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Flight Characteristics of Shaping the Membrane Wing of a Micro Air Vehicle

Mujahid Abdulrahim,* Helen Garcia,* and Rick Lind†
University of Florida, Gainesville, Florida 32611

Biologically inspired concepts are rapidly expanding the range of aircraft technology. Consideration is given to merging two biologically-inspired concepts, morphing and micro air vehicles, and the resulting flight characteristics are investigated. Specifically, wing shaping is used to morph the membrane wings of a micro air vehicle. The micro air vehicle has poor lateral control because hinges, and consequently ailerons, are difficult to install on a membrane wing. Instead, a set of torque rods, aligned along the wings, are used to twist the membrane and shape the wing. The resulting morphing is shown to provide significant control authority for lateral dynamics. A set of flight tests are undertaken to determine the flight characteristics by commanding pulses and doublets to the control actuation. The vehicle demonstrates excellent roll performance in response to wing shaping. Futhermore, the vehicle demonstrates several types of spin behavior related to combinations of elevator deflection and the wing shaping.

I. Introduction

AIRCRAFT systems are continually evolving to expand their capabilities and mission effectiveness. Some of the missions that are now being conceived include short-distance surveillance, local target acquisition, biological agent detection, and operation within an urban environment. Two evolutions that are particularly relevant to these missions are the design of micro air vehicles (MAV) and the design of morphing structures.

The concept of morphing is generally envisioned as changing, potentially dramatically, the shape and structure of an aircraft in a manner somewhat analogous to variations seen by birds and insects.[1] The adoption of morphing is typically being considered for fighter-size aircraft and small-size or medium-size unmanned air vehicles (UAV). Theoretical studies clearly indicate an increase in metrics, such as agility and lift-to-drag ratio, proportional to the amount of morphing[2]; however, actuation mechansims do not yet exist to achieve the desired morphing for these vehicles.

Similarly, MAV are being designed along sizes and scales observed in biological systems.[3] A MAV is essentially a flight vehicle but with dimensions, such as wing span and airspeed, smaller than traditional systems. Most types of MAV have a common feature, namely, they are quite difficult to pilot. Remote piloting is difficult because their size makes attitude estimation difficult for human eyes. Also, the control surfaces are designed to limit power requirements and weight by providing adequate, but not excessive, authority to maintain merely a basic level of control.

This paper considers the application of morphing to a MAV. Specifically, a scheme to twist the wings for roll control of a particular class of MAV is considered.[4] The notable feature of this class of MAV is thin under-cambered wings contructed of plastic membrane over composite battens. These membrane wings are lightweight and aerodynamic while providing strength to support loads; however, ailerons cannot easily be included due to the lack of internal structure. Early flight tests have shown that ailerons cannot be successfully encompassed into the flexible wing without compromising its beneficial characteristics. Consequently, the maneuvering performance of the vehicle is limited because authority is provided using only a rudder and elevator.

The actual morphing is quite simple and results from twisting the wing tips using torque rods and servos. As such, this paper considers the effects of morphing rather than the optimal actuation strategies. The wing twisting may seem too simplistic to be considered morphing; however, the wings are actually twisted quite significantly. The size of twist is small, but the size of twist relative to the wing span is dramatic. The MAV indeed undergoes shape changes sufficient to term as morphing due to this wing shaping.

The MAV is an ideal platform on which to demonstrate morphing because the power required is quite small, whereas the benefit is quite large. The membrane wings of the MAV provide the difference from traditional aircraft, which makes active shaping such an attractive approach. Membrane wings are obviously highly flexible so that morphing can be accomplished with little power. Also, membrane wings do not allow the inclusion of ailerons, and so morphing provides a tremendous improvement for pilots by allowing improved lateral controllability.

II. MAV

A. Background

Relatively small versions of UAV known as MAV are receiving considerable attention in the flight test community.[5] The University of Florida has been particularly active in the field of MAV design and testing. Ifju et al.[3] have designed, built, and flown many unique designs ranging from 2 ft to 4 in. in wing span that are remotely piloted using vision feedback to a ground station.

Several of the MAV designed at the University of Florida use membranes as wing surfaces. These membranes are extremely light so that the wings are large enough to generate sufficient lift without excessive weight. Also, their flexibility results in passive washout, which changes angle of attack along the wing to reduce inherently sensitivity to disturbances.

