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Design and Control of an Experimental Tiltwing Aircraft

Linnea Persson
KTH Royal Institute of Technology
Ames Research Center, Moffett Field, California

Ben Lawrence
San Jose State University Research Foundation
Ames Research Center, Moffett Field, California

March 2017

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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Design and Control of an Experimental Tiltwing Aircraft

Linnea Persson[1] and Ben Lawrence[2]

Ames Research Center

INTRODUCTION

The focus of this project was the conceptual design of experimental tiltrotors. The main tools used were NDARC (NASA Design and Analysis of Rotorcraft) and SIMPLI-FLYD. NDARC is a conceptual design tool for rotorcraft, and it is used to find trim points under various flight conditions. SIMPLI-FLYD is an integrated collection of software tools that enables a flight dynamics and control assessment of the rotorcraft vehicle design generated from NDARC.

Two different tiltrotors were investigated. Initially, work was done with the Bell XV-15 tiltrotor. NDARC's ability to correctly model the tiltwing transition between airplane mode and hover mode was explored. In addition, data from old flight tests were compared to the NDARC output to see how accurately performance could be predicted.

After the Bell XV-15 analysis, an NDARC model of a novel tiltwing concept from Elytron Aircraft was written and analyzed together with SIMPLI-FLYD. Elytron 2S is an experimental tiltwing aircraft, consisting of a joined-wing design with a small central wing for the proprotor. An alternative approach to hover control is used, where the typical rotor hub and swash plate are substituted for actuated louvers and blowing controlling pitch, yaw, and roll. The objective of the Elytron 2S analysis was to obtain a more complete understanding of the maneuverability and possible performance of this alternative aircraft configuration.

BACKGROUND

TILTROTOR AIRCRAFT

Tiltrotor and tiltwing aircraft are designed to combine the long-range and high-speed flight capability of airplanes with the vertical takeoff and landing (VTOL) ability that conventional helicopters have. This is achieved with the use of rotors that either pivot on nacelles attached to a fixed wing or with rotors that pivot together with the wings. When the rotors are placed so that the plane of rotation is horizontal, the tiltrotor behaves like a VTOL rotorcraft. As the tiltrotor starts gaining speed, it gets ready to start behaving like an airplane. By tilting the wings and/or

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[1] KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden.

[2] San Jose State University Research Foundation, San Jose, California.

rotors forward and down, the tiltrotor is put into cruise mode, also referred to as airplane mode. The rotors now act as propellers giving thrust to the flight. The concept of tiltrotor and tiltwing aircraft is old, however the only such aircraft in production today is the V-22 Osprey.

As a tiltrotor or a tiltwing aircraft operates in hover mode, it typically uses rotors to control attitude and motion. Thrust can be controlled using collective blade pitching as in a conventional helicopter. Pitch control can be achieved using cyclic blade pitching on both rotors simultaneously. Tiltrotor aircraft do not have tailrotors, so lateral control needs to be done by using differential cyclic—similar to what is used for tandem helicopters. This is the case, for example, in the XV-15 [1] where yawing is achieved by differential cyclic pitch. Differential thrust can be used to induce a rolling moment on the aircraft.

In cruise mode, the tiltrotor behaves much like a normal airplane. Control actuators in this mode include ailerons, elevators, and rudder. The tilted propellers offer thrust to the airplane. Conversion between helicopter mode and airplane mode is done within a corridor of airspeed and nacelle angle combinations. The airplane control actuators remain active at all times, while the hover control is phased out as the flight configuration changes.

NDARC

NDARC is a conceptual design tool used in this project for performance evaluations and to find trim values for different operating conditions. Running NDARC requires the user to define at least two files. The first one is the '.list' file, defining the aircraft itself, including aerodynamic properties of all parts, geometry, and rotor properties. This file also describes how the aircraft is controlled.

The main control inputs in NDARC are collective stick, cyclic stick, and pedal (see Table 1). How these inputs affect the different control actuators is defined through a set of control "T-matrices." The way that the control inputs and the actuators are connected might change as the aircraft transitions between different states. For example, it can be the nacelle angle that defines the tilting of the rotors. In airplane mode, the nacelle is at 0 degrees, so only the airplane control surfaces should be affected by control inputs. In hover mode, the aircraft is flying at low speed or is stationary, so the airplane control surfaces are not effective at this point. In addition to the airplane controls, the aircraft now has a set of helicopter controls. The helicopter control actuators are also partially in use during the transition between the modes. Exactly how this is done is defined in a set of T-matrices.

The other file that the user needs to provide to run NDARC is the '.run' file. This file defines the tasks that NDARC is to perform. These tasks could, for example, include sizing, mission performance analyses, or in this case, a flight performance analysis. The flight performance analysis is done by defining some states of interests at which NDARC should find trim points. It is possible to evaluate a sweep of one or two variables at the same time. The .run file also includes definitions regarding the solution procedure such as the tolerance and the maximum number of iterations.

TABLE 1. SUMMARY OF THE CONTROLS IN NDARC FOR A TILTROTOR.

Control Input	NDARC Control Matrix	Description
Collective stick	T_coll	This is connected to whatever is controlling thrust, using collective pitching of rotor blades.
Cyclic stick	T_latcyc, T_lngcyc	The longitudinal control input controls the pitching of the aircraft. In helicopter mode, this is typically achieved using cyclic pitching of the blades, and in airplane mode this is controlled by the elevators. The lateral control input controls rolling of the aircraft about the longitudinal axis. In helicopter mode this is done by differential collective pitching of the rotors and in airplane mode by using ailerons.
Pedal	T_pedal	The pedals control yawing motion. This is done with differential cyclic in helicopter mode and with rudder in airplane mode.
Nacelle tilt	T_incid	This is the control of the nacelle angle of the rotors.

Several output files are written by NDARC. The '.perf' file contains information about the flight performance. The '.acd' file contains the aircraft design. These are the two output files that are later used in SIMPLI-FLYD.

SIMPLI-FLYD

The conceptual design data is generated in NDARC at a range of predefined points of interest with varying nacelle (tilt) angles, velocities, and altitudes. The .list file and the .acd file are then passed to SIMPLI-FLYD where the flight dynamics are evaluated.

SIMPLI-FLYD is an integrated collection of software tools that enables a flight dynamics and control assessment from the rotorcraft vehicle design generated with NDARC. First it generates linear models at the chosen points of interest. These linear models combined can be used to generate real-time models to run in Simulink with X-plane. Conduit [2] is incorporated in SIMPLI-FLYD to enable the optimization of a control system if the user chooses to apply a control system to the vehicle model.

XV-15 MODEL EVALUATION

BACKGROUND

The Bell XV-15 (Figure 1) is an experimental rotorcraft developed jointly by NASA, the U.S. Army, and the U.S. Navy in the 1970s as a tiltrotor “proof-of-concept” aircraft. It was the second successfully flown tiltrotor aircraft after the Bell XV-3. Two XV-15’s were built, and experiments were conducted throughout the 1980s demonstrating the high-speed performance of the vehicle and supporting the development of the Bell Boeing V-22 Osprey.

As a part of this project, the XV-15 trim characteristics were analyzed using NDARC [1]. The results were then compared with experimental data from XV-15 flights found in technical reports of experiments conducted in the late 1980s [3], [4]. These experiments aimed at validating a flight simulation called Generic Tiltrotor Simulation (GTRS).

Figure 1. The Bell XV-15 at the Dallas Convention Center Heliport [5].

NDARC MODEL

An existing XV-15 model was provided in the form of an NDARC .list file. To get a more accurate model of the conversion between helicopter mode and airplane mode, this model was extended to include T-matrices defined for 10 different control states, where each control state corresponded to a certain nacelle angle. Each control state then defined matrices that mixed the airplane control and the helicopter control in an appropriate manner for the current nacelle angle.

The .run file contained a number of conditions under which speed sweeps were made. The conditions had varying nacelle angles and altitudes. The speed sweeps were made according to what was feasible under the considered nacelle angle, as shown in Figure 2.

