

Vertical Motion Simulator Handling Qualities Testing of a Piloted eVTOL Vehicle Having a Degraded Powertrain

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ABSTRACT

This paper presents handling qualities (HQs) research findings for electrical Vertical Take-off and Landing vehicles. Testing in the Vertical Motion Simulator (VMS) investigated handling qualities of vehicle configurations having a degraded powertrain. Powertrain components, including batteries and electric motors, can degrade as the vehicle is flown. This paper investigates the impact of low battery charge and high motor temperature degradations on the pilot's ability to execute precise maneuvers. Pilot comments and ratings that were collected from four rotorcraft test pilots in VMS testing are used to quantify the effects that powertrain degradations had on the HQs of the vehicle.

NOTATION

AC	Alternating Current
ACAH	Attitude Command Attitude Hold
Amp	Ampere
A_L	Lateral/Longitudinal Axes Pilot Aggressiveness
A_V	Vertical Axis Pilot Aggressiveness
C	Celsius
Cmd	Command
deg	Degrees
eVTOL	Electric Vertical Takeoff and Landing
EMF	Electromotive Force
ft	Feet, Foot
fps	Feet Per Second
ft*lb	Foot Pounds
FW	Flux Weakening
FW_e	Flux Weakening Engaged Percentage
HQs	Handling Qualities
HQRs	Handling Qualities Ratings
IC	Initial Condition
I_d	Magnetizing Axis Current
I_q	Torque Axis Current
I_{NFW}	Current Command Before Flux Weakening Control
k_t	Motor Torque Constant
LPC	Lift-Plus-Cruise
L_d	Motor D-Axis Rotor Self-Inductance
L_q	Motor Q-Axis Rotor Self-Inductance
MCT	Max Continuous Torque
MTE	Mission Task Element Motor Pole Pairs
NASA	National Aeronautics and Space Administration
NFW	No Flux Weakening
Nm	Newton Meters
PMSM	Permanent Magnet Synchronous Motors
PIO	Pilot-Induced Oscillation
rad	Radians
RPM	Revolutions Per Minute
SOC	State of Charge
TCL	Thrust Control Lever

TRC	Translational Rate Command
UAM	Urban Air Mobility
V	Voltage
VMS	Vertical Motion Simulator
α_c	Current Angle
λ	Motor Flux Linkage
u_f	Flux Weakening Control Current Scaling Factor
P	Motor Power
τ_e	Motor Electromagnetic Torque
τ_s	Motor Shaft Torque
ω	Motor Shaft Speed

INTRODUCTION

Research is under way to advance electric vertical takeoff and landing (eVTOL) rotorcraft vehicles for use in urban locations. The National Aeronautics and Space Administration (NASA) is investigating design technologies that will provide new travel and transport options. The new travel options will comply with the Urban Air Mobility (UAM) mission and will focus on safety and comfort. Rotorcraft designs should be robust to disturbances, maneuver loads, rotor vibration, cabin noise, and degraded actuation.

This paper focuses on the effects that degraded powertrain configurations have on the pilot's ability to precisely execute a maneuver, also known as handling qualities (HQs). The simulated powertrains under investigation include but are not limited to battery models, thermal models, and electric rotor and stator models. To investigate HQs, a data set was collected in the Vertical Motion Simulator (VMS) located at the NASA Ames Research Center (ARC) (Moffett Field, California) in 2022. This data set has yielded research into HQs for different eVTOL reference vehicle designs with different test configurations, some of which has been previously published (Refs. 1-4). This collection of data is referred to as VMS Test 1. This paper focuses on the Lift-Plus-Cruise (LPC) concept vehicle shown in Figure 1 because it was flown with a mid-fidelity powertrain model. A mid-

fidelity powertrain model is a physics-based model that incorporates detailed equations to represent an actual motor. The amount of detail represented by these equations allows researchers to investigate low battery charge and high temperature motor degradation that would be unavailable in a model of lower fidelity. The detail of these equations – and therefore the accuracy of the powertrain – comes at the expense of computation speed. Details pertaining to the architecture of the mid-fidelity powertrain are described in depth in a companion paper (Ref. 5). The effects of the mid-fidelity powertrain on LPC handling qualities are planned to be investigated during a Vertical Maneuver mission task element (MTE) and Hover Maneuver MTE as described in Ref. 5.

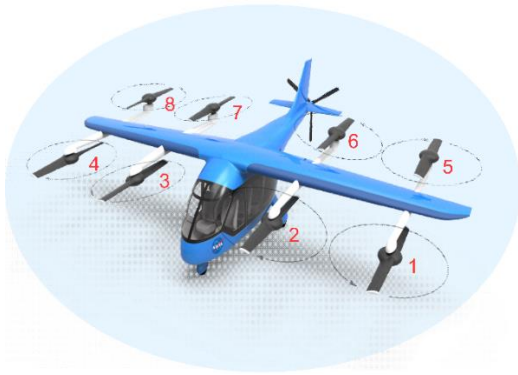


Figure 1. Lift-Plus-Cruise (LPC) Concept Vehicle.

This paper describes the VMS Test 1 setup including the test facility and the test point matrix, followed by a description of the methodology used to implement two degraded configurations into the LPC vehicle powertrain: low State of Charge (SOC) batteries; and high motor coolant temperatures. The effects of powertrain degradation on vehicle dynamics are illustrated using the data collected during VMS Test 1. A comparison is made between the degraded configurations and a baseline healthy aircraft to highlight the effects of powertrain degradation on handling qualities. Handling qualities findings are presented in the form of pilot ratings, pilot comments, and other HQs metrics. Conclusions gathered from VMS Test 1 are summarized at the end of the paper.

