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Flight Testing and Response Characteristics of a Variable Gull-Wing Morphing Aircraft

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Contemporary morphing designs are focused towards enabling a vehicle to transition from one distinct flight regime to another. Such a change often requires highly complex morphing that is designed to address both aerodynamic performance and handling criteria. The University of Florida has developed a morphing demonstrator to investigate the effect of a biologically-inspired gull-wing morphing on the flight characteristics of a small aircraft. The vehicle, equipped with sensors and data logging devices, is flight tested using a variety of maneuvers and techniques. The flight data from several morphing conditions is analyzed to determine the extent of the change in the dynamic properties. Modeling of the lateral-directional dynamics indicates that gull-wing morphing has a considerable effect on the handling qualities and stability.

I. Introduction

Morphing aircraft design continues to evolve as new technologies in actuators and flexible structures become available. New ideas in morphing encompass more than the simple span extension or wing twisting initially envisioned. Instead, these new designs allow vehicles to undergo a much more complex shape change than can easily be described by one or two parameters. This form of morphing is in-line with the original need for the technology, which is to change the vehicle shape dramatically to address two or more sets of conflicting requirements.

As envisioned morphing designs become increasingly complex, the need for accurate flight dynamic analysis become even more important.[15] The complex shapes achievable by the new generation of actuators and structures can create difficulties in representing the vehicle using existing methods. For instance, an aircraft that morphs asymmetrically can undergo aerodynamic and inertial changes that cannot be described by the commonly used equations of motion. Thus, in order to properly model a morphing aircraft with many degrees of freedom, the complete nonlinear coupled equations must be used. Such a requirement eliminates many or all of the simplifications that are necessary for the equations to be practical.

The modeling predicament underscores one of the current realities of morphing research; the majority of morphing is being conducted in optimal aerodynamic shapes and static aeroelastic effects. The field of morphing vehicle flight dynamics is still highly underdeveloped. Part of this void is understandable, since few, if any, morphing aircraft exist today to perform flight test experiments. However, the lack of work also points to potential future problems in morphing research. Flight dynamics work must be developed in parallel to other morphing efforts in order to be able to assess and control prototype vehicles.

The work presented here represents an initial foray into such an effort. The focus is the changing flight dynamics of a simple morphing vehicle (Figure 1). Vehicle design and morphing actuators are considered only enough to develop a testbed for flight dynamics experiments. No claim is made as to the optimality of the vehicle shape or morphing method. However, it is sufficient to consider that the morphing used causes a change in the flight performance, which is then the basis for studying any accompanying change in stability and control characteristics. In addition to the variable gull-wing morphing, the vehicle is equipped with articulating wingtip mechanism at that morphs the outboard section of the wing in twist. This form of morphing has been implemented on several vehicles at the University of Florida and is similar to the roll control used on the NASA AAW F-18.[10] It is used here to preserve the flexibility of the structure while retaining effective roll control.

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Figure 1. Variable gull-wing morphing vehicle

The enabling factor for this work is rapid prototyping of aircraft designs at the University of Florida Center for Micro Air Vehicles. Developing an experimental unmanned air vehicle from concept to initial flight test occurs within one or two weeks. Fabrication tools such as CNC milling and composite lay-up facilities allow the entire airframe to be manufactured in-house.[5] Small instrumentation and avionics are commercially available, reducing development time and cost significantly. Using these resources, inexpensive testbeds can be produced quickly to test new concepts in aircraft design and flight control.

The data presented in this paper is from flight tests of a morphing vehicle developed at the University of Florida in early 2004. The vehicle makes use of a simple actuator to emulate the variable gull-wing morphing commonly seen on seagulls and other birds. A jointed spar system allows the wing to morph in a variety of configurations. The wing morphing is used as a quasi-static effector, so only fixed geometry responses will be considered. The initial modeling approach taken is based on simple transfer function approaches. Initial models are developed under the assumption of linearity in order to understand the broad effect of the variable geometry on the aircraft dynamics. More sophisticated modeling that can truly express the vehicle dynamics is left for a later study.

II. Vehicle Geometry

Variable gull-wing morphing is implemented on small-remotely piloted air vehicle. Naming of the morphing action is derived from seagulls, which articulate the wings such that the inboard segment is at a positive dihedral angle while the outboard segment is at a negative dihedral angle. Morphing of the wings is enabled by a jointed spar system controlled by a linear actuator in the fuselage. The wings are morphed from fully extended (0^o gull-wing) to positive gull-wing and also inverted or negative gull-wing.

Figure 2 shows a bird in gliding flight using a gull-wing configuration. The purpose of this variable gull-wing action in birds is likely for a variety of reasons, including static aerodynamic,[2] physiology, and for flapping control. However, it is studied here solely to investigate the quasi-static aerodynamic benefit and the corresponding effect on the vehicle dynamic response.

Biological emulation in flight systems can be a difficult task. Nature does not require access to rotating mechanisms such as turbines or propellers. Similarly, aircraft designers cannot easily implement muscle-like actuation or nerve-like sensing in systems. Furthermore, most aircraft today are significantly larger, faster, and more massive than birds. Such factors make direct biological-inspiration of little practical use for conventional aircraft.

Small and micro air vehicles, however, provide an ideal platform for implementing biologically-inspired flight systems. The mass, speed, Reynolds number, and flight environment of small flight vehicles are close to or identical to those of birds. Thus, changes in vehicle shape and control are likely to have a similar effect on these aircraft as it has on birds. The goal of the variable gull-wing morphing is then to see whether this form of morphing can have beneficial effects on the flight performance and dynamics of an otherwise conventional vehicle.

Conventional configuration guidelines are used in the design of the vehicle. A single wing is accompanied by horizontal and vertical stabilizers mounted on the tail. The wing planform and airfoil shape are borrowed from a previous aircraft design to reduce additional design effort. Thin, flat tail surfaces are used for simplicity and light weight. Similarly, the airfoil is thin and undercambered, apart from a cylindrical spar attached to the underside. The thin flight surfaces perform as good or better than conventional airfoiled structures at low Reynolds numbers,[7].[14]

Figure 2. A seagull descends at a steep angle in gliding flight

However, thin, flexible surfaces have the distinct advantage that they are relatively easy to morph.[4] The aircraft is shown in Figure 3 in the unmorphed configuration.