Nacelle (deg)	0	10	20	30	40	50	60	70	80	90
Control state	10	9	8	7	6	5	4	3	2	1

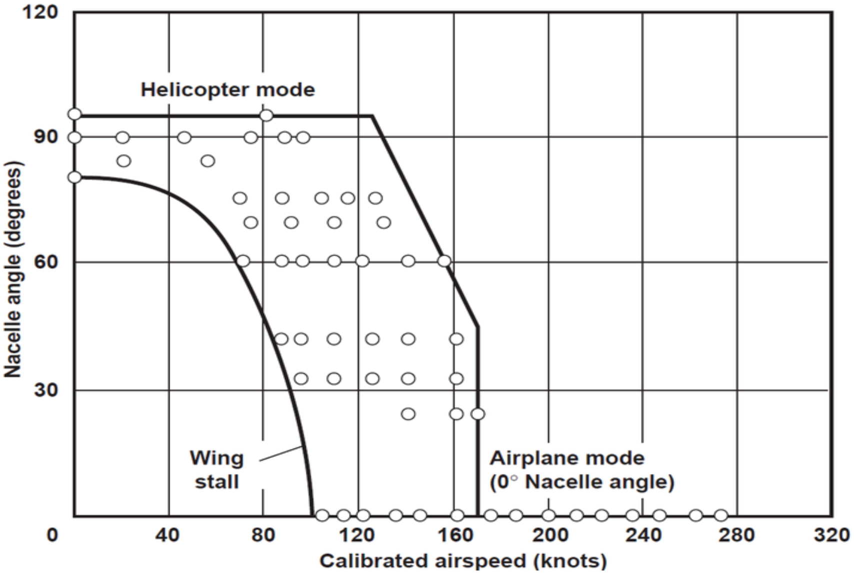


Figure 2. Conversion corridor of the XV-15 [5]. This provides the possible velocities at all nacelle angles.

RESULTS

Figure 3 and Figure 4 show the trim values of the elevator, and the pitch angle for varying velocities and nacelle angles. The results are reasonable, and show that NDARC can model the transition between airplane mode and hover mode fairly well. Figure 4 can be compared to Figure 5, which shows the same data but for the original NDARC .list file that did not model the control matrices. The improvement is evident; Figure 4 has a much smoother transition and is missing some of the more extreme values.

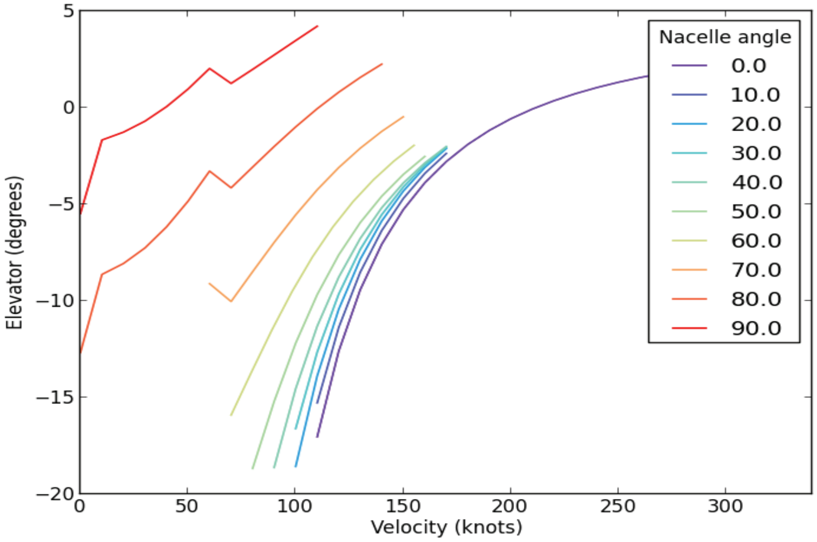


Figure 3. NDARC sweep of different velocities and nacelle angles to elevator deflection at trim.

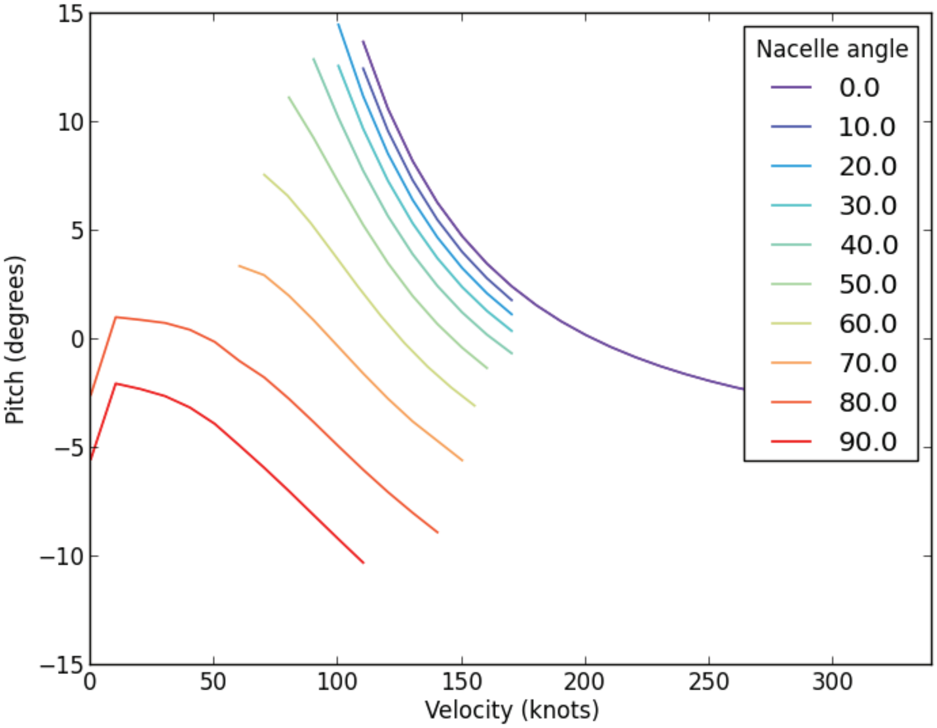


Figure 4. NDARC sweep of different velocities and nacelle angles to pitch angle.

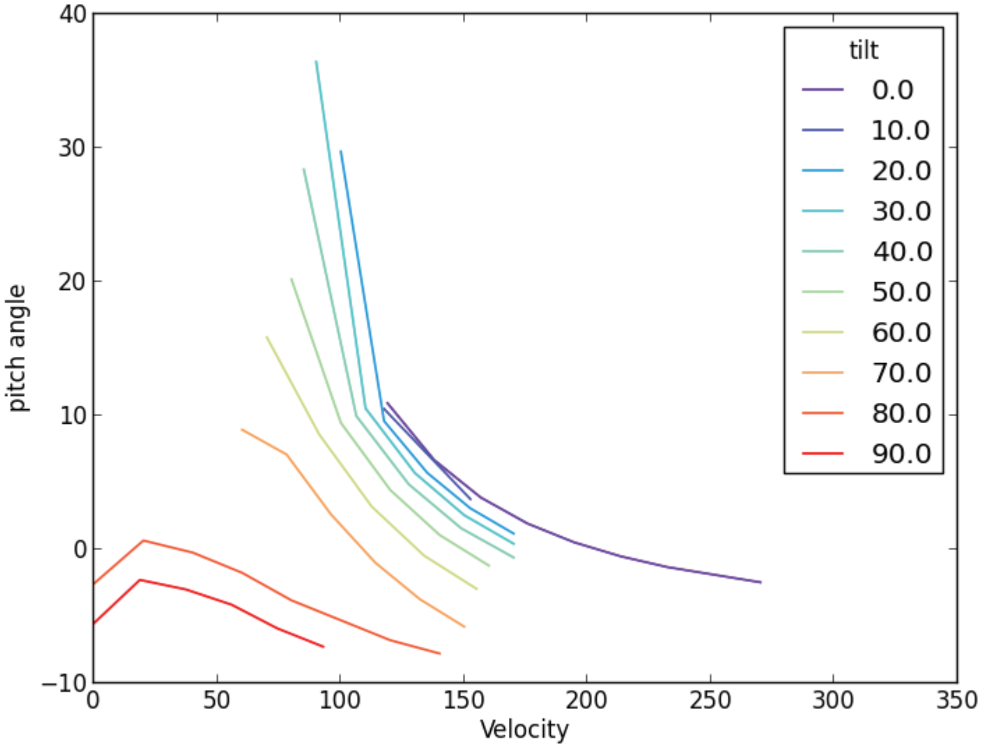


Figure 5. NDARC sweep of different velocities and nacelle angles to pitch angle. This is the result with the original file before different control matrices were defined for every 10 nacelle angles.

COMPARISION WITH FLIGHT DATA

A comparison between the NDARC model and two XV-15 models is shown in Table 2. Comparison with flight data is shown in Figure 6 and Figure 7. The NDARC model follows the general trend well. The pitch angle is a few degrees smaller than the experimental data, but with a smaller dCLda (change of lift with angle of attack) value and a smaller weight, this is expected. Changing these values in NDARC makes the fit better, particularly for small angles, but there is still a difference at high velocities. The hover mode case shows the same result—the NDARC values are a few degrees smaller (Figure 8).

TABLE 2. EXAMPLES OF DIFFERENCES IN THE ANALYZED DATA. DATA FOR THE XV-15 AND GTRS VALUES ARE PROVIDED IN REFERENCE [5].

