

Flight Log based Analysis of Test Environment Effects on Navigation and Control Behavior in eVTOL Tethered Hover Tests

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Abstract

Large electric vertical takeoff and landing aircraft require staged verification before untethered flight because propulsion, avionics, navigation, and flight-control functions are strongly coupled during hover. Tethered hover testing reduces operational risk, but the test environment itself can introduce anomalies that are not representative of free flight. This paper analyzes flight logs obtained from a 210 kg-class multirotor electric vertical takeoff and landing demonstrator during tethered and untethered hover tests. The tethered configuration used a crane-suspended safety line and an aluminum connection structure, whereas the untethered configuration was flown without the tether hardware under comparable flight-control settings. Logged Global Positioning System, attitude, vibration, and control output data were compared to evaluate the effect of the test configuration on hover stability. Preliminary results show that the tethered condition produced larger roll/pitch variations and increased attitude control error, although conventional Global Positioning System quality indicators such as satellite count and horizontal dilution of precision did not show severe degradation. This suggests that tether-induced anomalies should be analyzed through system level consistency among navigation, inertial, and control loop signals rather than from a single sensor metric. The results provide a flight log-based basis for artificial intelligence assisted flight test anomaly diagnosis and safer verification of large electric vertical takeoff and landing systems.

Keywords: eVTOL, navigation inconsistency, flight control stability, vibration, tethered hovering, anomaly diagnosis

Acronyms/Abbreviations

ACE	Attitude Control Error
AI	Artificial Intelligence
EKF	Extended Kalman Filter
eVTOL	electric Vertical Takeoff and Landing
FC	Flight Controller
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
IMU	Inertial Measurement Unit
MTOW	Maximum Takeoff Weight
UAM	Urban Air Mobility

1. Introduction

eVTOL aircraft are increasingly relevant to UAM, autonomous aerial transport, and future aerospace mobility demonstrations. Compared with small unmanned aircraft, large eVTOL demonstrators combine high stored electrical energy, multi-kilowatt propulsion, large rotating components, structural vibration, and tightly coupled avionics, navigation, and flight-control functions. Direct transition from ground integration to untethered hovering can therefore expose the vehicle, operators, and test site to unacceptable risk.

Tethered hovering is commonly used as an intermediate verification step for multirotor systems, and prior tethered-UAV studies have treated cable dynamics and taut-cable control as important parts of the vehicle boundary condition [1,2]. A safety line connected to an overhead crane or support structure allows the propulsion system and FC to operate under near hover loads while limiting excessive vertical or lateral motion. In this role, the tether is often regarded as a passive safety device. For large vehicles, however, the tether system is part of the test boundary condition. The crane, cable, metallic brackets, altered mass distribution, local electromagnetic environment, and mechanical constraints can change the behavior observed by the onboard sensors and estimator.

This study was motivated by a flight test campaign in which a 210 kg-class multirotor eVTOL demonstrator showed unstable hover behavior when a crane-suspended safety line and an upper aluminum connection structure were installed. Subsequent untethered hovering, performed after removing the tether hardware and using comparable FC settings, showed more stable behavior. Such a case is diagnostically important because conventional single-channel indicators can be misleading: satellite count and HDOP may remain favorable even when position consistency or sensor fusion behavior is degraded, because such indicators do not fully describe

local multipath or GNSS, inertial fusion consistency [3,4]; vibration magnitude may increase or decrease depending on the flight condition; and attitude excursions alone do not identify the causal path.

This paper addresses the problem as a multi-channel anomaly diagnosis task, following the broader aerospace information fusion principle that abnormal behavior should be interpreted from correlated evidence across sensors and control states rather than from a single measurement [5]. Instead of attributing the event to a single sensor or component, flight-log channels are compared across navigation, inertial, attitude, and control-output domains. The contribution is twofold: first, a quantitative comparison of tethered and untethered hover behavior in a large eVTOL demonstrator; and second, an AI ready feature framework for detecting test environment induced anomalies during staged flight verification.