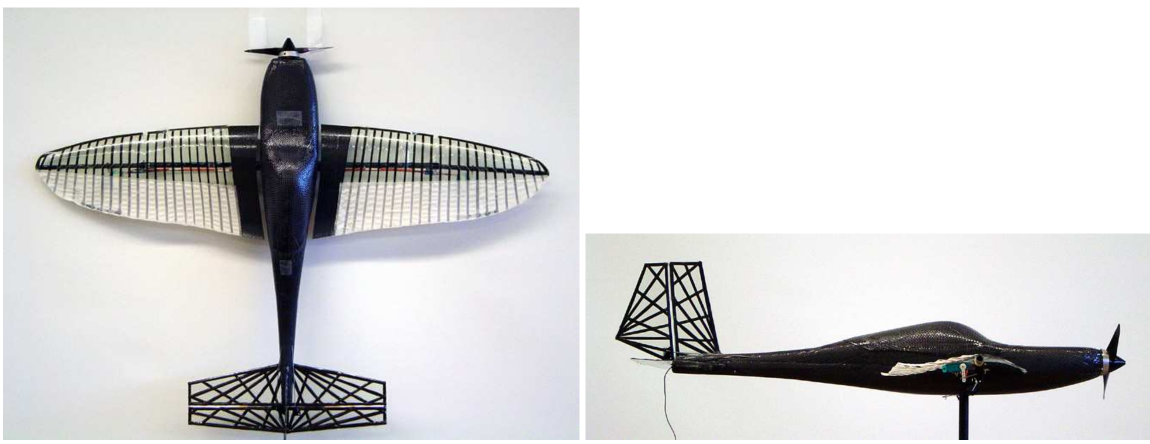

Figure 3. Top and side view of variable gull-wing aircraft

Airframe elements are constructed entirely of carbon fiber and nylon film. Fuselage and bulkhead components are made of composite cloth molded over a male fuselage tool.[3] The fabrication process yields a monocoque fuselage shell that is lightweight but strong enough to withstand flight and crashing loads. Wing and tail surface structures are comprised of a carbon-fiber skeleton covered with a nylon film for a skin. The construction allows the structure to withstand flight loads, yet easily complies and deforms under actuator forces. This particular characteristic makes the structure well suited for morphing.

With the wings fully extended, the wingspan of the variable gull-wing vehicle measures 26*in*. The wing planform shape provides sufficient area to keep the fully-instrumented aircraft at a reasonable wing loading, yet is also high enough in aspect ratio to provide good aerodynamic performance. Morphing the wings changes the wing geometry in several parameters. Table 1 lists the basic geometry changes incurred during gull-wing morphing. Figure 4 shows a frontal view of the vehicle during three configurations resulting from gull-wing morphing.

A hinged spar structure, based loosely on bird skeletal physiology,[13] provides the degree of freedom needed for gull-wing morphing. Each spar side consists of two tubular spars with one hinge at the fuselage joint and another between the two spars. The angle of the inboard spar is controlled by a vertical linear actuator. A telescoping shaft connects the spar with the output arm of the actuator. The shaft allows the actuator to move over the entire range without mechanically binding the spar. The angle of the outboard spar is passively controlled via a mechanical linkage parallel to the inboard spar. This linkage connects the control arm on the outboard spar directly to the fuselage. During actuation, the linkage causes the inboard and outboard sections to deflect in opposite directions. The ratio of these

Parameter	Min	Max
Wingspan	20 *in*	26 *in*
Planform area	77.7 in^2	101.4 in^2
Inboard wing relative to fuselage	-40^o	40^o
Outboard wing relative to fuselage	-40^o	40^o

Table 1. Wing geometry change over variable gull-wing morphing range

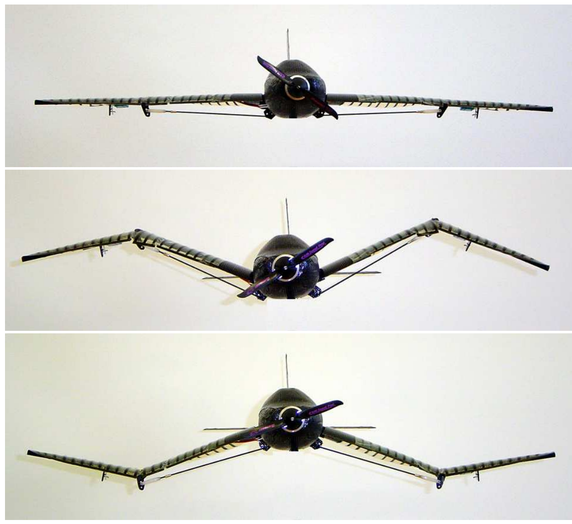

Figure 4. Vehicle undergoing neutral (top), positive (center), and negative (bottom) gull-wing morphing

relative deflections is adjusted by changing the moment arm on the fuselage control arm and/or the outboard spar control arm. An important feature of the system is its ability to withstand flight loads without active control or energy consumption. Figure 5 shows the left side of the hinged spar in a positive gull-wing position.

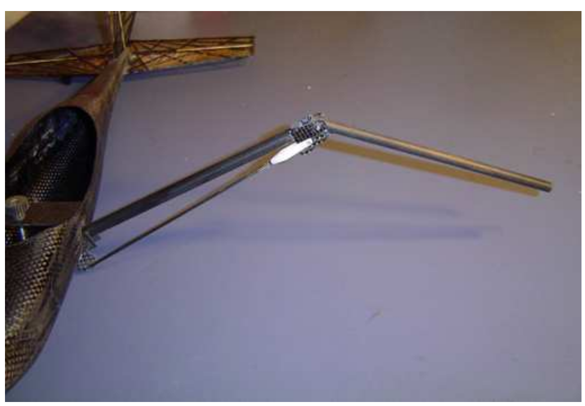

Figure 5. Variable gull-wing spar structure and control linkage, linear actuator visible inside fuselage at left

A flexible wingskin is attached to the jointed spar so that the spar comes under the point of maximum camber. This position approximately corresponds with the point of minimum pitching moment, in addition to reducing the frontal area of the wing. The wing skin consists of chordwise carbon-fiber battens and a single spanwise leading-edge member. Each batten is free to deform within the limits of the wing skin extension and carbon-fiber flexibility. In flight, this compliance allows the airfoil sections to deform in response to buffeting or steady airloads. As a result, the wing passively deforms and reduces the effect of atmospheric perturbations such as gusts and wind shear on the vehicle's flightpath.

Conventional elevator and rudder control surfaces are used for pitch and yaw control. These surfaces are hinged to the fixed stabilizing surfaces with strips of Tyvek. Rotary actuators mounted in the fuselage control the surface deflection. Control actuation limits are +/- 30^o of travel, with actuation rate limits of 400$^o/s$.

Roll control is provided by articulating wing tips on the outboard spar section. A rotary servo mounted to the wingskin actuates against the spar, causing the wing surface to rotate about the spar. The surface is attached to the outboard spar so that rotation about the spar is unrestrained, except by the actuator motion. However, since the wingskin is continuous along each side of the aircraft, the result is a twist deformation centered at the actuator and extending both inward toward the fuselage and outward toward the wingtips. Figure 6 shows a close-up view of the wing twist mechansim, outboard spar, and actuator.