	NDARC Value	**XV-15 1 Value**	**XV-15 2 Value**	**GTRS Value**	**Unit**	**Source**
Center of Gravity (CG)	296.4	299.6	299.3		*in.*	P. 41-43 [3]
Gross Weight (GW)	13000	13219	13934		*lb.*	P. 41-43 [3]
dCLda (wing)	5.2			4.6	*1/deg*	P. 28 [4]
dCLda (tail)	4.1			4.2	*1/deg*	P. 36 [4]

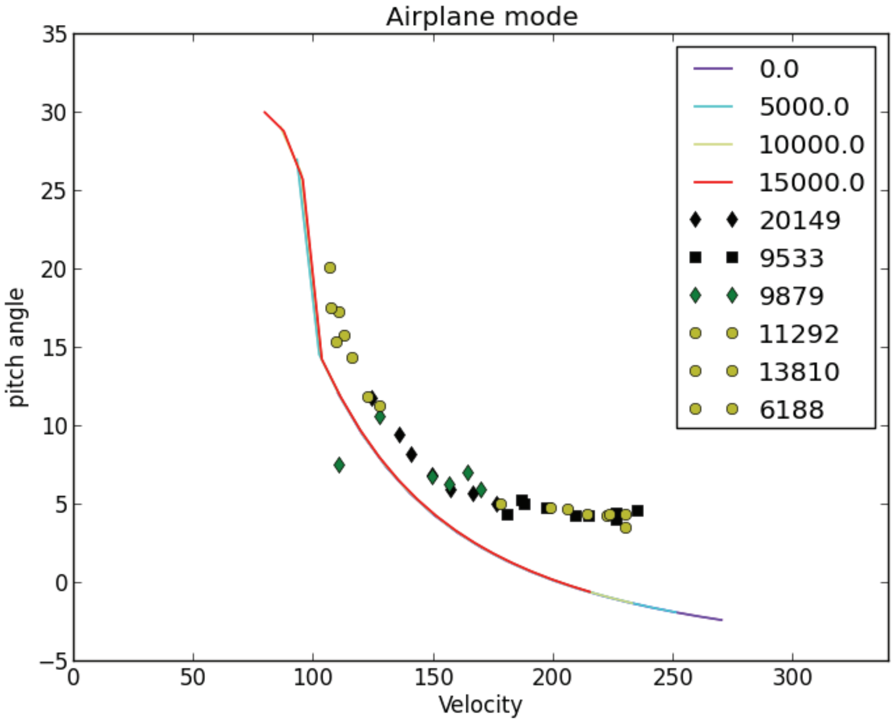


Figure 6. Comparison between the trim pitch angle in NDARC XV-15 model (lines) and flight data from reference [3] (marks). The labels show the altitude in ft.

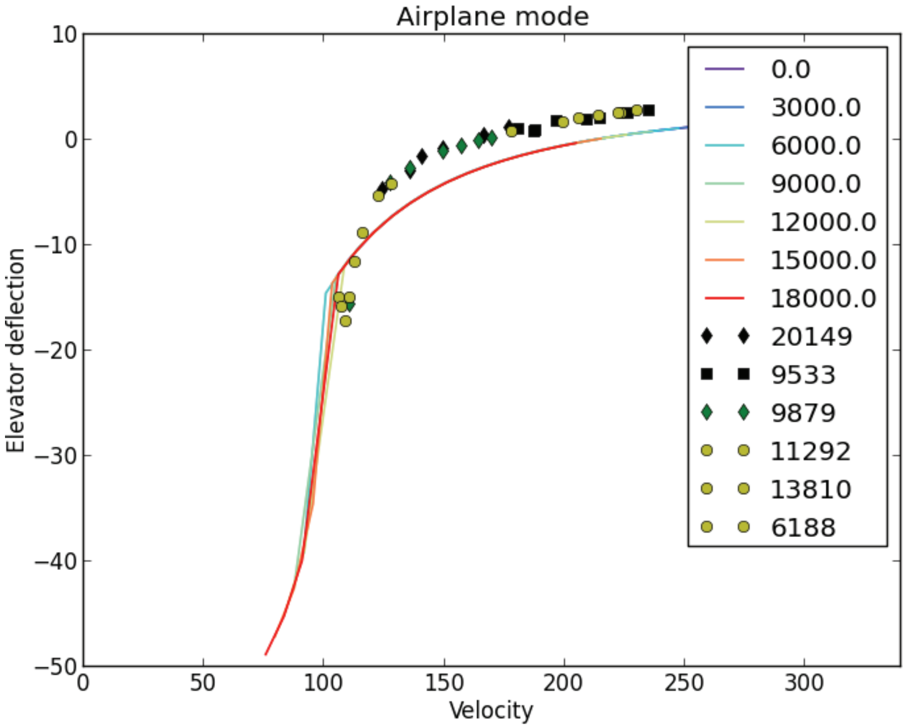


Figure 7. Comparison between the trim elevator angle in NDARC XV-15 model (lines) and flight data from reference [3] (marks). The labels show the altitude in ft.

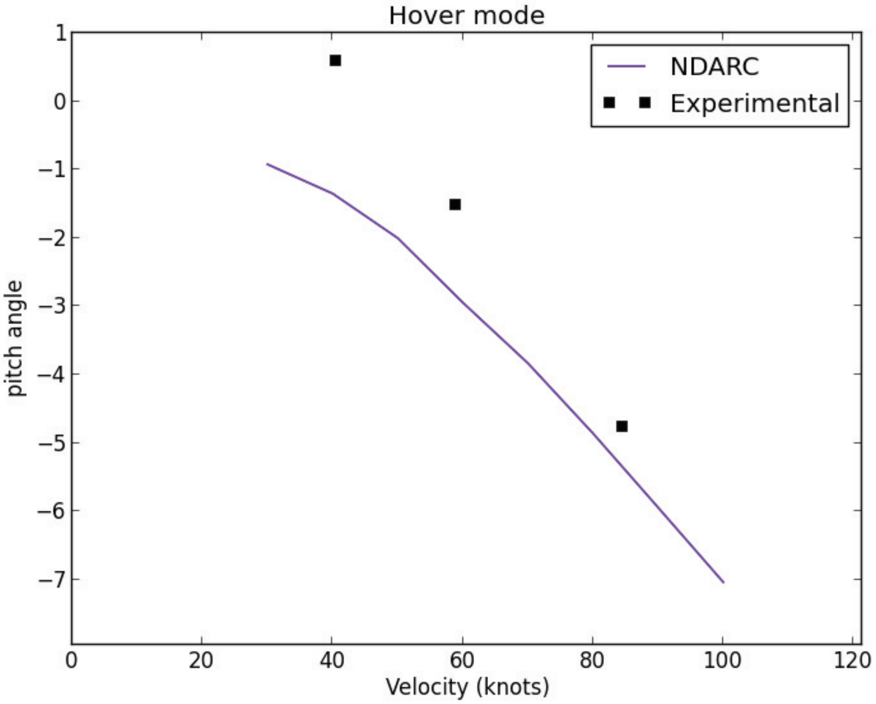


Figure 8. Comparison between the trimmed pitch value when the XV-15 nacelle is at 85 degrees (lines) and flight data from reference [3] (marks).

ELYTRON 2S

The Elytron 2S is an experimental tiltwing aircraft that combines the advantages of a VTOL rotorcraft and the speeds of a fixed-wing aircraft, but at a reduced complexity and cost compared to existing tiltrotor and tiltwing aircraft. It could be suitable for various uses, including emergency medical services, search and rescue, air taxi, and oil exploration. A full-scale prototype of the aircraft has been built and is ready to start flight testing.

The aircraft has three sets of wings. The rotors are positioned on a small wing close to the center of the aircraft. The entire wing and rotor rotate together as the aircraft goes between hover mode and cruise mode. The other two wings are joined together by a long winglet on the wing tip. A picture of the aircraft in its two main configurations is shown in Figure 9. The joined wing design is such that the lower wing pair is placed toward the front and the upper wing pair is displaced toward the back. The wing pairs are swept toward the winglet joining them together. This design decreases the interference between the thrust of the proprotors and the flow on the front and aft wings. The winglets also reduce wingtip vortices and induced drag.

