

유인 멀티로터 eVTOL의 시스템 통합 설계 및 단계적 계류 비행시험을 통한 성능 검증

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Staged Tethered Flight Testing and log-based Performance Validation of a Manned Multirotor eVTOL System

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Abstract : In a manned eVTOL platform, the propulsion, electrical power, and flight control subsystems interact closely enough that anomalies in one readily propagate to the others. This paper describes the system integration design of the VS-210, a manned quadrotor eVTOL prototype at 210 kg maximum takeoff weight (MTOW), and presents results from a staged hover test campaign structured as three sequential phases: ground integration testing, tethered hovering, and untethered hovering. Real-time flight log data—battery terminal voltage and current, attitude angles, IMU vibration index, and GNSS horizontal dilution of precision (HDop)—were examined before and after each corrective action. Three issues were encountered and resolved: GNSS signal degradation caused by electromagnetic interference (EMI) from the high-current ESC power bus, IMU noise from broadband structural vibration transmitted through the airframe, and transient battery voltage sag that approached the ESC under-voltage protection threshold during high-load hover. Wiring segregation, damping reinforcement at the IMU mount, and ESC current limit reassessment were applied in sequence, and the corresponding log metrics showed clear improvement in each case. The procedures and findings serve as a practical reference for teams conducting early integrated testing on manned eVTOL prototypes.

Key Words : Manned eVTOL, Multirotor, System Integration, Tethered Flight Testing, EMI Mitigation, Vibration Analysis

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I . Introduction

Electric vertical takeoff and landing (eVTOL) aircraft are considered a key platform for urban air mobility (UAM) because they can take off and land vertically without the mechanical complexity of conventional rotorcraft [1]. Among the various

configurations, the multirotor layout is particularly attractive for its structural simplicity and software-defined control, though it places the flight controller, power distribution network, and motor-ESC chain in continuous high-bandwidth interaction. Managing that interaction safely is straightforward in small unmanned platforms, where iterative outdoor testing is low risk. For a manned platform the threshold is

different: a power interruption or attitude estimation failure that would merely crash an unmanned vehicle can endanger a pilot, so each integration step must be validated before the next one begins [2].

The VS-210 is V-PACE's first manned multirotor prototype, configured as a quadrotor at 210 kg MTOW. Because no in-house predecessor existed, the integration test campaign was structured conservatively: ground testing first, then tethered hover, then free hover—with each phase gated on the results of the previous one. This paper documents what was identified during the tethered phase and how it was resolved. The three anomalies encountered—GNSS degradation from EMI, IMU noise from structural vibration, and battery voltage sag under high-load hover—are each treated with a before-and-after comparison of the relevant flight log metric.

II. System Design

The VS-210 uses four brushless DC motors driven by dedicated ESCs in a symmetric quadrotor configuration. The battery pack is assembled as 96 cells in series, single parallel (96S1P), with a total stored energy of 7.8 kWh and a nominal terminal voltage of approximately 355 V—consistent with the voltage traces recorded during hover testing (Fig. 4). The avionics suite includes a multi-constellation GNSS receiver, a three-axis IMU, a battery management system (BMS), a barometric altimeter, and an RC receiver.

From the outset of the integration build, ESC power cables were routed separately from the GNSS coaxial feed and avionics signal harness to limit conducted and radiated EMI coupling [3]. Vibration isolation pads were placed under the IMU mount to reduce mechanical noise from the rotor-motor assemblies [5]. Flight controller gains were set conservatively and adjusted iteratively based on log data from each session.

Table 1. Main Specifications of the VS-210

Item	Description
Model	VS-210
Type	Manned multirotor eVTOL
MTOW	210 kg
Battery System	96S 1P 7.8 kWh
Propulsion System	4 × BLDC motors + 4 × ESCs
Sensors	GNSS, Receiver, IMU, BMS, etc.



Fig. 1 VS-210

III. Method

Testing proceeded in three phases. Ground integration testing covered electrical compatibility, sensor initialization, and control software behavior with motors installed but not running at flight power. Tethered hover testing followed: the vehicle was anchored at multiple points with tethers sized to a defined tension limit, mechanically bounding vertical climb and lateral excursion independent of flight controller output. This constraint allowed anomalies to be identified and characterized without exposing the vehicle to unconstrained failure modes. The full tether configuration—anchor positions, attachment hardware, tether material, tension limit, and emergency abort procedures—will be documented in the final version of this paper. Untethered hover testing began only after all anomalies identified in the tethered phase had been resolved and verified through log review.

Throughout all phases, the flight controller

logged battery terminal voltage (V), pack current (A), roll and pitch attitude angles (deg), IMU vibration index (Vibe), and GNSS horizontal dilution of precision (HDop) at the native controller sample rate. Post-flight, segments corresponding to steady hover windows were extracted and compared across sessions before and after each corrective action.

