System Identification Guidance For Multirotor Aircraft: Dynamic Scaling and Test Techniques

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ABSTRACT

State-space system identification was performed in order to extract flight dynamic models for hovering flight of a 56 cm, 1.56 kg hexacopter unmanned aerial vehicle (UAV). Different input excitation techniques were tested to determine which maneuvers provided high quality system identi

flight test data. A small scale hexacopter (1.56 kg, 56 cm diameter) operated by the University of Portland was used to study system identification of small-scale multirotor UAVs using CIFER® [4]. Although

The UP hexacopter also shares information with a ground control station (GCS) using a wireless 3DR 915MHz telemetry radio [1]. The ground control station, Mission Planner, was utilized to show real-time data on the UAV's position, upload commands, and set parameters. Mission Planner was also used to analyze downloaded missions, and use telemetry to monitor, record, and view mission logs [1].

A tethering system was developed in order to ensure that the hexacopter would not depart from the testing area. The tether was designed to avoid interference with the dynamics of the hexacopter. Light-weight survival Kevlar cord (rated to 200 lb) was tied to each leg of the hexacopter and to a thirty-pound kettle bell with double figure eight knots used to secure the cord to each arm. Two lightweight aluminum rings were attached to segments part way down the cord in order to weigh the Kevlar cord down enough so that it did not lift and interfere with the blades of the hexacopter during flight but was light enough that it did not effect the dynamics of the vehicle. A bungee cord with a carabiner was attached to the kettle bell and cord in order to prevent sudden tugging of the cord when the hexacopter is out of range. The cord was limited to 35 feet based on the dimensions of the testing area.

System Identification Software

CIFER® (Comprehensive Identification from Frequency Responses) is an integrated software, used for system identification [3]. CIFER® was utilized for the work herein because it is a well-established frequency domain method, which is well suited for unstable dynamics and high vibration due to the six rotors of the hexacopter. The software was used to extract non-parametric control-to-vehicle frequency responses from flight data, develop flight accurate identification for the lateral-directional model were [4]:

6 " P , , , R , S , T (5)

The angular rate gyro sensors and the lateral accelerometers are built into the Pixhawk. The lateral velocity rate is reconstructed (at hover U, U, " %<:

" 5 VW (6)

When using the equations of motion, the assumption is that the center of mass is where the data measurement device is located. If the measurement device cannot be placed directly at the center of mass, an offset term is used to account for the displacement between the center of mass and the measurement

Table 3. Lateral-Directional Model Eigenvalues at Hover.

Eigenvalue Number, ‡ˆ	Mode	Real (rad/s)	Imaginary (rad/s)	Damping Ratio	Natural Frequency (rad/s)
1	Yaw	0	0	-	-
2	Roll Oscillatory	1.63	2.93	- 0.485	3.35
3	Roll Oscillatory	1.63	- 2.93	- 0.485	3.35
4	Roll Mode	-3.46	0	-	-
5	Motor Lag	-15	0	-	-
6	Motor Lag	-15	0	-	-

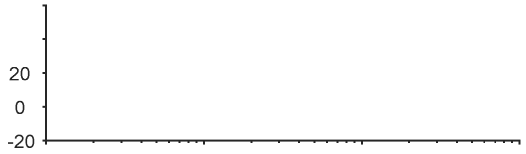

Figure 4. Lateral Body Velocity Rate and Roll Rate Models versus Flight Data.