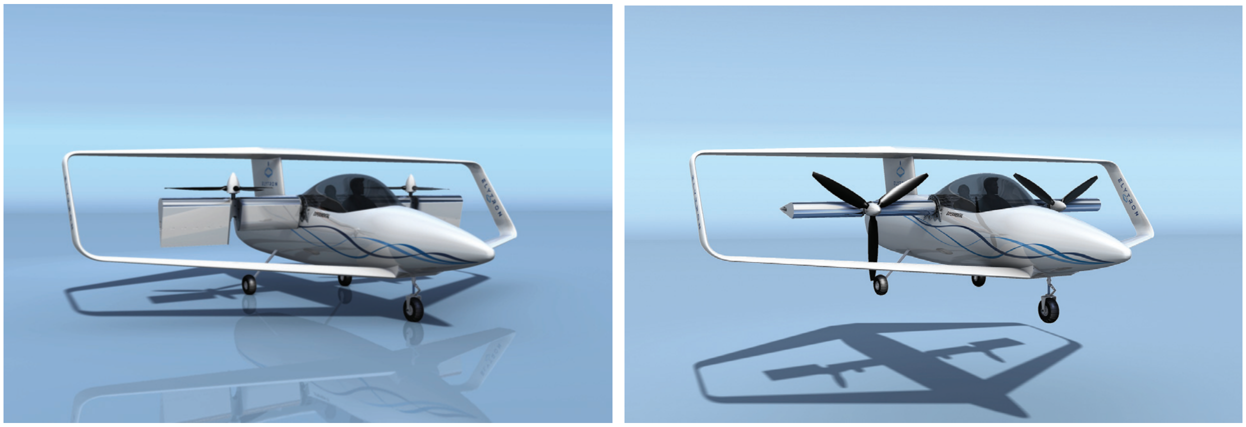


Figure 9. The Elytron 2S in hover mode with the rotors in 90 degrees tilt (left image) and in cruise mode (right image). The central wing with the proprotors is shown rotating in between the front and aft part of the box wing.

ELYTRON 2S CONTROL SYSTEMS

The Elytron 2S takes a different approach to hover control than what is traditionally used in tiltrotor aircraft. The rotors have no swash plate, therefore eliminating the possibility of the previously mentioned hover control. A reason for removing the swash plate is that it requires a relatively complex rotor hub with many parts.

HOVER CONTROL

Elytron uses alternative control actuators to replace the swash plate. Split louvers are placed in the wake of the proprotors on the trailing edges of the tiltwing. An image of the entire center wing structure is shown in Figure 10. Each louver can be deflected to the front or to the back. They also have the ability to split, meaning that both sides of the louvers are symmetrically deflected outward from their centerlines. This is shown in Figure 11.

Splitting a louver changes the download on the wing coming from the proprotors. If both louvers are split equally at the same time, the download stays symmetric and the total lift force changes. This can be used to change the ascent or descent rate in a controlled manner.

Rolling and yawing moments are induced on the aircraft by performing coordinated anti-symmetrical combinations of louver deflections. If only one louver is split, there is an unequal download and this causes the aircraft to roll. Yawing can be achieved by deflecting the louver on one side to the front, and the other to the back. The louver under splitting and deflection is shown in Figure 11.

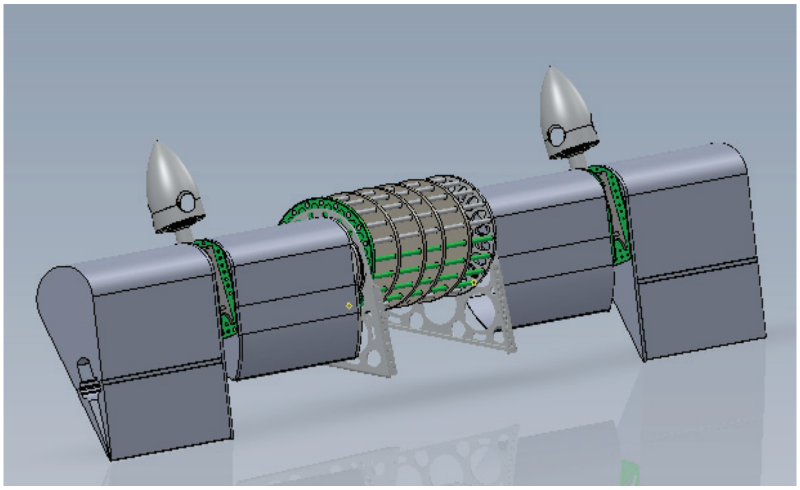


Figure 10. The center wing structure. The louvers are placed on the edges on both sides and are the parts furthest down. The entire wing rotates, but only the louvers have the ability to split and deflect.

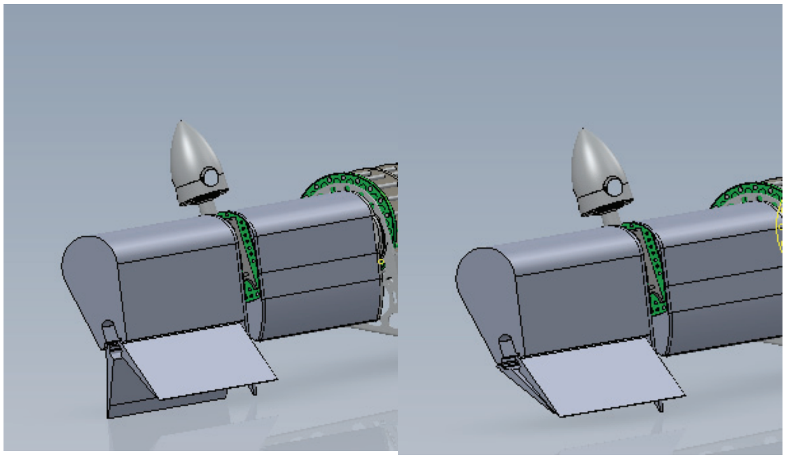


Figure 11. Louver split is shown on the left, and a complete louver deflection is shown on the right.

For the pitch attitude, control is done with the use of an air-blowing-based control system mounted in the tail, as opposed to the traditional method using longitudinal cyclic control. There is one hatch on the top of the tail and one on the bottom of this system. By opening the hatch, air is expelled at a high speed, and a pitching moment is induced.

CRUISE MODE

There are ailerons on the trailing edges of the front wing pair, close to the winglets. The elevators are placed on the aft wing pair. The vertical tail connecting the aft wing pair and the fuselage has the rudder mounted on it. To get varying thrust, the louvers are split in a manner similar to that used to control ascent and descent.

Furthermore, as the vehicle is converting to cruise mode and gaining speed, the control influence of the aircraft control surfaces increases. This means that the hover control can be phased out as the aircraft is getting closer to airplane mode. By looking at how the forces and moments from hover control change with nacelle angle, a suitable mix of controls at different angles can be determined. A sketch of the control actuators on the Elytron 2S is shown in Figure 12.

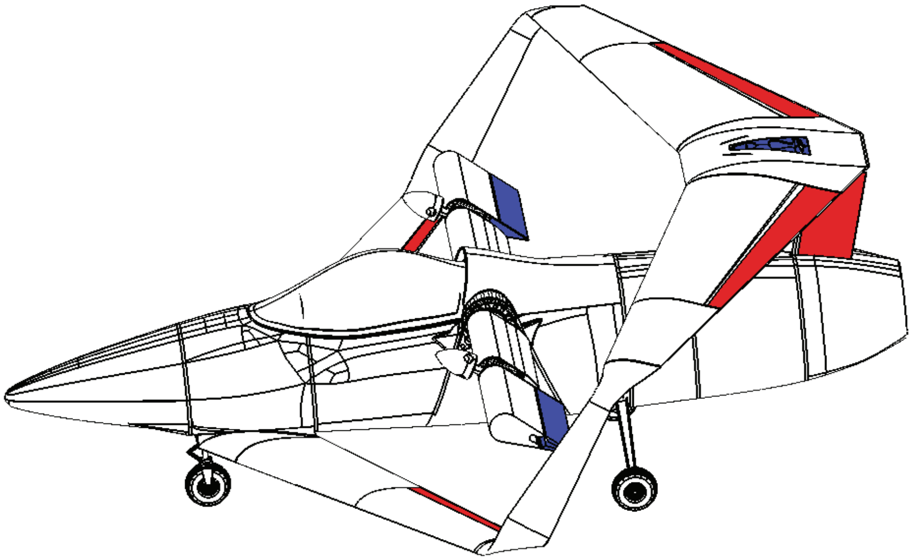


Figure 12. The Elytron 2S with the control actuators highlighted in red for cruise control and blue for hover control. The ailerons are placed on the front wing, the elevators on the aft wing, and the rudder on the vertical tail. The louvers are farthest out on the central wing. The air-blowing pitch control, mounted in the tail, is not shown in this picture.

AIRCRAFT STABILITY

With the untypical design of the Elytron airframe, a thorough stability analysis is of great importance. Two factors that determine whether or not the airframe is stable are the center of gravity (C.G.) placement and the shape of the wings.

An analysis of the stability dependence on C.G. was performed. First, the C.G. was estimated to lie as shown in Figure 13. This C.G. is not stable, as Figure 14 shows.

