Autonomous Flight of a Samara MAV

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Abstract

Conventionally Micro/Nano scaled hovering flight presents a myriad of challenges and unique design opportunities. The culmination of microelectronics and state of the art measuring devices has enabled the creation of a Micro-air-vehicle (MAV^1) resembling one of nature's most efficient fliers, the seed of the Maple tree. The planform design of the VTOL mechanical samara is based on previous work², which characterized autorotation efficiency, and is employed as the main lifting surface of the vehicle. The collective pitch is controlled by a servo actuator, and the rotation rate is maintained by a propeller oriented parallel to the plane of rotation and is offset from the center of mass. Vertical speed and height are controlled by variation of collective pitch at constant propeller rpm, or variation of propeller rpm at a constant collective pitch. Precise attitude data is collected by a VICON³ motion capture system. The commanded altitude of the Samara is maintained by feeding back the error in position to a control loop which contains the system and actuator dynamics. Identifying the relationship between vertical velocity and collective pitch for a given thrust is one of the main goals of these experiments. Two vehicles are presented and compared in this study. The first vehicle, Samara-I has a maximum dimension of 27cm, and weights 75 grams. The second vehicle. Samara-II has a maximum dimension of 18cm, and weighs 38 grams. The vehicles can be launch from the ground, or by hand and have been flown outdoors in winds up to 10 mph. Advantages over traditional micro-scaled VTOL configurations include passive stability, efficient autorotation, low body drag, mechanical simplicity, low cost, high payload capacity, and substantial damage tolerance.

Introduction:

Samaras or winged seeds are the sole method by which several species of plants propagate their seed. Geometric configurations for maximal seed dispersal has evolved into two main classes of seeds. Both of which execute autorotational flight as they fall from the tree, and one of which additionally rotates about its longitudinal axis. This discussion is limited to Samaras which execute only autorotational flight.

Advancements in technologies associated with the sensing and control aspect of unmanned vehicles has allowed conventional micro-scaled vehicles to be equipped with real-time avionics and control systems. The vast capabilities this provides to these small systems is limited by the battery life and power consumption of all on-board electronics and actuators. The majority of the power consumed in an aerial system is sustaining a desired flight mode, whose primary focus is to negate the effects of gravity.

Perhaps a new paradigm is needed, whose focus is the design of a vehicle with a passively stable primary mode of operation, one which requires little or no additional power to attain/maintain this mode of transit. The natural flight of a Samara is one of elegance and balance; trading gravitational potential energy for rotational kinetic energy which perpetuates an aerodynamically stable helical descent.

The concept of passive stability has enabled the construction of the smallest autonomous samara to date, Figure 1,2. The vehicle is designed around the concept of efficient autorotation, allowing it to take full advantage of updrafts and thermal currents in the atmosphere.

The dynamics of this vehicle have not been studied in detail, and as such no models exist for the development of vehicle control. This paper presents the identification of a linear dynamic model of Samara-I,II operating in steady hover using flight data as apposed to

first principals vehicle modeling. To estimate the transfer function between wing collective input and heave velocity output, a frequency response system identification method was utilized. The frequency response method was based on prior work of Conroy⁸ for a similarly sized helicopter, and Tischler¹⁰ for larger helicopters including the Yamaha R-max. Frequency response analysis was performed using the Comprehensive Identification of Frequency Responses (CIFER®) software developed at Army Aeroflightdynamics Directorate (AFDD) located at Moffett Field, CA.

A primary goal of this study was to identify a linear model capable of capturing the heave dynamics of the Samara-I vehicle. This model is then compared to a similar one identified for a smaller vehicle, Samara-II. These models will be useful for future model-based controller and observer design.