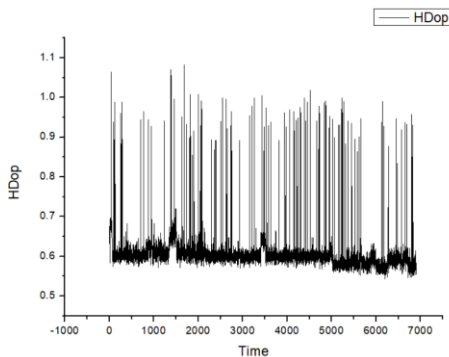
IV. Results and Discussion

Three anomalies were identified during the tethered hover campaign. Each is described below with the log evidence and the corrective action applied. Table 2 summarizes all three.

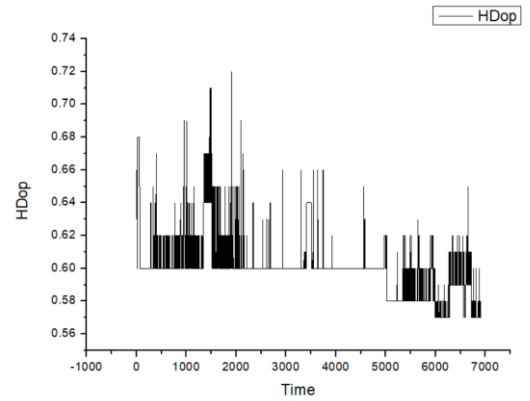
A. GNSS Degradation

During early tethered sessions, HDop spiked frequently to values near 1.1 while the motors were running at hover thrust (Fig. 2a). The spikes occurred consistently during periods of high current draw, which pointed to the ESC power cables as the interference source rather than the external RF environment. PWM switching noise from the ESC power stage is a known source of conducted and radiated EMI in multirotor platforms, and its coupling into GNSS coaxial feeds is sensitive to the physical proximity of the two harnesses [3].

The ESC power cables were re-routed to maintain physical separation from the GNSS feed and avionics signal bundle. After this change, HDop during comparable hover segments remained below approximately 0.74 (Fig. 2b), and the GPS-derived velocity estimates no longer showed the outlier bursts visible in earlier logs.



(a) Before wiring separation



(b) After wiring separation

Fig. 2 Comparison of GNSS Reception Quality before and after wiring separation

B. Vibration

The IMU vibration index peaked near 25 during hover (Fig. 3a), with broadband energy visible across the roll and pitch channels. At that amplitude, high-frequency content in the attitude estimate is large enough to degrade rate-loop performance, and can induce limit-cycle behavior if notch filter tuning does not account for the dominant excitation frequencies [5]. The rotor fundamental and its harmonics were the primary excitation source; the original IMU mount provided insufficient mechanical isolation.

Additional viscoelastic damping pads were installed at the IMU mount, and the rate-loop gains were reduced to lower the controller's sensitivity to residual high-frequency content. The vibration index subsequently peaked near 16 (Fig. 3b), and roll and pitch attitude traces showed noticeably less high-frequency noise. The amplitudes of the dominant excitation frequencies decreased, as observed in spectral inspection of the log data. Battery internal resistance variation under load was also examined as a potential secondary noise source, consistent with load-dependent discharge characterization methods reported for lithium-based cells [4].

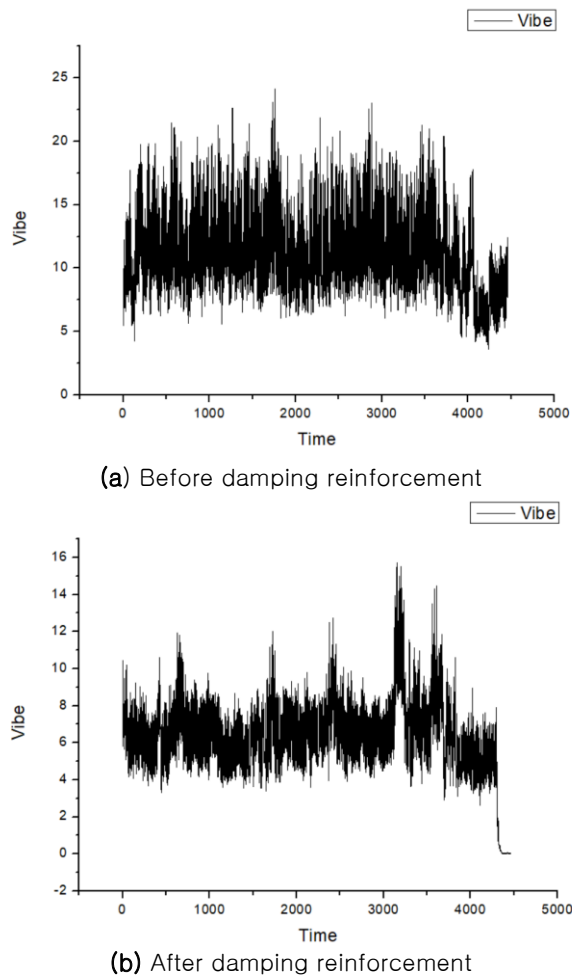


Fig. 3 Comparison of structural vibration measurements before and after damping reinforcement