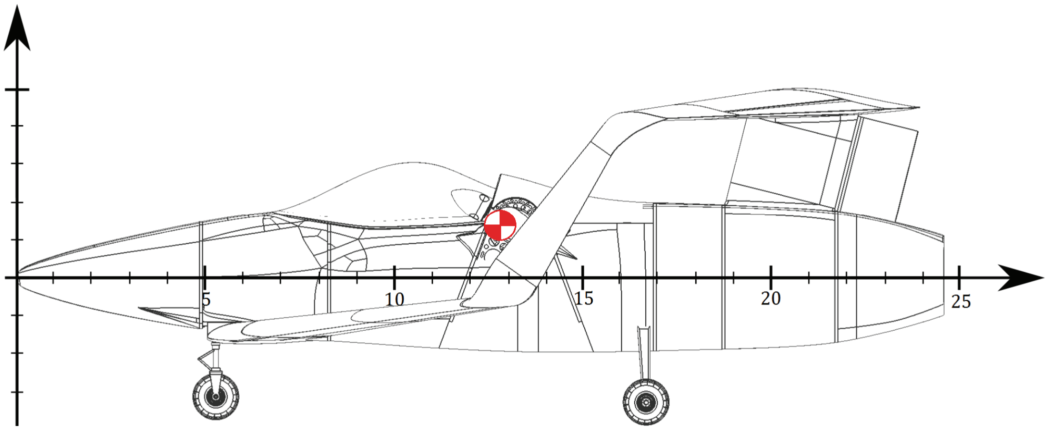


Figure 13. The initially estimated C.G.

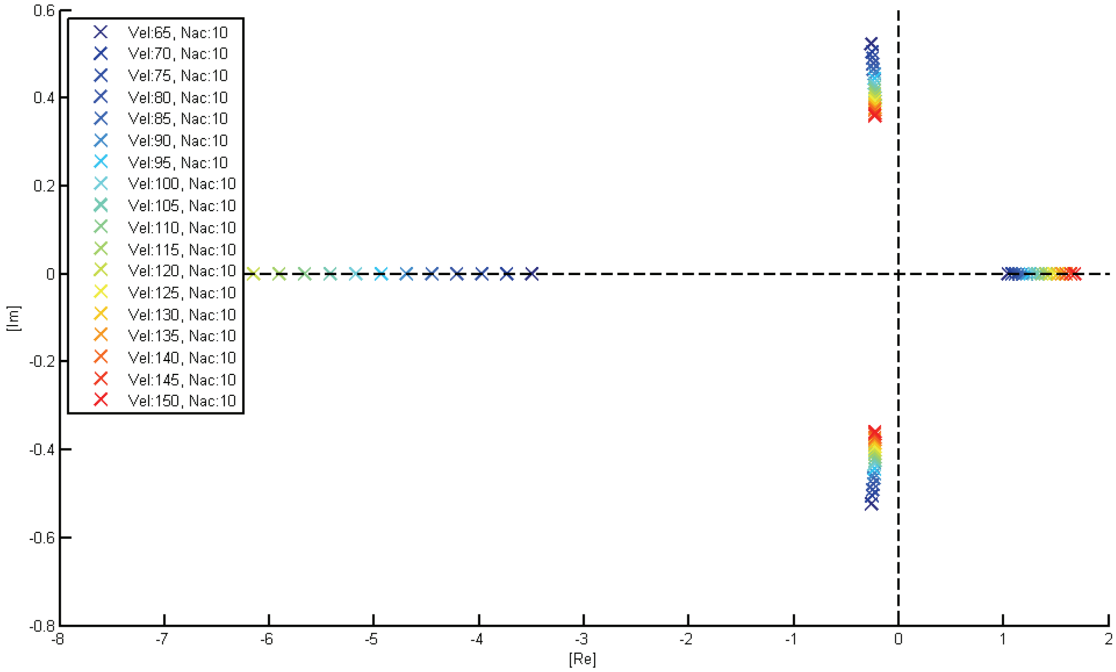


Figure 14. The pole placement as a function of velocity for the initially estimated C.G.

MOVING THE LONGITUIDNAL C.G. POSITION IN X-COORDINATE (CRUISE MODE)

Figure 15 shows how the poles of the longitudinal system move as the C.G. in x (longitudinal coordinate) is moved. The C.G. is moved between 14 feet and 11.35 feet when it stops trimming in NDARC. What is shown is that the unstable pole is going toward the imaginary axis as the C.G. is moved forward. It never gets stabilized, but becomes slightly closer to being stable. At the same time, there is a complex pole pair that becomes less oscillatory at first, and then becomes more oscillatory. The trimmed angle-of-attack change with C.G. is shown in Figure 16. The forces and moments dependence on C.G. calculated by NDARC is shown in Appendix A.

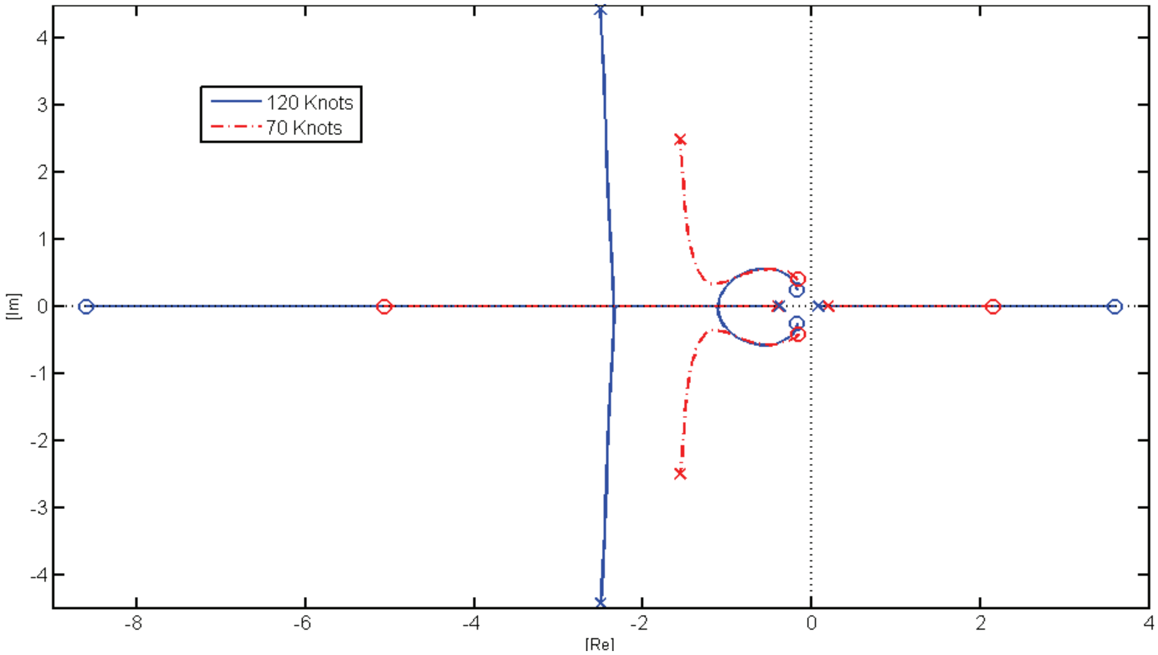


Figure 15. Pole plot when C.G. in x is varied from 14.0 ft. (circle) to 11.4 ft. (cross).

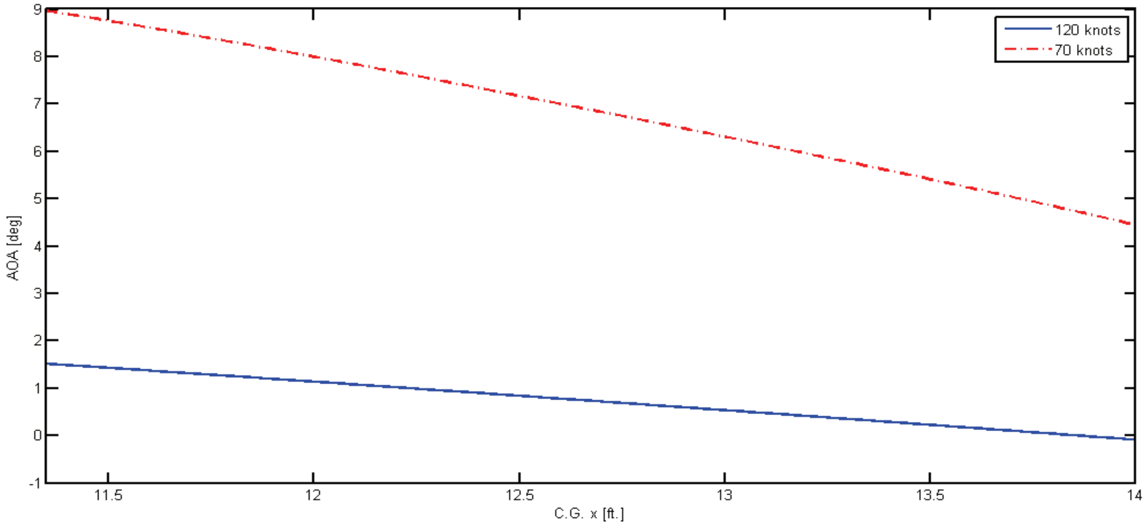


Figure 16. As the C.G. is moved further back, the angle of attack at trim decreases.