2. Material and Methods

2.1. Test eVTOL and configurations

The test eVTOL was a four rotor, 210 kg-class multirotor eVTOL demonstrator equipped with an onboard FC, GPS receiver, IMU, electronic speed controllers, electric motors, high voltage battery, and onboard flight data logging system. The available log fields were interpreted using the corresponding autopilot DataFlash log documentation [6,7]. The vehicle parameters used for this short-paper analysis are summarized in Table 1.

Table 1. Test eVTOL Specifications used in the Analysis

Parameter	Value
MTOW	210 kg
Battery	88S1P Li-ion, 325.6 V, 7.16 kWh (22 Ah)
Inverter	30 kW $\times$ 4 (120 kW total)
Motor	27 kW $\times$ 4 (108 kW total)
Propeller	63 in diameter, 9.8 in pitch
Measured Hover Power	49.5kW

Two test configurations were compared. In the tethered configuration, the vehicle was connected to a crane suspended safety line through an upper aluminum connection structure mounted above the airframe. The tether constrained excessive motion while allowing the propulsion system to generate lift. In the untethered configuration, the safety line and upper connection hardware were removed, and the vehicle was operated without mechanical constraint. The FC settings used for the comparison were kept comparable so that the analysis focused on the influence of the test configuration rather than on a deliberate controller change.

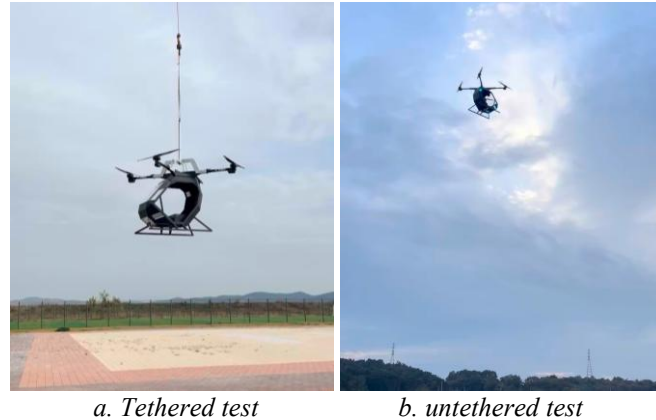


Fig 1. Flight Test Configuration [a. Tethered / b. untethered]

2.2. Flight log dataset feature extraction

The flight test campaign was organized into two hover test configurations: tethered hovering and untethered hovering. In the tethered configuration, the eVTOL was connected to a crane suspended safety line through an upper aluminum bracket mounted on the airframe. In the untethered configuration, the safety line and bracket were removed, and the eVTOL was flown under comparable flight control settings. The recorded flight logs were classified according to these two test conditions and used for the comparative analysis.

During the initial data screening, two records were found to contain no sustained active hover intervals and were therefore retained only as low activity reference cases. The primary quantitative comparison was consequently performed using three tethered hover records and three untethered hover records. Active hover intervals were identified from the normalized throttle output channel using a preliminary threshold of $ThO > 0.1$, together with a minimum continuous duration requirement. Throttle output and motor command channels were

interpreted according to the flight log message specification [7]. For the final submission, the selected interval boundaries should be cross checked against flight test video and operator notes to ensure that the extracted intervals correspond to actual hover operation.

Four groups of flight log signals were extracted for analysis: GPS related measurements, attitude response, IMU vibration, and control output response. The GPS related measurements included satellite count, HDOP, ground speed, vertical speed, and horizontal position change per sample. The attitude response variables included roll, pitch, yaw, and ACE. Vibration was evaluated using the onboard IMU vibration channels, while control activity was represented by normalized throttle output and motor-output variation.

For each active hover interval, scalar features were computed to enable condition level comparison between tethered and untethered hovering. These features included roll and pitch standard deviations, roll/pitch peak to peak ranges, the 95th percentile ACE, mean HDOP, mean satellite count, the 95th-percentile horizontal position jump per sample, mean vibration magnitude, and the mean standard deviation of motor outputs across the motor channels.