VMS Test 1 Setup

Vertical Motion Simulator Test 1 investigated pilot HQs of several NASA UAM reference vehicles. The VMS was equipped with instruments, displays, and inceptors for pilots to perform VMS Test 1 MTEs. More information on the VMS Test 1 setup is found in Ref. 6. Eight test pilots flew different configurations of the RVL T Quadcopter, Hexacopter, and LPC reference designs. Each configuration consisted of a unique combination of flight control laws, control modes, powertrain degradations, and disturbances.

The VMS Facility

The VMS facility at ARC creates a realistic flight experience within a simulation setting. The VMS shown in Figure 2 is integrated with a motion platform that is operated with powerful motors and hydraulic actuators. The platform is set

within a 60-ft (vertical) by 40-ft (horizontal) room that allows for a large range of motion to accurately mimic the feeling of aircraft flight rates and accelerations. The interior of the simulation is dependent on the cab being used. The simulator cabs are configurable based on the application being tested in the VMS. Within these cabs are representative instrument panels and flight instrument controls. More detailed information about the VMS facility and capabilities is found in Ref. 7. The pilot displays and out-of-window visuals that were integrated into the simulation cab for VMS Test 1 are shown in Figure 3 to portray what the pilots see while performing an aircraft maneuver in the cab. The VMS Test 1 facility setup is described in more detail in Ref. 6.



Figure 2. Vertical Motion Simulator (VMS) Cab and Actuator System Located at NASA Ames (Ref. 8).



Figure 3. Inside the Piloting Cab of the Vertical Motion Simulator (VMS).

The capability for motion within this simulation is critical for the evaluation of handling qualities. HQs depend heavily on pilot perception of the vehicle responses to commands. The vehicle visuals are coupled with vehicle motion to provide the pilots with perception feedback to the vehicle response to their commands.

LPC Vehicle Description and VMS Test Points

The LPC vehicle illustrated in Figure 1 has eight lifting rotors that are fixed pitch and variable speed. In low translational speeds below 30 fps and in hover, most of the vehicle lift comes from these rotors. In high-speed forward flight above 30 fps, the aircraft transitions to wing-borne flight with a pusher propeller for thrust. Thirty fps is used as the speed transition value because the LPC low speed control mode, Translational Rate Command (TRC), can command a maximum vehicle rate of 20 fps. During VMS Test 1, testing was completed in low speed/hover conditions, putting more

emphasis on the lifting rotors and their corresponding powertrains.

The LPC test points that are investigated in this paper are shown in Table 1. These configurations are of interest because they tax the motors by operating at high torque settings. Four rotorcraft test pilots made HQs evaluations of the LPC in the VMS with two types of powertrain degradation implemented using a mid-fidelity powertrain model: low SOC batteries and high temperature motors.

Table 1. LPC Test Matrix for VMS Test 1.

Degradation	MTE	Control Mode	Disturbance
None	Vertical	ACAH	Off
Low SOC	Hover		On
High Temp.			

The Vertical Maneuver and Hover Maneuver MTEs are described in ADS-33E-PRF (Ref. 9). The Attitude Command Attitude Hold (ACAH) control mode was used for these MTEs. In ACAH, the pilot directly commands vehicle pitch and roll angles with stick inputs. Disturbances during MTEs were either on or off. When on, the vehicle experienced a prerecorded turbulence profile in all axes.

VEHICLE RESPONSE TO POWERTRAIN DEGREDDATION

Mission task elements were evaluated both with and without degraded powertrains. When the degraded powertrain models were active, all eight of the lifting rotors were affected. In the low SOC battery degradation, the batteries for each of the eight lifting rotors were reduced to 20 percent of their full capacity. The high temperature configuration increased the motor coolant temperature for all eight of the lifting rotors

from the nominal value of 60 °C (140 °F) to 130 °C (266 °F), simulating a systemic coolant failure.

Low SOC Battery Effect on Vehicle

When battery SOC is reduced, the available battery voltage is commensurately reduced according to the battery voltage and charge relationship, shown in Figure 4. Initial battery voltages are shown for a healthy vehicle and a degraded low SOC vehicle. This voltage curve is generated using the mid-fidelity powertrain model (see powertrain architecture in Figure 5), with battery parameters that were generated using the NASA Design and Analysis of Rotorcraft (NDARC) software. An explanation of the battery and thermal modeling is found in a companion paper (Ref. 5).

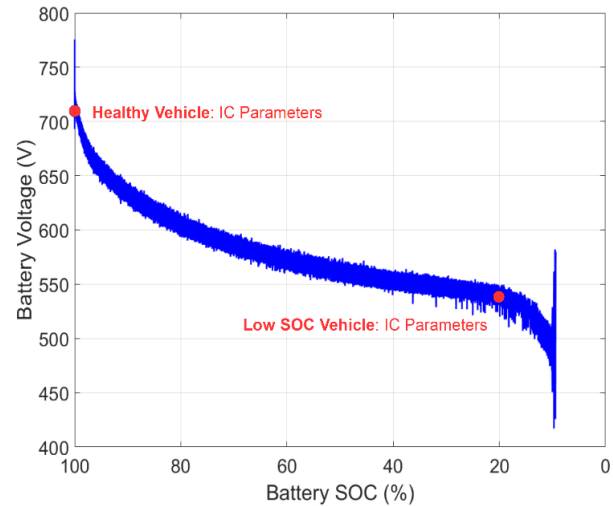


Figure 4. LPC Battery Voltage Curve Using the Mid-Fidelity Powertrain Model.