MOVING THE VERTICAL C.G. POSITION IN Z-COORDINATE (CRUISE MODE)

As the C.G. is moved further down, the longitudinal dynamics are stabilized, as shown in the pole plot in Figure 17. The decrease in angle of attack is shown in Figure 18. In order to stabilize the aircraft in cruise mode, it is important that the C.G. is chosen in an appropriate way in z.

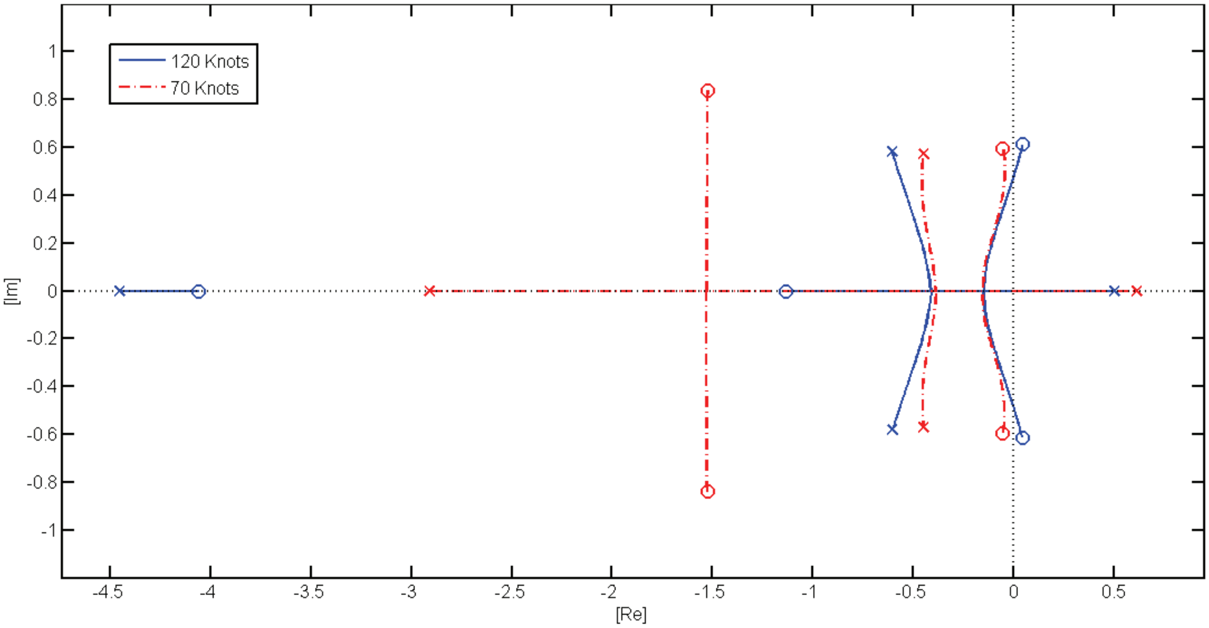


Figure 17. Pole plot showing how the longitudinal dynamics change with C.G. in z. C.G. was varied from 1.6 ft. (cross) to –1.2 ft. (circle).

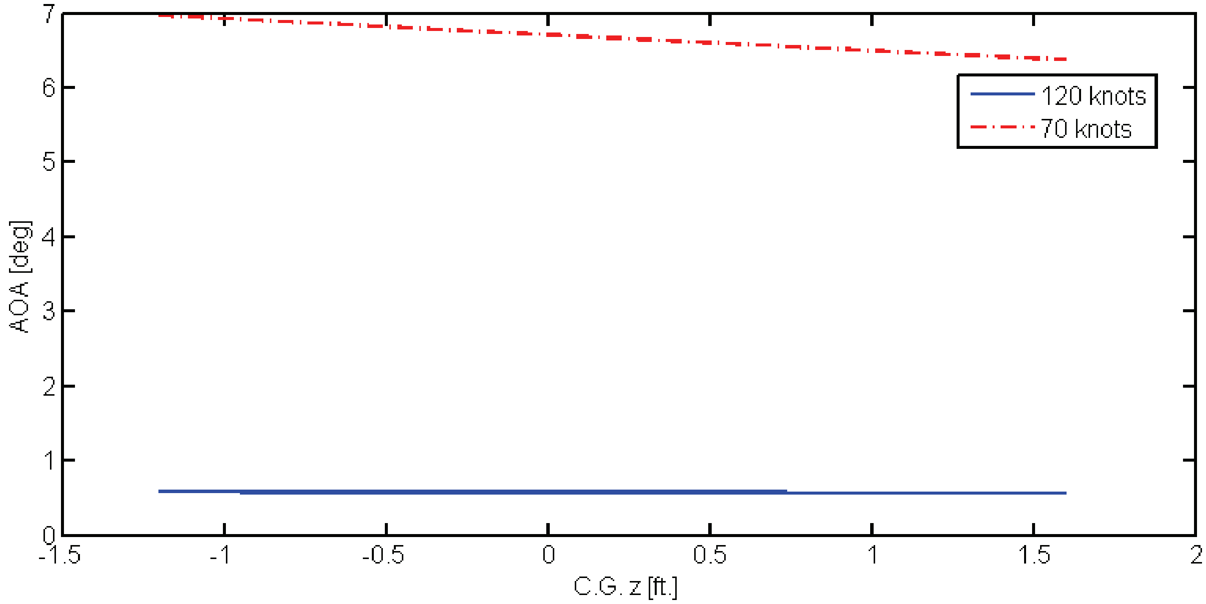


Figure 18. The angle of attack decreases as the C.G. is moved from –1.3 ft. to 1.55 ft.

CONCLUSION

The work done with the Bell XV-15 showed that NDARC captures the overall trend well. There is a difference in the values of pitch of a couple of degrees, but this can be improved by changing the coefficients in NDARC.

The main result regarding Elytron is that it is sensitive to C.G., and that is something that needs to be considered in the design. By appropriately changing the C.G., it is possible to stabilize it in airplane mode. The model is still being developed, and with a more accurate model better results might be obtained. An improved version of the aerodynamics is being updated and will provide new results with higher fidelity.

Future work includes making the NDARC model valid in hover mode to extend the stability analysis to this case. When a working NDARC model exists, it is possible to perform further analyses regarding, for example, a comparison of this alternative hover control to conventional hover control with a swash plate.

REFERENCES

[1] Johnson, W.: NDARC—NASA Design and Analysis of Rotorcraft, Theoretical Basis and Architecture. American Helicopter Society Aeromechanics Specialists’ Conference, San Francisco, Calif., Jan.20–22, 2010.

[2] Tischler, M. B.: Conduit—A New Multidisciplinary Integration Environment for Flight Control Development. NASA TM-112203, AIAA Guidance, Navigation, and Control Conference, New Orleans, La., 1997.

[3] Ferguson, S. W.: Development and Validation of a Simulation for a Generic Tilt-Rotor Aircraft. NASA Ames Research Center, Mountain View, Calif., 1989.

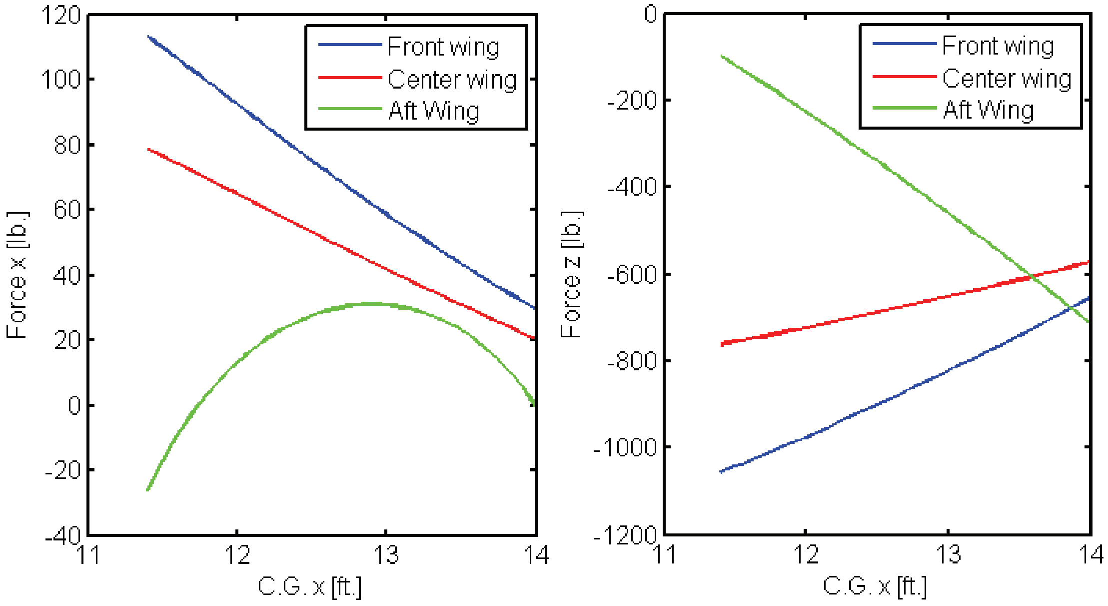
[4] Ferguson, S. W.: A Mathematical Model for Real Time Flight Simulation of a Generic Tilt-Rotor Aircraft. NASA Ames Research Center, Mountain View, Calif., 1988.