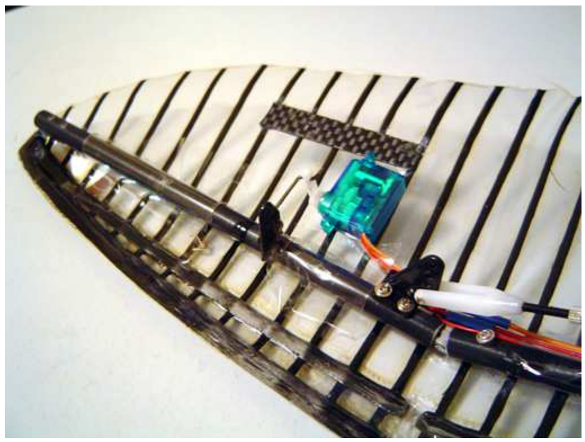

Figure 6. Underside view of left wing showing wing twist effector

Control of the gull-wing is accomplished using a linear lead-screw actuator driven by a rotary servo. Rotating the lead-screw causes the output arm to slide vertically within the fuselage. At the lowest position, the inboard spars are deflected 40^o upward. The lead-screw provides control of the wing shape without having to withstand the lifting loads directly; however, the actuation rate of the morphing is quite slow in comparison to the other surfaces. This slow actuation is not problematic since the morphing is being investigated strictly as a quasi-static effector.

Command and response data are measured in-flight using an on-board micro data acquisition system. The device supports 30 channels of analog sensor input and samples between 50Hz to 500Hz. The data presented here is measured at 100Hz. Several external sensors are interfaced to the data logging, including 3-axis rate gyros, linear accelerometers and control surface position sensors for the elevator, rudder, wingtwist, and gull-wing angle.

III. Flight Performance

The variable gull-wing morphing sufficiently changes the flight performance for the vehicle to operate in several distinct flight regimes. Morphing the wings controls several aerodynamic and dynamic parameters, including lift to drag ratio, sideslip coupling, and roll stability. These factors in turn affect the handling qualities of the vehicle to make certain flight tasks easier to perform in a particular morphing configuration.

The change in flight performance is the primary incentive behind the morphing; however, this paper is strictly concerned with the change in handling qualities and dynamic characteristics that accompany the performance changes. A more detailed analysis of the performance benefit enabled by gull-wing morphing was previously published.[1]

A. Gliding Performance

Power-off gliding performance is tested to identify the effect of the morphing configuration. Glide performance is an important measure of lift to drag ratio. In turn, lift to drag ratio is representative of the aircraft's capability in range, endurance, maneuvering, airspeed range, and efficiency. Thus, by testing the glide performance, inferences can be made about much of the remainder of the flight envelope, which is often more difficult to test.

Glide tests are performed by cutting off motor power and allowing the vehicle to stabilize in a constant airspeed dive. The shallowest, sustainable dive angle corresponds to the maximum lift to drag ratio for a specified configuration. The numerical value of the lift to drag ratio is exactly equal to the glide ratio, which is the horizontal distance traveled divided by the altitude lost during the dive. The glide ratio can be determined using airspeed and altitude measurements from on-board the aircraft or by estimating distances from the ground.

In the unmorphed configuration (0^o gull-wing angle), the vehicle attains an approximate maximum glide ratio of 11. This value is typical for aircraft of this size and shape. As the wing is morphed in the positive direction, the glide ratio become progressively lower. At 15^o gull-wing angle, the glide ratio is noticeably reduced, causing the aircraft to descend at a much steeper angle. However, the glide ratio remains relatively good.

At 30^o, the lift to drag ratio becomes very low. Ground estimates for the glide ratio are between 1 and 2. The result is that the aircraft is capable of descending at a 45^o angle without gaining airspeed. Furthermore, the high gull-wing angle adds considerable lateral-stability, allowing the vehicle to attain a steep, stabilized dive without control departure tendencies. Such a configuration could be beneficial in allowing the vehicle to descend safely without requiring much horizontal distance.

Negative gull-wing morphing has a similar effect on glide ratio. At -20^o gull-wing angle, the glide ratio is approximately 3. The effect of the morphing on a stabilized dive is similar to the positive morphing, except that the benefits of sideslip to roll stability is greatly reduced. In fact, control input required to maintain a constant airspeed and glide angle is higher than both neutral and positively morphed cases.

Actuating the gull-wing morphing during a glide test illustrates the impact on lift to drag performance. During a steep, stabilized dive at -30^o morphing, the gull-wing angle was slowly increased to 0^o. The resulting flight path, when viewed from the side, resembled an exponential decay. As the morphing became less negative, the glide ratio became progressively shallower. Pitch control was used during this maneuver to find a trim airspeed corresponding to the maximum glide performance. Thus, the gull-wing morphing is sufficiently effective to control the glide angle of the aircraft and can be used to change the glide angle throughout the descent.

B. Climb Performance

The effect of gull-wing angle on climb performance is similar in nature to the effect on glide angle. Maximum climb performance is attained at a neutral gull-wing angle. Morphing the aircraft either in the positive or negative direction reduces climb rate, although the effect is more pronounced for positive gull-wing angles.

C. Stall Characteristics

Stall flight testing is performed to determine the effect of the morphing on departure characteristics. In particular, it is used to determine conditions where a stabilizing controller may be required to prevent loss of control. Additionally, the stall characteristics are useful in assessing whether certain stall-spin modes may be useful as evasive or high-performance flight maneuvers.

Flight testing a vehicle for stall characteristics requires a pilot to fly at high altitudes and be well versed in recovery techniques.[12] The stalls are entered by reducing the airspeed and using the elevator to pitch above the critical angle of attack. Elevator pressure is applied slowly to help eliminate any dynamic effects that might influence stall entry. Stalls are allowed to fully develop by holding positive elevator pressure throughout the test. Recovery from the stall or ensuing spin is performed when the aircraft has clearly demonstrated a particular mode or when altitude loss has become substantial.

Stalls performed at neutral morphing are relatively benign and resulted in moderate altitude loss during recovery. The wing planform has a tendency to stall abruptly, but then regains control quickly. Control is lost for only a brief period as the aircraft pitches down and reduces angle of attack.

Stalls at positive gull-wing angles are more difficult to enter and result in a smaller altitude loss during recovery. At high angles of attack and large positive elevator pressure, the vehicle simply enters a dive and buffets slightly. When provoked to stall with aggressive elevator deflection, the stall break is of lower intensity that the previous configuration. Recovery from a stall at high positive gull-wing angle is more immediate. Part of this improved resilience comes from a significantly decreased tendency to depart into a spin. The high angle of the wings has a stabilizing effect and seems to favor a symmetric stall when at high angles of attack.

Negative morphing contributes to a much more aggressive stall mode than observed with the previous configurations. The stall recovery also requires a greater amount of altitude and control input. Stalls also have a greater tendency of escalating into a spin. The spins are generally non-terminal, although one stall test resulted in an unrecoverable spin that resulted in some vehicle damage.