3. Theory and calculation

3.1. Attitude and Control Response

Table 2. Quantitative Comparison of tethered and untethered hover intervals

Metric	Tethered	Untethered
Active duration per log (s)	84.8	155.1
Roll standard deviation (deg)	4.87	1.62
Pitch standard deviation (deg)	2.42	1.86
ACE, 95th percentile	0.150	0.043
HDOP, mean	0.637	0.594
Satellite count, mean	28.0	28.0
Horizontal position jump	0.228	0.393
Vibration magnitude, mean	5.21	6.10
Motor output standard deviation, mean	59.9	36.5

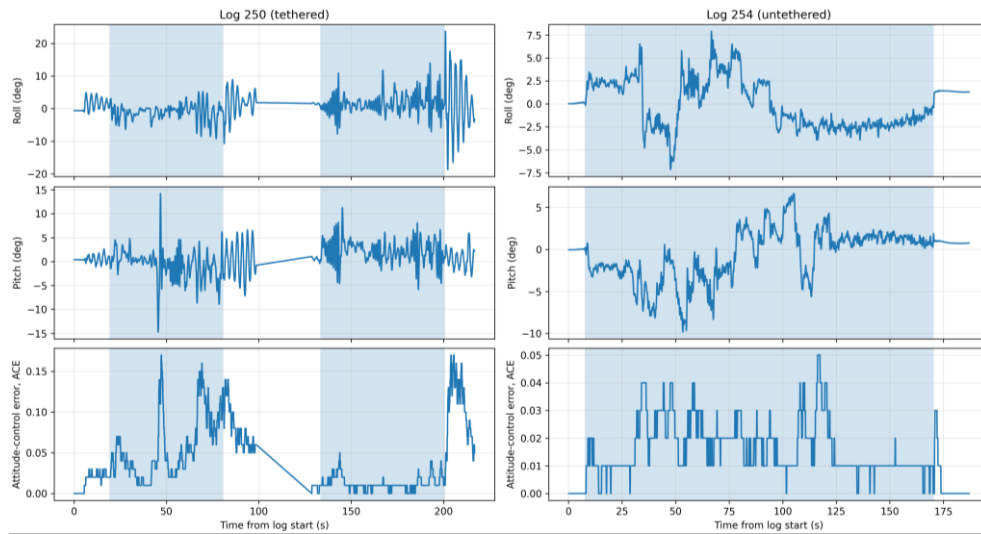


Fig 2. Representative attitude response comparison between tethered and untethered hovering

The tethered configuration produced larger attitude variation and greater control activity than the untethered configuration. As summarized in Table 2, the group mean roll standard deviation increased from 1.62 deg in untethered hovering to 4.87 deg in tethered hovering, corresponding to a 3.0 fold increase. Pitch standard deviation also increased, although less strongly. The 95th percentile ACE increased from 0.043 to 0.150, approximately 3.5 times higher in the tethered case.

The motor output statistics show the same trend. Mean motor output standard deviation increased from 36.5 in the untethered condition to 59.9 in the tethered condition, a 64% increase. This indicates that the FC was issuing more variable motor commands during tethered hovering, consistent with either external disturbance, sensor fusion inconsistency, altered boundary conditions, or a coupled combination of these effects.

3.2 Navigation Quality and Vibration Response

The GPS quality indicators did not show a conventional loss of signal pattern. Mean satellite count remained approximately 28 in both configurations, and mean HDOP stayed below 0.7. These values would normally be interpreted as acceptable GPS reception in many autopilot log-review workflows [6,7]. Therefore, the observed hover instability should not be described simply as a GPS outage.