[5] Maisel, M. D.; Giulianetti, D. J.; and Dugan, D. C.: The History of the XV-15 Tilt Rotor Research Aircraft—From Concept to Flight. The NASA History Series, 2000.

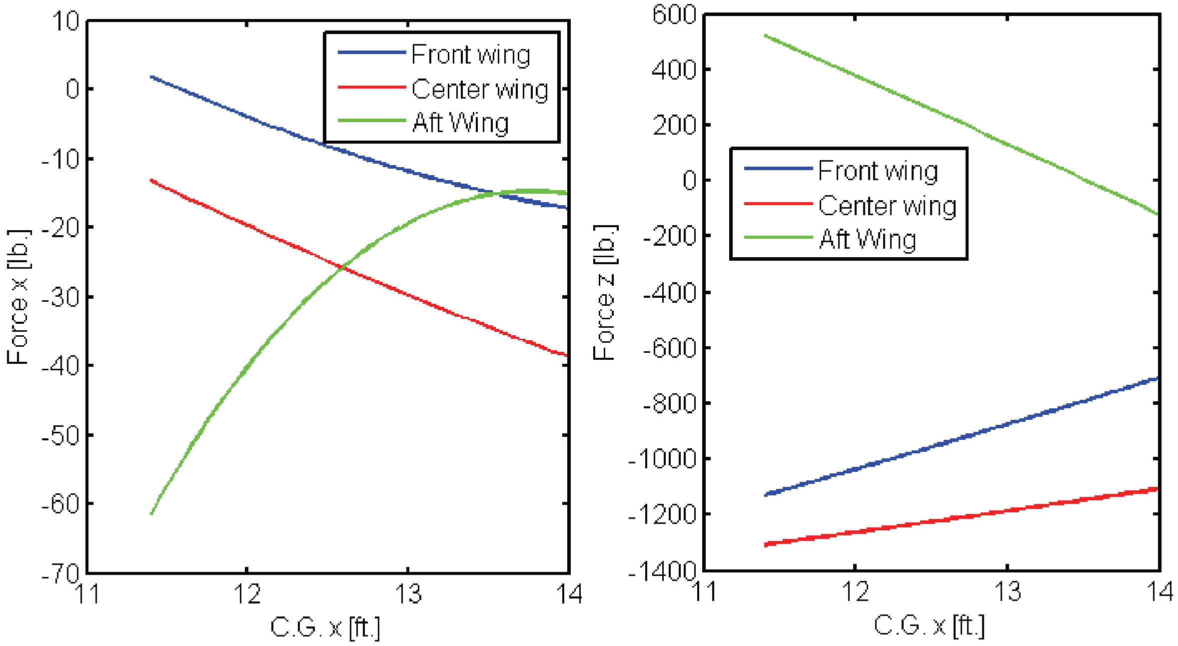
APPENDIX A

C.G. X-POSITION—FORCES COMPUTED BY NDARC

The forces in x and z, resulting from the wings at 70 knots (x forward, z down).

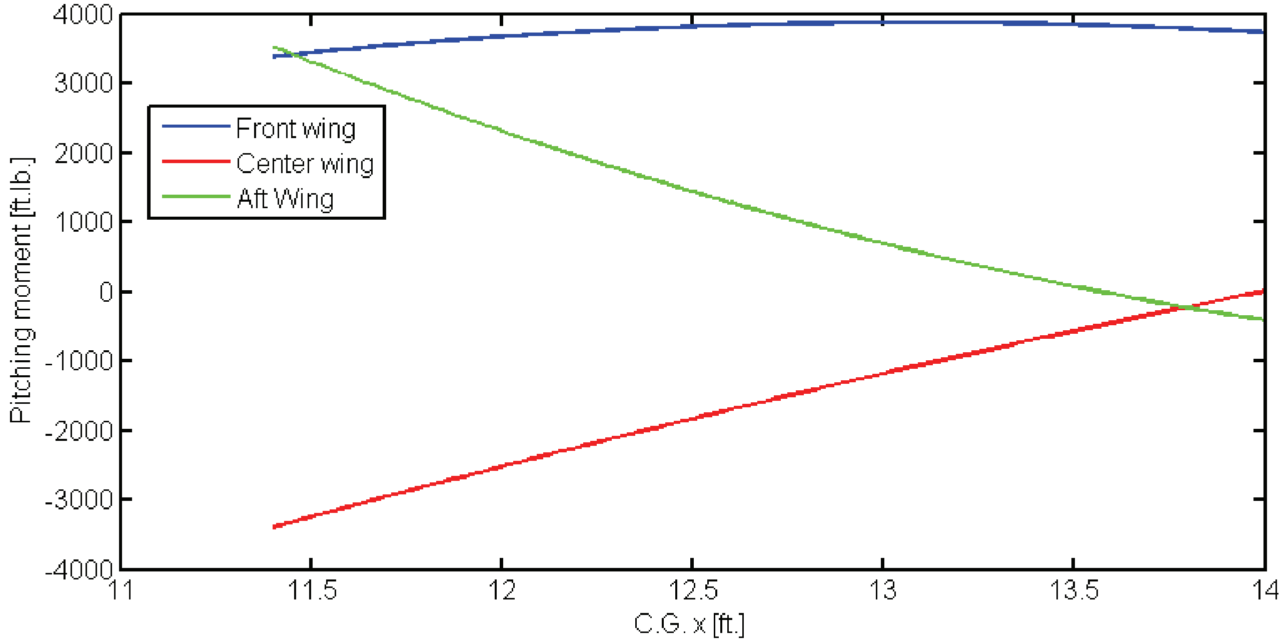


The forces in x and z, resulting from the wings at 120 knots (x forward, z down).

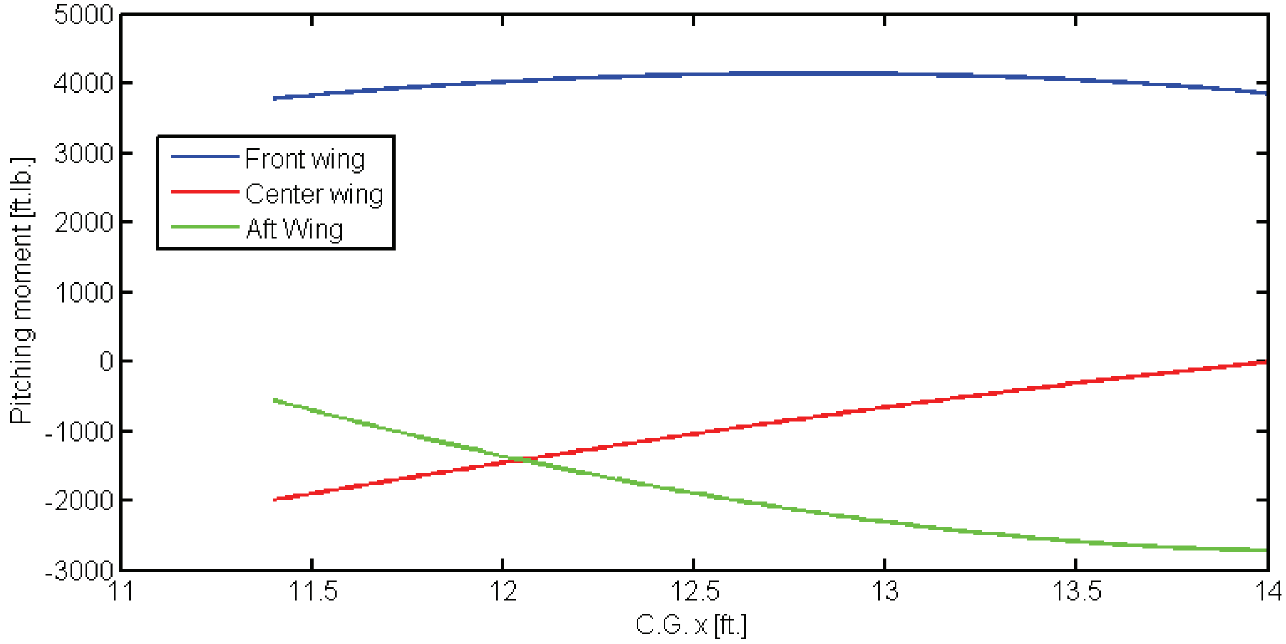


C.G. X-POSITION—MOMENTS COMPUTED BY NDARC

The pitching moment resulting from the wings at 70 knots.