Although the testing performed is hardly exhaustive, the observed characteristics indicate that the positive gull-wing contributes to highly desirable stall and recovery characteristics. However, the testing did not reveal any spin modes that could be useful as flight maneuvers.

IV. Stability and Control Characteristics

Morphing aircraft introduce considerable complexity to the field of flight dynamics because of variable geometry of the airframe. The variable gull-wing aircraft in particular morphs the wings in a manner that has considerable effect on many of the stability and control derivatives that control the lateral-direction modes.

Modeling of the lateral-directional dynamics is restricted to Dutch roll and roll convergence. Spiral mode identification was not possible, considering that the data sets in analysis were relatively short in duration. Proper identification of this mode would require long data sets with little or no pilot input. Such tests are difficult to accomplish using small remotely piloted vehicles.

A. Roll Convergence

The roll mode is one of the most fundamental descriptions of the aircraft lateral-directional motion. The mode essentially describes resistance to rolling, whether through a control surface deflection or a perturbation. Aircraft handling qualities and lateral controller designs are highly dependent on the roll mode.

The roll mode, or roll convergence, is largely a function of the C_{l_p} derivative, which describes the change in rolling moment as a function of roll rate. This derivative in turn is a function of the vehicle geometry. As the vehicle shape changes, as in the case of a gull-wing morphing aircraft, the C_{l_p} parameter and the corresponding roll mode are expected to change. The change in roll mode with morphing deflection then becomes a basic assessment of the change in handling qualities incurred due to morphing.

Wing-twist pulses are used to perturb the vehicle from a trimmed flight condition. The response of the vehicle to these pulses is used to identify important stability and control characteristics, namely the roll mode and the wing twist effectiveness. Pulse maneuvers are performed at cruise airspeed from straight and level flight. The pulse is repeated for a variety of command magnitudes and morphing positions.

The pulse maneuvers are performed such that the aircraft's perturbation from the entry trim condition is relatively small. Larger pulses may exceed the range of aircraft responses that can be adequately represented by a linear model; however, the small size of the vehicle requires that the maneuver be large enough to be clearly evident to the remote pilot. In practice, the control pulses are performed to 30 or 40^o bank angle in each direction.

A typical wingtwist control pulse is shown in Figure 7. Commanded wingtwist deflection is measured along with the roll and yaw rate response. The roll angle data shown is estimated from the roll rate. The estimate is assumed to be a reasonable representation over short time periods and small angles of attack. Although the estimate may be off in absolute magnitude due to calibration or estimation errors, the trends clearly show the relative bank angle response.

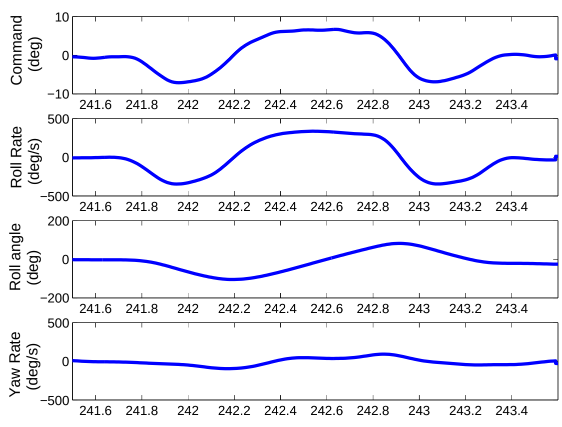

Figure 7. Wing-twist command and response from flight data

The top two plots in Figure 7 show a close correspondence between command input and roll response. Such response is typical of aircraft with high aileron control power. The yaw rate incurred during the maneuver is closely in phase with the estimated bank angle.

The roll mode is modeled by computing a transfer function between the roll command and the roll rate response,[8].[6] Secondary effects of the command such as adverse yaw and pitch coupling are neglected due to relatively small disturbance magnitudes. Other yaw effects such as sideslip or bank angle induced yaw rate are also not considered in the model.

A MATLAB Auto-Regressive with Exogenous Input (ARX) discrete-time model is used to represent the roll mode. The coefficients of the model are computed from least-squares fit to the data. The discrete-time model is used in simulation to determine the accuracy of the computed model. A final transformation is made to represent the model as a continuous-time state space formulation. The formulation of the model assumes first order rigid body dynamics. Although structural modes may very well be present, the model structure and filtering techniques assume that any response above 7 *Hz* is strictly noise and is therefore not considered in the model.

Pole locations for the roll mode at several gull-wing positions are shown in Figure 8. The plot shows the poles migrating to a less negative value as the wing is morphed in the positive or negative direction from neutral. This migration accounts for the decreased sensitivity to command input as the wing is morphed.

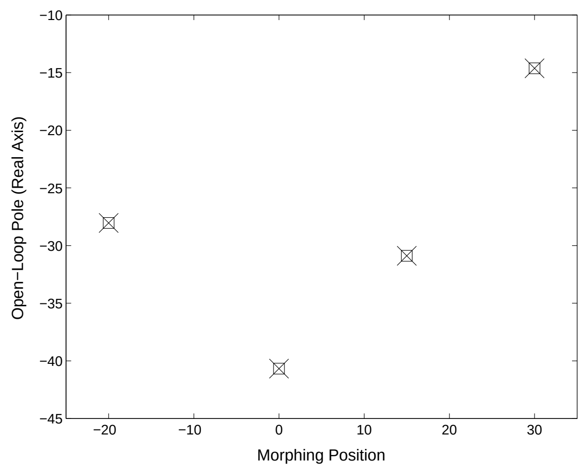

Figure 8. Pole migration as function of gull-wing morphing angle

The physical significance of the change in poles is the effect on the lateral-directional handling qualities throughout the morphing range. The most negative value, occurring at 0^o morphing position, indicates that the vehicle quickly attains a steady state roll value when subjected to a control input or disturbance. Increasing the gull-wing morphing in the positive direction increases the response time of the vehicle to similar inputs. At the most positive morphing position of 30^o, the vehicle is considerably less responsive than at the neutral morphing position. Morphing the gull-wings in the negative direction produces a similar effect on the roll mode. The migration of the open-loop poles from neutral to -20^o is similar to a 15^o positive morphing from neutral.

The controllability of the simulated systems also undergoes a change with gull-wing morphing position. Figure 9 shows the change in the b-matrix values over the tested range of morphing. The qualitative shape of the plot appears as a mirror image of the pole locations. In particular, the neutral gull-wing position here is a maxima while the b-matrix value falls as the wing is deflected in either direction. The plotted values represent the control effectiveness of the twisting wingtips in producing a roll acceleration. The higher the b-matrix value, the higher the control power of the wingtips.

