developed from the stability and control coefficients available from 1992 testing of the NASA GRC DHC-6 Twin Otter (Ref. 8). The emphasis on this study is on the tailplane, though, so a database of tailplane aerodynamic characteristics was required. Hinge moment characteristics were of special interest, since very little information on them was available, and they directly impact pilot control forces.

It was desired to utilize as much experimental data as possible during the course of this study, so wind tunnel tests of the tailplane were a logical choice to acquire data on tailplane characteristics. Two wind tunnel tests in the Ohio State University Aeronautical and Astronautical Research Laboratory Low-Speed Wind Tunnel Facility were conducted to determine the section characteristics of the Twin Otter tailplane with and without ice shapes (Ref. 16 and 17). Ice shapes for this testing were generated by NASA GRC from historical data, the LEWICE icing program, and an entry in the NASA GRC Icing Research Tunnel. This 2-D section data did not fully represent the tailplane, so 3-D tailplane characteristics had to be estimated to create a tailplane database for each ice shape tested.

The requirement of creating a tailplane database dictated separating the tailplane contribution from the available aircraft database, which already included the tailplane effects in its coefficients. Considering the wing/body and tailplane characteristics separately is typically not done for simulation analysis. Specific methods were required to accomplish this, using the standard aircraft/tailplane interface parameters, downwash angle and tailplane dynamic pressure ratio. Various methods were used to incorporate the data from these different sources into a single database, and to extend the database to the required range of angle-of-attack and flap deflection. Empirical methods from well-known sources were only used when test data was not available to define required parameters such as downwash angle.

Because the ICTS phenomenon is typically accompanied by tailplane hinge moment and, therefore, stick force variations, it was required to model the reversible control system. As noted above, analyzing the impact of hinge moment characteristics on aircraft responses was a requirement of this study. It was clear early in the course of this study that some control of the simulated aircraft was required, to realistically determine the response to tailplane hinge moment variations. A pilot model was chosen for this control, as it would duplicate typical responses and generate information on handling qualities. The $n_z$ pilot model (See Reference 18) was especially beneficial as it provided compensation for inaccuracies in the database.

## 2.0 Results and Discussion of Flight Test and TAILSIM Responses

### 2.1 Overview

Reference 18 describes the extensive analysis that was generated using TAILSIM in support of the TIP project. TAILSIM was used to estimate the tailplane flow environment during trimmed flight and Zero G pushover maneuvers. Analysis was performed with the baseline, uniced tailplane, and the tailplane with the LEWICE ice shape. Results from the Refs 16-17 indicated that the tailplane aerodynamic characteristics with the S&C ice shape and LEWICE ice shape were equivalent, allowing comparison to flight test data with the S&C ice shape. A reduced-G pushover with more sensitive pass/fail criteria was suggested as a more relevant tailplane stall discriminator. Additional work defined the limits on negative G pushover capability due to tailplane stall angle-of-attack in relevant engineering terms by use of a V-n diagram.

Overall, the Reference 18 analysis using TAILSIM identified aircraft configuration and flight condition combinations that lead to ICTS similar to those defined during the flight testing. Results of trimmed flight at low airspeed showed that with an ice shape attached the tailplane angle-of-attack reached the stall angle-of-attack at the higher range of the allowable flap extension airspeeds at $\delta_f = 40°$. This suggested reduced stability as well as reduced maneuverability, and was validated by the full tailplane stall at full flap deflection noted in Section 1.2. Results of TAILSIM pushovers to near Zero-G with $\delta_f = 20°$ resulted in a tailplane stall, as well. This was a similar result to the control reversals noted in Section 1.2.

## 2.2 Pushover Maneuver Comparison

To show the capability of TAILSIM to predict a tailplane stall, a maneuver that showed tailplane stall tendencies is shown for comparison. The flight test maneuver chosen was 9749PO23, a pushover to low-G with a flap deflection of $\delta_f = 20°$ and the S&C ice shape on the tailplane. This configuration was shown during flight testing to allow aggressive pushover maneuvers to be performed without causing a full tailplane stall, but with noticeable control force reversal. Therefore, this specific maneuver can be considered to define the tailplane stall boundary.

In order to obtain a good match with flight test, an $n_c$ command profile was generated that resulted in a good match in airspeed as well as $n_Z$. This required some "tuning" of the $n_c$ command input, including an approximate 1-second lead (this will be discussed later in Section 3). Comparison time histories are shown in Figure 5 to Figure 12.

The $n_Z$ and airspeed responses show reasonably good agreement except for the overshoot responses in TAILSIM as a result of tailplane stall. The flight test data also shows tailplane stall, as indicated by the stick forces, but does not show a similar overshoot response due to quicker pilot reaction to these changes in stick force. TAILSIM stick force shows some of the recovery peaks that are seen in the flight test data, but they are delayed. This is partly because the pilot model reacts to the integrated $n_Z$ command error caused by tailplane stall and so lags the actual $n_Z$ error. Both TAILSIM and the flight test data show signs of stick force gradient reversal, or lightening, indicating that the tailplane hinge moment break has been reached. The flight test data also indicates stick force reversal from the tailplane stall, while TAILSIM does not clearly show reversal. An example of this can be seen in the flight test data by the rapid positive increase in elevator deflection beginning at time t = 38 sec, with no corresponding increase in push (negative) stick force. Pull force starts to increase at time t = 38.5 sec, but negative recovery elevator does not start until time t = 40 sec. With TAILSIM, the hinge moment break can be seen by the accelerating rate of more positive elevator deflection, without a corresponding increase in stick force. TAILSIM generally shows the normal sign of force versus elevator deflection. Overall, neither the TAILSIM stick force results nor the TAILSIM elevator deflection results show good quantitative agreement to the flight test data.

The effects of the control force reversal can be seen in the flight test data by "breaks" in $n_Z$, angle-of-attack, tailplane angle-of-attack, and pitch rate, primarily at times t = 38 sec, 51sec and 64 sec. TAILSIM parameters of interest show good agreement with the flight test data and show these breaks, but also show responses with large overshoots. Angle-of-attack shows qualitatively good agreement remaining within $\Delta\alpha = 1°$. Pitch angle and tailplane angle-of-attack show, qualitatively, very good agreement, maintaining their respective trim mismatches. (Note that these trim mismatches may be evidence of possible inaccuracies in the basic lift curve data). Pitch rate shows excellent agreement, except for the overshoot at both positive and negative peaks.

Overall, the TAILSIM program agreement with flight test is mixed. Qualitatively, TAILSIM shows overall good agreement with flight test data, and does reveal the existence of control and tailplane stall problems. The physics of the program seem correct, as represented by the good $n_Z$ versus pitch rate comparison. The attitude parameters show good accuracy, qualitatively, but are not as quantitatively accurate as desired. Additionally, it is clear that the stick, pilot model, and elevator deflection dynamics are not quantitatively as accurate as desired. The match of these parameters can only be described as fair.

The more significant question, though, is how well the TAILSIM program predicts a tailplane stall condition for the aircraft. Flight test notes and flight test data indicate that noticeable control force reversal occurred on this pushover maneuver. The TAILSIM response clearly shows a tailplane hinge moment break and stall break causing a large overshoot. Therefore, the TAILSIM response prediction is considered to be qualitatively good, but conservative.