The structural and flight dynamics of a MAV with membrane wings have been extensively studied. A fully three-dimensional computational simulation of the fluid dynamics has revealed the effect of unsteady flow reacting to structural deformation.[6] A wind tunnel has also been used to identify the parameters associated with the flight mechanics.[7] Similarly, the wind tunnel was used to identify the wing deformations during flight.[8]

The MAV developed at the University of Florida are notoriously difficult to fly. Such difficulty is somewhat expected given that the aircraft are highly agile and maneuverable but must be flown remotely. The team is currently investigating methods of active control for the MAV that would allow autonomous operation and greatly extend the applications for which such vehicles may be considered.[9,10]

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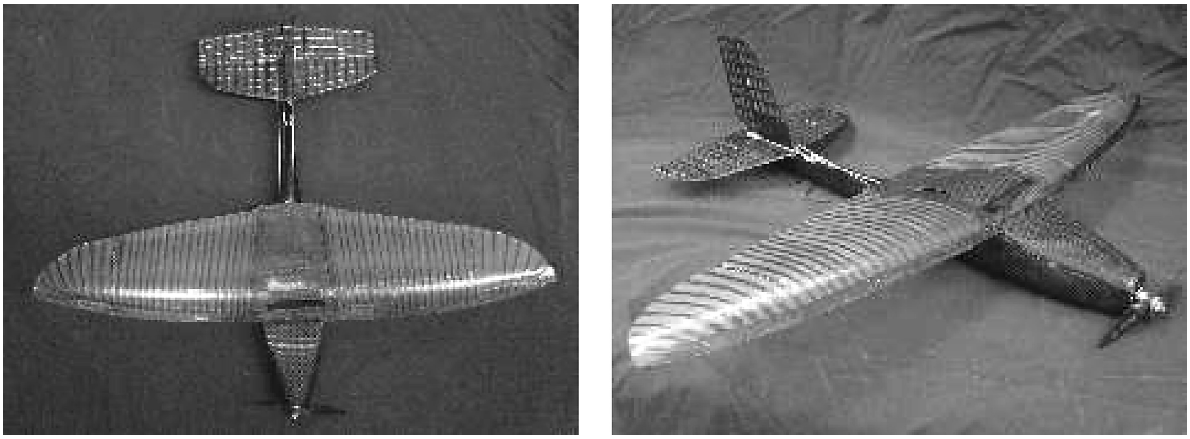
*Graduate Student, Department of Mechanical and Aerospace Engineering. Student Member AIAA.

†Assistant Professor, Department of Mechanical and Aerospace Engineering. Senior Member AIAA.



a) b)

Fig. 1 MAV: a) overhead view and b) side view.

The use of innovative control effectors is an area being explored as an enabling technology for designing a stability augmentation system. The current generation of MAV use traditional effectors, specifically an elevator and rudder, whose positions are commanded by the remote pilot. The elevator presents adequate effectiveness for longitudinal control, but the rudder presents some difficulty for lateral–directional control. The rudder primarily excites the Dutch roll mode so that steering and gust rejection are really accomplished using the coupled roll and yaw motion resulting from Dutch roll dynamics. Such an approach is obviously not optimal, but traditional ailerons are not feasible on this type of aircraft because hinges can not easily installed on membrane wings.

B. Aircraft Description

This paper will consider the MAV, shown in Fig. 1, which is based on a family of flexible-wing MAV designed at the University of Florida. The airframe is constructed entirely of composite carbon fiber. The fuselage is a two-piece monocoque structure designed to house flight components, control effectors, and instrumentation. A conventional empennage is affixed to the fuselage with elevator and rudder control surfaces hinged to the horizontal and vertical stabilizers, respectively.

The wing, which is mounted to the top of the fuselage, is constructed using similar composite techniques as the fuselage and empennage. The leading edge consists of multiple layers of unidirectional carbon fiber. Battens of similar material extend from attachment points on the leading edge. The composite wing skeleton is covered with an extensible membrane skin of thin translucent plastic. The resulting structure can be grossly deformed via mechanical actuation, yet is capable of withstanding flight loads. The flexible nature of the wing also gives rise to the mechanism of adaptive washout, which permits small changes in wing shape in response to gusty wind conditions as noted in flight testing and wind-tunnel testing.

The MAV is equipped with instrumentation that is housed within the fuselage. This instrumentation includes servos for actuation, sensors for measurement, and a board for data acquisition. The measurement devices consist of three-axis gyros and three-axis accelerometers along with the servo command. All sensing and actuation data is recorded using a 7-g micro data acquisition board (μDAS) developed by NASA Langley Research Center specifically for MAVs. The μDAS has the capability to record 27 analog channels, which is sufficient for the current sensor package. The data are sampled at 50–100 Hz and are resolved using a 12-bit analog–digital converter. The data are recorded in a 4-MB flash chip onboard the DAS and is downloaded to a personal computer at the end of each flight.

This vehicle, whose physical properties are given in Table 1, actually has a wing span of 24 in. Such a large dimension might seem too large to be considered a MAV; however, the vehicle clearly falls into a class of MAV. Most notably, the vehicle has the same thin undercambered membrane wing unique to this class. The airspeed and flight dynamics of the vehicle are clearly more similar in nature to other members of the class of MAV than they are to any general type of UAV.