Physically, this is likely a result of a combined effect of the increased gull-wing angle, decreased wingspan, and angled control surfaces. The latter change occurs because of the normal direction of the wingtips deviates from perpendicular to the span as the wing is morphed. Thus, some component of the added lift from the wingtip twisting occurs in the spanwise direction and has no effect on the roll moment. The change in the roll moment produced by the wingtips varies approximately with the cosine of the deflection angle of the outboard wing section.

Figures 10 through 13 show results of the simulation models compared to flight data. Measured and simulated roll rates are generally in close agreement for all the models.

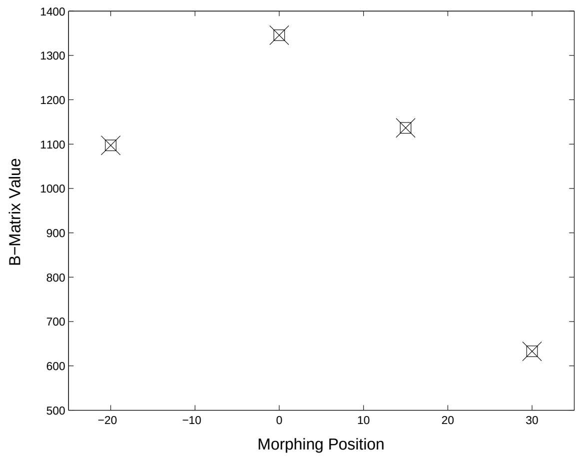

Figure 9. B-matrix value for first-order roll mode systems

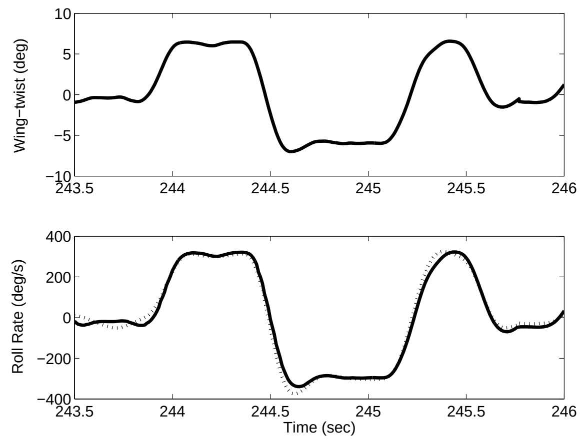

Figure 10. Wing-twist command (top) at -0^o gull-wing, measured roll rate (:) and simulated roll rate (-) (bottom)

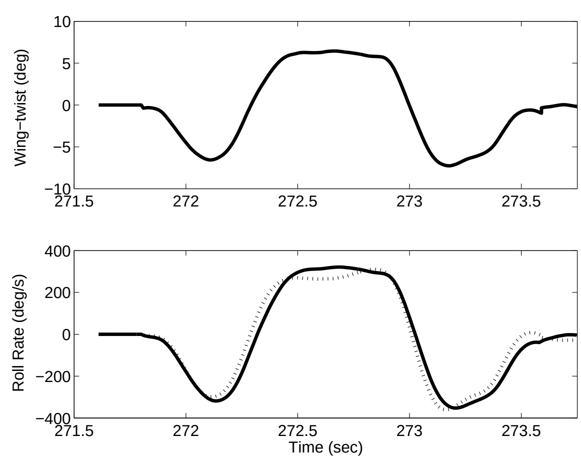

Figure 11. Wing-twist command (top) at 15^o gull-wing, measured roll rate (:) and simulated roll rate (-) (bottom)

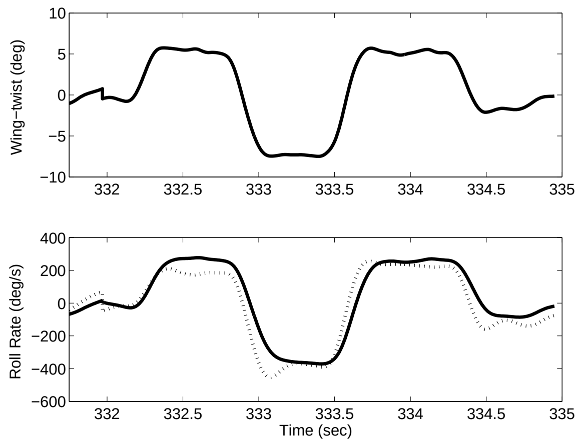

Figure 12. Wing-twist command (top) at 30^o gull-wing, measured roll rate (:) and simulated roll rate (-) (bottom)

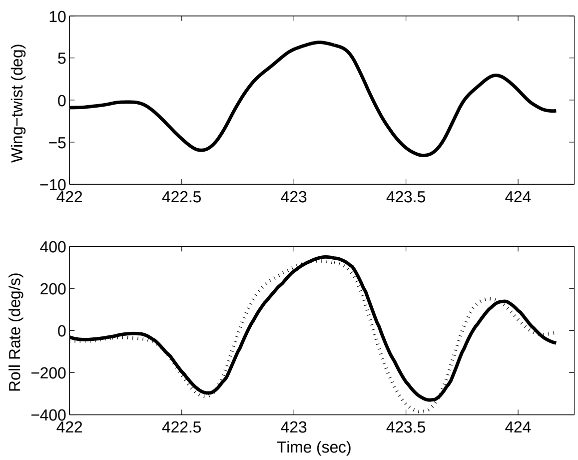

Figure 13. Wing-twist command (top) at -20^o gull-wing, measured roll rate (:) and simulated roll rate (-) (bottom)

B. Dutch Roll Mode

The Dutch roll mode is an important measure of oscillation damping and coupling between roll, sideslip, and yaw.[11] Poor Dutch roll properties can cause difficulties in stabilization and control, causing poor flight path tracking.[9]

Unlike the roll mode, the Dutch roll mode involves significant coupling between the lateral-direction states and often with the longitudinal states. The characteristics of the mode are highly dependent on wing geometry. The wing shape directly affects factors such as roll and yaw damping, sideslip cross-coupling, and inertial properties, all of which in turn affect the Dutch roll characteristics. In terms of vehicle geometry, the mode is largely dependent on dihedral angle, wingspan, vertical area distribution, and vertical center of gravity.

Rudder control pulse maneuvers are used to excite the Dutch roll mode of the vehicle at two different gull-wing positions. The pulses are a series of consecutive step inputs in opposite directions. Each pulse perturbs the vehicle from trimmed flight in sideslip, roll, and yaw. The resulting vehicle response is then largely an indication of the Dutch roll mode. Control pulses are performed at 0^o and 15^o gull-wing angles.

Command and response data from rudder control pulses at 0^o and 15^o gull-wing angle are shown in Figures 14 and 15, respectively. The most apparent difference between the two pulses is the two-fold increase in the roll response magnitude for the 15^o gull-wing case. Roll coupling with rudder and/or sideslip has increased dramatically with positive gull-wing deflection. The response at this morphing position is dominated by roll. Recovery oscillations in both roll and yaw are smaller and damp out faster than the neutral morphing case.