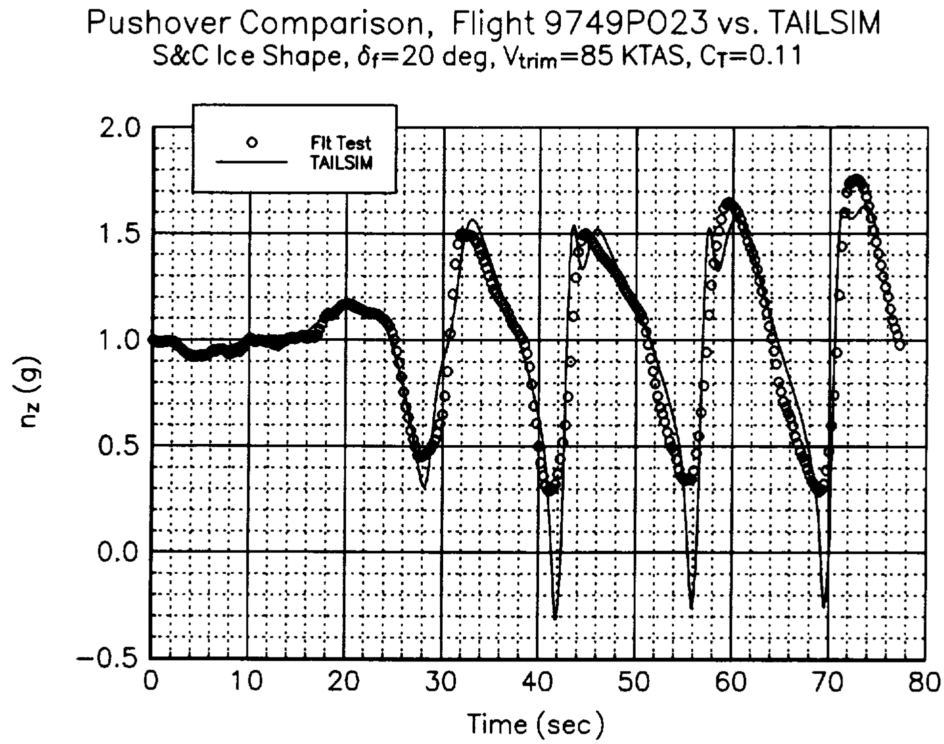


Figure 5. Pushover Maneuver: $n_Z$ Comparison

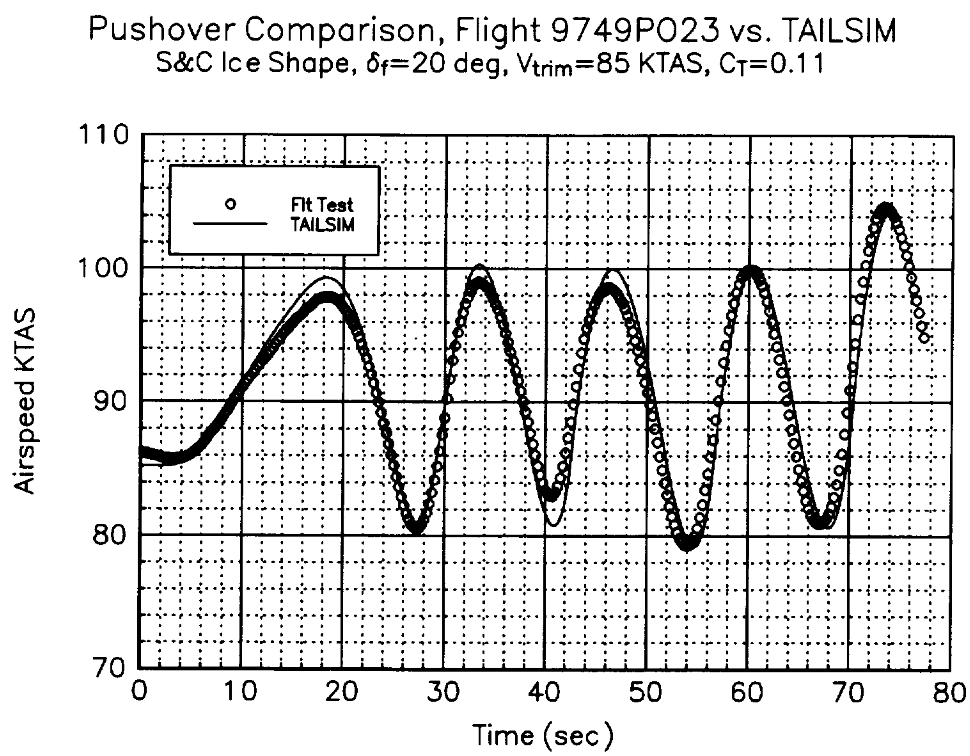


Figure 6. Pushover Maneuver: Airspeed Comparison

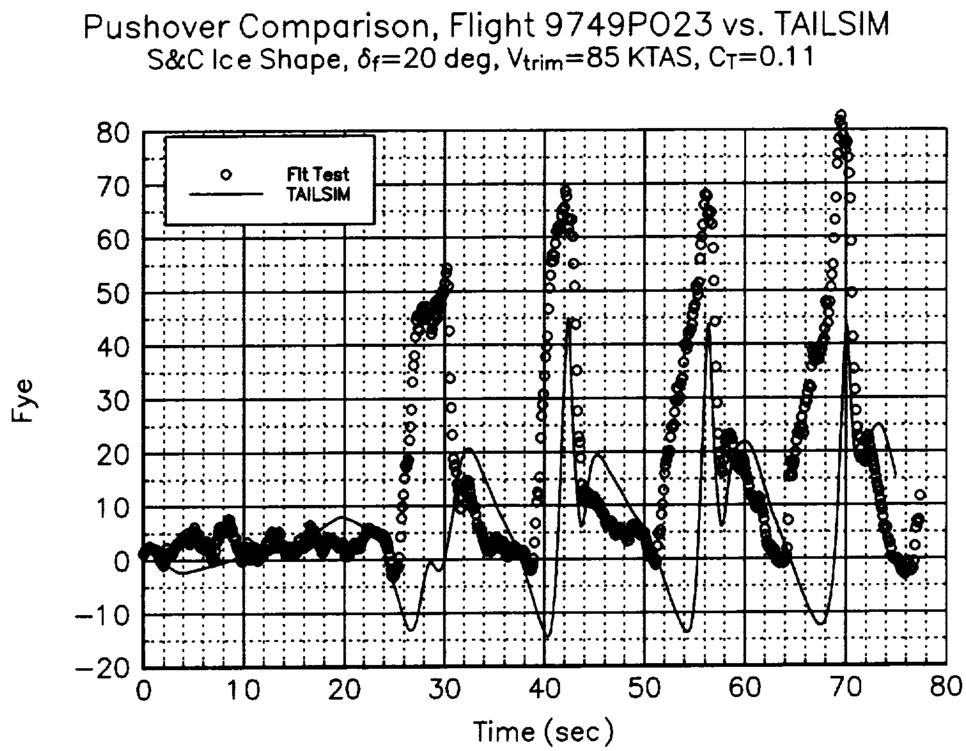


Figure 7. Pushover Maneuver: Stick Force Comparison

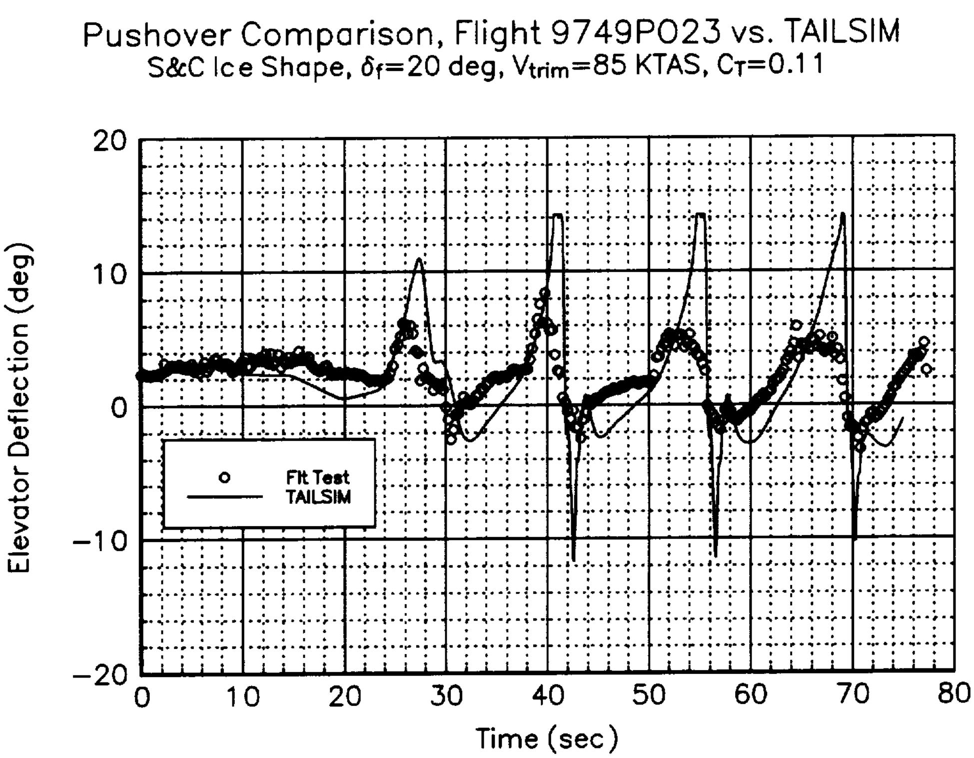


Figure 8. Pushover Maneuver: Elevator Deflection Comparison

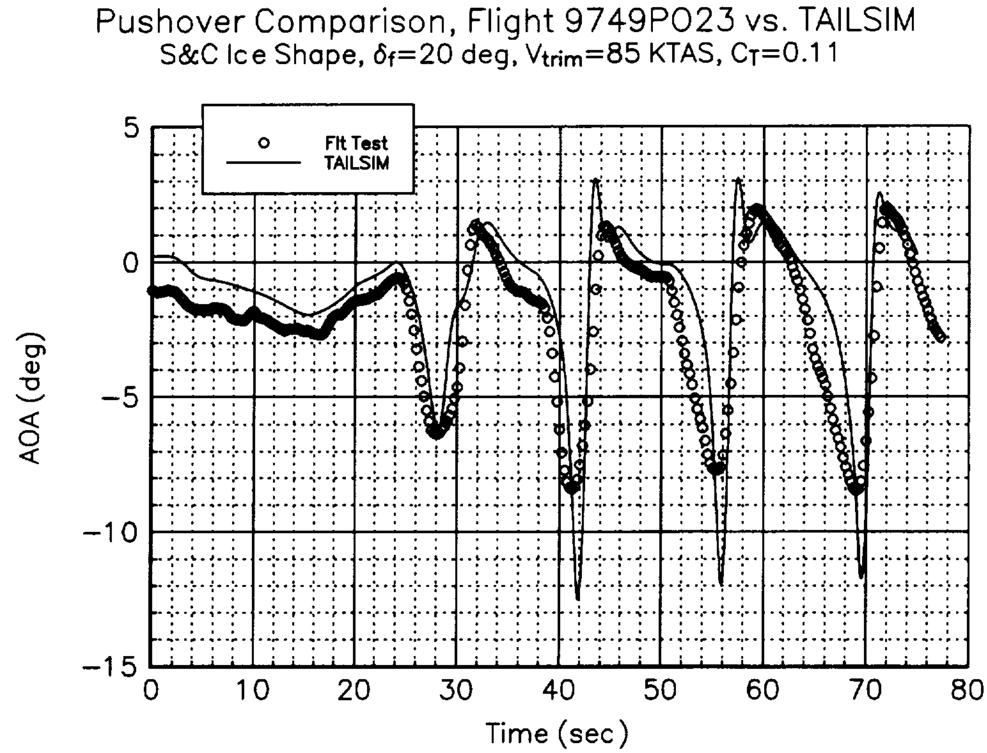


Figure 9. Pushover Maneuver: AOA Time History Comparison

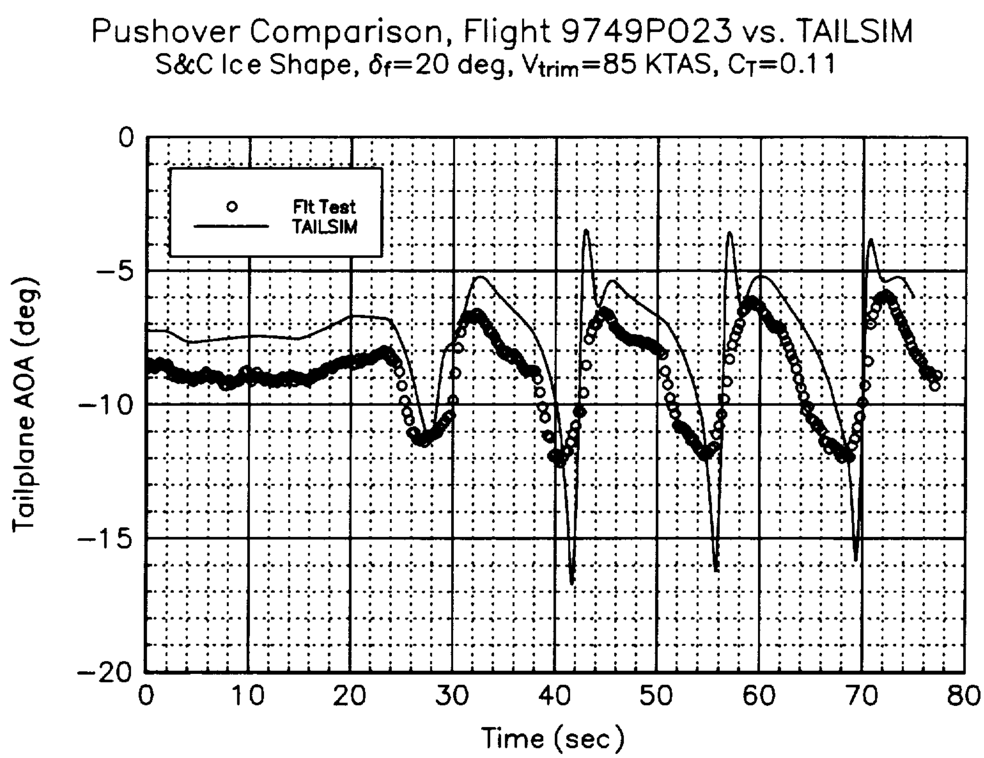


Figure 10. Pushover Maneuver: Tailplane AOA Comparison

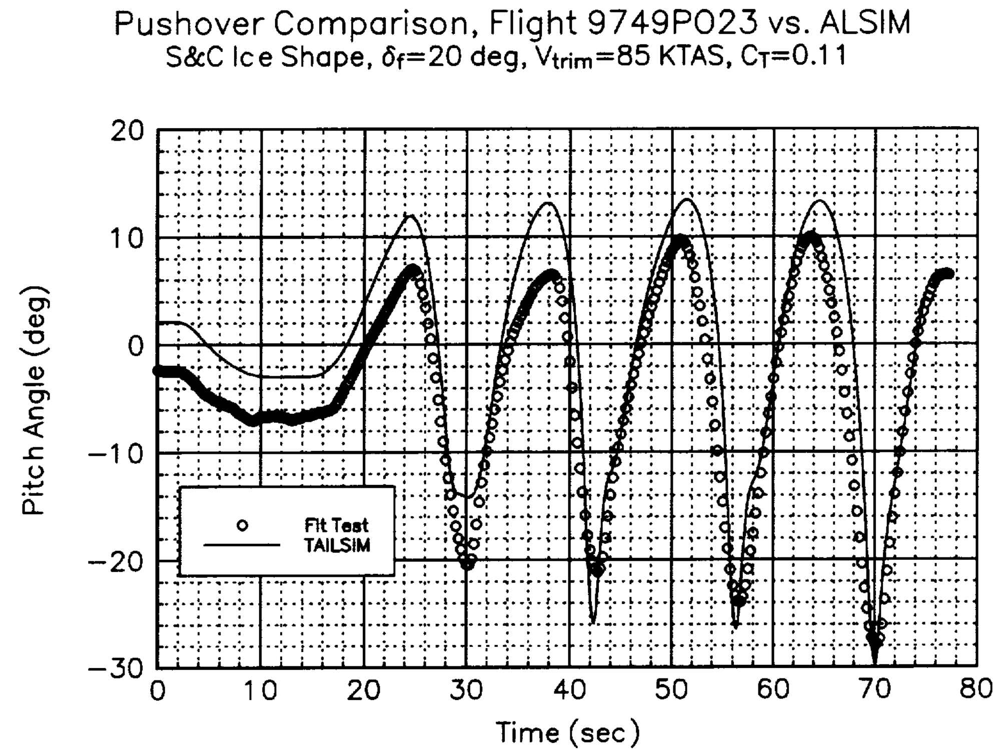


Figure 11. Pushover Maneuver: Pitch Angle Comparison

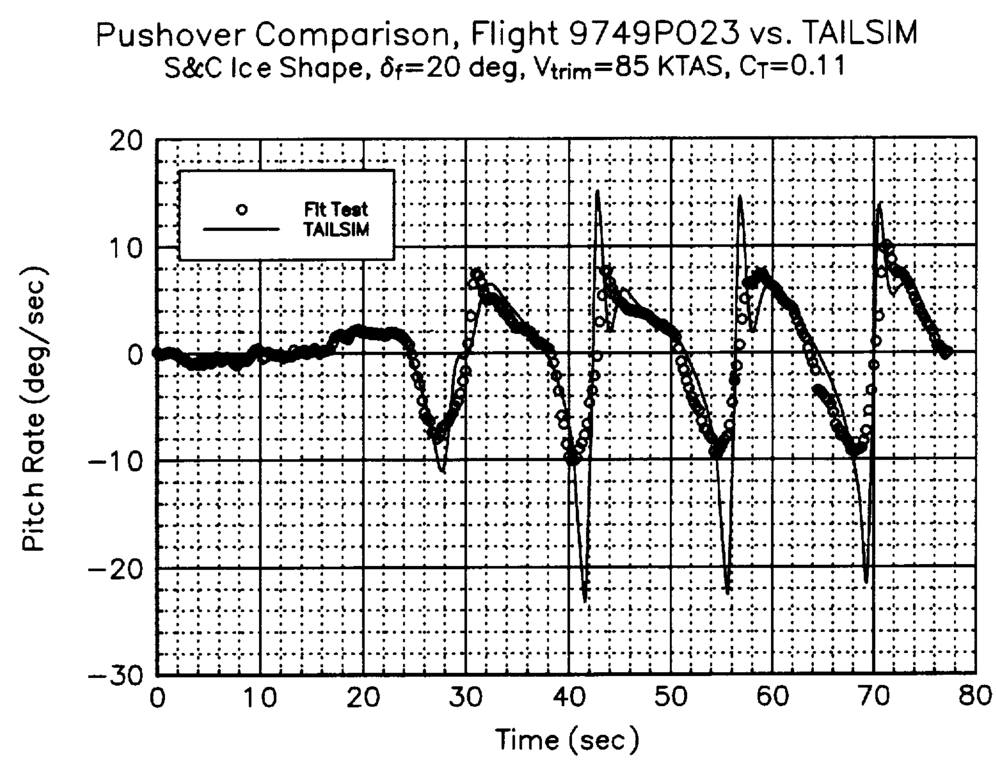


Figure 12. Pushover Maneuver: Pitch Rate Comparison

## 2.3 Thrust Transition Maneuver Comparison

The thrust transition maneuver was found during flight testing to be able to bring the tailplane to near stall, and to a full stall in one case. Most importantly, it allowed the aircraft to be maneuvered into the critical low airspeed and high thrust flight conditions in a controllable way. This allowed the effects of increased tailplane flow separation on aircraft stability and control to be effectively demonstrated. As such, the thrust transition was one of the more useful maneuvers performed during the flight test program.