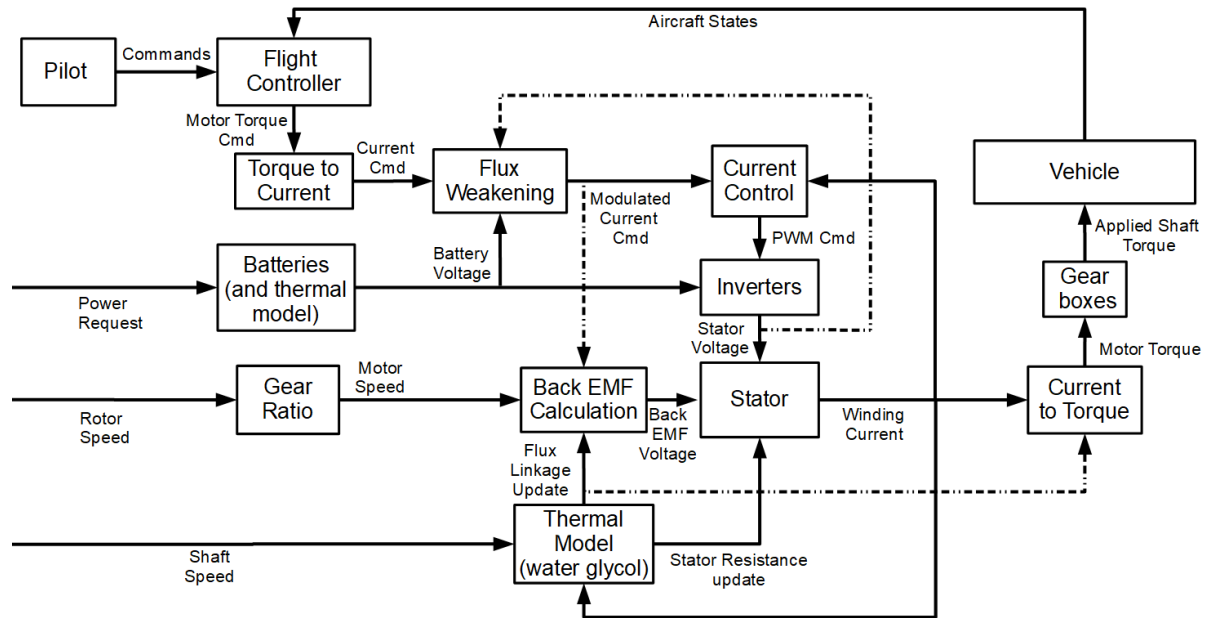


Figure 5. Mid-fidelity Powertrain Architecture within the LPC Vehicle Simulation.

A healthy powertrain configuration initializes battery SOC to 100 percent, providing the powertrain with the highest available battery voltage to ensure adequate battery voltage for the duration of an MTE. A low SOC powertrain configuration initializes battery SOC at 20 percent, providing the powertrain with a lower available battery voltage. A vehicle operating at or below 20 percent of battery SOC will have little remaining flight time as the available battery voltage approaches a drop-off that occurs at approximately 0-15 percent battery SOC. The vehicle battery drains rapidly at this drop-off; thus, at this point pilots can begin to lose vehicle control authority.

Extremely taxing vehicle maneuvers that require high torque will drain the batteries faster, restricting pilots to low-rate inputs to avoid reaching dynamic motor voltage limits. When motor voltage saturates, the available battery voltage is insufficient to provide the torques to meet pilot commands. The ratio of required to available battery voltage is “Percent of Battery Voltage Limit” plotted in Figure 6(a). Figure 6(a) shows a comparison of the average voltage limit across all eight lifting motors during a Vertical Maneuver MTE for a healthy vehicle and for a vehicle with low SOC. Every control input by the pilot causes a current to be drawn through the motor stator component. If the percent of battery voltage limit reaches one hundred percent, additional current can’t be drawn through the motor; see Figure 6(b). Motor current is proportional to the output motor torque, so limiting additional current will limit additional torque.

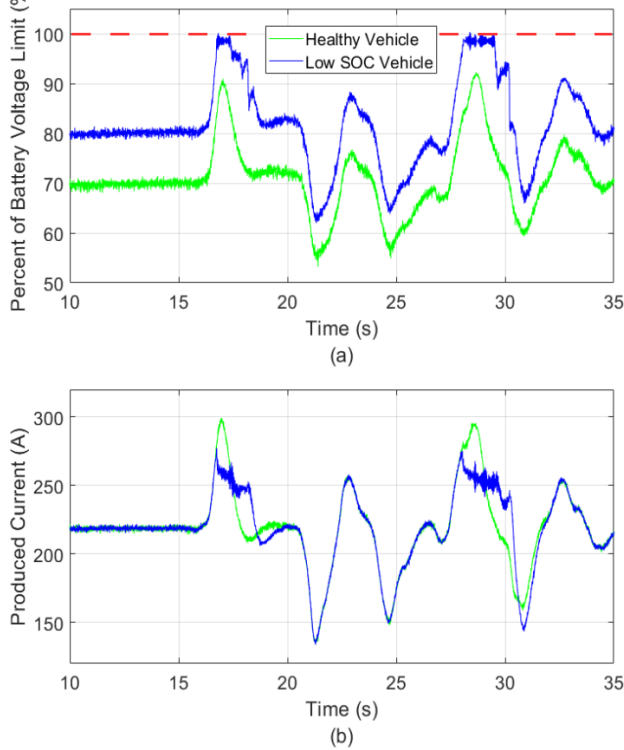


Figure 6. Healthy and Low SOC Vehicle Comparison During Vertical Maneuver MTE: (a) Voltage Limit; and (b) Produced Current.