The model formulation required that the system account for both the roll rate and yaw rate response to rudder

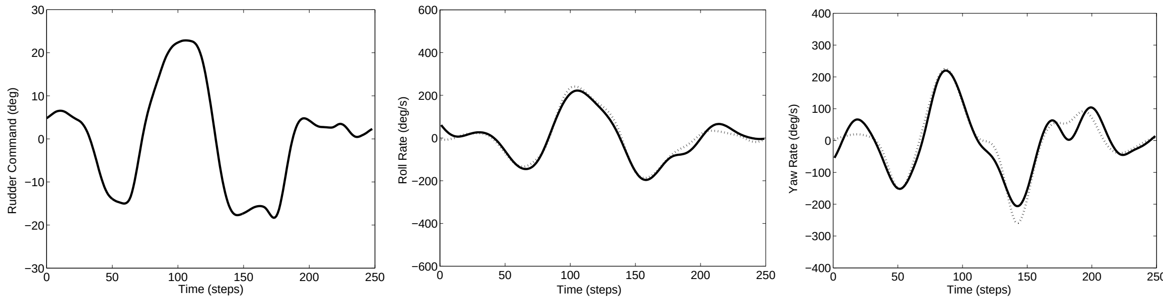

Figure 14. Rudder control pulse at 0^o gull-wing angle with measured data (...) and simulated response (-).

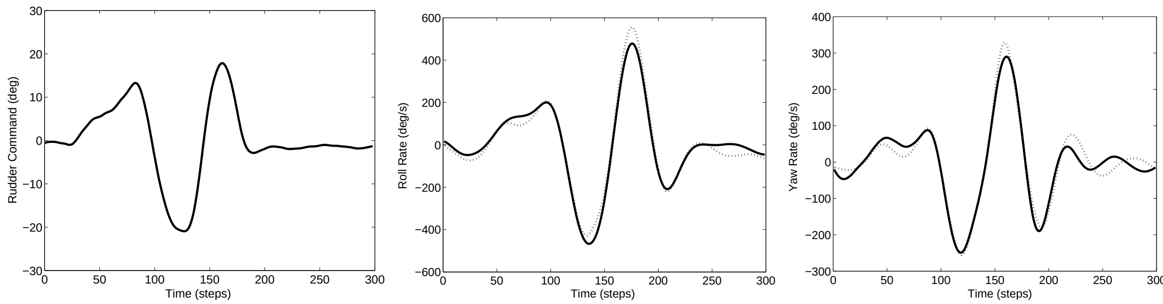

Figure 15. Rudder control pulse at 15^o gull-wing angle with measured data (...) and simulated response (-).

deflection. With one input and two outputs, a different system identification method was needed than was used previously. Using the ARX approach to modeling the Dutch roll dynamics resulted in a relatively poor fit compared with the roll mode modeling.

A 4th-order state-space model is used to identify the lateral dynamics from the rudder control pulse data. Attempting to model strictly the Dutch roll mode as a second order system resulted in poor fit in both roll rate and yaw rate. Increasing the order of the system to 4 considerably improved the fit for both states. The resulting model has two pairs of complex conjugate poles, although classical Dutch roll modes for conventional aircraft have only a single pair.

The identified Dutch roll dynamics for two morphing models are shown in the equations below. The dynamics are given in state-space format, where

$$x\dot{=}Ax + bu \tag{1}$$

and

$$y = cx + du \tag{2}$$

The state-space matrices are shown for the 0^o gull-wing system in Equation 3-6 the first set of equations and for the 15^o system in Equation 7-10.

$$A = \begin{bmatrix} -0.00728 & -0.07607 & 0.06432 & 0.001042 \\ 0.1299 & -0.04688 & 0.01308 & 0.05232 \\ -0.06621 & 0.004354 & -0.02822 & 0.05985 \\ 0.02396 & -0.08451 & -0.0712 & -0.05431 \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \end{bmatrix} \tag{3}$$

$$b = \begin{bmatrix} -0.001507 & -0.0004478 & -0.001323 \\ 0.0003071 & -0.001497 & -0.0002368 \\ 0.0003202 & -0.004137 & -0.007136 \\ -0.001106 & -0.01099 & 0.003608 \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \end{bmatrix} \tag{4}$$

$$c = \begin{bmatrix} 34.99 & -488.6 & 3.619 & -9.66 \\ -869 & 176.5 & -22.61 & 2.435 \end{bmatrix} \begin{bmatrix} y1 \\ y2 \end{bmatrix} \tag{5}$$

$$d = \begin{bmatrix} 0 & 0.9822 & 0 \\ 0 & 0.2639 & 1.82 \end{bmatrix} \begin{bmatrix} y1 \\ y2 \end{bmatrix} \tag{6}$$

$$A = \begin{bmatrix} -0.00963 & -0.07148 & 0.05012 & 0.002864 \\ -0.1124 & -0.04497 & 0.01106 & -0.03917 \\ -0.07133 & -0.06225 & -0.03205 & 0.1023 \\ -0.01097 & 0.01318 & -0.08323 & -0.02391 \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \end{bmatrix} \tag{7}$$

$$b = \begin{bmatrix} -0.001524 & -0.0004311 & -0.0009517 \\ 0.0002664 & 0.0006908 & 8.541e-005 \\ -0.0001861 & 0.001469 & -0.006974 \\ -0.001101 & -0.006893 & -0.001574 \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \end{bmatrix} \tag{8}$$

$$c = \begin{bmatrix} -46.5 & 1348 & 5.786 & -19.65 \\ -901 & -222.3 & -18.36 & 1.216 \end{bmatrix} \begin{bmatrix} y1 \\ y2 \end{bmatrix} \tag{9}$$

$$d = \begin{bmatrix} 0 & 1.556 & 0 \\ 0 & -0.9075 & 1.335 \end{bmatrix} \begin{bmatrix} y1 \\ y2 \end{bmatrix} \tag{10}$$

The pole migration shown in Figure 16 depicts a considerable change in the aircraft characteristics during morphing actuation. The two complex pole pairs shift toward the right-hand plane during positive gull-wing angle changes. This pole migration has the effect of decreasing both the average natural frequency and the damping of the modes. The particular modal properties are listed in Table 2 and Table 3. The two modes listed are not necessarily Dutch roll modes; rather, they represent the more general rudder pulse response dynamics. For this reason, the dynamics are represented by two complex conjugate poles as opposed to the single pair associated with most conventional aircraft.