Table 1 Properties of the MAV

Property	Value
Wingspan	24 in.
Wing area	100 in.^{2}
Wing loading	17.9 oz/ft^2
Aspect ratio	5.76
Powerplant	Brushless electric motor with 4.75-in. propeller
Total weight	13.4 oz

III. Morphing

A. Concept

The concept of morphing is not, strictly speaking, a well-defined idea. A morphing aircraft is generally accepted to be an aircraft whose shape changes during flight to optimize performance.[1] Such changes might include span, chord, camber, area, thickness, aspect ratio, planform, and any other metric related to shape or twist.

The morphing investigated here essentially acts like a control effector in that the shape is changed to alter the flight dynamics. As such, a simple form of morphing is wing twist. Such a morphing was used for control on the Wright Flyer where the pilot directly twisted the wing using cables. The idea is also being used for control on the active aeroelastic wing, where the wing is twisted in response to moments induced by control surfaces.[11]

The value of morphing must be evaluated by relating the benefit to the cost. As such, morphing is not currently practical for traditional piloted and unpiloted aircraft because high power is required to alter the shape of a rigid structure designed to carry airloads at high speeds. Conversely, a MAV is an ideal platform for morphing because only a small amount of energy is required to alter dramatically the shape of the flexible wings throughout the low-speed regimes in which they operate.

Generating wing twist for the class of MAV considered in this paper relates to twisting the membrane wing. Such twist is easily achieved using standard actuation schemes. Twist can be achieved by connecting parts of the wing to a servo in the fuselage. Twist can also be achieved by embedding torque rods into the structure. Either way, the wing is never loaded much at these low speeds so that only a small amount of energy is needed for the twisting.

Additionally, morphing of a membrane wing can consider actuation strategies designed for gossamer space structures. These structures use lightweight components, including membranes and inflatable elements, whose shapes are easily altered. Many approaches, for example, electroactive polymers embedded in the structures[12] and piezoactuators attached to the boundary of a membrane,[13] can be used to control the shape. Such approaches are being considered for future use, but the power requirements for such materials may require more weight and space than is available on a MAV.

B. Wing Shaping

The current study considers morphing the MAV to achieve roll performance. As such, the morphing mechanism is limited to antisymmetric shaping of the wings. The morphing could be easily extended to augment control of the longitudinal dynamics; however, restricting the morphing to lateral control allows the benefits to be easily realized. The wing morphing is accomplished using torque rods attached to the wing, as shown in Fig. 2. Separate servos are mounted in the fuselage to command separately the rotation of the rod on each side of the vehicle. These servos, although currently used only for lateral control, allow morphing to be used in both a lateral and longitudinal fashion.

Commanding a deflection of the servo causes the rod to rotate by acting against the leading edge. This leading edge is quite stiff so that the deflection is almost entirely constrained to the trailing edge. Figure 3 shows the nominal wing and the morphed wing when each servo is commanded to its equal but opposite value. The morphed wing shows the deflection for a left twist, which causes negative roll.

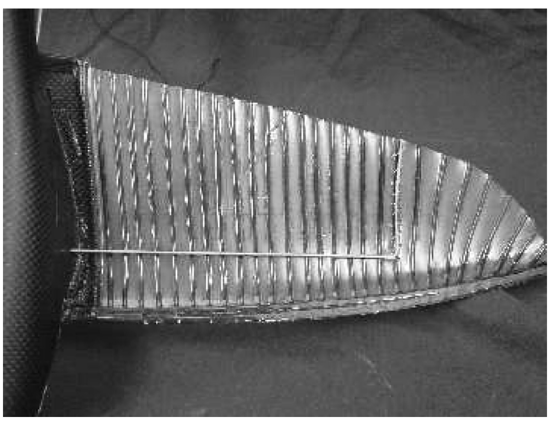


Fig. 2 Wing with torque rod.

The deformation from the wing shaping is seen by visual inspection to be concentrated near the trailing-edge outboard. Thus, the morphing acts as a control effector similar in nature to an aileron. Ailerons on traditional aircraft are often the main effector for roll because the response contains only slight yaw motion. The morphing should provide a similar role for the MAV and, consequently, greatly increase controllability of the lateral–directional dynamics.