To perform this maneuver in TAILSIM, airspeed feedback was used in the pilot model. A straightforward proportional plus integral airspeed error feedback was added to the $n_z$ error feedback. The total feedback was then used to drive the elevator through the reversible control system model. Feedback gains that kept the airspeed within a few knots of the trim airspeed were found by trial and error.

A comparison of a thrust transition maneuver is shown in Figure 13 to Figure 21. The flight test maneuver chosen for comparison was 9750PT18, which started with a trim at V = 70 kts and thrust coefficient of $C_T = 0.011$ at a flap deflection of $\delta_f = 20°$ with the S&C ice shape on the tailplane. Figure 21 shows that the input thrust coefficient used to drive TAILSIM was able to be kept simple and provide a good match to that of the aircraft. It also shows that the thrust coefficient reached $C_T = 0.24$, 60 percent more than the highest level seen during development flight testing for the database, $C_T = 0.14$. Note that the TAILSIM database was set to allow linear extrapolation beyond $C_T = 0.14$ for this comparison, but the data should be considered suspect for such extrapolation.

The flight test data, plotted at 20Hz, clearly shows the effects of separated flow on the tailplane, but no tailplane stall. These flow separation effects are readily seen in the large scatter in the flight test data that starts at approximately time t = 25 sec. Tailplane angle-of-attack of the aircraft is in the $\alpha_t = -9°$ to $-10°$ range when this separation begins. The effect of this separation on elevator hinge moment is readily seen by the large spikes in positive (pull) stick force at time t = 24 and t = 28 sec, with no corresponding spike in elevator deflection. The control and stability of the aircraft are much reduced at this time in the maneuver, but a full tailplane stall does not occur.

TAILSIM does not model the dynamics of flow separation. However, the tailplane aerodynamic models do contain the hinge moment break that occurs prior to full tailplane stall. For the elevator deflections shown in 16, and, using the information in Reference 18, the hinge moment break was found to be approximately $\alpha_t = -8°$, while stall angle-of-attack was approximately $\alpha_t = -10.5°$. The hinge moment break is clearly seen in the TAILSIM response at approximately time t = 38 sec, at approximately $\Delta\alpha_t = 1°$ more positive than that indicated by the flight test data, a similar error to that seen during the pushover maneuvers. After this time, stick activity, and all other parameters, show qualitatively similar activity to that seen in the flight test data. The stick force shows lower magnitude, but all other parameters show similar magnitude to flight test data. The frequency of the responses is more difficult to quantify, but TAILSIM appears to be slightly faster than the flight test aircraft.

While TAILSIM can show representative affects of tailplane separation, overall, the TAILSIM response agreement with flight test is only fair. Throughout the maneuver airspeed agrees within V = 5 kts, which is considered good for the TAILSIM airspeed feedback. However, the trim angle-of-attack is $\Delta\alpha = 2.3°$ higher than that of the aircraft. Trim tailplane angle-of-attack is approximately $\Delta\alpha_t = 4°$ more positive. Elevator and stick forces start out at similar values, but TAILSIM shows the opposite force trend. This may be due, in part, to the larger decrease in tailplane angle-of-attack during the thrust increase. For TAILSIM the total change during the maneuver is approximately $\Delta\alpha_t = -5°$, while the flight test data shows approximately $\Delta\alpha_t = -2°$. Except for elevator deflection and stick force, all parameters show similar trends.

This comparison has shown that TAILSIM can simulate the utility of the thrust transition maneuver. Tailplane stall characteristics are shown in a controlled manner, as demonstrated during flight test. The TAILSIM response clearly shows a tailplane hinge moment break and control difficulties similar to those seen on the aircraft at similar tailplane AOA. However, the comparison also shows that the TAILSIM aircraft model aerodynamics and thrust effects are only of fair accuracy.