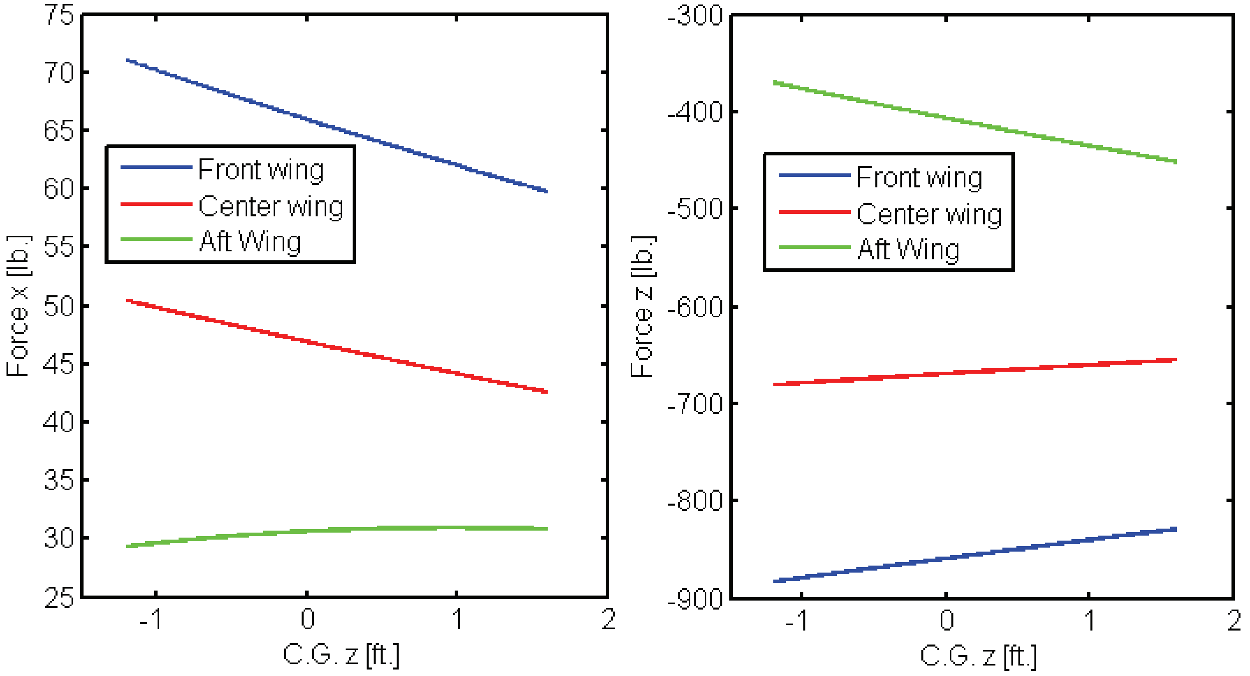


The pitching moment resulting from the wings at 120 knots.

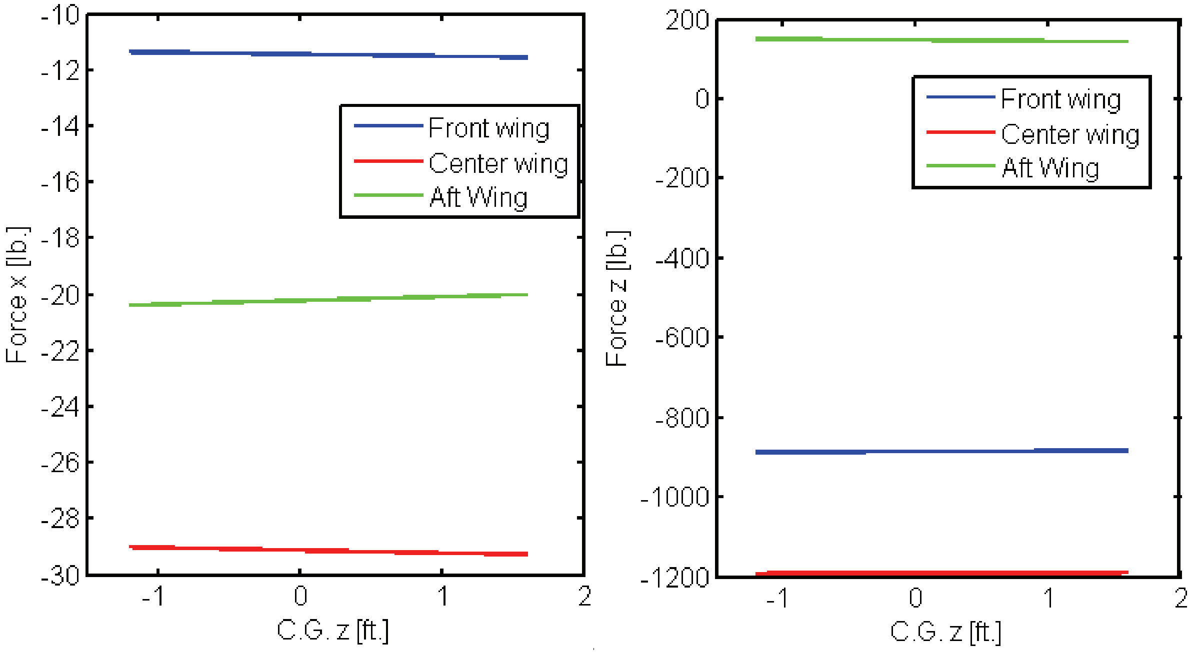


C.G. Z-POSITION—FORCES COMPUTED BY NDARC

Forces acting on the aircraft at v = 70 knots for varying C.G. in z.

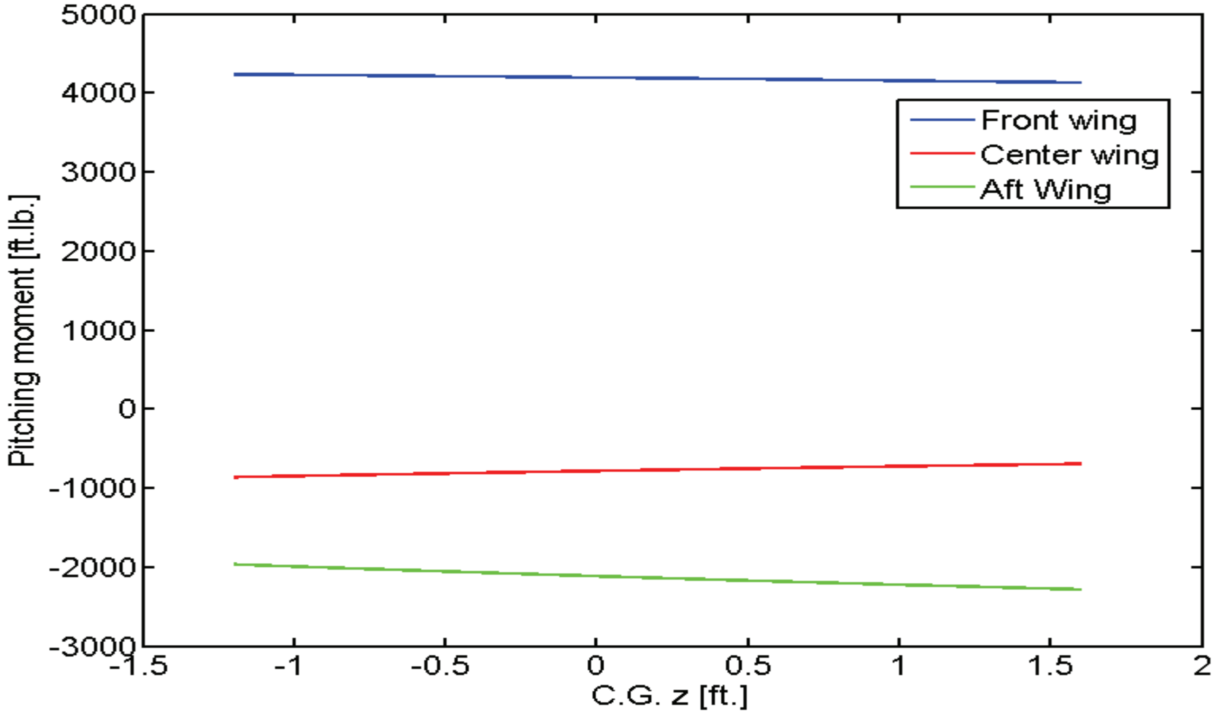


Forces acting on the aircraft at v = 120 knots for varying C.G. in z.



C.G. Z-POSITION—MOMENTS COMPUTED BY NDARC

The pitching moment resulting from the wings at 70 knots.



The pitching moment resulting from the wings at 120 knots.