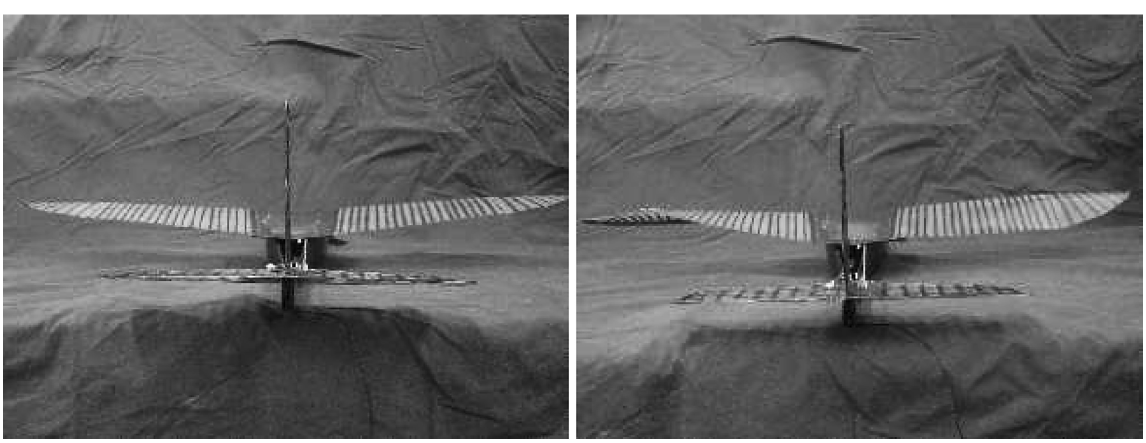
Figure 4 provides a side view of the wing as it undergoes morphing. The amount of twist imparted to the wing is quite significant using this simple mechanism. Such wing shaping clearly demonstrates the applicability of morphing to MAV. The shape of the wing is considerably altered by this morphing; however, the morphing mechanism is quite primitive. The extreme flexibility of the wings for this type of MAV allows significant morphing without requiring significant power or complexity of the actuation system. Because the actuator used to drive the morphing is identical to the rudder or elevator servos, the morphing control integrates readily into the existing control system.

IV. Flight Testing

A. Procedures

A series of flight tests are performed to identify the flight characteristics of the MAV. These tests attempt to note features of the flight mechanics in response to commanded deflection of the elevator and rudder along with commanded morphing. The actual deflection of the wing during morphing is not directly measured; instead, the sensor package indicates the response of the aircraft to different levels of commanded morphing.

The flight testing of the MAV follows procedures developed by NASA Dryden Flight Research Center. These procedures define maneuvers that are designed to identify certain aircraft characteristics. Specifically, the control pulse maneuver is used extensively on the MAV. This type of maneuver allows identification of control effectiveness, damping, and oscillatory modes. The control pulse



a) b)

Fig. 3 Rear view of the MAV with a) undeflected wing and b) morphed wing.

a) b) c)

Fig. 4 Side view of the MAV with a) negative, b) neutral, and c) positive morphed wing.

maneuver is characterized by an abrupt deflection of a control surface. The deflection can occur in one or both directions of motion for various time periods. Numerous types of control pulses, including singlets and doublets pulses, are performed on the MAV. Such a maneuver is initiated from a trimmed flying condition. The pilot commands a pulse to the actuators then returns the stick to the neutral position. The aircraft is allowed to oscillate and return to trim without further inputs.

B. Modeling

Linear models are developed to represent the flight mechanics of the aircraft by applying system identification techniques to the flight data. One purpose of the model is to identify the linearity of the dynamics. Another purpose is to indicate flight characteristics that must be addressed by changes to the vehicle configuration or active controllers.

A model of the flight mechanics is generated by analyzing the responses to doublet commands given to morping and rudder actuators. These commands, shown in Fig. 5, last for approximately 60 s. A set of coefficients for an autoregressive model with exogenous input is found using a least-squares approach. This discrete-time model is converted to a state-space representation. Finally, a Tustin transformation is applied so that the resulting model is a continuous-time state-space realization.

Figure 6 shows the responses of the model to the inputs given in Fig. 5. These responses are shown in comparison to the flight data measured in response to the same commands. The model is able to predict roll rates fairly accurately but has some difficulty predicting yaw rates. The main source of difficulty with the yaw rate is a high-frequency component that requires an unrealistically high number of states in the representation. Roll rate also shows some high frequency components, but the magnitude of the low-frequency components is considerably larger than the magnitude of the high-frequency components.

The model was identified with 10 states that includes four convergences and three modes. The convergences correspond to poles at 100 rad/s. The natural frequencies and dampings of the remaining modes of this model are given in Table 2. A feature of the model is the Dutch roll dynamics. This mode is assumed to have a natural frequency somewhere near 2 Hz. The presence of two modes around this frequency is attributable to nonlinearities and unmodeled responses to turbulence in the data.

Another feature of interest is the response to the morphing. A linear model was able to represent the morphing aircraft, which implies this particular type of morphing can be treated as a conventional control effector for purposes of flight mechanics. Such an implication is clearly advantageous for developing a MAV with autonomous capability because control design should be relatively straightforward using this morphing.