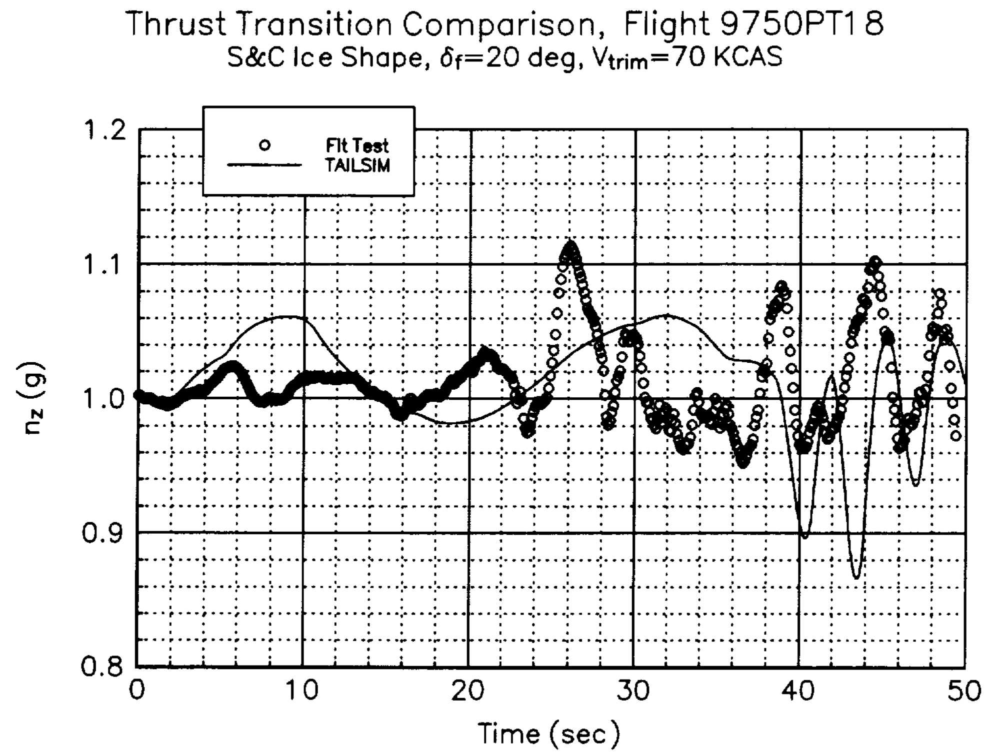


Figure 13. Thrust Transition Maneuver: $n_Z$ Comparison

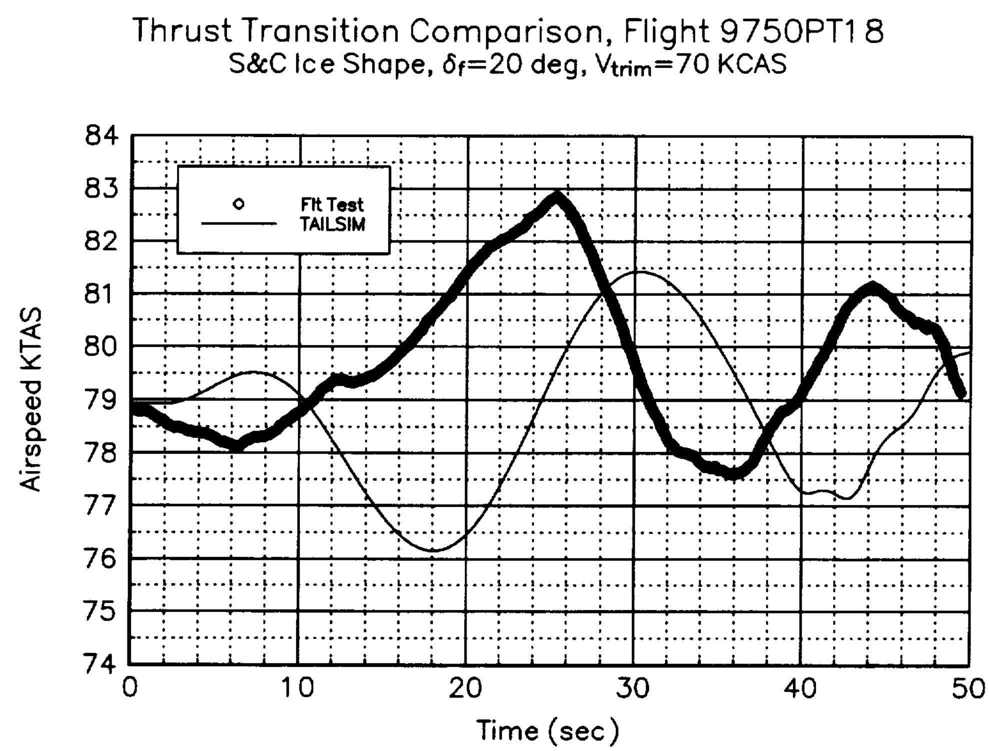


Figure 14. Thrust Transition Maneuver: Airspeed Comparison

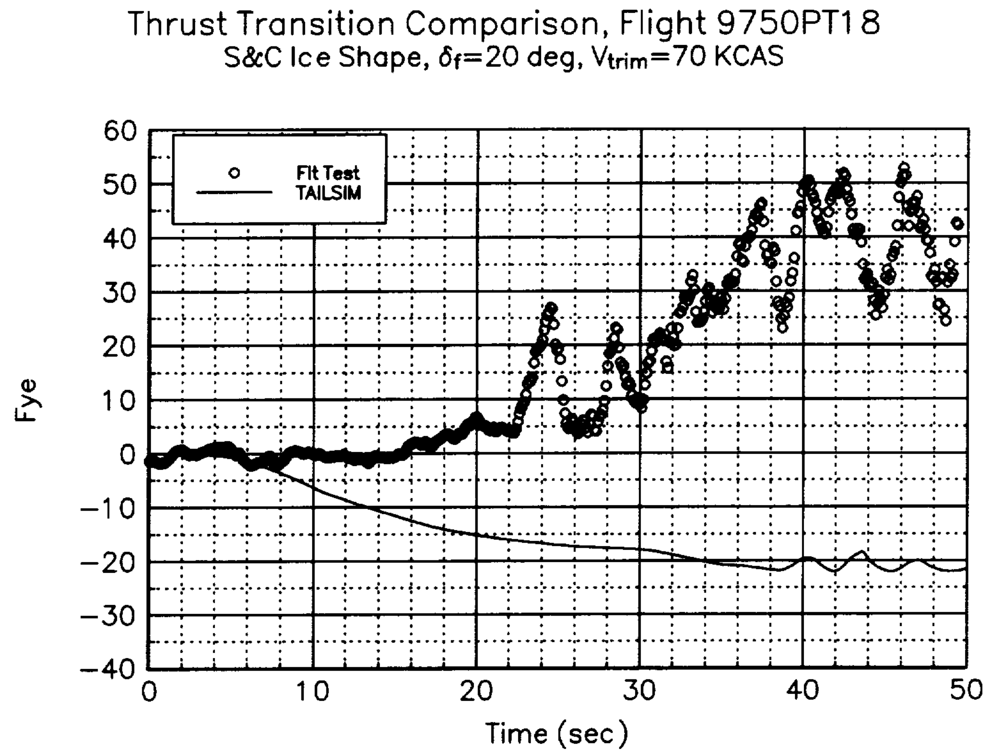


Figure 15. Thrust Transition Maneuver: Stick Force Comparison

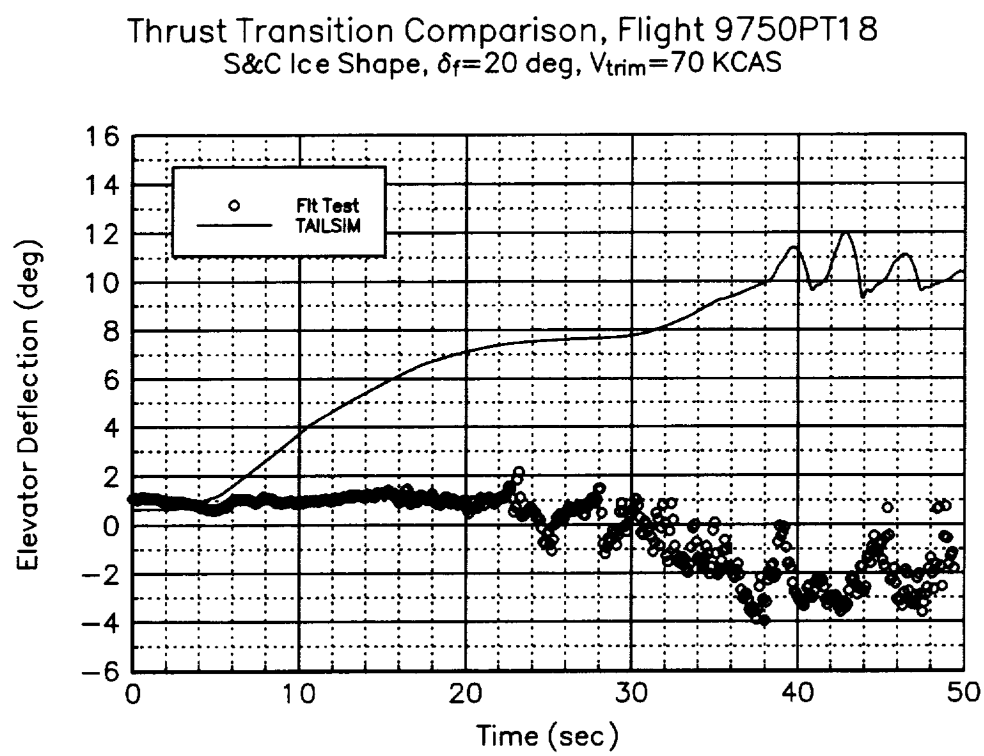


Figure 16. Thrust Transition Maneuver: Elevator Deflection Comparison

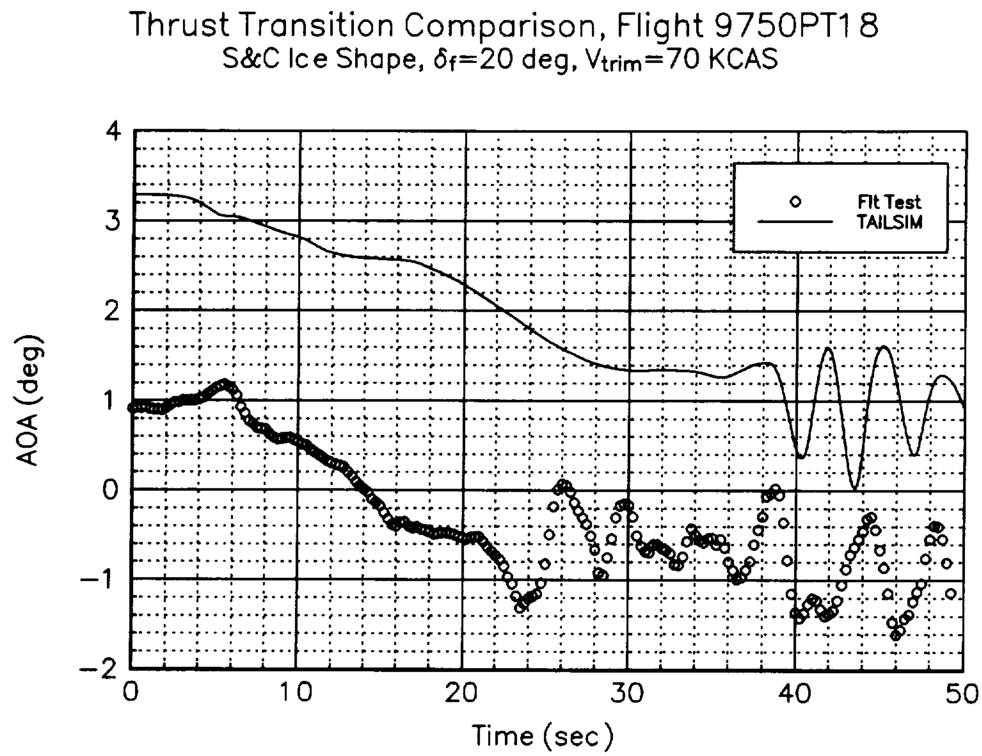


Figure 17. Thrust Transition Maneuver: Aircraft AOA Comparison

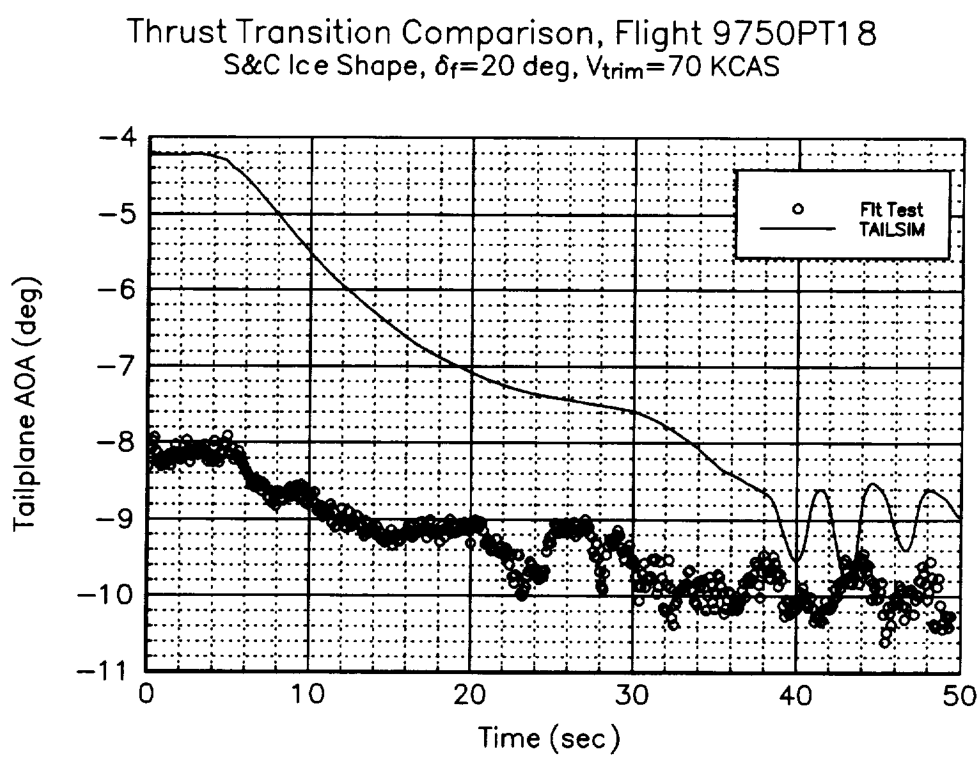


Figure 18. Thrust Transition Maneuver: Tailplane AOA Comparison

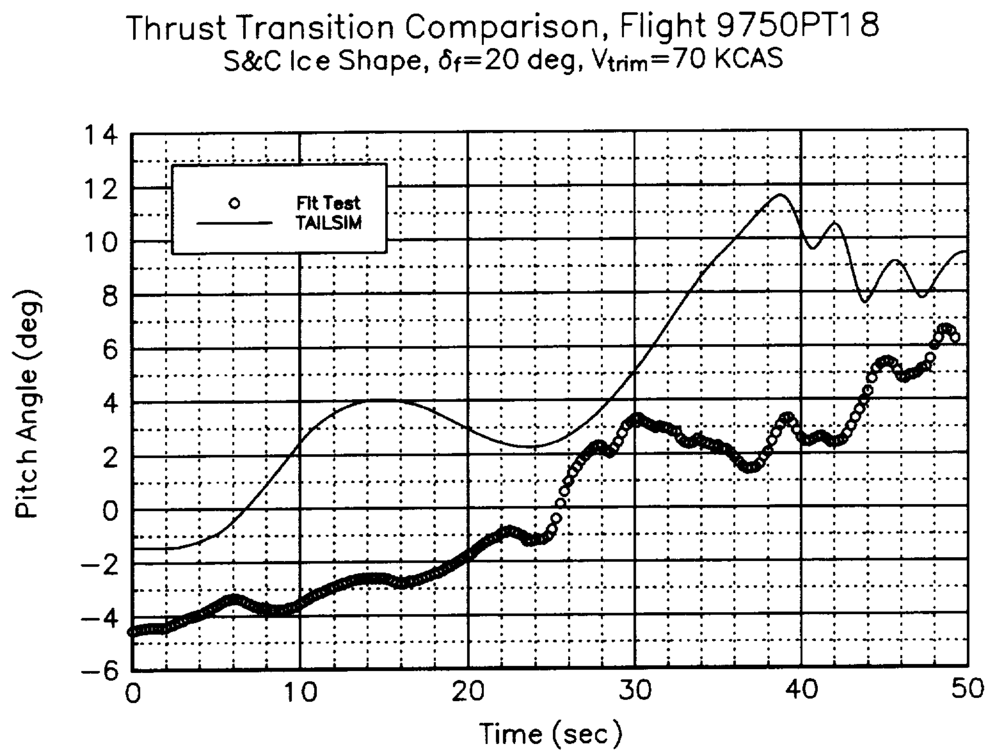


Figure 19. Thrust Transition Maneuver: Pitch Angle Comparison

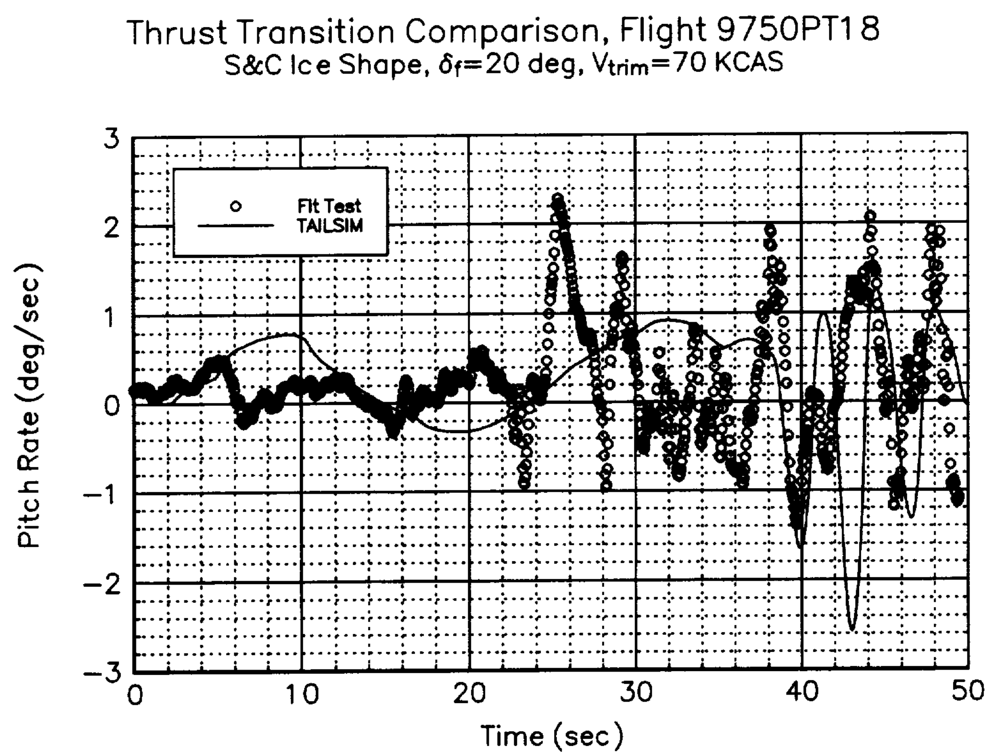


Figure 20. Thrust Transition Maneuver: Pitch Rate Comparison

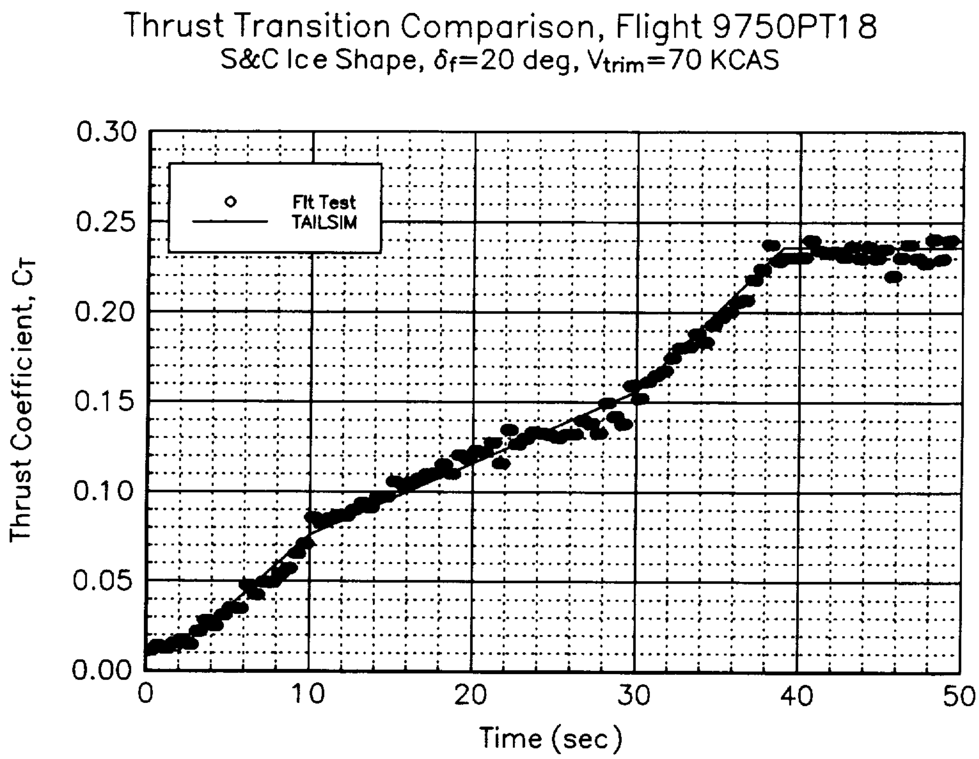


Figure 21. Thrust Transition Maneuver: Thrust Coefficient Comparison

### 2.4 Failed Boot and Inter-cycle Ice Shape Testing

The Failed Boot and Inter-cycle ice shapes were tested in the OSU Low Speed Wind Tunnel in the fall of 1996 (Ref. 17). The tailplane characteristics with the Failed Boot ice shape showed distinctive stall and hinge moment breaks. The stall break occurred at approximately $\alpha_t = -15°$ at maximum nose down elevator deflection, while the hinge moment break occurred at approximately $\alpha_t = -13°$. Prior to these breaks, a slight reduction in lift curve and hinge moment slope was noted. The breaks themselves were of similar strength to those of the S&C ice shape, which occurred at $\alpha_t = -8°$ (Ref. 16). However, the S&C ice shape characteristics showed no flattening of the lift and hinge moment slopes prior to the breaks. The Failed Boot ice shape offered more margin to tailplane stall, so it was considered to be less critical than the S&C ice shape.