To mitigate the amount of current/torque limiting that takes place when voltage saturates, a control method called flux

weakening (FW) control is implemented. Flux weakening control is a control law that engages right before voltage saturation occurs to gradually reduce current requirement or current command. Flux weakening control changes the initial current command into a modulated current command (see Figure 6) that prevents voltage saturation from occurring. Figure 7 displays a motor map that shows the benefit to a motor with FW control versus a motor with no flux weakening (NFW) control.

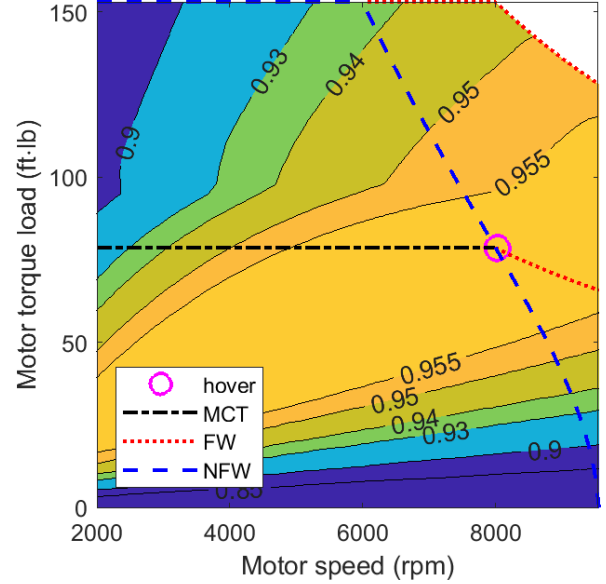


Figure 7. Motor Torque vs. Speed Map Comparing Flux Weakening Control: On (FW); and Off (NFW) (Ref. 5).

The motor map drawn with lines of constant motor efficiency in Figure 7 illustrates two different configurations: (1) a powertrain with NFW; and (2) the powertrain with FW that was implemented in VMS Test 1. The NFW configuration represents the powertrain in its baseline configuration evaluated at the rated voltage of the motor. The FW powertrain used in VMS Test 1 assumed that battery voltage was larger than the rated voltage of the powertrain, allowing for the motor base speed to shift right and ultimately allow for higher rated peak torque loads (approximately 150 ft·lb) at higher motor speeds.

Flux weakening powertrain motors that begin to approach motor speeds to the right of the hover point during an MTE enter what is called the constant power region or the flux weakening region. At higher speeds, the allowable motor torque must decrease to maintain constant power according to Eq. 1. In this region the envelope for rated motor torque loads begins to narrow, restricting the peak torques that motors can achieve during an MTE.

$$P = \tau_s \omega \quad (\text{Eq. 1})$$

The FW configuration assumes the constant power relationship in Eq. 1, while the NFW configuration does not. The two powertrain configurations therefore exhibit different torque reduction rates as speed increases from their respectively different base speeds. The FW powertrain

reduces torque authority in a gradual manner; the NFW powertrain loses torque authority very suddenly. Pilots who participated in VMS Test 1 benefitted from FW control and a larger battery because they were provided more torque to preform MTEs when motors were operating in the FW region. The NFW torque curve illustrates that motors that operate without FW control are limited to operating with lower torque margins than an FW powertrain.

During VMS Test 1, the LPC vehicle motors initialized at the hover torque and speed condition indicated in the Figure 7 motor map. The motor torque and speed initially reside on the Max Continuous Torque (MCT) line at the motor's rated efficiency of 96 percent. As an MTE is performed, torque or speed control command requests cause motor operating conditions to change, moving the motor torque and speed location around on the motor map and leading to higher or lower torque margins.

Flux weakening control affects a gradual reduction in torque in the FW curve in Figure 7 by mitigating the effect of back-electromotive force (EMF) voltage. Back-EMF voltage opposes the battery voltage that is pushing current through the motor. At high motor speeds, back-EMF increases and drives motors toward voltage saturation, restricting current flow and, therefore, motor torque. Flux weakening control is used in permanent magnet synchronous motors (PMSMs) to reduce the effect of back-EMF voltage by reducing the magnetic flux. The strength of the magnetic flux is affected by magnetizing axis current (i_d) in the direct-quadrature (DQ) axis of the PMSM. When flux weakening control is engaged, some of the current command from the flight controller; (see Figure 5); is dedicated to producing negative i_d , instead of positive torque axis current (i_q) in the DQ axis of the PMSM. The reduction in i_q is necessary to maintain constant current magnitude and avoid violating the PMSM i_d . More information on flux weakening control modeling is found in a companion paper (Ref. 5).

High Temperature Motor Effect on Vehicle

The high temperature degradation implemented in VMS Test 1 resulted in similar effects to the low SOC degraded LPC vehicle. When motor temperatures are elevated, motor voltages are pushed toward saturation. The sequence leading to voltage saturation differs, however, from the low SOC degradation. High temperature motors adjust motor constants to reduce the motor torque output while the low SOC batteries restrict motor torque output according to the available battery voltage. Motor constants that change during high temperature motor degradation are shown in Table 2.

Table 2. Temperature Model Constants and Values.

Vehicle Condition	Torque Constant $\frac{Nm}{Amp}$	Stator Resistance $ohms$	Flux Linkage $\frac{V}{rad/s}$
Healthy/Nominal	0.445	0.0196	0.0495
Low SOC	0.456	0.0182	0.0507
High Temp.	0.402	0.0243	0.0447

When motor temperatures increase, the contributing variables that are changing are flux linkage (λ) and stator resistance. Flux linkage is the magnetic flux that passes through a motor coil while stator resistance is the electrical resistance of the copper windings located in the motor stator. These variables are outputs of the thermal model simulated within the mid-fidelity powertrain, Figure 5. These variables directly affect the stator winding current, the back-EMF voltage, and the torque constant (k_t), which ultimately can influence the output motor torque.