Vehicle description

The concept of a single-wing rotating aircraft is not a new one, and in fact the first vehicle of this type flew in 1952 in the woods surrounding lake Placid, New York by Charles W. McCutchen⁴. A more recent vehicle was developed and flown by a team led by Lockheed Martin Advanced Technology Laboratories⁵. The prototype called MAVPro incorporated an outrunner motor with an 8 inch diameter propeller, weighed 514 grams, rotated at a stable 4 Hz, and could climb to 50 ft with radio controlled actuation of a trailing edge flap. The MAVPro incorporated the AG38 airfoil, and exhibited a rectangular planform geometry. The various single winged rotating aircraft developed over the years have made no attempt to utilize the most basic mode of transit of natural Samara, autorotation. Additionally, airfoil cross sections and planform designs have had no similarity to that found in natural Samaras.

The Authors intent in the design of the vehicles discussed herein was to emulate the natural Samara, and in doing so take advantage of the highly efficient autorotation which it employs. As such, Samara-I and Samara-II use unconventional and Samara-inspired planform geometry and airfoil cross-sections. These vehicles perform stable autorotation and are capable of landing at terminal velocity without sustaining any damage. In the event of motor failure, the vehicles gently autorotate back to the ground. Conventional monocopter designs apply torque to the vehicle with a thrust device slightly off-set from the Y-axis, and in the case of MAVPro the propeller spins in the Y-Z plane and influences the stability about the Y-axis.



Figure 1: Samara-I,II Coordinate System.

This configuration results in the propeller fighting the pitch input from the flap and reduces controllability of the vehicle. The 5-inch diameter propeller of the Samara-I,II is spinning in the X-Z plane and opposes applied torque about the X-axis providing additional stability. The sign convention and corresponding vehicle orientation is shown in Figure 1.

The design and construction of the Samara used in these experiments was done with the intent of providing a stable vehicle that could be tested in a limited area. The unconventional wing and body structure are the result of an iterative design process which has produced on the order of one-hundred vehicles. The resultant vehicles are extremely damage tolerant as they employ flexible structures which deflect upon impact, effectively increasing the time over which the impact load is applied to the vehicle. The configuration and relative size of the vehicles are shown in Figure 2.

The primary load bearing structure of the vehicle is 0/90 ply .025" thick carbon-fiber composite laminate, with opposed parallel tension and compression members mounted to the motor and wing. In this configuration the structure provides a high degree of flexure in the Z-direction and a high degree of stiffness

in the plane of rotation. The angle which the motor is held provides protection from ground impingement on take-off, after which, the centrifugal loads deform the structure increasing the distance the motor is from the center of rotation thus increasing the applied torque.

Flight time of the Samara-I is roughly 20 minutes with a 25 gram, 480mAh 7.4 V two-cell Lithium-Polymer battery, for a total vehicle mass (GW) of 75 grams. The maximum gross take-off weight (GTOW) of the vehicle is 125 grams, and the maximum dimension is 27 cm. Table 1 details the mass breakdown of Samara-I,II as well as two hobby radio controlled rotorcraft.



Figure 2: Samara in Flight Configuration

The mass breakdown is similar for the four vehicles, however the Samara benefit from a less complex and therefore lighter Propeller/Rotor system and require no transmission as it directly drives the propeller. This decrease in complexity makes for an overall more robust and reliable system.

Table 1: Weight Data (In terms of percent GW)

			1	,
	Samara-II	Samara-I	Hobby Rotorcraft ⁶	
	0.038 Kg	0.075 Kg	0.3 Kg	1.8 Kg
	% GW	% GW	%GW	%GW
Propeller/	5.3	2.6	11.0	11.2
Rotor System				
Tailboom	2.6	3.3	8.0	9.1
Assembly				
Main Motor	10.5	10.7	15.4	10.5
(electric)				
Fuselage/	26.3	27.6	7.0	15.1

structure				
Main Transmission	Direct	Direct	2.0	3.4
Landing Gear	2.6	2.7	2.3	3.4
Control System	18.4	16	5.7	18.3
Flight Control	7.9	4	29.4	2.4
Avionics				
Power Source	26.3	33.3	19.2	26.6
Payload	0	0	0	0
Flight Time	>10min	>20min		
Maximum	.048 Kg	.125 Kg		
GTOW				

The second and smaller Samara tested, called Samara-II is designed and constructed in a similar fashion to Samara-I, however the total mass is 38 grams, and maximum dimension is 18cm, Figure 2.