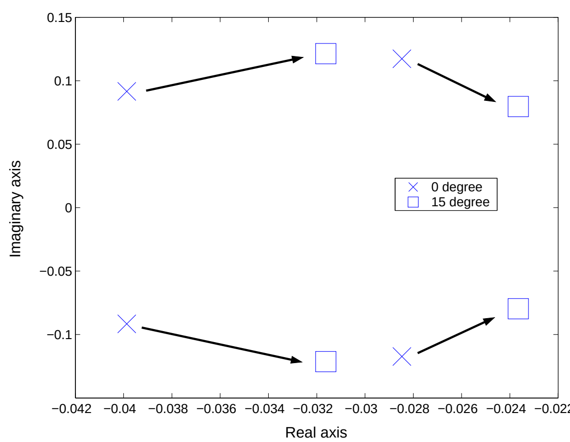

Figure 16. Open-loop Dutch roll mode pole migration for two morphing positions

-	Natural frequency	Damping
Mode1	0.6276 Hz	0.3993
Mode2	0.7584 Hz	0.2359

Table 2. Dutch roll modes for 0^o gull-wing

The eigenvectors associated with each morphing system are shown in Tables 4 and 5 for gull-wing cases 0^o and 15^o, respectively. The 15^o case shows that the morphing causes increased coupling between the states, in addition to

-	Natural frequency	Damping
Mode1	0.5220 Hz	0.2847
Mode2	0.7879 Hz	0.2522

Table 3. Dutch roll modes for 15^o gull-wing

introducing considerable phase changes. Such changes are apparent by examining the rudder control pulse data from Figures 14 and 15, where the coupling of the rudder input to roll rate and yaw rate changes with morphing.

State	Magnitude	Phase (deg)
Mode1		
x1	0.4769	74.4588^o
x2	0.7309	0^o
x3	0.0753	101.3212^o
x4	0.4824	96.7250^o
Mode2		
x1	0.0323	71.4868^o
x2	0.4240	78.8885^o
x3	0.4948	83.0143^o
x4	0.7575	180.000^o

Table 4. Dutch roll mode Eigenvectors for 0^o gull-wing

State	Magnitude	Phase (deg)
Mode1		
x1	0.4525	67.8550^o
x2	0.3209	146.2772^o
x3	0.7064	180.000^o
x4	0.4396	-96.0538^o
Mode2		
x1	0.3758	-84.8100^o
x2	0.5526	50.4414^o
x3	0.4516	-83.7154^o
x4	0.5912	0.00000^o

Table 5. Dutch roll mode Eigenvectors for 15^o gull-wing

Figure 17 shows bode plots for the two morphing systems. The top two plots depict the magnitude and phase response from rudder input to roll rate while the bottom two plots show the responses from rudder input to yaw rate. The most notable change between the two occurs in the magnitude of the roll rate response. For the 15^o case, the peak response has a larger amplitude and occurs at a lower frequency than the neutral case. This result is in agreement with the eigenvalues, which show a lower natural frequency for the 15^o morphing position.

V. Longitudinal Dynamics

Longitudinal system identification is performed on elevator pulse data to determine the short period pitch mode and the Phugoid mode. Two morphing conditions are considered for this analysis, 0^o gull-wing and 15^o gull-wing. A transfer function is computed between the elevator deflection and pitch rate response data using an output-error model. Tables 6 and 7 shows the results of the modeling in terms of the frequency and damping of the longitudinal

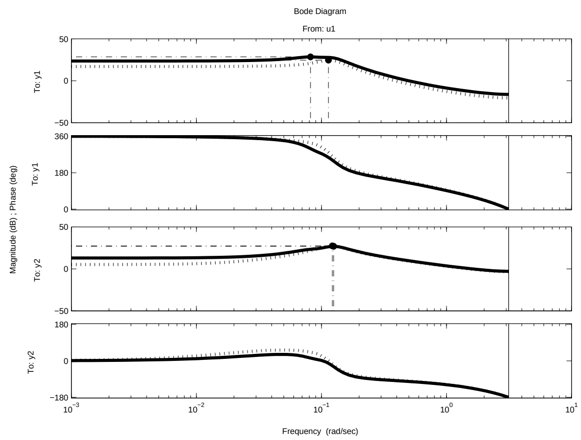

Figure 17. Frequency response diagram for 0^o gull-wing (dotted) and 15^o gull-wing (solid)

modes. For each of the longitudinal dynamic models, the system identification process also predicted a negative real pole near zero. The contribution of this pole to the dynamics is unclear, although it is suspected to be an artifact of the identification process using noisy data.

-	Natural frequency	Damping
Phugoid Mode	0.2945 Hz	0.5422
Short Period Mode	19.75 Hz	0.0303

Table 6. Longitudinal modes for 0^o gull-wing

-	Natural frequency	Damping
Phugoid Mode	0.6131 Hz	0.3912
Short Period Mode	19.95 Hz	0.1445

Table 7. Longitudinal modes for 0^o gull-wing

The system poles show a distinct change in the longitudinal dynamics during morphing. Specifically, the short period damping ratio has increased dramatically. The natural frequency of the mode is predicted to remain constant over the 15^0 change in gull-wing angle. For the Phugoid Mode, the simulation prediced an increase in the natural frequency with a corresponding decrease in the damping. These results, especially in the short period mode, are in agreement with pilot feedback. Pitch control during high gull-wing morphing is highly damped and responds sluggishly to elevator deflection. However, the limited data set precludes rigorous evaluation of the predicted models. Additionally, the noise in the data during the elevator pulse sequence flight test seemed higher in magnitude than noise in other data sets. The noise level creates difficulties in differentiating physical dynamics with sensor noise or vibration.

Figure 18 shows simulated pitch rate response to an elevator pulse sequence plotted against measured pitch rate. The pulse is performed with a gull-wing angle of 0^o. The simulated response is in good agreement with the general trends of the measured response, although has a poor fit of the high frequency content. As a result, the predicted models are useful only as basic descriptions of the actual dynamics. Figure 19 shows the measured and simulated responses for a 15^o gull-wing configuration. Again, the simulation model exhibits discrepancies with the measured data at high frequency oscillations. The data from the elevator pulse sequences is plotted against simulation time steps, with each step equal to 1/100th of a second.