Though there is approximately a 24-percent increase in the stator resistance from both the healthy and low SOC LPC vehicle configurations, this parameter contributes more to the alternating current (AC) frequency than to the decrease in output torque. The main thermal model contribution to decreasing the motor torque is the flux linkage. The flux linkage constant within the simulation decreases by approximately 12 percent from the other vehicle configurations, resulting in a 12-percent decrease in the high temperature motor torque constant. The relationship between flux linkage and torque constant are shown in Equation 2. The torque constant defines the relationship between the motor current and its corresponding torque output represented with units Nm divided by Amps. The consequence of a lower torque constant is reduction of the torque output for a given motor current input (see Equation 3).

$$k_t = 1.5\lambda n_p + i_d(L_d - L_q) \quad (\text{Eq. 2})$$

$$\tau_e = i_q k_t \quad (\text{Eq. 3})$$

A notional comparison between current-to-torque relationship for different LPC vehicle configurations is shown in Figure 8.

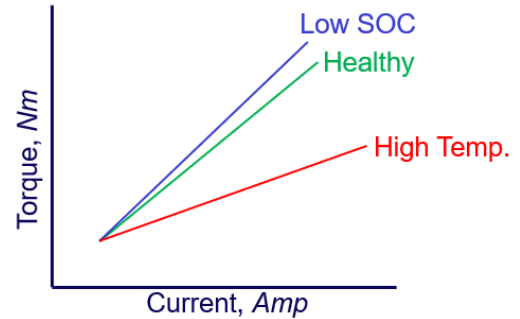


Figure 8. Notional Torque Output vs. Current Input Relationship for LPC Vehicle Configurations.

A vehicle with a lower torque constant requires an increased current to operate at the desired motor torque. The high temperature configuration is similar to the low SOC configuration in that the torque command from the vehicle flight controller compensates to maintain the pilot's desired vehicle response. Simulation time-history data including high temperature configuration torque command compensation are shown in Figure 9. The degraded configuration is compared to a healthy configuration, and both are injected with the same commands for a comparison of flight controller commands.

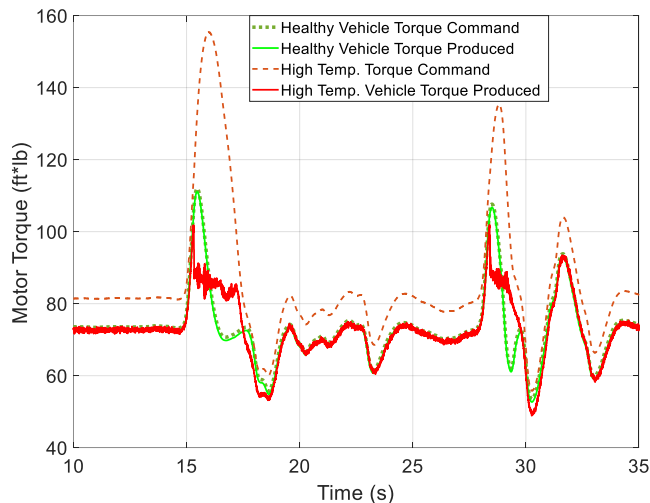


Figure 9. Vertical Maneuver Motor Torque Response to Healthy and to High Temperature Configurations.

For the high temperature configuration, the torque being commanded into the system does not match the torque being produced by the motor. The flight controller responds with a large torque command to compensate for the lower torque achieved due to the low torque constant. When an intensive torque is commanded by the flight controller or pilot, the command becomes too large for the battery voltage source to drive the required current, and voltage saturation occurs. Flux weakening control will then engage in order to gradually decrease the command to a magnitude that can be driven by the battery voltage source.

Low SOC Battery VMS Test 1 Data

The low SOC degradation drove the motors to voltage saturation in VMS Test 1. Multiple pilots operating a degraded low SOC vehicle commented on the “sluggish” or delayed response of the vehicle to their commands. Delayed vehicle response occurred when pilot commands requested torque margins that were unavailable due to voltage saturation. Simulation time-history data for an ADS-33 Vertical Maneuver task are shown in Figure 10. In these data sets, a single vertical rate command input from a VMS Test 1 run is injected into both a healthy and low SOC LPC vehicle. A difference in response is evident in Figure 10(a) between these vehicle configurations, where the low SOC configuration appears to have a slower response in the vertical axis to the injected vertical rate command.

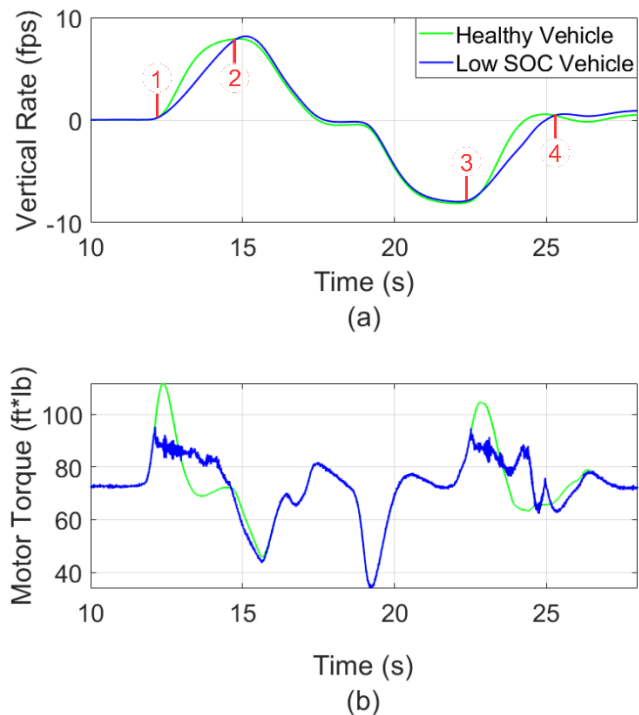


Figure 10. Healthy and Low SOC Vehicle Response to Single Vertical Rate Command: (a) Vertical Rate Response; and (b) Motor Torque.