A substantial advantage of the Samara-I vehicle is that it is a passively stable system. A simple qualitative stability analysis of the Samara-I in a steady hover, or autorotation illustrates this point.

In a steady hover the thrust from the propeller is balanced by the drag from the body and wing, resulting in a near constant rotational rate about its principal axis, I_Z . Alternatively, in autorotation the resistive torque of the wing drag is equal to the driving torque of the lift, for a net zero torque. Consider the assumed motion $r = r_0$ and $p,q \ll r_0$ in steady hover, or autorotation. To investigate whether the motion is stable or not, neglecting aerodynamic contributions, a small moment is applied to the body such that after the moment is applied the resultant angular velocities are as follows:

$$p = \varepsilon_p \tag{1}$$

$$q - \varepsilon_q \tag{2}$$
$$r = r_0 + \varepsilon_r \tag{3}$$

Where ε_i (i = 1,2,3) are small quantities. To determine the evolution of these perturbed angular velocities in time it is convenient to use the Euler equations as follows:

$$I_{z}(\dot{r}_{0} + \dot{\varepsilon}_{r}) + (I_{x} - I_{y})\varepsilon_{p}\varepsilon_{q} = 0$$

$$(4)$$

$$I_x \dot{\varepsilon}_p - (I_y - I_z)(r_0 + \varepsilon_r)\varepsilon_q = 0$$
⁽⁵⁾

$$I_{y}\dot{\varepsilon}_{q} - (I_{z} - I_{x})(r_{0} + \varepsilon_{r})\varepsilon_{p} = 0$$
⁽⁶⁾

The change in angular velocities is small, and as such allows linearization of the above equations by eliminating quadratic and higher order terms in ε_i yielding:

$$I_{z}\dot{\varepsilon}_{r} = 0 \tag{7}$$

$$I_x \dot{\varepsilon}_p - (I_y - I_z) r_0 \varepsilon_q = 0 \tag{8}$$

$$I_{y}\dot{\varepsilon}_{q} - (I_{z} - I_{x})r_{0}\varepsilon_{p} = 0$$
⁽⁹⁾

This implies ε_r is constant. The behavior of the remaining angular velocities can be understood with eigenvalue analysis. Assuming a solution of the form:

$$\varepsilon_p(t) = E_p e^{\lambda t} \tag{10}$$

$$\varepsilon_a(t) = E_a e^{\lambda t} \tag{11}$$

Next, introducing the expansions into Eq8,9:

$$\begin{bmatrix} I_x \lambda & (I_z - I_y) r_0 \\ (I_x - I_z) r_0 & I_y \lambda \end{bmatrix} \begin{bmatrix} E_p \\ E_q \end{bmatrix} e^{\lambda t} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
(12)

The solution of Eq12 requires that the determinant of the coefficient matrix be zero, which yields the characteristic equation:

$$I_{x}I_{y}\lambda^{2} - (I_{x} - I_{z})(I_{z} - I_{y})r_{0}^{2} = 0$$
(13)

The solution is:

$$\lambda = \pm i \sqrt{\frac{(I_x - I_z)(I_z - I_y)r_0^2}{I_x I_y}}$$
(14)

Two types of solutions are possible and depend on the principal moments of inertia. If $I_x>I_z$ and $I_y>I_z$, or if $I_x<I_z$ and $I_y<I_z$ (characteristic of Samara-I and Samara-II) both roots of the characteristic equation are imaginary. In the absence of nonconservative forces, the system is critically stable⁷.