Indications of tailplane stall effects were still seen during TAILSIM pushover responses. However, the responses showed limited overshoot and were more controlled compared to those for the S&C ice shape. Because of this it was somewhat surprising that control reversals and a full tailplane stall were experienced with the Failed Boot ice shape. TAILSIM analysis of the Failed Boot ice shape was not as extensive as for the S&C ice shape. However, a general assessment has to be that TAILSIM is optimistic in its response prediction of the effects of tailplane stall with the Failed Boot ice shape.

Data for the tailplane with the Inter-cycle ice shape showed no strong lift or hinge moment break. However, there was a noticeable flattening of the lift curve and hinge moment slopes. Because of these benign characteristics little TAILSIM analysis was accomplished. What was accomplished showed no overshoot during pushover maneuvers and good control. These benign characteristics were, in general, validated during flight test.

## 3.0 Discussion of TAILSIM Capability and Accuracy

As noted in Section 2.2, the $n_Z$ feedback used in generating TAILSIM comparison responses had to be "tuned" to provide a good match. Some of this "tuning" is due to the lags caused by the integrated $n_Z$ feedback. In addition, there are, as discussed previously, inaccuracies in the TAILSIM program that also contribute to the inaccuracies in the responses. A discussion of these issues follows.

To investigate the effects of pilot model lags on TAILSIM responses another comparison was run with the 9749PO23 pushover maneuver. For this maneuver, proportional pitch rate error was also used, providing 25 percent of the error feedback, while the integral feedback provided 75 percent. The results of this comparison are shown in Figure 22 to Figure 29.

The plots show slightly less overshoot than for full integrated pitch rate error feedback. However, the TAILSIM responses are qualitatively the same. There is noticeable overshoot, however, indicating that TAILSIM is still conservative in its prediction of tailplane stall with the S&C ice shape on the tailplane. The elevator deflection and stick force plots show the same characteristics as those of Section 2.2. This indicates that the pitch rate error feedback pilot model characteristics have not changed significantly with the addition of proportional feedback. It also indicates that this form of pilot model is too simple for accurate duplication of typical pilot performance.

Figure 30 and Figure 31 show a comparison of the commanded $n_Z$ by TAILSIM and the actual $n_Z$ of the 9749PO23 flight test maneuver. This shows the amount of "tuning" required to generate a good airspeed/$n_Z$ match with flight test data. The "tuning" seems small and is representative of the sensitivity of the TAILSIM program, and simulation programs in general. To show how significant this sensitivity is, Figure 32 to Figure 39 show the TAILSIM response with the 9749PO23 $n_Z$ input directly as the $n_c$.

The most noticeable differences in the TAILSIM response are the large error in airspeed and the 1 to 2 sec lag in the response. The aircraft is accelerating for the entire maneuver. The angle-of-attack and pitch angle show that a component of this airspeed increase is from an increased nose down attitude. The higher airspeed then causes the angle-of-attack, pitch angle, and tailplane angle-of-attack excursions to be smaller. Tailplane angle-of-attack, pitch rate, and $n_Z$ show fairly good agreement with flight test data, and also show signs of tailplane stall. Of interest is that the magnitude of the elevator deflection more closely matches that of flight test, indicating that the tailplane dynamic pressure as modeled may not be correct. The hinge moment shows the same large differences seen in earlier comparisons.

These plots serve to show the difficulty in generating an accurate database for the aircraft. As noted, the aircraft is very sensitive to small changes in command input. The TAILSIM data was generated with only an approximate match in gross weight, altitude, and dynamic pressure, but, it is clear that there are slight inaccuracies in all database parameters as represented by the trim differences. The evidence presented here suggests that there are inaccuracies in the basic lift, drag, and moment data of the database. These inaccuracies would contribute to errors in downwash angle, which are also caused by a calculation method that has only first order effects. The result is a conservative prediction of tailplane hinge moment break and stall angle-of-attack, occurring at approximately $\Delta\alpha_t = 2^o$ more positive than indicated by flight test data. Additionally, it is clear that the stick, pilot model, and elevator deflection dynamics are not quantitatively as accurate as desired.

The overall match of TAILSIM to flight test data can only be described as fair. However, qualitatively, TAILSIM has provided a useful assessment of problem areas. While conservative, TAILSIM has pointed out that tailplane stall is a potential problem with $\delta_f = 20°$. It has also been useful in assessing the tailplane angle-of-attack throughout the aircraft flight envelope (Ref. 18). Clearly, refinement is needed, but TAILSIM has shown itself to be a useful tool for improving the understanding of the aerodynamics and flight dynamics of tailplane stall.