Also, these models are generated to describe only the roll rate and yaw rate in response to rudder and morphing commands. The size of the commands was limited to ensure the aircraft dynamics remained near the linear regime around a trim condition. This paper is only concerned with antisymmetric morphing, but the concept is easily extended to include longitudinal dynamics.

Table 2 Modal properties of the model

Natural frequency, Hz	Damping
1.86	.613
2.71	.291
12.09	.988

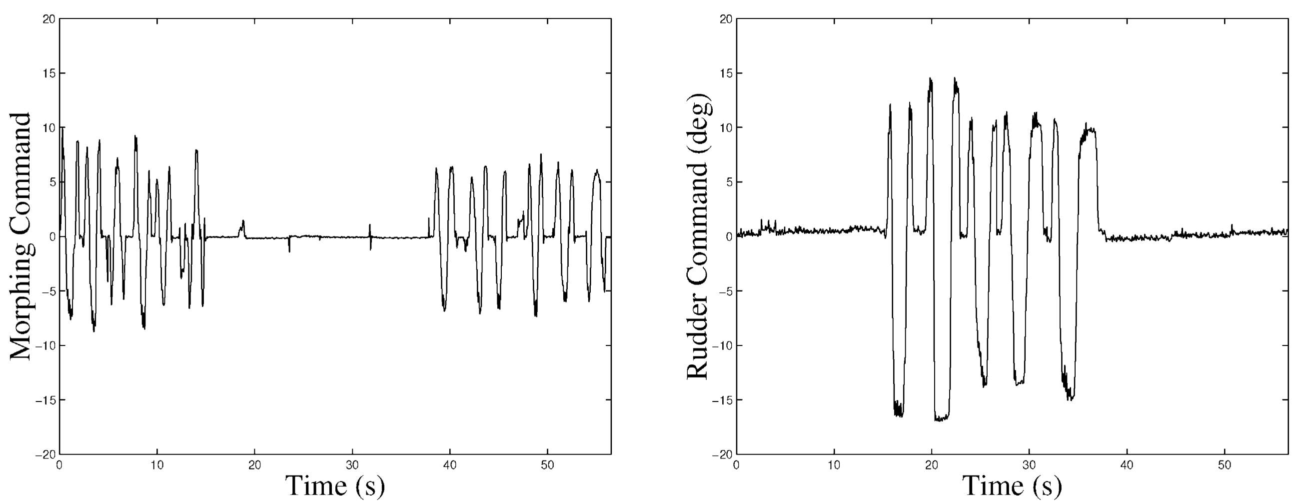


Fig. 5 Pilot commands to the MAV.

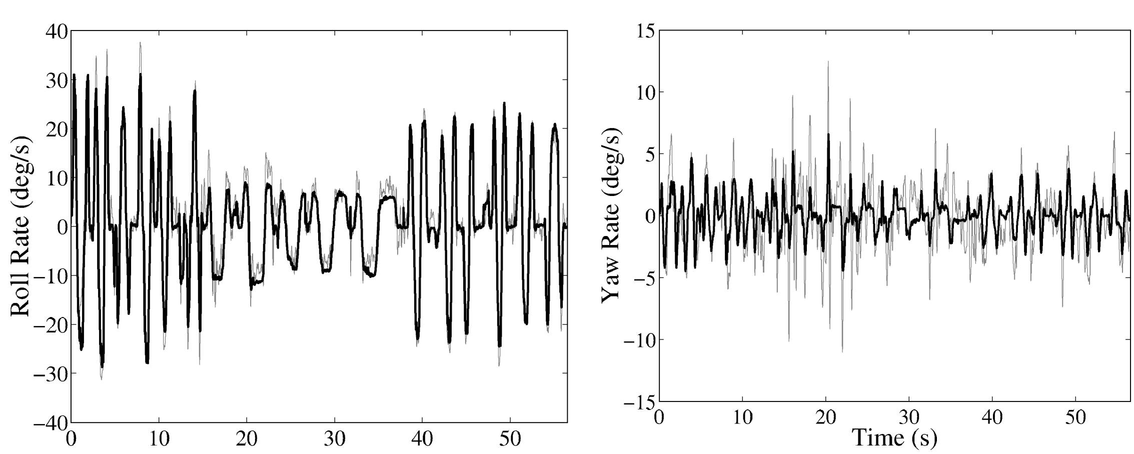


Fig. 6 Responses of the MAV: ——, measured and ━━, simulated.

V. Flight Characteristics

A. Turns

The flight characteristics associated with turns is the issue of most interest for morphing. The MAV was previously flown manually by a pilot, but autopilots are currently being designed to allow for fully autonomous operation. The piloting of these vehicles, by human or computer, will obviously be simplified by ensuring that turn coordination is achievable.

This MAV was originally designed for surveillance missions using only rudder and elevator for control. The design was sufficient to control benign turns; however, the inherent coupling of bank angle and yaw angle created some difficulties. A rudder deflection would excite the Dutch roll mode so that maintaining aircraft attitude in a crosswind situation required considerable pilot workload. The resulting flight path was generally erratic while the pilot attempted to balance the bank and yaw angles. Clearly this vehicle was originally not appropriate for close-in surveillance missions, such as within urban environments, that require aggresive maneuvers.

The improvement in the vehicle response is illustrated using control pulses to each of the control mechanisms. Such inputs isolate the effect of an individual control surface on the aircraft. The response of the vehicle to commanded rudder and morphing pulses demonstrates these improved flight characteristics. Figure 7 shows the commands and responses for a representative command to the rudder input from 0 to 3 s and then the morphing input from 4 to 7 s.

The responses to the rudder actuation demonstrate the undesirable characteristics that make turning difficult. Specifically, the rudder deflection produces a yaw rate out of phase with roll rate that is indicative of Dutch roll.

In-flight, the vehicle appears to assume an oscillatory motion in response to rudder actuation. The frequency of this oscillation, as seen in Fig. 7, corresponds to the identified modal dynamics. After a single pulse, the aircraft has rolled 45 deg and yawed approximately 30 deg. The flight path resulting from a three-step pulse is s shaped from the change in yaw angle. Additionally, this maneuver also generates an unwanted pitch coupling, which sets the aircraft into a slight dive.

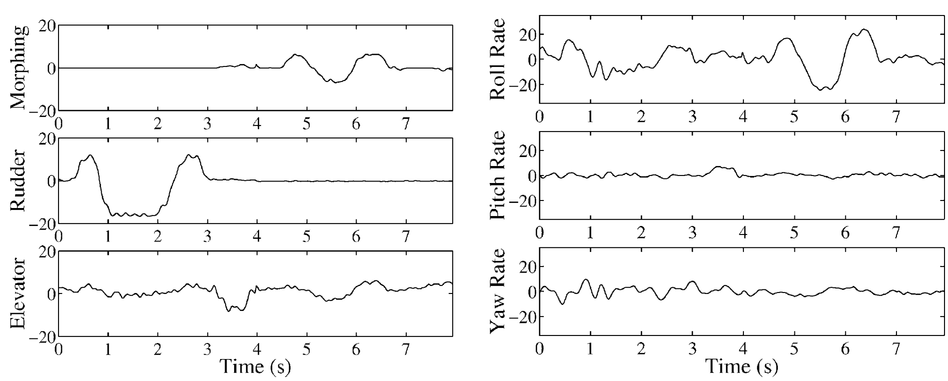
Conversely, the responses to the morphing demonstrate flight characteristics that are advantageous for piloting. The response of the aircraft to a morphing pulse is almost entirely in roll. A small amount of yaw rate is induced, but this response is lower in magnitude and frequency than the yaw rate induced by the rudder command. Consequently, each step of the control pulse maneuver banks the aircraft without significant change to the yaw or pitch attitude. In other words, morphing here has the effect largely uncoupling roll from yaw. A brief comparison between the morphing aircraft and a rigid-wing MAV of similar geometry has shown an improvement in control over both rudder and aileron controls.

B. Spins

Control of a morphing vehicle beyond the stall boundaries is another relevant facet of the flight dynamics. A greater degree of control over the vehicle geometry may improve stall/spin avoidance or, conversely, even command a developed spin maneuver. The large degree of control afforded by the morphing mechanism could be beneficial in generating antispin forces and recovering from a stabilized spin.

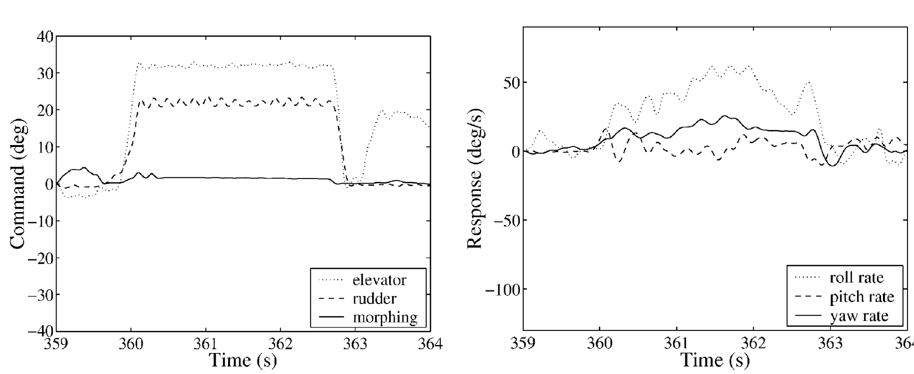
The spin characteristics of the vehicle are investigated by manually piloted maneuvers. Spin modes are identified using classical spin entry techniques.[14] The individual modes are produced by trial and error and have been reproduced over several flight tests. The following discussion presents some of the predominant spin types encountered during these flight tests. Note these spins all use morphing because the spin characteristics were not nearly as significant using only rudder and elevator.

Figure 8 shows the command and rotation rates during a conventional spin. This maneuver is initiated from level flight by commanding positive elevator to increase the pitch rate and angle of attack. Right rudder command is then applied to generate a yawing moment as the aircraft approaches stall. In this case, the yaw causes an asymmetric stall and starts the spin rotation. The aircraft response is



a) b)

Fig. 7 MAV a) pilot commands and b) responses.



a) b)

Fig. 8 Conventional spin a) pilot commands and b) responses.

relatively constant throughout the maneuver, although the roll rate tends to build up as the flight path changes from level to a vertical. The autorotation continues as long as the positive elevator and rudder commands are held. Once the commands are neutralized, the rotation slows and comes to a stop with little or no opposite rudder input. Positive elevator is used to recover the aircraft to level flight at 363 s.

Although this type of spin has been experienced several times, the entry procedures tend to be difficult to reproduce. Specifically, applying rudder command at a low angle of attack (too early) prevents a stall from developing and results in a high-speed spiral dive. Both wind tunnel and computational fluid dynamics analysis have shown that the thin-undercambered airfoils used on the vehicle have delayed stall response. This affords such vehicles increased resistance to stall/spin departure, at least for positive loadings.

The effect of morphing on positive (upright) spins is to accelerate the onset of the spin and to assist in the recovery process. This effect is most pronounced during cross-coupled controls, where the rudder direction is opposite to that of the morphing. In such a case, the high angle of attack at the inside wing tip is further increased by the morphing actuation, leading to an observed stall/spin. Releasing the morphing command effectively reduces the wing angle of attack and produces nearly immediate recovery from an upright, conventional spin.

Conventional spins are also performed with negative (down) elevator actuation to produce a starkly different response. In particular, the spin modes observed are of considerably higher energy. The rotation rates of a negative spin compared with an upright spin tend to be between 2 and 6 times greater. Based on rudimentary analysis, the stall characteristics of a thin-undercambered wing at negative angles of attack are far more severe than the characteristics at high angles of attack. In flight, the airplane is observed to have a very immediate and violent response to large negative elevator commands. Such an input is believed to cause a negative stall quickly, where any asymmetry about the yaw axis produces a large rate of rotation.

Figure 9 shows an identified negative spin mode initiated by a morphing command with elevator and rudder. At 401 s, the aircraft responds to the constant control deflection by building up rotation rates on all three axis. The entry into the maneuver is relatively gradual, and only after 1 s of control inputs have the pitch, roll, and yaw rates become significant.

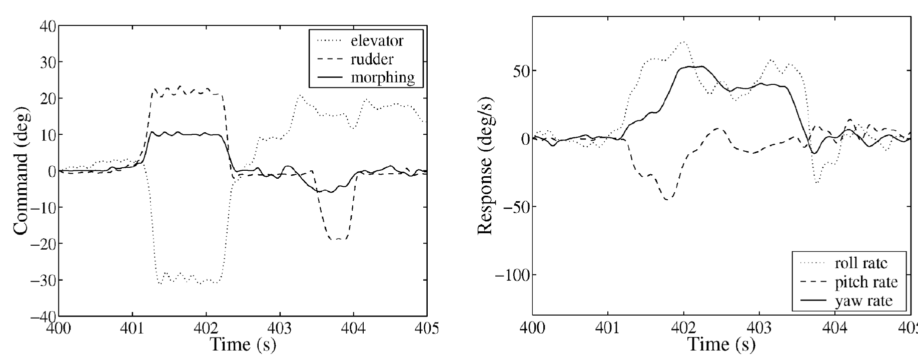
This particular type of spin tends to stabilize independently of the initial pro-spin control deflections. At $t = 402$ s, the controls are released while the aircraft continues to spin. The application of positive elevator (for recovery) shortly afterward appears to maintain the spin for some time. It is only with corrective opposite rudder command that the aircraft arrests the rotation and recovers from the spin.

It is difficult to draw solid conclusions from this spin sequence. However, the researchers attribute the two distinct modes observed to be a case of primary and secondary spin characteristics, where the latter is caused by a premature recovery attempt. Similar spins have been observed from in both left and right directions.

Alternatively, Fig. 10 shows a considerably different spin behavior. Although initiated by commands similar to the preceding spins, this type of spin exhibits a cylcic or periodic motion. It is perhaps with the timing of the control inputs that a difference can be found. Whereas in Fig. 9 the elevator input lagged behind the rudder and morphing inputs, the spin shown in Fig. 10 shows the elevator leading slightly. The precise effect this has on the airflow is unknown. However, the resulting aircraft response is shown to be six times greater in magnitude than a conventional spin.

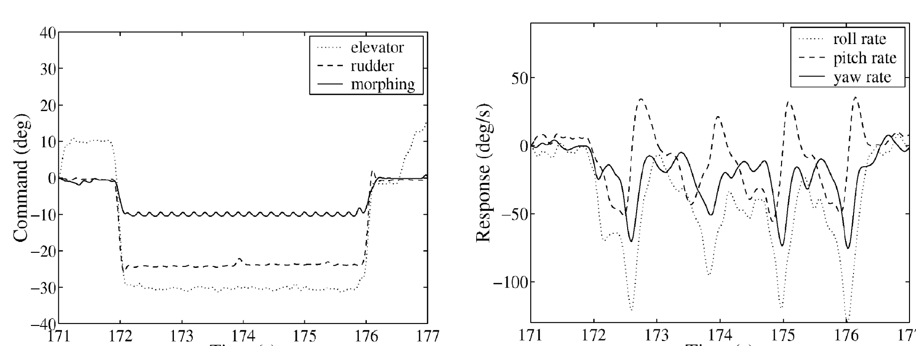
From level, trimmed flight, the aircraft is subjected to full left wing morphing, full left rudder, and full negative elevator command. The initial reaction of the aircraft is to pitch down at a constant rate and incur a left roll and yaw from the wing morphing and rudder deflections. Once the wing has reached the negative stall angle, presumably facilitated by the deflected wing, a rapid spin ensues, nearly doubling the roll and yaw rates and reducing pitch rate. This pattern is repeated four times throughout the spin, all while pilot commands are held constant. Each cycle is proceeded by a period of low momentum, followed by a sharp change in pitch rate along with peaks in both the roll and yaw rates.

Although the dynamics of such a maneuver are not very well understood, it appears that the morphing of the wing plays a large roll in both inducing and recovering from the spin. For instance,



a) b)

Fig. 9 Spin a) pilot commands and b) responses.



a) b)

Fig. 10 Cyclic Spin a) pilot commands and b) responses.

similar spin entries performed without morphing are characterized by considerably lower rotation rates and a continuation of the spin after command inputs are neutralized. However, the recovery of this cyclic spin mode occurs nearly immediately after the controls are neutralized. As seen at $t = 176$ in Fig. 10, the aircraft is at the period of highest moment during return to neutral command. The rotation rates continue to follow the characteristic spike pattern and finally converges to zero rotation rates.

In flight, this has the effect of stopping the aircraft in midrotation. Unlike the other spin modes observed, the cyclic spin mode has no apparent recovery apart from neutralizing the controls. The aircraft will continue to the end of a given cycle, cease rotation, and simply fly away. The nose-down recovery typical of other spin modes is contrasted with an immediate recovery to level flight.

The usefulness of the cyclic spin mode shown in Fig. 10 is perhaps questionable, although it may give rise to a different mode of maneuvering for morphing aircraft. For instance, the described maneuver may be useful for a controlled vertical displacement. On initiating the entry, the airspeed quickly decays and starts the aircraft on a relatively slow vertical flight path. During this portion of the maneuver, the aircraft incurs a series of high rate of rotations, each separated by a period of low momentum. As evidenced by the recovery from the maneuver, this period can be used to recover the aircraft into stable flight. Whereas the earlier spin modes required corrective rudder and significant altitude losses for recovery, this cyclic spin mode stopped once the controls were neutralized.

Attitude and airspeed entry conditions into the spin trials have been observed to have some impact on the stabilized spin modes; however, accurate measurements of the entry conditions were not possible. The lack of pressure sensors on the airframe precluded the gathering of such data. Excitation of a particular spin mode depended on the pilot ability to position the aircraft properly based on control feel and vehicle observations.

The spin entry maneuvers were also attempted for other control combinations. Specifically, cyclic spins were attempted without wing twisting by using negative elevator and rudder deflection. These trials resulted in a stabilized spin but with considerably lower rotation rates than the cyclic spin. Additionally, this mode did not exhibit the periodic behavior achieved through wing twisting during a spin.

VI. Conclusions

This paper demonstrates that morphing is particularly suitable for a class of MAV. The membrane wings on these vehicles can be morphed with little power but with significant benefits. The authority provided by the wing shaping allows decoupled lateral–directional and longitudinal flight dynamics so the MAV is easier to pilot. Also, the wing shaping provides dramatic stall and spin characteristics that may be exploited for high-agility maneuvering. As such, the wing shaping is an enabling technology providing some level of mission capability to this class of MAV.

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