The horizontal position jump statistic also did not increase in the tethered case. This result is important because it prevents an over simplified interpretation. If multipath or local reflection was present, it may have appeared as a slowly varying position or velocity bias rather than as discrete sample to sample jumps, which is consistent with established GNSS, inertial navigation behavior under biased measurements [3,4]. Such a bias can still disturb the EKF and downstream attitude control even when HDOP, satellite count, and single sample position jumps appear acceptable.

Vibration magnitude likewise did not provide a single cause explanation. The mean vibration magnitude was lower in the tethered logs than in the untethered logs. This does not rule out mechanical coupling through the tether or bracket, but it indicates that raw vibration amplitude alone is not the distinguishing feature. The diagnostic signature is the cross channel combination: elevated roll variation, elevated ACE, and increased motor output variation without corresponding degradation in the usual GPS quality metrics.

4. Discussion

4.1. System level Interpretation

The results support a system level interpretation of the tethered hover anomaly. The tethered condition changed the test boundary condition through the crane-suspended line, upper aluminum connection structure, and mechanical constraint. These elements can affect the aircraft through several coupled pathways: local GPS reflection or obstruction, low frequency tether motion, bracket mediated structural coupling, altered mass or inertia, and constrained attitude dynamics.

The most defensible conclusion from the current data is not that one of these pathways has been isolated as the sole cause, but that the tethered configuration produced a measurable multi channel instability signature. The same broad FC setup produced lower attitude variation and lower motor output variation in untethered hovering, while GPS satellite count and HDOP did not explain the difference. This distinction matters for engineering diagnosis. A narrow GPS quality threshold would miss the event; a vibration only threshold could be misleading; and a gain only explanation would not account for the configuration dependent behavior.

The GPS related result is particularly instructive. Satellite count and HDOP represent geometry and receiver tracking quality, but they do not fully capture local multipath, low frequency position bias, or inconsistency between GPS derived motion and IMU integrated motion [3,4]. In a hover test, small estimator biases can be converted into attitude corrections, and the FC may then command motor outputs to compensate for a state that does not correspond to the true free flight motion. This creates a plausible path from test environment hardware to navigation inconsistency and then to flight control activity.

4.2. Implications for AI Assisted Flight Test Monitoring

The anomaly pattern is well suited to AI assisted flight test monitoring because it is not reliably captured by one scalar threshold. A practical diagnostic system should evaluate relationships among GPS consistency, EKF or estimator residuals, attitude tracking, vibration content, and motor output activity, consistent with multi sensor information fusion approaches used in aerospace systems [5]. The features extracted in this study form an interpretable feature vector for a first stage classifier: roll variation, pitch variation, ACE percentile, HDOP, satellite count, position consistency, vibration magnitude, and motor output variation.

For near term engineering use, a shallow classifier or rule based anomaly score may be preferable because it remains explainable to flight test engineers. For larger datasets, recurrent or transformer based time series models could localize the onset of tether-induced inconsistency and distinguish it from propulsion imbalance, controller saturation, wind disturbance, or sensor failure; however, such models should be introduced only after a larger labelled dataset is available to avoid overclaiming. In either case, the present result suggests that labelled flight test data should be organized by test configuration and by system level causal hypothesis, not only by individual sensor alarms.

5. Conclusions

This paper analyzed tethered and untethered hover logs from a 210 kg-class multirotor eVTOL demonstrator. The tethered configuration increased roll standard deviation by a factor of 3.0, increased 95th percentile attitude control error by a factor of 3.5, and increased motor output standard deviation by 64%, while satellite count and HDOP remained favorable. The anomaly is therefore best understood as a multi channel sensing control inconsistency introduced or amplified by the tethered test environment, rather than as a simple GPS outage or vibration only event.

The practical implication is that large eVTOL tethered hover tests should include multi channel consistency checks before engineers change FC gains or attribute instability to airframe defects. The extracted features provide an AI ready basis for anomaly classification and flight test health monitoring. Future work will refine hover interval selection, add synchronized video confirmation, include EKF innovation and raw GNSS observables where available, and repeat the comparison across different tether geometries, bracket materials, and antenna locations.

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