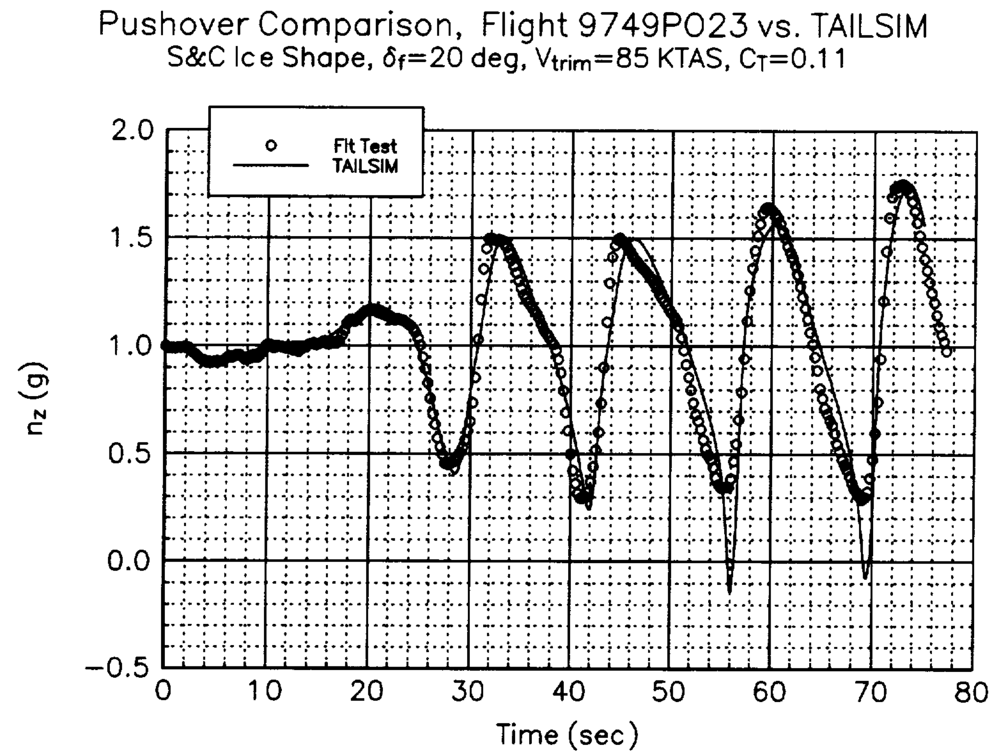


Figure 22. Pushover $n_Z$ Comparison, QPFR=0.25

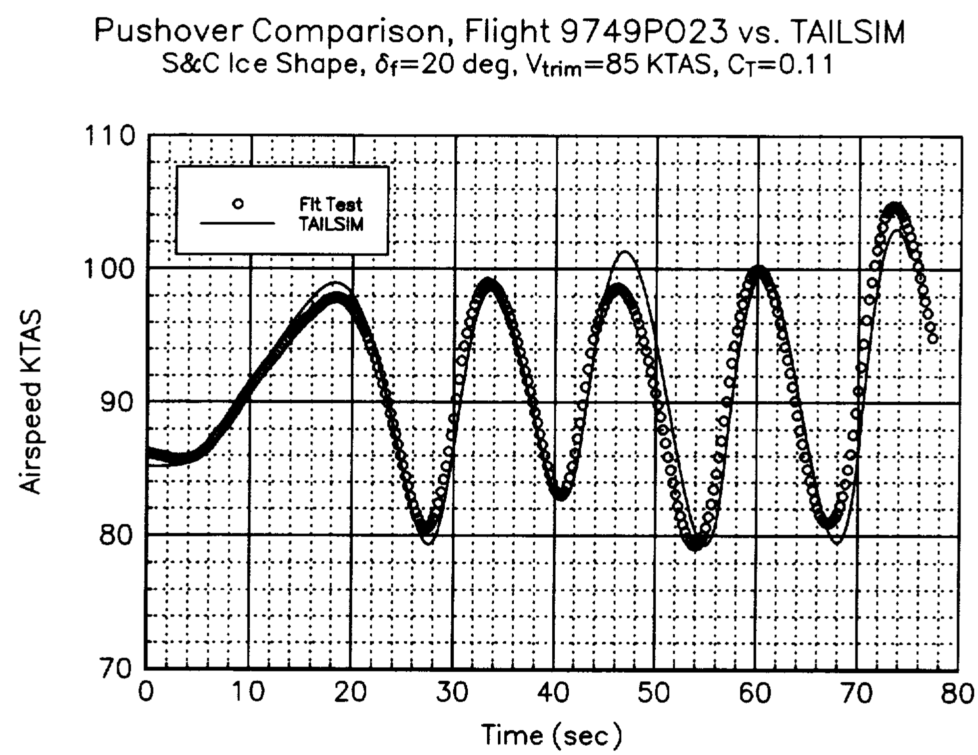


Figure 23. Pushover Airspeed Comparison, QPFR=0.25

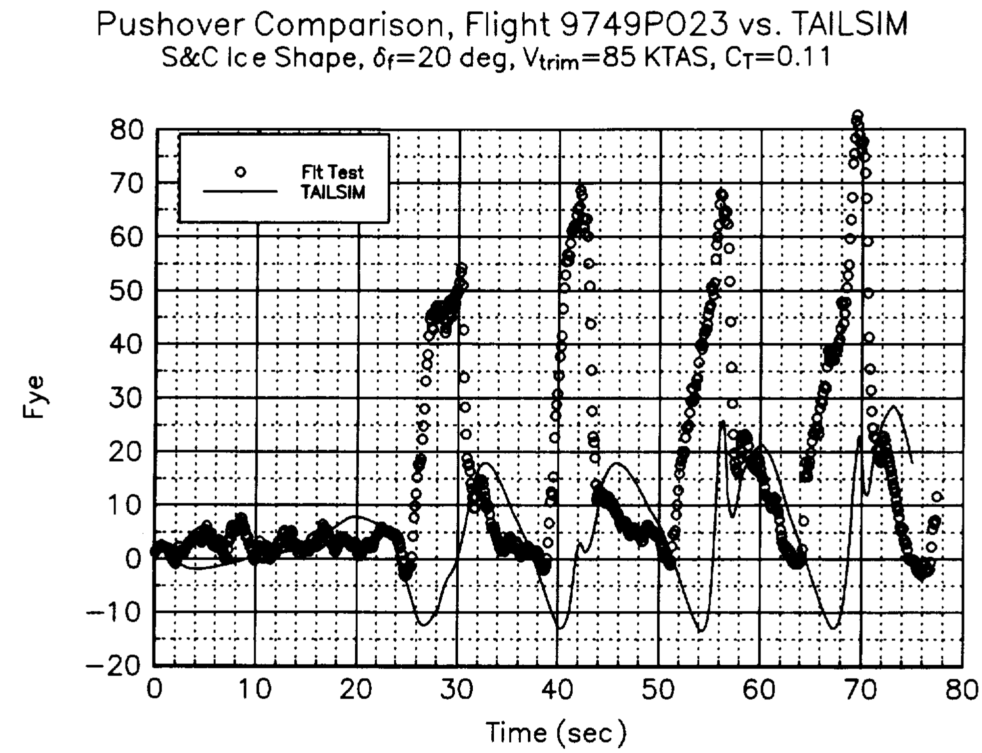


Figure 24. Pushover Stick Force Comparison, QPFR=0.25

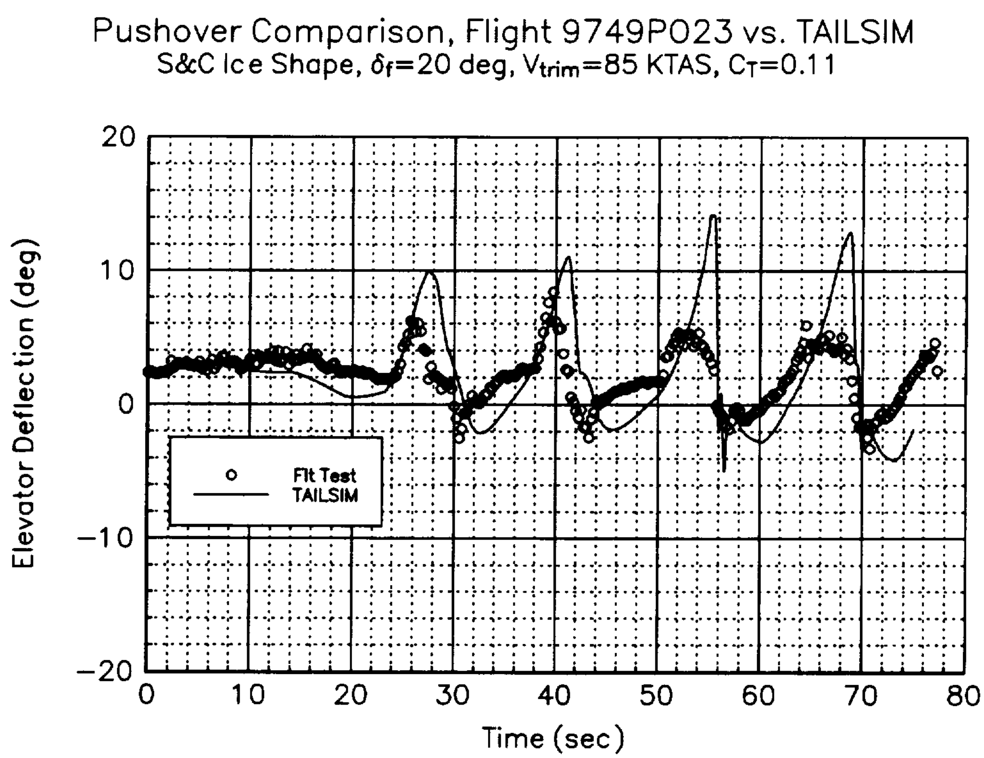


Figure 25. Pushover Elevator Deflection Comparison, QPFR=0.25

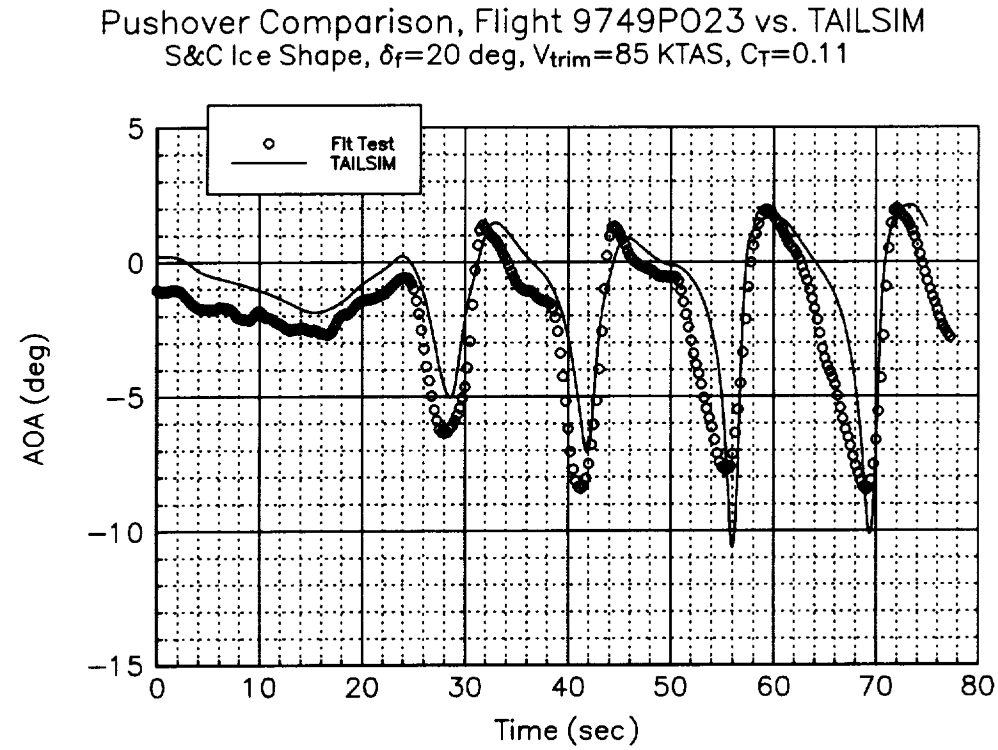


Figure 26. Pushover Aircraft AOA Comparison, QPFR=0.25

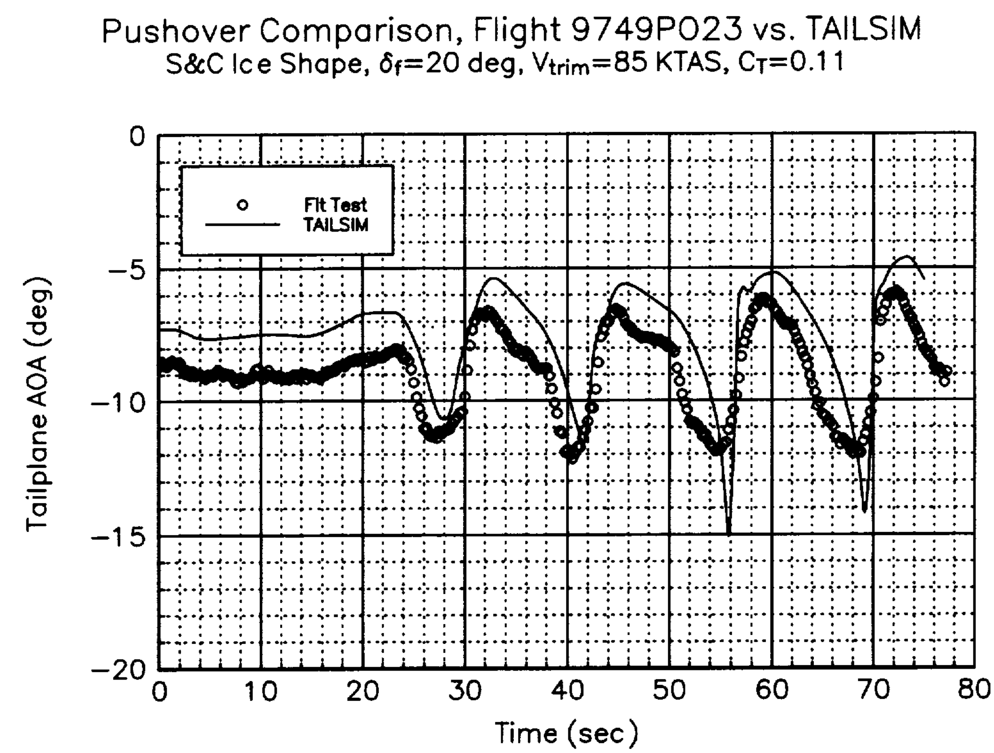


Figure 27. Pushover Tailplane AOA Comparison, QPFR=0.25

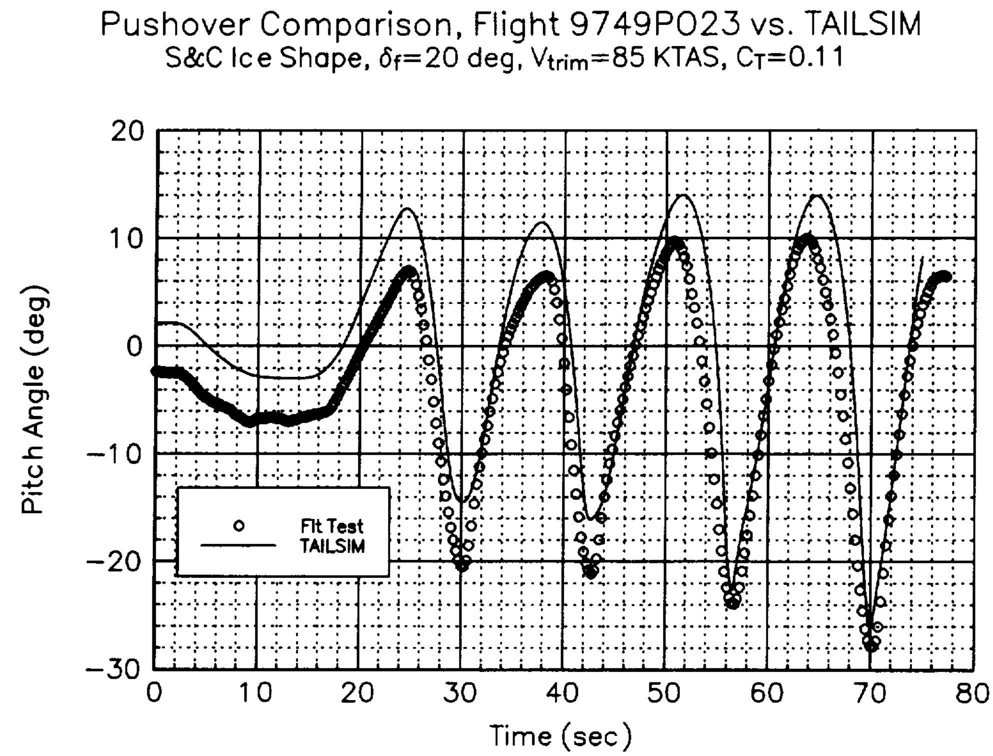


Figure 28. Pushover Pitch Angle Comparison, QPFR=0.25

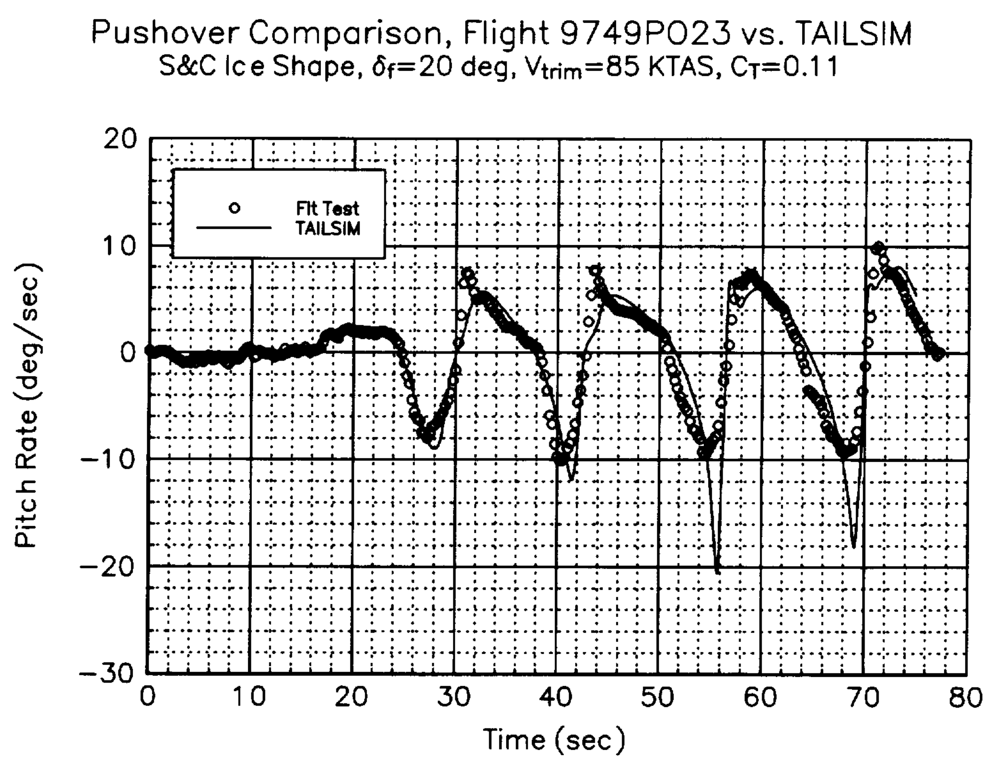


Figure 29. Pushover Pitch Rate Comparison, QPFR=0.25

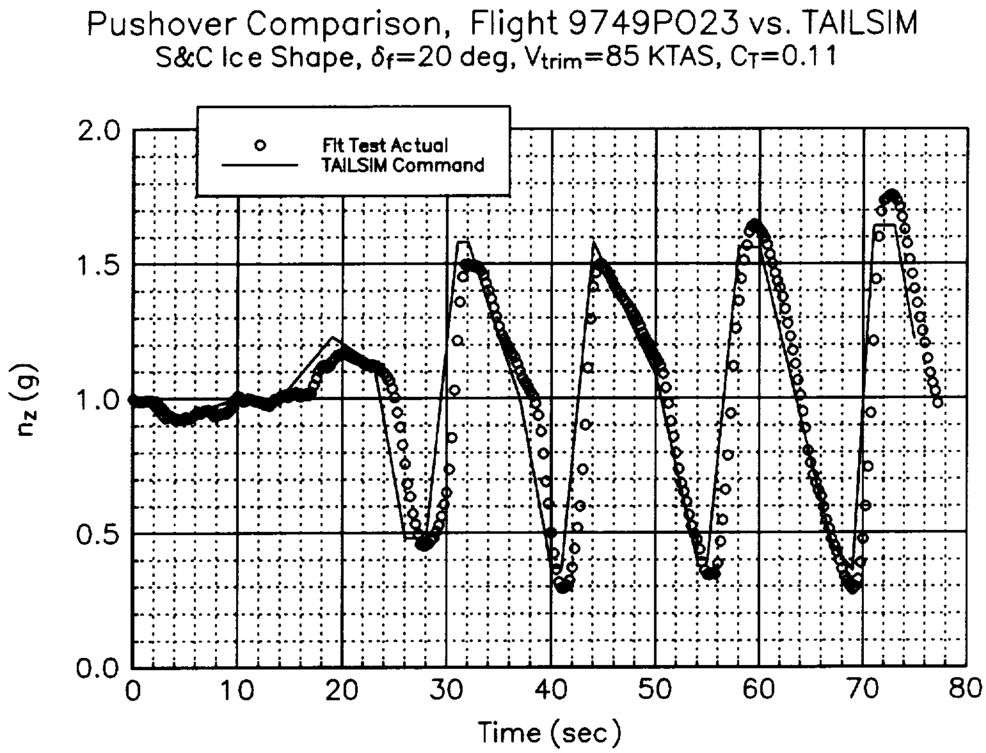


Figure 30. Pushover Actual and $n_Z$ Command

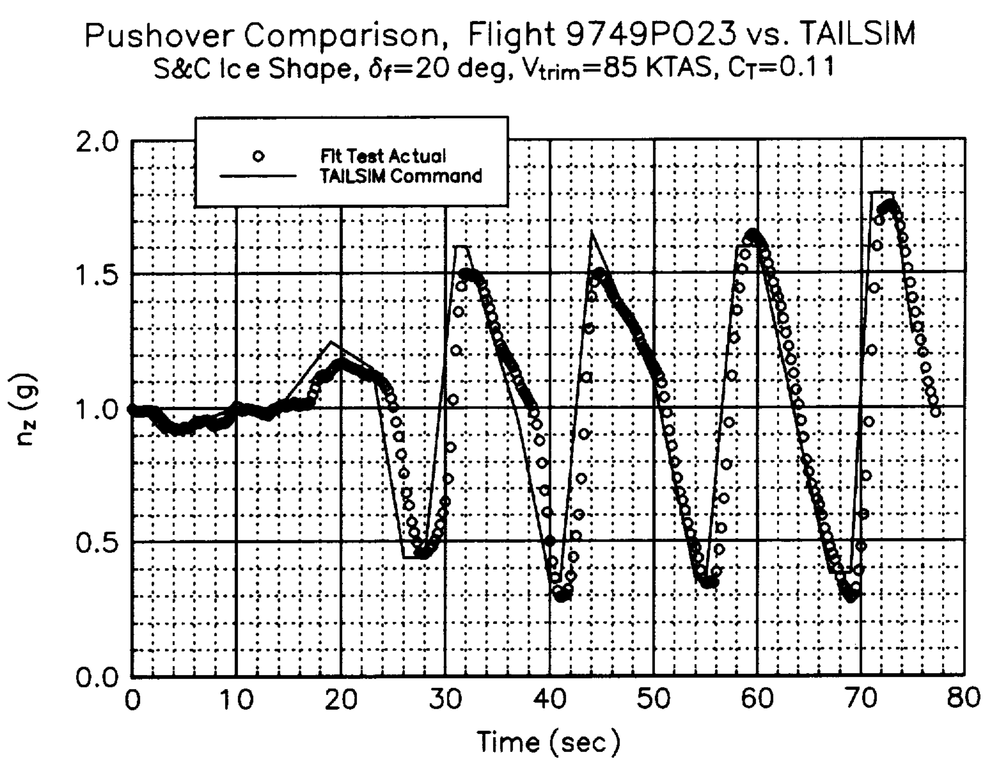


Figure 31. Pushover Actual and $n_Z$ Command, QPFR=0.25

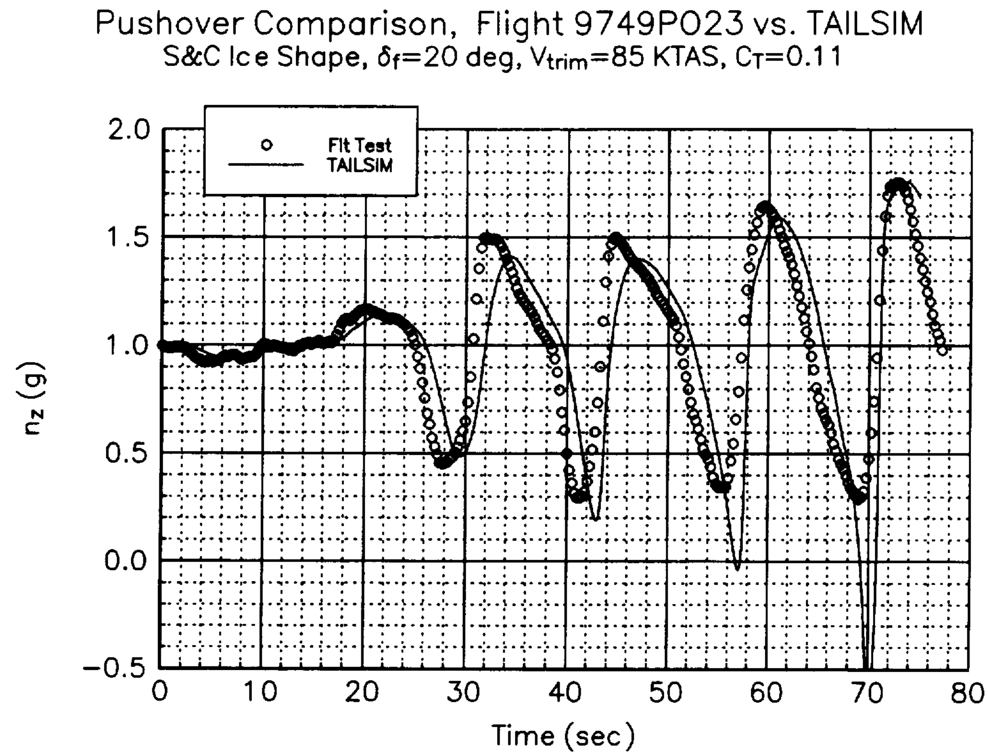


Figure 32. Pushover $n_Z$ Comparison, $n_Z$ Input

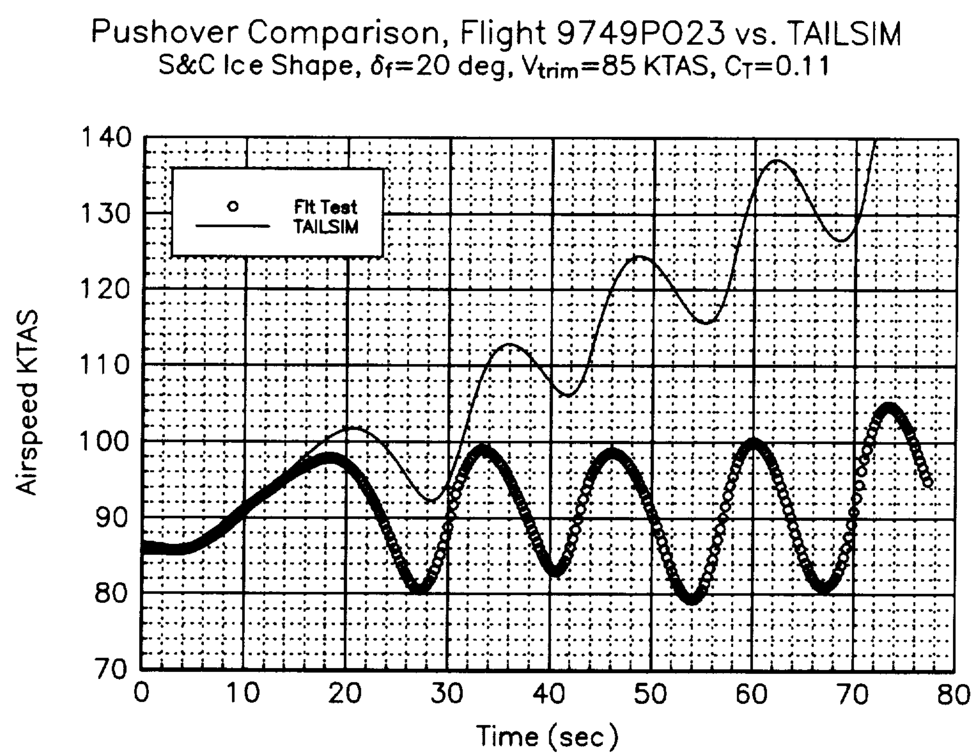


Figure 33. Pushover Airspeed Comparison, $n_Z$ Input

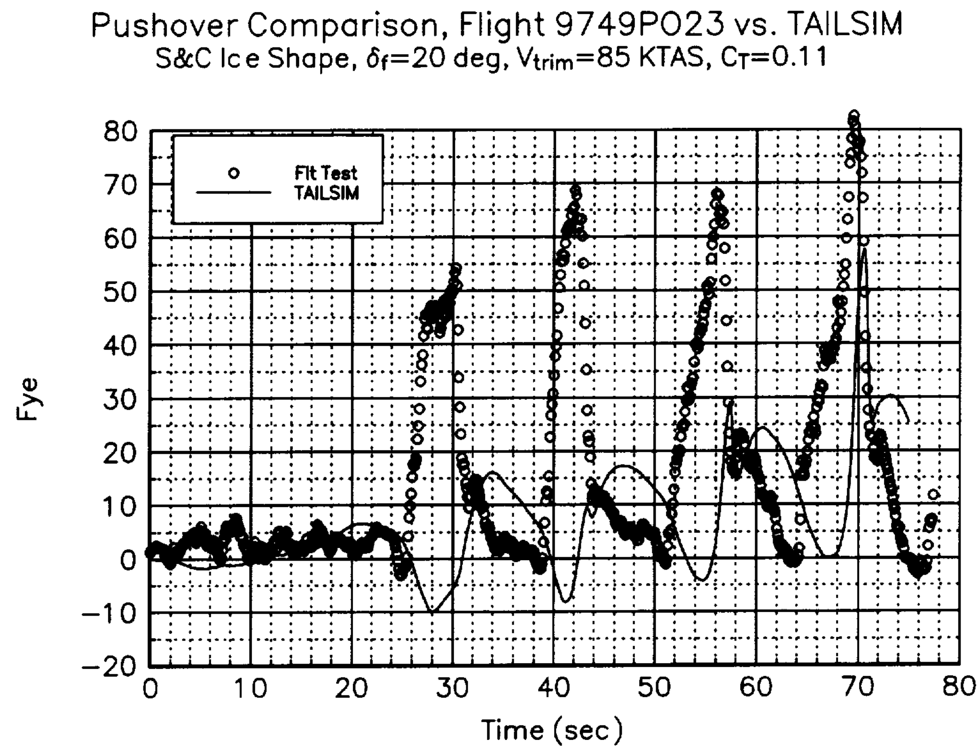


Figure 34. Pushover Stick Force Comparison, $n_Z$ Input

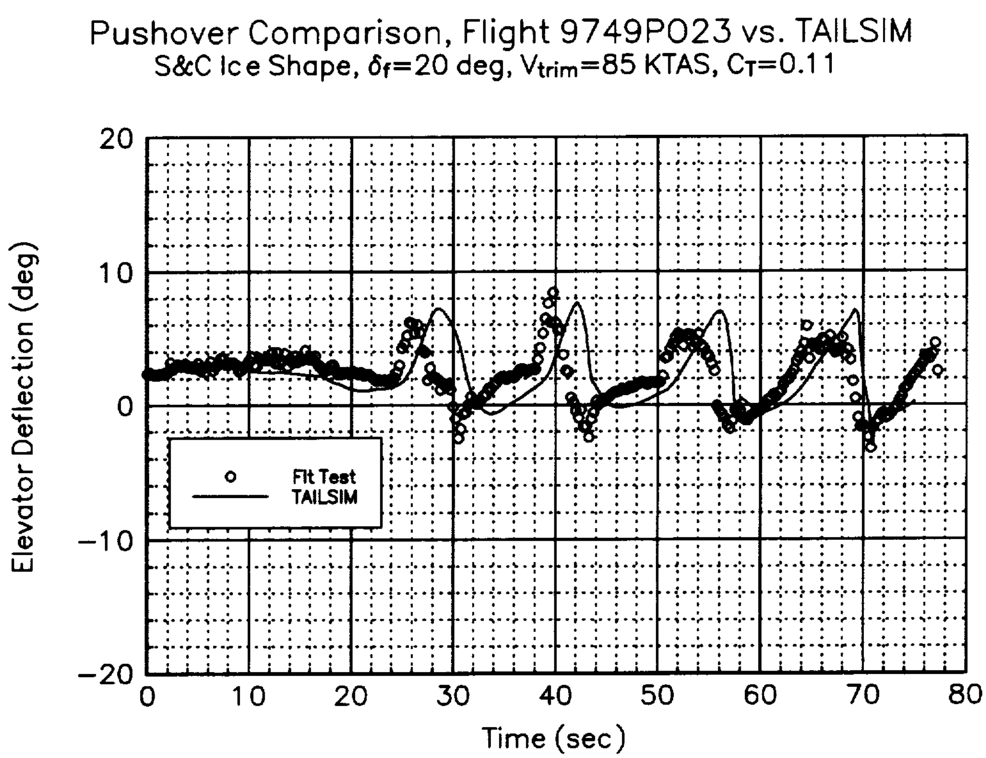


Figure 35. Pushover Elevator Deflection Comparison, $n_Z$ Input

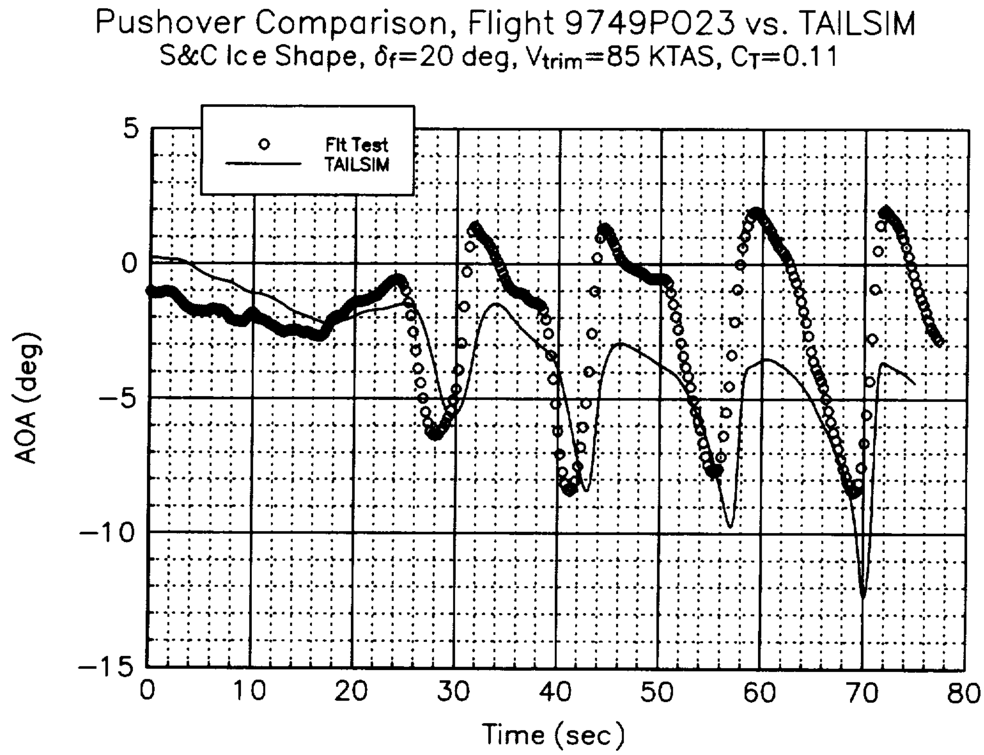


Figure 36. Pushover Aircraft AOA Comparison, $n_Z$ Input

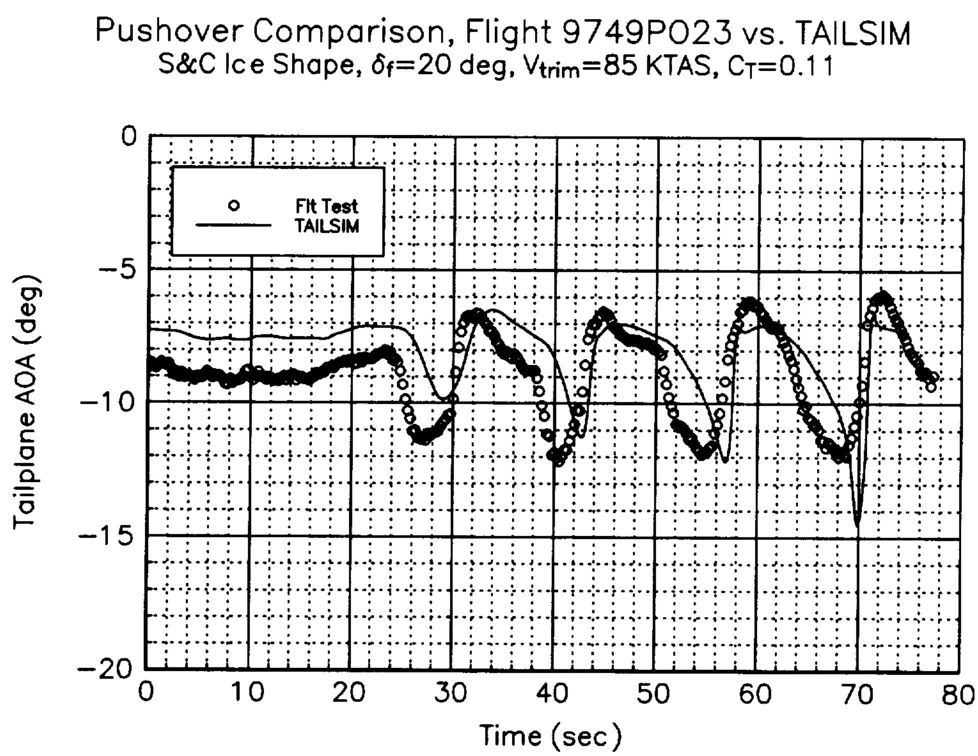


Figure 37. Pushover Tailplane AOA Comparison, $n_Z$ Input

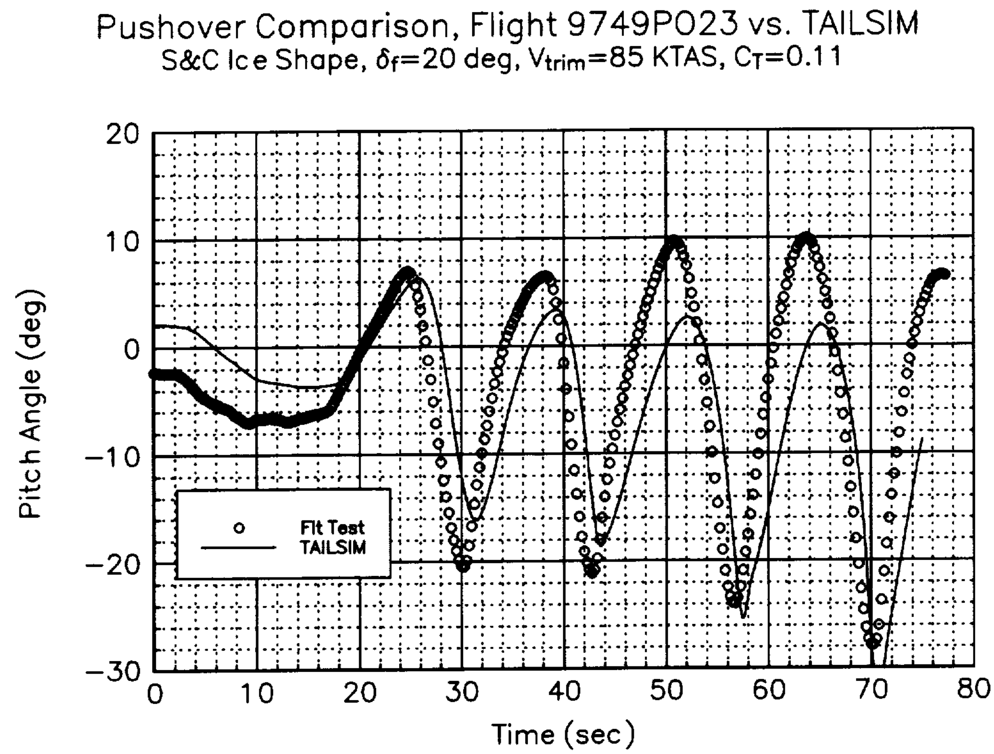


Figure 38. Pushover Pitch Angle Comparison, $n_Z$ Input

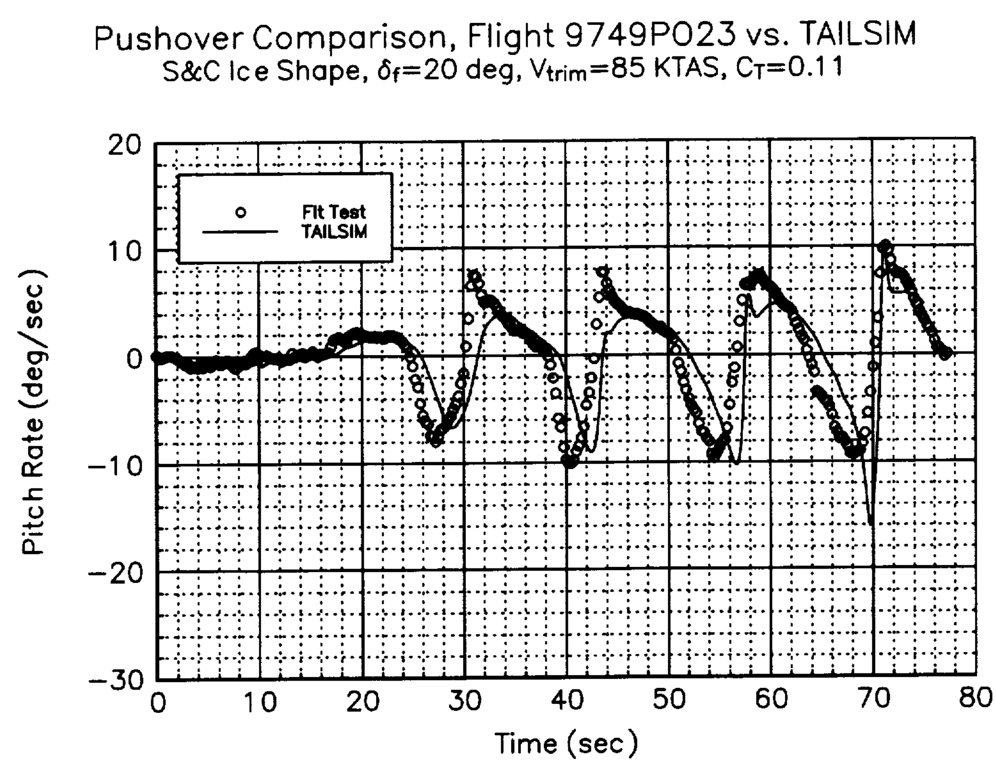


Figure 39. Pushover Pitch Rate Comparison, $n_Z$ Input

## 4.0 Conclusions

The TAILSIM program has been shown to provide increased insight into the aerodynamics and flight dynamics of ice contaminated tailplane stall. This insight was useful in preparing for flight testing with ice shapes on the tailplane and in confirming flight test results. A comparison of TAILSIM and flight test responses showed qualitatively similar tailplane stall characteristics and aerodynamic responses. This validated the basic aerodynamic and flight dynamic assumptions used in creating TAILSIM and analyzing the flight test data. Providing this type of validation justifies the use of a simulation program in conjunction with flight testing.