The slower response for the low SOC vehicle is due to limited motor torque - the LPC vehicle motors cannot produce the torque that is being commanded into the system. When the produced torque is no longer able to keep up with the commanded torque, the low SOC vehicle vertical rate response begins to diverge from a healthy vehicle response. Locations one and two in Figure 10(a) indicate the beginning and end of torque saturation at the beginning of the simulation run. Torque saturation prevents the vehicle from achieving healthy vehicle response for approximately two seconds before the torques and vehicle responses reconverge. The same is evident between points three and four later in the simulation run, where the vehicle responses reconverge after approximately three seconds.

Torque saturation and slow vehicle response is an indication that motor voltage has saturated, and FW control has engaged. The motor torque output will no longer increase, nevertheless, the flight controller will attempt to compensate for slow vehicle behavior by increasing the torque request (it is not communicated to the flight controller that motor torque is unable to increase due to motor voltage saturation). The flight controller only computes the torque command required to meet the command from the pilot, even at the expense of saturating the motor voltage.

Miscommunication between motor torque command and torque response can result in a pilot-induced oscillation (PIO) as the flight controller or the pilot overcompensate for the unexpected lack of vehicle torque response. Pilot-induced oscillations occur when the pilot inadvertently commands a series of overcorrections into the vehicle which become out of phase with the vehicle response. The result is often an

uncommanded increasing oscillation in one or more axes, sometimes leading to Loss of Control (LOC). An occurrence of PIO and eventual LOC from VMS Test 1 can be seen in Figure 11. This time-history data set shows Pilot B performing a Hover Maneuver MTE.

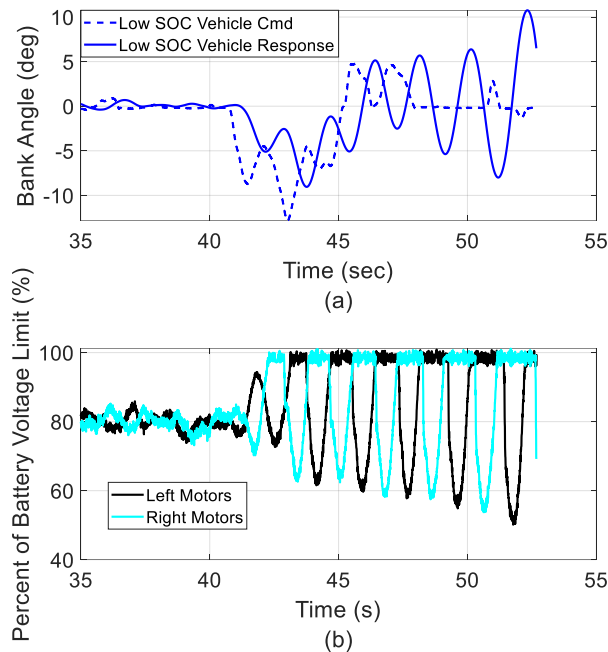


Figure 11. Roll Angle PIO During Hover Maneuver/ Pilot B: (a) Roll Angle; and (b) Battery Voltage Limit Percentage.

Pilot-induced oscillation takes place in the lateral axis, as is evident when examining the oscillating roll angle at the end of the maneuver in Figure 11(a). The roll angle fails to follow the pilot commands, resulting in an out-of-phase response. The vehicle response begins to diverge from the pilot command when the motors start to saturate, alternating between saturation in the left motors and the right motors; see Figure 11(b). The left and the right motors are numbered in Figure 1, where motors one, two, five, and six are the left motors, and motors three, four, seven, and eight are the right motors. The sequence of motor saturations causes the vehicle to go unstable, resulting in LOC in the lateral and vertical axes.

Unexpected vehicle responses to vehicle inputs were common in VMS Test 1 for degraded LPC vehicle configurations. Low SOC batteries tended to cause the vehicle to experience either PIO or undesirable cross-axis coupling. During the Vertical Maneuver MTE, Pilot A experienced coupling between the pitch and roll axes in response to vertical rate commands shown in Figure 12.