Experimental Setup:

Visual Tracking System

Position and orientation of the vehicle was collected at a rate of 500 Hz, using a Vicon visual tracking system. Tracking errors for the trials included here are less than 1mm of position uncertainty. An example of one of the flights discussed can be seen in Figure 3a. During a flight test, the tracking system utilizes eight cameras to track the three-dimensional position of three retro-reflective markers placed on the Samara wing. The markers are placed as to cause minimal interference to the aerodynamics of the vehicle. Each marker is spherical with a diameter of 5 mm. The three dimensional shape of the marker allows for better tracking by the Vicon system. A model of the vehicle geometry and the exact locations of the markers are used for least-squares estimates of the position of the center of mass. Figure 3b displays images of the virtual capture volume and the rigid body of the Samara wing created by the retro-reflective markers.

Pitch input is measured by two methods, both on, and off-board the vehicle. The state of the actuator is measured off-board the Samara on an identical system receiving commands from the same transmitter. Two markers are placed on an arm attached to the offboard actuator to track the input to the vehicle. During a flight test the Samara and off-board actuator are simultaneously tracked allowing the angular displacement measured on the ground to be correlated to the motion of the Samara.

It is advantageous to track the wing pitch angle via the off-board system as it provides the ability to track the collective inputs when the vehicle is not flown within the capture volume of the Vicon vision system. The on-board method includes measuring both pitch angle, θ , and coning angle, ϕ , via the markers placed on the wing. It is interesting to compare the on-board and off-board measurements as the on-board angles are influenced by the aerodynamic forces acting on the vehicle.



Figure 3b: Representative VICON workspace

Nothing was presumed to be known about what forces or deflection angles were generated given a change in the actuator, therefore all control inputs are normalized⁸. The input command is given by μ_{col} for collective input. This input is normalized such that $\mu_{col} \in [-1, 1]$.

Open-Loop Flight Test Data

The first step in a system identification is to pilot the vehicle in a flight envelope where the dynamics of interest are thoroughly excited. The vehicle was piloted within the capture volume of the vision system while simultaneously collecting the inputs and vehicle kinematics. The pilot attempted to excite the vehicle over a wide range of frequency content to best determine the relationship between input and output. For proper system identification, it is important to collect flight data open loop as a closed loop feedback system would alter the natural dynamics of the vehicle. The open loop setup is shown in Figure 5.



Figure 5: Open Loop Setup.

Typical portions from recorded open loop data sets are shown in Figure 6ab. The heave velocity, w, is found by applying the central difference approximation to the vehicle vertical position data collected by the Vicon system. Figure 4 also compares the inputs given to the vehicle during one flight test as calculated both on-board and off-board the Mechanical Samara. Both on-board and off-board methods demonstrate similar pitch inputs, but the on-board measurements display more oscillations, demonstrating the effects of the aeroelastic forces acting on the wing.



Figure 6b: Flight data collected for Samara-II

Closed-Loop Flight Test Data

Implementation of closed loop flight is enabled by an off-board feedback system. The ground control station setup is shown in Fig 7. During closed loop flight, the position and orientation of the Mechanical Samara are tracked by the Vicon visual system, which sends the information to a LabVIEW controller program⁹. The LabVIEW program takes into account the vehicles' vertical position and heave velocity to create wing collective commands which are sent through a PIC 18F8722 microcontroller. The PIC microcontroller in turn sends the commands to the vehicle through a Spektrum Transmitter.



Identification Method

A beneficial step in the identification process is computing the coherence function. This step provides a measure of the extent to which an output is linearly related to the input over some frequency range⁷. The magnitude squared coherence is given by:

$$\gamma_{xy}^{2}(\omega) \triangleq \frac{\left|R_{xy}(\omega)\right|^{2}}{\left|R_{xx}(\omega)\right|\left|R_{yy}(\omega)\right|}$$
(15)

where R_{xy} is the cross spectral density between the input and output, R_{xx} is the auto-spectral density of the input and R_{yy} is the auto-spectral density of the output. An input/output pair with low coherence implies either the input has no effect on the output or the effect is nonlinear. However, an input/output pair with high coherence implies the relationship can be modeled well by a linear model such as a transfer function or state space model. Tischler¹⁰ suggests a coherence of 0.6 or above for some useful frequency range is necessary for accurate transfer function identification.