However, the TAILSIM prediction of tailplane hinge moment and stall breaks during pushover maneuvers was shown to be conservative with the S&C ice shape on the tailplane, and optimistic with the Failed Boot ice shape on the tailplane. A representative thrust transition maneuver comparison also showed TAILSIM accuracy to be less than desired. The most significant factor in the accuracy of the simulation is the database and force and moment build-up equations. It was shown that a simulation program such as TAILSIM is highly sensitive to small changes in inputs, and therefore, would be sensitive to similar changes in the database coefficients. To be useful as a predictive tool, more accurate database and build-up equations are needed, possibly including an implementation of aerodynamic lift and hysteresis effects.

A key factor in the usefulness of the TAILSIM program was shown to be the pilot model. The pilot model allowed the aircraft to be driven to the desired G levels of pushover maneuvers, and to maintain desired airspeeds during thrust transition maneuvers, in spite of inaccuracies in the elevator effectiveness of the database. Using the pilot model, TAILSIM responses were more accurately matched to flight test data. This provided more accurate insight into the aerodynamics of the tailplane flow field and their effect on the aircraft response. These benefits were noted, though the pilot model did not accurately model the typical responses of the flight test pilots during pushover maneuvers. This is another area that should be improved before TAILSIM can become an accurate predictive tool.

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# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY (*Leave blank*) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | December 2000 | Final Contractor Report |

**4. TITLE AND SUBTITLE**

An Evaluation of an Analytical Simulation of an Airplane With Tailplane Icing by Comparison to Flight Data

**5. FUNDING NUMBERS**

WU–711–21–23–00
NAG3–2007

**6. AUTHOR(S)**

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**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Ohio State University Research Foundation
1960 Kenny Road
Columbus, Ohio 43210–1063

**8. PERFORMING ORGANIZATION REPORT NUMBER**

E–12513

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

National Aeronautics and Space Administration
Washington, DC 20546–0001