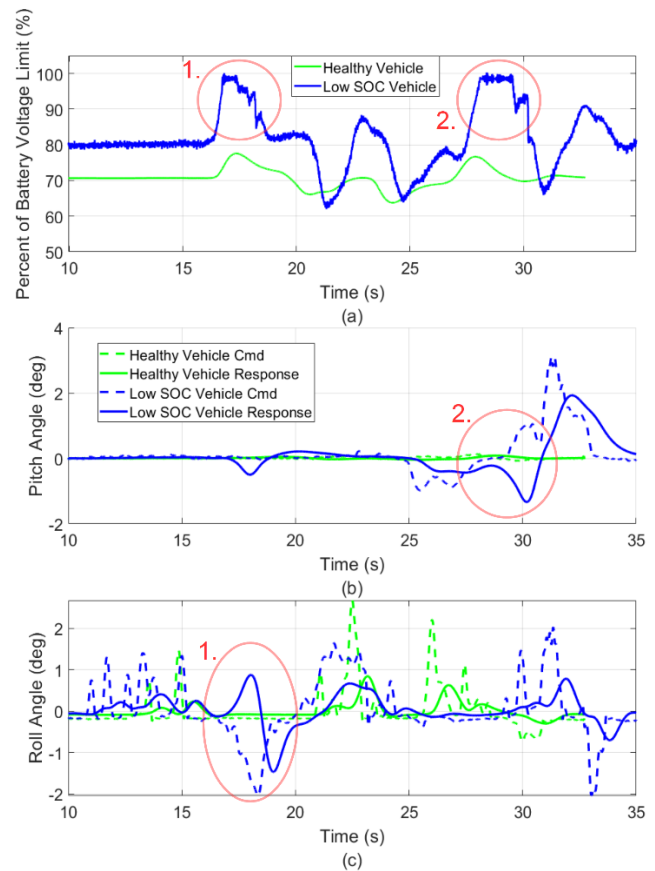


Figure 12. Axis Coupling at Locations Indicated by Red Circles During Vertical Maneuver/ Pilot A: (a) Battery Voltage Limit Percentage; (b) Pitch Angle; and (c) Roll Angle

The first saturation, at approximately 17 s, and highlighted in Figure 12 by the #1 circle, results in an unexpected roll angle coupling that the pilot attempts to counter with an opposing roll command. The second saturation, at approximately 28 s and highlighted in Figure 12 by the #2 circle, doesn't affect the roll angle, but instead produces a pitch excursion that requires correction. In the Vertical Maneuver, pilots use the vertical rate inceptor to control the vertical rate of the vehicle. A quick upward vertical rate command (large acceleration) was taxing on the vehicle motors and often resulted in motor voltage saturation. Whether pitch coupling or roll coupling takes place is a function of which motors saturate and in what sequence.

Pilots who operated the LPC vehicle with a low SOC degradation commented on the operation of the degraded vehicle:

Pilot A	"It was almost like I was getting a low predictability response." (Low SOC / Vertical MTE)
Pilot B	"More alternating (commands) at the bottom... I did start to see a little loss of control at the bottom." (Low SOC / Vertical MTE)
Pilot C	"Had to be as smooth as I could with power and try to anticipate power changes for the reversals." (Low SOC / Vertical MTE)

Many of the comments given by the pilots make mention of having difficulty controlling the vehicle with the low SOC. Even when acknowledging the need to adapt their technique to avoid PIO, executing the task still resulted in “low predictability response,” “loss of control,” and having to “anticipate power changes.” These comments verify that reduction in torque had a direct effect on the pilot’s perception of the ability of the vehicle to perform the desired task.

High Temperature Motor VMS Test 1 Data

For VMS Test 1, the effects of high temperature degradations were experienced during the critical subphases of the MTEs. At the end of the evaluation runs for a given task, the pilots were asked to identify a critical subphase portion of the MTE. Pilots identified the critical subphase portion of the MTE based on the section of the MTE that exhibited a high level of pilot performance to perform the task. The critical subphase for the Vertical Maneuver was identified by all the pilots as the deceleration to capture the lower position at the end of the task. The critical subphase for the Hover Maneuver was the deceleration to capture the hover position. These portions of the maneuvers proved the most difficult to pilots according to comments and ratings. The primary contributor to the difficulties was voltage saturation even though FW control was engaging to mitigate the consequences on handling qualities.

To quantify when voltage saturation was occurring during an MTE, the FW scaling factor u_f was measured. This scaling factor is used to reduce the torque current request, i_q . The more that u_f decreases, the more drastic of a reduction in i_q to prevent voltage saturation. This relationship is depicted in Equation 4, where the current prior to FW modulation is i_{NFW} .

$$\alpha_c = \text{atan2}(i_{NFW}, 0) \quad (\text{Eq. 4})$$

α_c is the current angle that is simulated within the LPC vehicle model using the MATLAB (The MathWorks, Inc., Natick, Massachusetts, U.S.A.) function, atan2 . This function returns the four-quadrant inverse tangent of i_{NFW} and the d-axis current assumed to be zero. The current angle α_c and u_f are used to compute the modulated i_q current command using Equation 5. The use of π within the equation is used to account for cases of negative and positive currents.

$$i_q = \sin(\pi - u_f * [\pi - \alpha_c]) \quad (\text{Eq. 5})$$

During the Vertical Maneuver MTE in VMS Test 1 with a high temperature configuration, u_f was seen reducing the current multiple times throughout the maneuver. Flux weakening control was engaged primarily at the beginning of the task and at the critical subphase. Figure 13 shows a number of pilot runs that exhibited a need for FW control to mitigate voltage saturation.

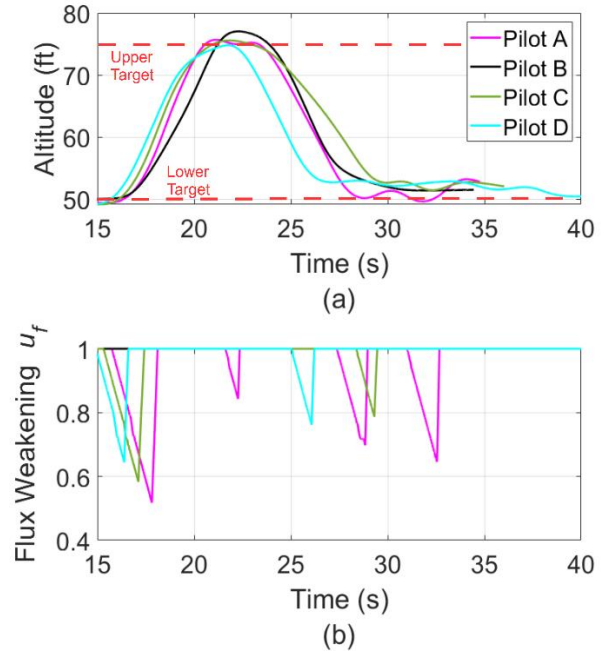


Figure 13. Pilot Altitude and Corresponding u_f Comparison for Vertical Maneuver / All Pilots: (a) Altitude with Upper and Lower Targets; and (b) Flux Weakening Scaling factor, u_f .