The magnitude squared coherence for the input/output relationship of Samara-I using the onboard actuator system for input measurement is shown in Figure 8. It can be seen that the useful frequency for this input/output pair lies in the range of about 0.3 to 10 Hz. The coherence and useful frequency range predicted by the on-board measured θ is equivalent to that of the off-board measurement, Figure 9. The similarity of the two predictions validates the hypothesis that off-board measurements of θ area capable of capturing the physics relevant for system identification. The on-board measurement of θ for Samara-II demonstrates some high frequency behavior above 55 rad/sec and may be a result of the aeroelasticity of the wing in flight, Figure 10. All three coherence plots demonstrate similar ranges for strong relationships between input and output.



Figure 8: Samara-I Identified model Bode diagram with corresponding data coherence, for On-Board data collection



Figure 9: Samara-I Identified model Bode diagram with corresponding data coherence, for Off-Board data collection



Figure 10: Samara-II Identified model Bode diagram with corresponding data coherence, for On-Board data collection

Experimental Results:

Open Loop Control

The transfer function, G, of the pitch input to heave dynamics was modeled as a first-order continuous-time process model:

$$G(s) = \frac{K}{1 + sT_{n1}} \tag{16}$$

where K is the static gain and T_{p1} is a time constant.

Given a flight data set with sufficient coherence, as seen in Figure 8-10, the MATLAB[®] System Identification Toolbox can be used to complete frequency response-based system identification. The input and output data is imported to the system identification GUI where it is filtered to 100 rad/sec using a fifth-order Butterworth filter.

Table 2 shows the values identified for the Mechanical Samara for the collective to heave velocity transfer function using data from both methods of measuring pitch input. In comparing the two methods of identification, it is important to note that both methods identify K and T_{p1} to be on the same order of magnitude, proving both methods have similar capabilities in capturing the input-output relationship. The transfer functions of the computed models are plotted in Figs. 16 and 17b in the Appendix. Figures 14 and 15 in the Appendix demonstrate a comparison of the two models in the time domain. As seen in the figure, both models capture the dynamics to a similar degree.

Table 2: Identified Mechanical Samara Parameters.

Samara-I			Samara-II
	Off-board	On-board	On-board
	θ	θ	θ
K	2805.1	6473.1	0.02356
T_{pl}	0.20555	0.26218	0.01394

Closed Loop Feedback Control

Feedback control is used to correct for perturbations in the system in order to keep the vehicle at a reference condition. The structure of the closed loop system is depicted in Figure 11.



Figure 11. Prototypical Feedback Control Loop.

 G_p is the plant transfer function, *K* is the controller, Y_d is the reference value, and Y is the output. Precise attitude data is collected by the VICON motion capture system. The commanded altitude of the Samara is maintained by feeding back the error in position to a control loop which contains the system and actuator dynamics. The closed loop system attempts to compensate for errors between the actual and reference height of the Samara by measuring the output response, feeding the measurement back, and comparing it to the reference value at the summing junction. If there is a difference between the output and the reference, then the system drives the plant to correct for the error¹¹.

A proportional plus derivative plus integral (PID) controller was chosen for feedback control of the Mechanical Samara. A PID controller is given by the equation:

$$K(s) = K_p + K_d s + K_i / s$$
(17)

where K_p is the proportional gain and K_d is the derivative gain, and K_i is the integral gain. A PID controller feeds the error plus the derivative of the error forward to the plant. The proportional gain provides the necessary stiffness to allow the vehicle to approach the reference height. The P gain improves steady state error but causes overshoot in the transient response, whereas the derivative gain improves transient response. The integral term is proportional to both the magnitude and duration of the error in position, with the effect of eliminating the steady-state error. Using the ground control station setup described in Figure 7 for closed loop feedback control, several gain combinations were tested in order to find the PID gains which provided the best transient response to a change in reference height. The gains in Table 3 provide the best transient response.

Table 3: PID Gains for feedback control.