C. Voltage Sag

During initial high-thrust hover segments, the battery terminal voltage dropped from a starting value near 395 V to approximately 350 V in response to current surges (Fig. 4a). The V-I profile in the log indicated that the pack was being operated near its maximum continuous discharge rate, leaving little margin above the ESC under-voltage protection threshold. For a manned platform, an ESC shutdown triggered by under-voltage during hover is a critical failure mode.

The ESC current limits were reassessed using V-I data extracted from the hover logs, applying load-dependent discharge characterization consistent with methods used for lithium-based cell state-of-health analysis [4]. More conservative current thresholds were

enforced, and the hover power setting was adjusted to maintain a defined voltage margin. Under the revised limits, terminal voltage during sustained hover remained stable and above the protection threshold (Fig. 4b), confirming safe operation within the revised envelope.

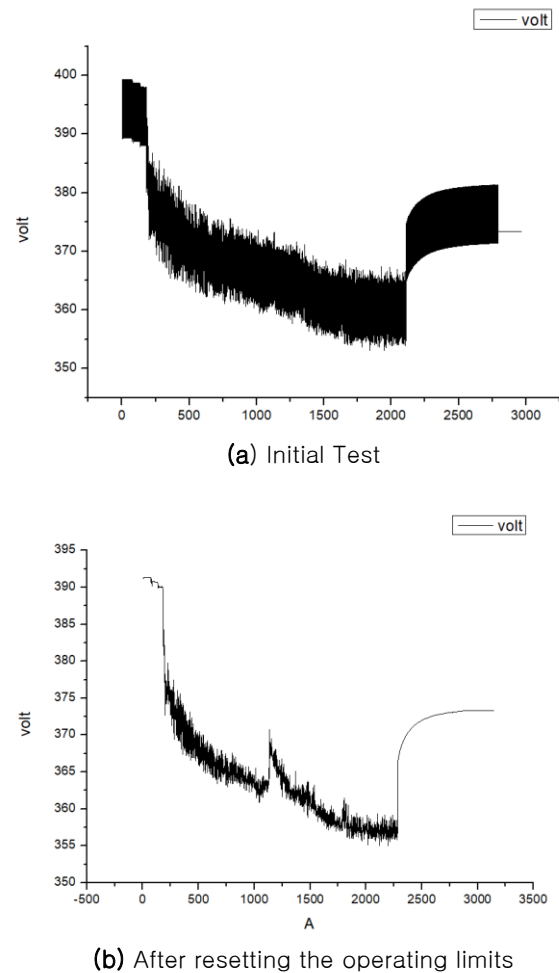


Fig. 4 Comparison of voltage variation during hovering before and after resetting the operating limits

Table 2. Summary of Issues and Improvement Effects

Issue	Log based	Corrective	Improvement
GPS noise	Increased position scatter and velocity outliers	Wiring separation	Reduction in outliers confirmed
Vibration	Increased roll, pitch amplitude and specific frequency components	Damping reinforcement, gain tuning	Reduction in amplitude observed
Voltage sag	Voltage drop during high current operation	Reassessment of operation limits and securing control margin	Voltage, current correlation identified and margin assessed


Fig. 5 Hovering after corrective actions

V. Conclusions

For the VS-210 manned multirotor eVTOL, a staged test campaign consisting of ground integration testing, tethered hovering, and untethered hovering was conducted to verify the basic performance of the integrated design. Three issues were identified and resolved during the tethered phase: EMI-induced GNSS degradation, IMU noise from structural vibration, and battery voltage sag under high-load hover. In each case, the hover-segment log metrics

showed clear improvement following the corrective action—wiring segregation, damping reinforcement with gain re-tuning, and operating limit reassessment, respectively.

The staged tethered approach proved effective at surfacing integration anomalies while keeping risk bounded. Anomalies that would have been harder to characterize and riskier to tolerate in free flight were identified and corrected while the vehicle's motion was mechanically constrained. Transitioning to untethered testing only after all issues had been log-verified provided a clear, defensible gating criterion.

Future work will focus on compiling quantitative metrics for each anomaly class—RMS vibration levels, HDop outlier rates, and voltage sag depth as functions of hover thrust setting—and on establishing a formal power margin budget that accounts for voltage sag across the expected range of operating conditions. Expanded free-flight testing will proceed once those metrics are in place.

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