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

NASA CR—2000-210561

**11. SUPPLEMENTARY NOTES**

Project Manager, Thomas Ratvasky, Turbomachinery and Propulsion Systems Division, NASA Glenn Research Center, organization code 5840, 216–433–3905.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**

Unclassified - Unlimited
Subject Categories: 08 and 61 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT *(Maximum 200 words)***

This report presents the assessment of an analytical tool developed as part of the NASA/FAA Tailplane Icing Program. The analytical tool is a specialized simulation program called TAILSIM which was developed to model the effects of tailplane icing on the flight dynamics of the NASA Glenn Research Center DHC-6 Twin Otter *Icing Research Aircraft*. This report compares the responses of the TAILSIM program directly to flight test data. The comparisons should be useful to potential users of TAILSIM. The comparisons show that the TAILSIM program qualitatively duplicates the flight test aircraft response during maneuvers with ice on the tailplane. TAILSIM is shown to be quantitatively "in the ballpark" in predicting when Ice Contaminated Tailplane Stall will occur during pushover and thrust transition maneuvers. As such, TAILSIM proved its usefulness to the flight test program by providing a general indication of the aircraft configuration and flight conditions of concern. The aircraft dynamics are shown to be modeled correctly by the equations of motion used in TAILSIM. However, the general accuracy of the TAILSIM responses is shown to be less than desired primarily due to inaccuracies in the aircraft database. The high sensitivity of the TAILSIM program responses to small changes in load factor command input is also shown to be a factor in the accuracy of the responses. A pilot model is shown to allow TAILSIM to produce more accurate responses and contribute significantly to the usefulness of the program. Suggestions to improve the accuracy of the TAILSIM responses are to further refine the database representation of the aircraft aerodynamics and tailplane flowfield and to explore a more realistic definition of the pilot model.

**14. SUBJECT TERMS**

Aircraft icing; Tailplane icing; Stability and control; Flight dynamics; Flight simulation

**15. NUMBER OF PAGES**

43

**16. PRICE CODE**

A03

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | |