

A MORPHING UAV WITH ROTARY AND FIXED-WING MODES

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Abstract

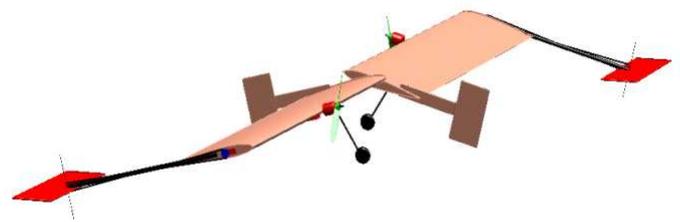
A conceptual study has been carried out of the Morphing UAV with Rotary and Fixed-wing Modes (MURFM), an aircraft concept that greatly minimizes the compromises inherent in previous VTOL aircraft. The MURFM is an all-rotating vehicle in rotary flight, but becomes a conventional fixed-wing aircraft in forward flight.

This paper first examines the performance and control characteristics of the MURFM concept through a computer simulation of the vehicle in rotary-wing flight. The simulation is then compared to experimental data obtained with a prototype MURFM vehicle mounted on a test stand. Finally, the prototype is flown by radio control in rotary and fixed-wing modes and through the transitions. The flight testing provides a qualitative assessment of stability in rotary flight, flying qualities in cruise, and ease of transition between rotary and fixed-wing modes.

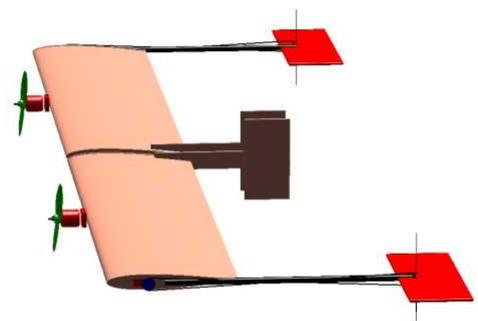
Successful flight demonstrations have proven the MURFM to be a feasible concept. Further development may yield valuable gains in performance and utility over existing UAVs.

1 Introduction

This paper is a conceptual study of the Morphing UAV with Rotary and Fixed-wing Modes (MURFM), an aircraft concept that greatly minimizes the compromises inherent in previous VTOL aircraft.



In its most basic form, the MURFM concept begins with a set of two wings that rotate similar to a helicopter rotor to provide VTOL capability, but with all aircraft systems contained within the wing structure. Wing-mounted piston or turbine engines provide thrust to keep the wings rotating.



Forward flight occurs with the wings having pivoted around the spanwise axis until their leading edges face the same direction. In this mode, the vehicle flies as a conventional fixed-wing aircraft, with the wing-mounted engines providing thrust for forward flight. The transition from rotary flight to forward flight is

accomplished by reducing the pitch of the wings until their leading edges are both pointing towards the ground and rotation is stopped, then pulling out of the resulting dive in forward-flight mode. To return to rotary flight, the vehicle dives towards the ground and the wings pitch in opposite directions to initiate rotation. Rotational rate and wing pitch continue to increase until the descent is arrested and the vehicle is hovering.

The compromises in cruise and hover efficiency that plague VTOL aircraft are almost completely eliminated by this concept.

The aims of this paper are to quantify the potential performance of the MURFM concept and to demonstrate both hover and forward flight capability, including transition. A computer code was created in MATLAB to predict performance, and data obtained with the prototype vehicle mounted on a test stand is used to validate the computer code. Stability in hover, flying qualities in cruise, and ease of transition between rotary flight and cruise is qualitatively assessed via flight testing. Based on the results of these activities, the feasibility of this concept is determined.

2 Development of MATLAB Simulation

A MATLAB-based simulation was created that models the MURFM vehicle in rotary flight. Three degrees of freedom are modeled: vertical translation, rotation about the vertical axis, and main wing pitching about the spanwise axis. The vehicle is assumed to have no lateral motion.

No attempt was made to simulate the vehicle in forward flight. Since the vehicle is of relatively simple configuration in forward flight, conventional methods of assessing forward flight performance are directly applicable.

2.1 Vehicle Configuration

The geometry of the as-built prototype matches the geometry used in the simulation to a large

degree. Factors that are not directly modeled include wing trailing edge bluntness, tail boom and fin aerodynamics, and drag from various protuberances.

The main wing and elevons are rectangular in planform. The wings employ a NACA 0012 aerofoil, while the elevons are flat plates approximately 5 mm thick with rounded leading edges and tapered trailing edges. The elevons are full-flying surfaces that pivot about an axis at 22% of their chord. Other dimensions of the vehicle are given below.

Wing span:	185.0 cm
Wing chord:	20.3 cm
Elevon span:	31.9 cm
Elevon chord:	9.8 cm
Fin height:	13.8 cm
Fin chord:	7.6 cm
Wing quarter-chord to elevon quarter-chord distance:	42.0 cm
Wing quarter-chord to fin quarter-chord distance:	26.1 cm

2.2 Methodology

Forces and moments are calculated relative to an axis system that rotates with the vehicle (see Fig. 1). The origin of the axes is at the wing pivot location (31% of the wing chord).

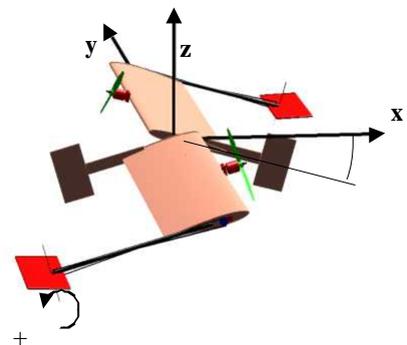


Fig. 1. MURFM configuration and coordinate system.

2.2.1 Aerodynamics

The aerodynamic forces on the components of the MURFM are modeled using the methods outlined in Table 1.

Table 1. Aerodynamic methodologies used in simulation.

Component	Quantity	Method
Wings	Lift, drag, pitching moment	Table lookup of NACA 0012 data. Forces and moments integrated using Blade Element Theory
	Induced downwash	Blade Element Momentum Theory
	Tip loss factor	One half of the wing tip chord
Elevons	Lift, drag, pitching moment	Table lookup of NACA 0012 data, forces and moments integrated using Blade Element Theory
	Induced downwash	Equal to the wing-induced downwash at radii less than that of the wing tips, assumed to be zero beyond the wing tips
	Tip loss factor	None

2.2.2 Propulsion

The motors and propellers contribute not only to the moment about the z-axis, but they also significantly affect the vertical force and the moment about the y-axis. The thrust produced by the motors/propellers is estimated using the commercially-available software *Motocalc*.

2.2.3 Mass Properties

The mass properties of the MURFM prototype are modeled in the simulation to a high degree of accuracy. Components such as motors, electronic speed controls, servos, elevons, wheels, and booms are modeled as either rectangular or cylindrical solids, using the textbook formulas for moments of inertia of such shapes. Irregular components such as foam wing cores and wing skins are decomposed into thin slices, each slice being modeled as a rectangular solid. The location and orientation of each component are used to calculate overall moments and products of inertia.

The simulation begins with initial conditions input by the user. Then the equations of motion are solved at each time step to yield the accelerations, which are then integrated to give the velocities and positions for the next time step. Since the simulation can be sensitive to the magnitude of the time step, all results shown in the current document are obtained using as small a time step as practical.

2.2.4 Pertinent Coefficients

Three pertinent coefficients appear in the discussion of the results of both the simulation and later experimental testing. These are the coefficient of thrust, CT, the coefficient of power, CP, and the pitching moment coefficient, CM. All three coefficients are defined in terms of the reference area, which is equal to the rotor disk area, R^2 . CM is also defined in terms of the reference length, which is equal to the wing chord, c.

The coefficient of thrust is employed to represent the vertical thrust created by the vehicle in the hover configuration, and is defined as:

$$CT = \frac{T}{\rho A_{ref} V_t^2}$$

where T is the thrust, ρ is air density, A_{ref} is the reference area, and V_t is the tip velocity. The coefficient of power is used to represent the power used to maintain rotation of the vehicle during the hover, and is defined as:

$$CP = \frac{P}{\rho A_{ref} V_t^3}$$

where P is the power. Finally, the pitching moment coefficient is used to represent the pitching moment about the y-axis (or wing pivot), and is defined as:

$$CM = \frac{M_y}{\rho A_{ref} V_t^2 L_{ref}}$$

where M_y is the moment about the spanwise pivot axis and L_{ref} is the reference length (wing chord).

Typically, these coefficients are used to quantify aerodynamic forces and moments. However, in parts of the current document, forces and moments from motor thrust, gravity, and other non-aerodynamic sources are often represented as an equivalent CT, CP, or CM. The exact source of the force or moment being represented will be clear from the context in which it appears.

2.3 Simulation Results

This section presents the most important results from the simulation. These results were used to assess the feasibility of the MURFM concept and to decide upon the appropriate size, configuration, and propulsion of the prototype vehicle.

2.3.1 Hover

The power required for the prototype to hover determines the choice of motors, propellers, and batteries. Furthermore, the RPM necessary to hover determines the structural requirements of the prototype. Finally, the simulation gives insight into the controllability of the vehicle in flight.

One of the more interesting results of the simulation is the prediction of the gravitational, aerodynamic, and inertial contributions to the moment about the y-axis (see Fig. 2). The upper plot shows the moments in N-m as a function of vehicle RPM, while the lower plot shows equivalent pitching moment coefficient, CM.

Because the center of gravity is nearly at the wing pivot, the gravitational contribution is almost zero. The wings contribute a positive moment because their center of pressure is approximately at the quarter-chord point, while the wing pivot is at 31% of the chord. The

elevons are at a negative angle of attack, thereby producing a positive moment. The moment produced by gyroscopic forces on the propellers is positive as well. This moment is quite significant, and is a driving force in selection of the propeller. (in fact, the gyroscopic moment produced by the propellers damaged the prototype’s motors and motor mounts during testing, necessitating a switch to lighter propellers of a smaller diameter.) The inertial force produced by the “tennis racquet effect” is the largest single contributor to the moment, tending to force the wings toward zero pitch. This effect results from the mass distribution created when the wings are at a non-zero pitch.

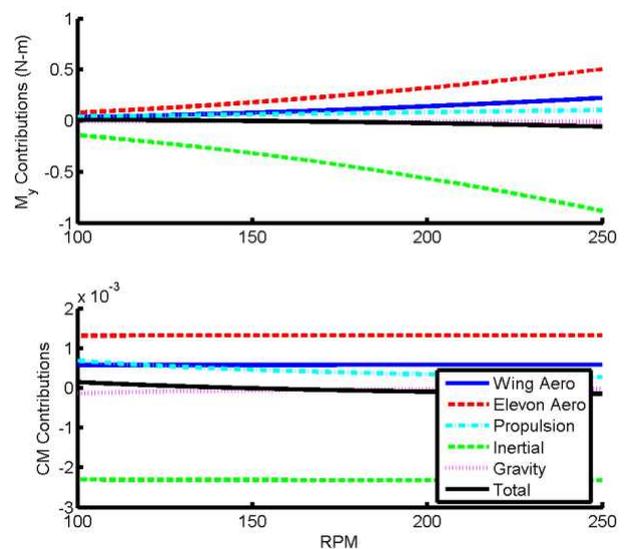


Fig. 2. Simulation: contributions to moment about wing pivot (M_y).

Another important result given by the simulation was the significant increase in power required to hover due to the drag of the elevons. Fig. 3 shows the power required for hover versus elevon deflection. Each line represents a different wing pitch. The “Elevons Trimmed” line indicates points where the moment about the y-axis is zero. If the vehicle has no mechanism to control wing pitch other than by changing the elevon deflection, then the “Elevons Trimmed” line represents the only condition at which hover is sustainable. Note that significantly less power would be required

to hover if the vehicle had a mechanism to directly control wing pitch, allowing the elevons to operate at a more favorable, positive angle of attack, or to be eliminated altogether.

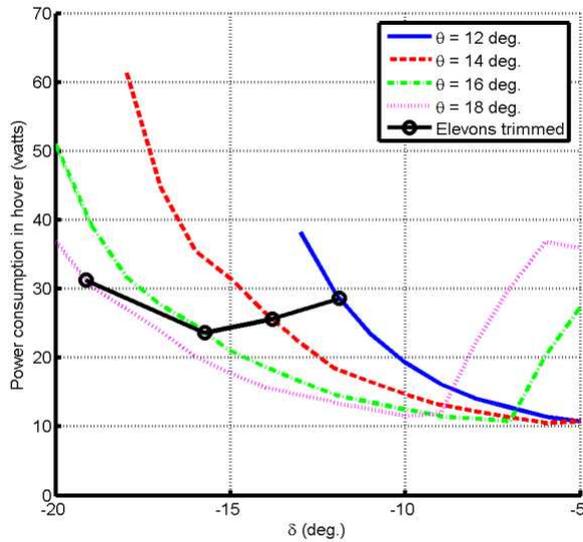


Fig. 3. Simulation: power consumption vs. elevon deflection.

2.3.2 Transition from Hover to Forward Flight

The simulation is also used to model the vehicle's behavior during the transition from hover to forward flight.

To investigate this transition, the simulation is begun with the vehicle in a hover at 175 RPM with the wings at 16 degrees pitch and the elevons at -15.5 degrees. The motor thrust is set to zero. After 0.5 seconds, the elevon deflection is changed to +25 degrees, forcing the wing leading edges down and initiating the transition. Once the wing pitch reaches -90 degrees (the forward flight configuration, with the vehicle in a dive and the leading edges pointing straight at the ground), the wing pitch is locked in place and the elevon deflection is changed to 0 degrees.

Fig. 4 shows the wing pitch and elevon deflection during the transition from hover to forward flight. The time between the elevon commands is approximately one second, which represents the time taken to complete the

transition maneuver. Note that after the transition is complete, the vehicle is diving straight towards the ground and must be recovered from the dive. This recovery is not modeled in the simulation.

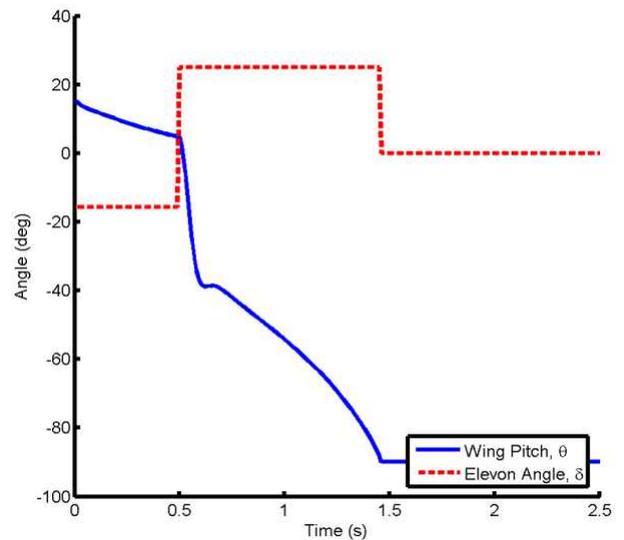


Fig. 4. Simulation: wing pitch and elevon deflection during hover-to-forward transition.

Fig. 5 shows the contributions to pitching moment (M_y) about the wing pivot during the transition from hover to forward flight. As noted above in regard to hovering flight, the inertial contribution is great, requiring significant control power from the elevons.

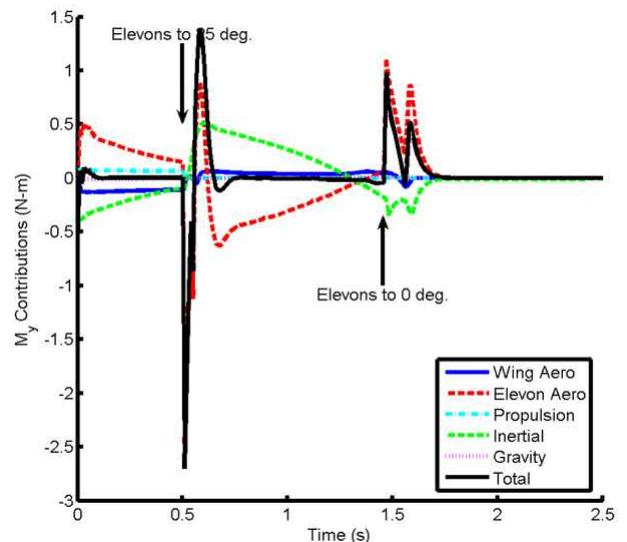


Fig. 5. Simulation: M_y contributions during hover-to-forward transition.

Fig. 6 shows the wing pitch and local angles of attack on the wings and elevons. During the transition, the wing tip remains at a nearly constant, negative angle of attack, producing the aerodynamic moment necessary to stop the rotation of the vehicle (dashed, light blue line). Note that the elevons remain near zero degrees angle of attack (dashed, pink line). After the wings are locked at ≈ -90 deg., the rotation gradually stops and the angles of attack approach zero. Note also how quickly the wing pitch (solid, blue line) changes from its value at hover to -40 degrees, then slowly continues to decrease to -90 degrees. This same behavior was seen in flight testing.

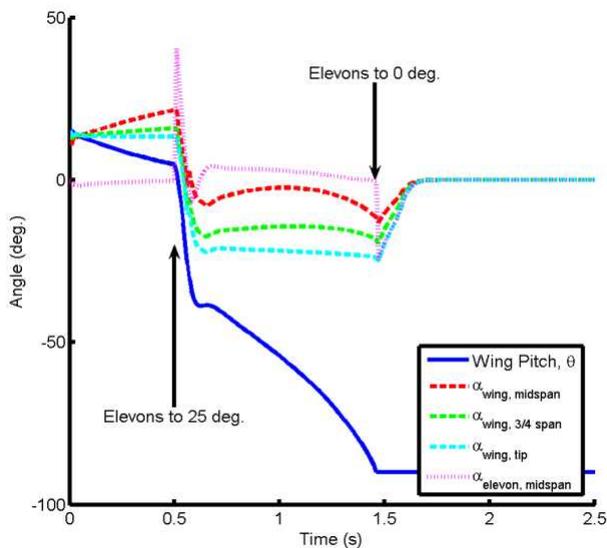


Fig. 6. Simulation: wing pitch and local angles of attack during hover-to-forward transition.

Fig. 7 shows the vertical velocity and position during the transition maneuver. The vertical velocity changes at an average rate of approximately -8 m/s², close to the acceleration due to gravity.

The exact results shown in these figures depend on many factors, such as the initial conditions prior to the transition, the commanded elevon deflections, and the exact mass properties of the vehicle. However, Fig. 7 indicates that the transition can be completed in just over one second and requires approximately 10 meters of

altitude, not including that required to pull out of the resulting dive.

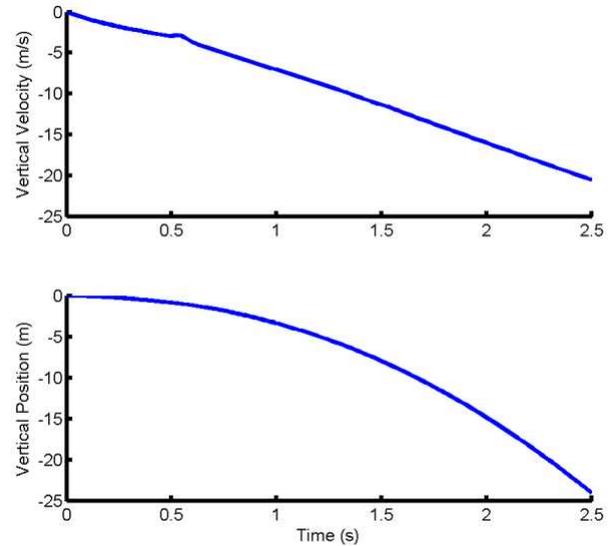


Fig. 7. Simulation: vertical velocity and position during hover-to-forward transition.

2.3.3 Transition from Forward Flight to Hover

The simulation is also used to model the vehicle's behavior during the transition from forward flight to hover. To investigate this transition, the simulation is begun with the vehicle in forward flight configuration, in a vertical dive with zero speed, zero rotation rate, and zero motor thrust. The transition is initiated at $t=0.5$ seconds, when the vertical speed has reached 4.9 m/s. At this point, the elevon deflection is changed to a negative setting, initiating a roll which causes the vehicle to spin up to a high rate of rotation in the hover configuration, with a low rate of descent. In an actual transition, the elevon deflection would then be further adjusted to achieve a stationary hover.

This maneuver is simulated at several different elevon deflections in order to determine what range of elevon deflections would produce a satisfactory transition. Fig. 8 shows the vertical velocity and position for each case. The -5 degree elevon deflection produces the lowest vertical velocity, with the -0.01 degree elevon

deflection slightly higher. The more negative elevon deflections produce a significantly higher vertical velocity, and it is notable that they all approach the same value, approximately -6 m/s.

Since the more negative elevon deflections produce a lower rotation rate and a higher rate of descent, it is reasonable to assume that a large portion of the wing is stalled in these cases. The next figure shows that this is indeed occurring.

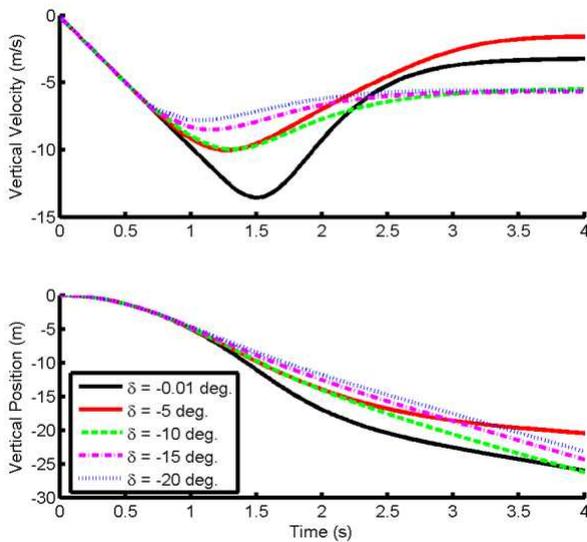


Fig. 8. Simulation: effect of elevon deflection on vertical velocity and position during forward-to-hover transition.

Fig. 9 shows the angle of attack at the $\frac{3}{4}$ -span location on the wing (top) as well as the angle of attack at the midspan location on the elevon (bottom) for different elevon deflections. At these Reynolds numbers, the wing can be expected to stall near 10 degrees angle of attack. Note that the -10, -15, and -20 degree elevon deflections produce a stalled wing, while the -0.01 and -5 degree elevon deflections avoid the stall. The elevon angle of attack is between 0 and -3 degrees in all cases, suggesting that the elevon control power is retained even as the wing stalls.

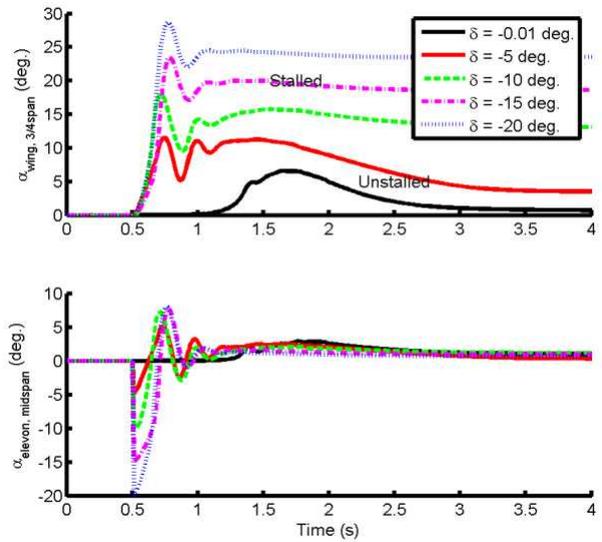


Fig. 9. Simulation: effect of elevon deflection on wing and elevon angle of attack during forward-to-hover transition.

From the above investigation of the effect of elevon deflection on the transition from forward flight to hover, it can be deduced that an elevon deflection of -5 degrees produces an acceptable transition, with the wing remaining unstalled and the vertical velocity sufficiently low. Higher deflections stall the wing and prevent full transition to hover.

2.4 Key Conclusions from Simulation Results

Several important conclusions can be made from the results presented above:

In hover:

- A significant inertial effect (the “tennis racquet effect”) tends to force the wings to zero pitch.
- The elevons provide the nose-up moment necessary to maintain a positive wing pitch. If wing pitch were mechanically controlled instead, the power consumption in hover would be greatly reduced.
- The most efficient wing pitch is approximately 15 degrees, where the wing tip is near its stall angle of attack.

In the transition from hover to forward flight:

- The wing pitch changes from its value at hover to approximately -40 degrees very quickly, then changes from -40 to -90 more gradually.
- The elevons remain at an angle of attack near zero for nearly the entire transition.
- The wings remain at a constant negative angle of attack, the value of which depends on the spanwise location on the wing, the outer portion of the wing being stalled.
- The vertical acceleration during the transition is nearly that of a freely-falling body.

In the transition from forward flight to hover:

- The transition will only be successful if relatively low elevon deflections are used (between 0 and -5 degrees). Otherwise, the wings will stall as the vehicle spins up and the vehicle will continue to descend.
- The RPM reached during transition can be quite high, and may drive the structural design of the vehicle.

3 Design and Construction of Prototype

Using preliminary results from the simulation, a prototype MURFM vehicle was designed and constructed (Fig. 10). This vehicle was used both on a test stand and in free flight.

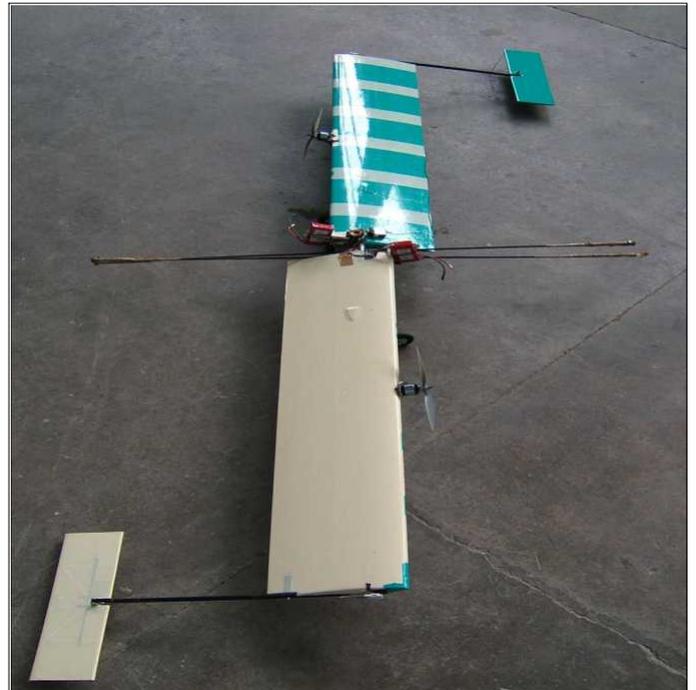


Fig. 10. Prototype MURFM (shown during hover testing).

3.1 Propulsion

The motors were Vortex 28/30/950 brushless motors, produced for use in R/C aircraft. During flight testing, the motors were powered by 1250 mah, 11.1 volt lithium polymer batteries with a maximum discharge rate of 18.75 amps ("15 C"). Three types of propellers are used: E-flite 8×4, APC 9×4.5 electric, and APC 8×6 "Slo-flyer." The motors were controlled with Apache Air 12-amp brushless electronic speed controls, which were mounted under the wings directly behind the motors.

3.2 Control

In forward flight, the right stick of the transmitter was used to control the elevons, providing conventional pitch and roll control. In hovering flight, the right stick must be moved side-to-side to provide "collective pitch" control. This is because a roll input (one elevon up, the other down) in forward flight configuration becomes a collective input (both elevons up or both down) in hover configuration. Up-and-down movement of the

right stick in hovering flight causes the vehicle to wobble, but does not cause lateral movement unless the input is periodic (similar to cyclic pitch in a helicopter). Motor power was controlled via the left stick.

4 Testing of Prototype on Test Stand

A test stand was constructed which allowed the prototype to be tested in the hover configuration. Instrumentation measured thrust, torque, and RPM. The power necessary to rotate the vehicle was provided by a motor mounted in the test stand and, in later tests, by motors and propellers mounted on the vehicle's wings. The vehicle was tested in many configurations, both with and without the elevons.

The objectives of testing the vehicle in rotary flight on the test stand were threefold:

1. Validate and refine the MATLAB simulation.
2. Determine what combination of motors, propellers, and batteries would provide sufficient power for radio-controlled flight.
3. Test the vehicle's structure and propulsion system under controlled conditions.

4.1 Experimental Setup

The prototype vehicle was mounted on the test stand as shown in Fig. 11. The test stand was clamped to a raised platform, positioning the vehicle slightly more than two meters from the floor.

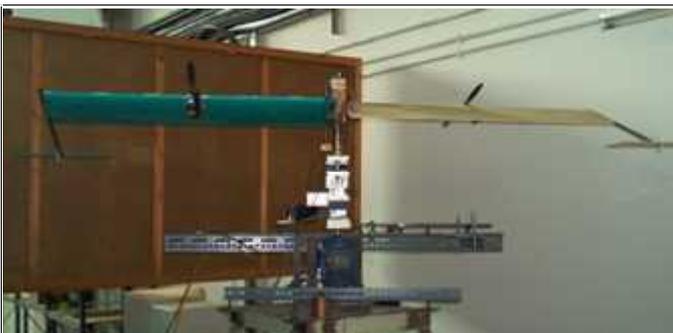


Fig. 11. Prototype mounted on test stand.

4.2 Key Conclusions from Test Stand Results

Testing the prototype vehicle on the test stand under various configurations yielded data regarding its aerodynamic characteristics and the performance of its propulsion system. Some key conclusions that can be made from this testing are listed below.

In the wings-only configuration:

- The CT and CP values predicted by the simulation are relatively accurate.
- There is a wide range of wing pitch over which the ratio of thrust to power is relatively constant.

In the wings-elevons configuration:

- The simulation models the effect of the elevon deflection on CT very poorly. The simulation predicts elevon stalling at moderate elevon deflections, while the test data shows little evidence of stalling.
- The simulation greatly under-predicts CP, even in the case where wing pitch and elevon deflection both equal zero, where the simulation under-predicts CP by 60%.
- The under-prediction of CP can be traced to the modeling of elevon drag. The test data indicates that the drag on the elevons is nearly three times that predicted by the simulation.
- The elevons provide ample control power.
- There is a small range of wing pitch angles, near 15 degrees, in which the power requirement is lowest for a given amount of thrust.

In general:

- The simulation's modeling of the wings is significantly better than its modeling of the elevons.
- It is advantageous to locate the motors as far inboard as possible to reduce drag from the motor installation.

- The moment of inertia of the propellers is a significant concern. A higher moment of inertia leads to increased gyroscopic forces on the motors.

5 Flight Testing of Prototype by Radio Control

The prototype MURFM vehicle was fitted with radio control equipment and flown in hover mode, in forward flight, and through the transition.

The main objectives of flying the prototype were twofold:

1. Assess the vehicle's stability in hover.
2. Verify the vehicle's ability to transition between hover and forward flight.

Because the MURFM is similar to a conventional fixed-wing aircraft in forward flight mode, more emphasis was placed on hover and transition than on forward flight. The prototype was not instrumented in any way during flight, and no measurements of its motion were attempted using video photography. Therefore, all assessments of flight characteristics were necessarily qualitative. However, several modifications were made to the prototype during testing, and its flying characteristics following each modification provide interesting insight into its dynamics.

5.1 Flight Test Results in Hover

The prototype was tested in hover mode over the course of nine flying sessions.



Fig. 12. MURFM prototype in hovering flight.

The prototype performed as expected in terms of the required wing pitch, RPM, and elevon deflection. The landing gear worked very well even during some hard landings. The elevons were found to be essential for stable hover, and their effectiveness was ample in controlling both vertical and lateral motion. In the initial configuration, with the wings free to pivot and no additional weights attached to the vehicle, it often exhibited a vertical, bouncing motion, as well as a precession-like motion. The bouncing motion could be eliminated by mechanically fixing the wing pitch and/or increasing the moment of inertia about the wing pivot axis. The precession-like motion was never fully eliminated, but it was greatly decreased by mechanically fixing the wing pitch and/or increasing the moment of inertia about the vertical axis. It also seemed to be less pronounced while climbing and more pronounced while descending.

5.2 Forward Flight Test Results

After testing the prototype MURFM vehicle in hover, forward flight was attempted from a grass field.

In forward flight, the prototype MURFM flew smoothly with adequate pitch control but very sluggish roll control. For forward flight, fins were added near the wing roots. The fins provided ample directional stability, however adverse yaw was present while turning. The vehicle took off and landed smoothly.

5.3 Transition Test Results

From the results of the hover testing, it was noted that the vehicle was more stable in hover while climbing than while descending. Therefore, it was decided to attempt the transition from hover to forward flight first, as this would entail an initial climb in hover mode prior to the transition. The transition from forward flight to hover would have entailed a descending hover following the transition, which was deemed risky.

A pin was fitted to the vehicle which could lock the wing pitch during hover. A servo connected to the pin permitted the operator to disengage the pin via radio control, allowing the wing pitch to change for the transition to forward flight. As the wings reached forward-flight configuration, a separate spring-loaded pin automatically fixed the wings parallel to each other for stable forward flight.

With the wings pinned at 16 degrees pitch, the vehicle took off in rotary flight. It climbed at nearly full power for approximately 25 seconds to between 100 and 150 feet of altitude. The first half of the climb was stable, with the vehicle only drifting sideways with the light wind. During the second half of the climb, however, the vehicle began a precession-like motion, making horizontal circles of ever-increasing size. Thus it was decided to begin the transition as soon as a reasonable altitude was reached.

To initiate the transition, the motors were turned off, the wings were unpinned, and the elevons were deflected to +20 degrees. The vehicle quickly entered a dive, following a somewhat irregular path towards the ground as the wings continued to pitch downward. After losing 30-40 feet of altitude, the wings locked into the forward-flight configuration and the vehicle was pulled out of the dive. The vehicle then flew several circuits around the field, banking in excess of 60 degrees without incident. The landing, as in previous flights, was uneventful.

A second flight was then attempted. As before, the vehicle took off in hover mode without incident. The climb rate, however, was much lower than in the previous flight, presumably because the batteries were partially discharged. At no time during the climb-out did the precession-like motion appear. After a climb-out of approximately one minute, the transition was accomplished with nearly the same altitude loss as before, but this time the vehicle tracked along a straight line towards the ground. The vehicle flew well for the remainder of the flight.

In both flights, the transition took approximately 2.5 seconds, not including the time necessary to pull out of the dive. As predicted by the simulation, the change in wing pitch from the hover setting to near -40 degrees happened very quickly, while the remaining change in pitch from -40 to -90 degrees was much slower.

For the transition from forward flight to hover, a servo was connected to the pin which holds the wings in forward-flight configuration, allowing that pin to be disengaged by radio control. The vehicle took off in forward flight and climbed to an altitude near 300 feet. The motors were turned off and the vehicle was slowed down and then pitched over into a vertical dive. The wings were released and a slight right-aileron command was given. The vehicle almost instantaneously transitioned to a smooth autorotation, its angular velocity between 100 and 150 RPM.

After several seconds of rotary flight, the author attempted to transition back to forward flight. At first the vehicle appeared to begin the transition, the wing pitch decreasing and the vertical descent accelerating. However, it quickly returned to rotary flight. The author tried several elevon and motor power settings, but the vehicle continued to autorotate, hitting the ground. The reason for the inability of the vehicle to transition back to forward flight is unknown, although it could be related to stalling.

Nevertheless, the initial transition to rotary flight was quick and smooth, and required very little altitude (perhaps 10-20 feet). Surprisingly, at no time during the long autorotation to the ground did the vehicle exhibit the precession-like motion seen in hover testing.

5.4 Key Conclusions from Flight Test Results

Successful flight testing of the prototype vehicle in hover, forward flight, and through the transition proved the feasibility of the MURFM concept. Some key conclusions that can be made from the flight testing are listed below.

In hover:

- An unstable, precession-like motion can occur in hover.
- Stability in hover improves greatly when the wing pitch is locked.
- With the given wing pivot location (31% of the chord), the elevons are essential for a stable hover.
- Increasing the moment of inertia about the vertical axis slightly increases the stability in hover.

In forward flight:

- The elevons provide adequate pitch control but sluggish roll control.
- Directional stability is adequate with two fins relatively close to the center of gravity.
- The MURFM's forward-flight characteristics are similar to those of conventional, fixed-wing aircraft.

In the transition from hover to forward flight:

- The elevons provide adequate control power to initiate and complete the transition.
- The process of transition occurs qualitatively as expected.

In the transition from forward flight to hover:

- The transition occurred very quickly.
- The resulting autorotation was stable, with no evidence of the precession-like motion.
- The vehicle was unable to transition back to forward flight for an unknown reason.

6 Summary and Conclusion

A conceptual study of the Morphing UAV with Rotary and Fixed-wing Modes (MURFM) has been carried out. The MURFM seeks to

combine the cruise efficiency of a fixed-wing aircraft with the operational utility of a VTOL aircraft.

This paper examined the MURFM concept through simulation, ground testing, and flight testing. A computer simulation was used to model the vehicle in hover and in the transitions between hover and forward flight. Results from the simulation led to the design and construction of a prototype MURFM. Hover performance data was obtained with the prototype mounted on a test stand. The resulting data was used to validate the simulation and to select an appropriate propulsion system for the prototype vehicle. The prototype was then flown by radio control in hover, forward flight, and through the transitions.

Through successful flight demonstrations, the MURFM proved to be a feasible concept. Further development of the MURFM concept may yield significant gains in performance and utility over existing UAVs.