Gain V	Samara-I	Samara-II	
$egin{array}{c} K_p \ K_d \end{array}$.2109375	0.3438 0.1328	
K_i	0.0276	0.02	

Figure 12 depicts a representative data set of a flight test with the implementation of the PID controller using the gains in Table 3, demonstrating that the actual height closely matches the reference height. The figure also shows higher frequency oscillations in the actual height (<0.1 m) at time interval 10 to 15 seconds, suggesting that the vehicle impinged on the ground and after which it experienced some ground effect.

The open loop transfer function, L(s), and closed loop transfer function, T(s), are given by the following equations:

$$L(s) = G(s) K(s)$$
(17)

$$T(s) = L(s)/(L(s) + 1) = Y(s)/Y_d(s)$$
 (18)

Solving for the closed loop transfer function for both the on-board and off-board collective measurements provides the values shown in Table 4. Samara-I Command Following



Figure 13: Implementation of PID control

These values demonstrate the effectiveness of the PID controller for both on-board and off-board methods of measuring collective input as both functions are very close to unity. This implies that $y_d(t) \approx y(t)$ where y_d is the desired state and y is the actual state. Figure 12-13 demonstrates that this is the case since the actual location and reference location are very close.

 Table 4: Closed Loop Transfer functions for on-board and off- board measurements.

On-board Samara-I	$T_{on}(s) = \frac{s^2 + 0.2373s + 0.03105}{s^2 + 0.2377s + 0.03105}$
Off-board Samara-I	$T_{off}(s) = \frac{s^2 + 0.2373s + 0.03105}{s^2 + 0.2375s + 0.03105}$
On-Board Samara-II	$T_{on}(s) = \frac{0.3675s^2 + 0.142s + 0.2138}{s^2 + 45.51s + 0.2138}$

Flight testing of Samara-II utilized a PID controller for altitude control. The vehicle is commanded to a specific height above the ground, which it is to hold until commanded otherwise. The blue dashed line in Figure 13 is the altitude specified by the ground station, and the red line is the vehicles vertical flight path. Figure 13 demonstrates the characteristic over-damping in climb, and under-damping in descent, of Samara-II. This phenomenon is the result of gravity's effect on the vehicle.

Error analysis

The estimated models compare well with the computed transfer functions estimates, implying that the relevant dynamics were captured. Figure 15 in the Appendix shows the transfer functions of the identified models plotted with the computed transfer function estimates from the flight data.

A state space model given by Eqs. 19-20 was created to allow for error estimation using the Cramer-Rao bounds, Eq22, and insensitivity percentages, Eq23.

$$\dot{x} = Ax + Bu \tag{19}$$

$$y = Cx \tag{20}$$

In Eqs. 19 and 20, x is the state vector, A is the dynamics matrix, B is the control matrix, and C is the output matrix. Due to the simplification of the vehicles' dynamics into a single input, single output system, the state space model for this identification reduces to

$$\dot{w} = Z_w w + Z_{\mu_{col}} \mu_{col} \tag{21}$$

where \dot{W} is the heave acceleration, Z_w is the stability derivative for heave velocity and $Z_{\mu col}$ is the collective input stability derivative¹². The Cramer-Rao bounds are theoretical minimum limits for the expected standard deviation in the parameter estimates which would be obtained from several experiments¹⁰. Tischler suggests the following conditions represent the most valid parameter estimates:

$$CR\% \le 20\% \tag{22}$$

$$\overline{I}\% \le 10\% \tag{23}$$

The *CR* and I percentages were found using the Comprehensive Identification of FRequency Responses (CIFER **(B)**) software developed at Army Aeroflightdynamics Directorate. Table 5 shows the parameter estimates and associated error bounds of the identified state space model. The table demonstrates the validity of the identified parameter estimates, as all parameters meet the conditions specified by Eq. 22-23.

The model computed from both on/off-board measurement of the collective angle input is capable of capturing most of the low frequency inputs, but can be seen to average higher frequency excitation. The model computed from the off-board measurement of collective angle input performs well at the lower frequencies, but tends to average the higher frequency excitation. The model tends to exhibits more overshoot than that of the model derived from on-board measurements. The small differences in the performance of the two methods of input measurement validate the ground based input observation method.