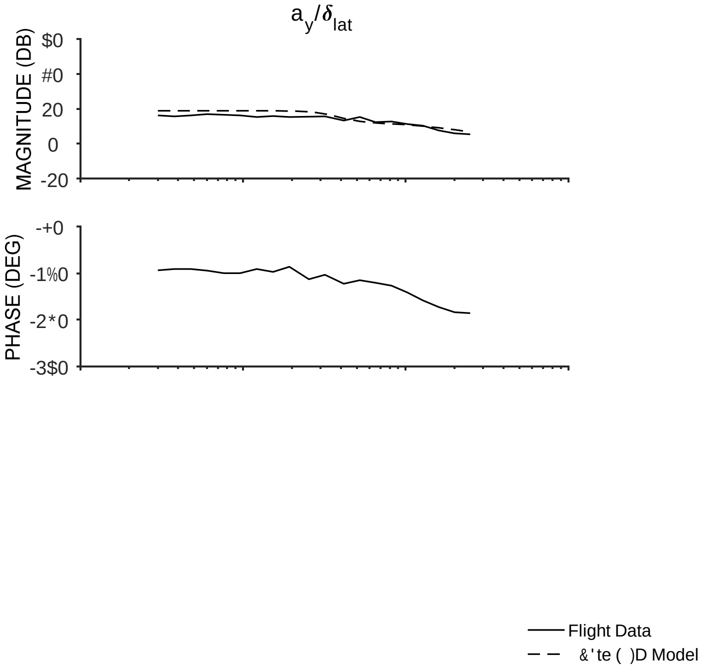

Figure 5. Lateral Body-Axis Accelerometer and Yaw Rate Models versus Flight Data.

Figure 6. Lateral-Input Time Domain Verification at Hover.

Figure 7. Yaw-Input Time Domain Verification at Hover.

Figure 11. Throttle-Input Time Domain Verification at Hover.

Figure 12. Block Diagram of Control Input.

TESTING GUIDANCE: SYSTEM ID OF MULTIROTOR AERIAL VEHICLES

A parametric variation of frequency sweep amplitudes was performed in all axes (roll, yaw, pitch and heave) in order to provide guidance on frequency sweep amplitude for small scale multirotor UAS. The

similarity requirement for rotorcraft models [5, 17]. Froude scale was shown to work well for scaling fixed-wing aircraft dynamic modes, as observed by Sanders [12]. There is some prior evidence in the literature that the characteristic length used in Froude scaling for multirotor aircraft should be based on the hub-to-hub distance◊ ª$_{\text{šb«}}$ as opposed to disk diameter that is commonly used for a single rotor helicopter [18, 11]. Using ª$_{\text{šb«}}$ as the characteristic length gives:

$$\text{.} \;\text{"}\; \text{·}_{\text{¬•-®}} \;\text{"}\; \frac{\text{¬•-®¯∘}}{\text{¬•-®}_{\pm}{}^{\text{2 2}}} \;\text{"}\; \frac{\text{šš\\³}}{\text{™´}} \;\text{"}\; \frac{}{\text{™\\™´}} \;\text{"}\; \text{%\\r r} \qquad (19)$$

This indicates that the UP hexacopter is $\frac{}{\text{™\\™´}}$ scale, or nearly half scale relative to the ADD hexacopter. The scaling results for the stability derivatives are shown in Table 9, against the true ADD hexacopter system identification results. The Froude scaled estimates are within œ22% of the true stability derivatives, with the exception of ◊Œ . This is likely because Œ is less accurately known in the identification as shown by the larger Cramer-Rao bound in *Table 4.* It should be noted that the ($_{)}$ and Ž$_{‹}$ derivatives could not be identified for the UP hexacopter at hover and therefore cannot be scaled. These parameters were insensitive, indicating that the angular rate damping does not affect the dynamics in the frequency range of interest for the identification (1-30 rad/s). These parameters are likely present, but very small and therefore not important for a good prediction of the dynamic behavior. Small (or zero) angular rate damping at hover is a common result for multirotor vehicles [2, 3, 13]. A comparison of the associated scaled eigenvalues in *Table 10* also shows that all modes are well predicted by Froude scaling based on ª$_{\text{šb«}}$.

Froude scaling as applied to the control derivatives is shown in Table 11. Scaling based on ª$_{\text{šb«}}$ predicted the control moment derivatives Ž$_{*_{+••}}$, ($_{*_{+,-}}$, ▪*

Figure 14. Frequency Responses for Scaled UP Hexacopter versus ADD Hexacopter System ID at Hover.

CONCLUSIONS

Frequency domain system identification was to ± 23 deg/s in full-scale angular rates (Froude scaled relative to the UH-60), twice the recommended amplitude for full-scale frequency sweeps (10-15 deg/s).

3. The frequency sweep input method resulted in

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[16] M. Lopez, M. Tischler, O. Juhasz, A. Gong and F. Sanders, "Development of a Reconfigurable Mlticopter Flight