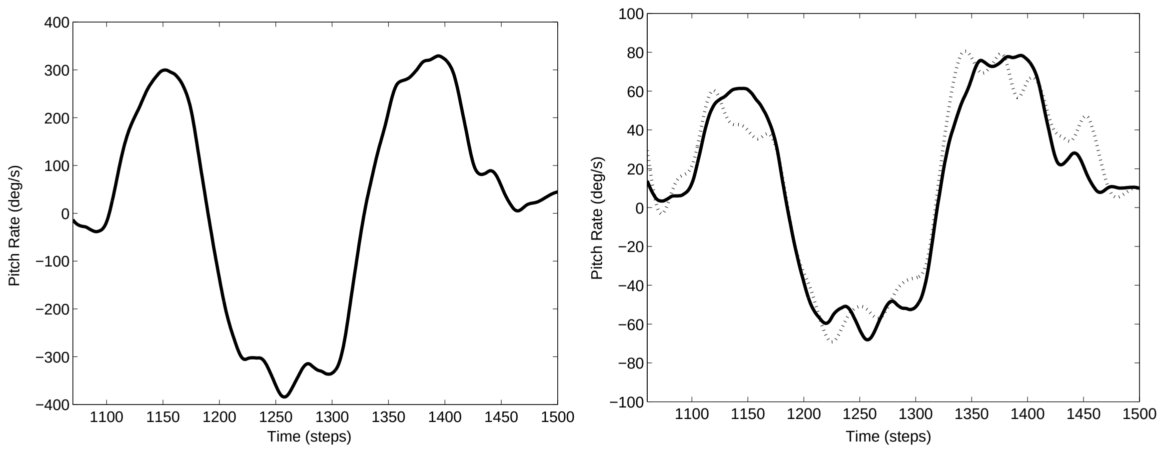

Figure 18. Elevator pulse command (left), Measured (:) and Simulated(-) pitch rate responses (right)

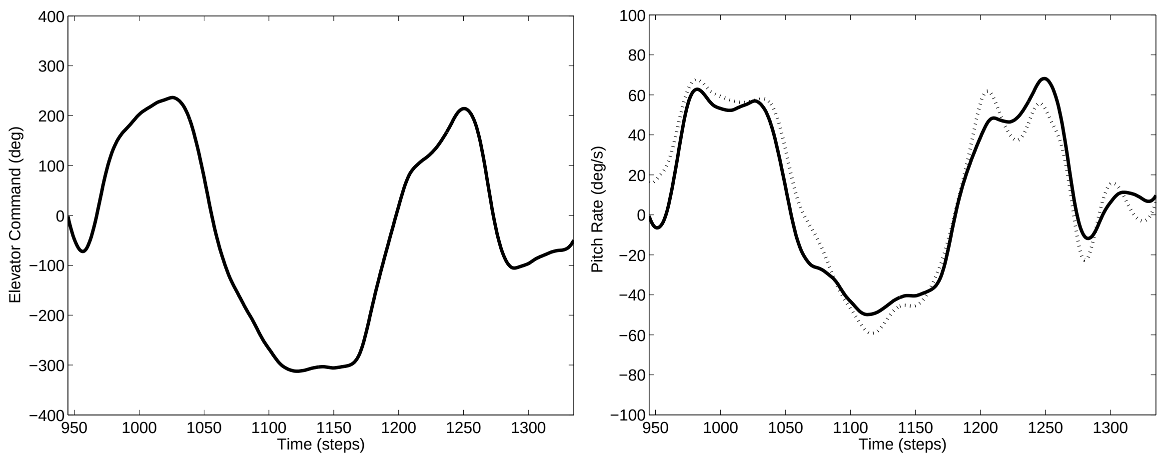

Figure 19. 15^o gull-wing elevator pulse command (left), Measured (:) and Simulated(-) pitch rate responses (right)

VI. Conclusion

Preliminary control pulse flight testing is completed for a prototype gull-wing morphing aircraft. The vehicle demonstrates aerodynamic performance changes through wing morphing. Modeling of control pulse response characteristics shows that the dynamic model changes along with the performance. Although the modeling techniques used are relatively simplistic, the simulation shows good agreement with the measured responses. Identified lateral-directional dynamic modes indicate that the aircraft model is highly affected by morphing of the wings. Both the magnitude and the shape of the responses change in the case of the Dutch roll mode. Such data will be useful in developing controllers to stabilize morphing flight vehicles over a range of airframe deformation. Longitudinal dynamics are identified from elevator pulse sequences and show reasonable fit to the data. Additionally, the work is the beginning in understanding the effect of a type of biologically-inspired morphing on the flight characteristics of a conventional aircraft. Ongoing work will focus on increasing the number of morphing conditions tested in flight and improving modeling technique.

References

[1] M. Abdulrahim "Flight Performance Characteristics of a Biologically-Inspired Morphing Aircraft" 54th AIAA Regional Student Conference, Memphis, TN, April 2004.

[2]J.B. Davidson, P. Chwalowski, and B.S. Lazos, "Flight Dynamic Simulation Assessment of a Morphable Hyper-Elliptic Cambered Span Winged Configuration," AIAA-2003-5301, August 2003.

[3]S.M. Ettinger, M.C. Nechyba, P.G. Ifju, and M.R. Waszak, "Vision-Guided Flight Stability and Control for Micro Air Vehicles," *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, October 2002, pp. 2134-2140.

[4]H. Garcia, M. Abdulrahim, and R. Lind, "Roll Control for a Micro Air Vehicle using Active Wing Morphing," AIAA-2003-5347, August 2003.

[5]P.G. Ifju, D.A. Jenkins, S.M. Ettinger, Y. Lian, W. Shyy, and M.R. Waszak, "Flexible-Wing Based Micro Air Vehicles," AIAA-2002-0705, January 2002.

[6]K.W. Iliff, "Aircraft Parameter Estimation," NASA-TM-88281, 1987.

[7]Y. Lian and W. Shyy, "Three-Dimensional Fluid-Structure Interactions of a Membrane Wing for Micro Air Vehicle Applications," AIAA-2003-1726, April 2003.

[8]L. Ljung, *System Identification*, Prentice Hall, Englewood Cliffs, NJ, 1987.

[9]R.C. Nelson *Flight Stability and Automatic Control* McGraw Hill, Boston, MA, 1998.

[10]E.W. Pendleton, D. Bessette, P.B. Field, G.D. Miller, and K.E. Griffin, "Active Aeroelastic Wing Flight Research Program: Technical Program and Model Analytical Development," *Journal of Aircraft*, Vol. 37, No. 4, 2000, pp. 554-561.

[11]W.F. Phillips *Mechanics of Flight* John Wiley & Sons, Hoboken, NJ, 2004.

[12]R.W. Stone, and B.E. Hultz, *Summary of Spin and Recovery Characteristics of 12 Models of Flying-Wing and Unconventional-Type Airplanes*, NACA-RM-L50L29, March 1951.

[13]H. Tennekes *The Simple Science of Flight - From Insects to Jumbo Jets* The MIT Press, Cambridge, MA, 1997.

[14]M.R. Waszak, L.N. Jenkins and P. Ifju, "Stability and Control Properties of an Aeroelastic Fixed Wing Micro Aerial Vehicle," AIAA-2001-4005.

[15]R.W. Wlezien, G.C. Horner, A.R. McGowan, S.L. Padula, M.A. Scott, R.J. Silcox, and J.O. Simpson, "The Aircraft Morphing Program," AIAA-98-1927, April 1998.