Table #	5: Mee	chanical	Samara	Identified	Parameter
with Cramer-Rao Error Estimates.					

	Parameter	Value	CR %	Ī%
On board	Z_w	-6.382	10.04	4.231
Samara-I	$Z_{\mu col}$	15880	4.733	1.994
Off board	Z_w	-4.303	9.413	3.808
Samara-I	$Z_{\mu col}$	28130	5.022	2.032
On-board	Z_w	-60.64	13.67	2.064
Samara-II	$Z_{\mu col}$	1.501	12.84	1.939

Validation of the identified model can be done by subjecting the system to a different set of inputs. A data was set collected under the same conditions and was used as a test case for Samara-II. In Figure 17a the prediction of the model designated by the dashed line, and the actual response of the vehicle designated by the solid line, are shown. It can be seen that the fit is capable of capturing the 1/revolution influence of pitch angle on the motion of the center of mass.

Conclusions:

The significant findings of this research include the following: 1) Introduced two prototype VTOL MAVs based on natural Samara. 2) Proposed linear model of Samara-I,II heave dynamics. 3) Proposed off-board measurement of vehicle control inputs, and validated method with on-board measurements. 4) Performed frequency based system identification for two vehicles of differing scales. 5) Verified linear model of heave dynamics. 6) Implemented closed loop control based on linear model.

The heave dynamics of the two vehicles tested have been characterized and found to reduce to first order systems represented by Eq21. The ratio of input to output is very close to unity and provides some physical insight. The forces induced on the body from a change in collective pitch are substantial compared to the inertia of the vehicle, and increases in heave velocity are quickly damped after excitation. This allows tremendous simplification over traditional helicopter models which model the rotor as an oscillating disk of force which requires estimation of inflow for proper modeling.





Figure 14: Representative Time Domain Comparison – On-Board, Samara-I



Figure 15: Representative Time Domain Comparison – Off-Board, Samara-I



Figure 16: Samara-I Identified model transfer function magnitude and phase plot. System identified by CIFER® for on/off board data collection



Figure 17a: Representative Time Domain Comparison – On-Board, Samara-II



Figure 17b: Samara-II Identified model transfer function magnitude and phase plot. System identified by CIFER® for on board data collection

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References:

- 1) http://en.wikipedia.org/wiki/Miniature UAVs
- Ulrich, E., Pines, D., 'Planform Geometric Variation, and its Effect on the Autorotation Efficiency of a Mechanical Samara,' AHS64th Annual Forum, Montreal Canada April 29-May 1, 2008.
- 3) Vicon Motion Systems Limited, <u>www.vicon.com</u>
- 4) Graham, F., 'Monocopters', Perigee Press, East Liverpool Ohio, 1999.
- Jameson, S., Allen, N., Youngren, H., 'SAMARAI Nano Air Vehicle - A Revolution in Flight.' Lockheed Martin, DARPA contract W31P4Q-06-C-0324, 2007
- 6) Young, L.A., Aiken, E.W., Johnson, J.L., Andrews, J., Demblewski, R., Klem, J., 'New Concepts and Perspectives on Micro-Rotorcraft and small Autonomous Rotary-Wing Vehicles' AIAA 2002-2816, Applied Aerodynamics Conference 2002
- 7) Baruh, H., Analytical Dynamics, McGraw-Hill 1999.
- Conroy, J., Humbert J., and Pines D. "System Identification of a Rotary Wing Micro Air Vehicle." American Helicopter Society, 2008
- 9) "LabView," <u>www.ni.com</u>.
- 10) Tischler, M. and Remple, R. "Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples." American Institute for Aeronautics and Astronautics, 2006.
- Nise, N.S. Control Systems Engineering, 4th ed., John Wiley & Sons, Inc., Hoboken, NJ, 2004.
- Celi, R., 'Helicopter Stability and Control' ENAE 635 course handouts, Aerospace Engineering Dept., Spring 2006.