The beginning of the task required involvement from FW control due to voltage saturation, resulting in large decreases in u_f . The critical subphase for the Vertical Maneuver began at approximately 25 s to 30 s and required less FW control involvement. Pilots identified the deceleration to the lower target as the critical subphase of the MTE, however, because this portion of the task requires high precision that is not required at the beginning of the task. The ADS-33E-PRF does not give precision criteria for the lateral, longitudinal, and altitude positions at the initial climb to the upper target - only at the targets themselves. Low voltage saturation at high precision parts of the Vertical Maneuver MTE appears to have affected pilot performance more than high voltage saturation at a low precision parts of the MTE.

Precise position keeping became more difficult when motor saturation occurred because this state could result in cross coupling in the lateral and longitudinal axis, and oscillations in the vertical axis. The pilots who required FW control to mitigate voltage saturation experienced oscillations after the critical subphase of the Vertical Maneuver task (Figure 13). Pilot B avoided engaging FW by commanding deceleration to the lower target at a slower rate.

Pilot A	"I started pretty aggressive but started watching the rate of thrust command get 'mushy.'" (High Temp. / Vertical MTE)
Pilot B	"If you kept inputs in every two-to-three seconds you stay within the desired bounds... If you started getting aggressive with collective (vertical rate), the attitude would start breaking free" (High Temp. / Vertical MTE)

Pilot C	<i>"I could not stay out of the loop, I had to make small pulse inputs to correct drift tendencies." (High Temp. / Vertical MTE)</i>
Pilot D	<i>"Definite heave to pitch coupling...so had to compensate for that. On the recovery (it) was definitely prone to PIO. It was a function of TCL input and rate of decent." (High Temp. / Vertical MTE)</i>

Pilots commented on the need for "perturbations" or "corrections" into the system to perform the Vertical Maneuver. The need for more command inputs due to voltage saturations means that the task is requiring higher pilot inceptor workload. A comparison between Pilot A and Pilot B (Figure 14) shows the different stick trace commands due to voltage saturation that engages FW control.

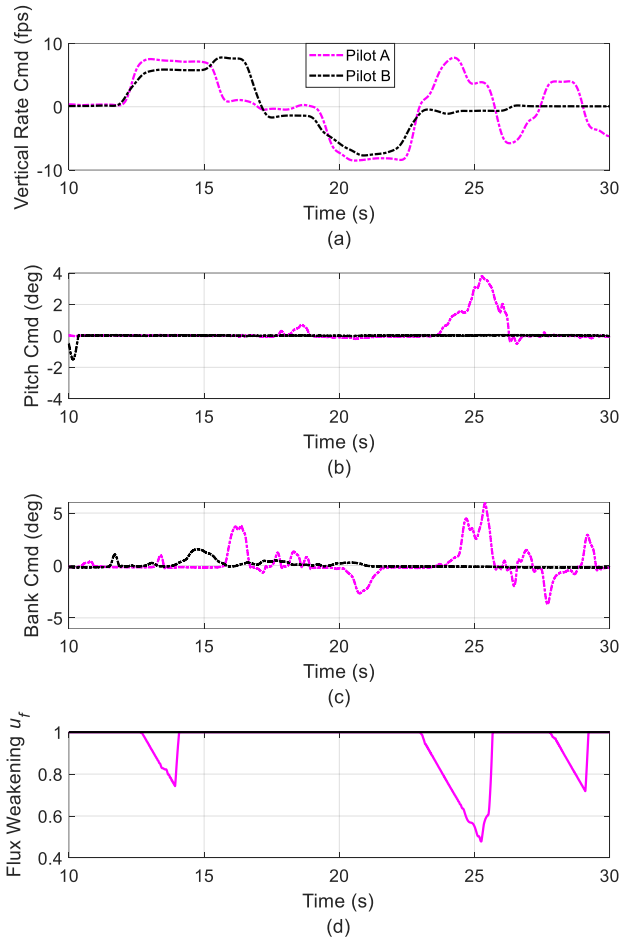


Figure 14. Pilot Stick Tracing Comparison for Vertical Maneuver / Pilot A and Pilot B: (a) Vertical Rate Stick Command; (b) Pitch Stick Command; (c) Roll Stick Command; and (d) Flux Weakening Scaling Factor, u_f .

Figures 14(a), 14(b), and 14(c) show large amplitude stick tracings for Pilot A at approximately 25 s. Figure 14(d) illustrates that Pilot A engaged FW control, making the vehicle prone to cross-axis coupling and vertical axis oscillations that required large amplitude inceptor corrections from the pilot. Vertical axis oscillations at the end of the time-

history data indicates there was difficulty in capturing the altitude at the lower target during the Vertical Maneuver MTE. Figure 14(d) illustrates that Pilot B avoided FW control mitigation during their evaluation run. The result was very minimal stick movement in the vertical, pitch, and roll axes (Figure 14(a), 14(b), and 14(c)).

HANDLING QUALITIES RATINGS AND METRICS

Handling Qualities Ratings (HQRs) were collected using the Cooper-Harper Rating Scale (Ref. 10). In addition to nominal Cooper-Harper Rating selections, pilots were alternatively provided the option to select a 4.5 HQR. This rating indicated that "desired performance required considerable pilot compensation." The HQRs shown in Figure 15 are for a Vertical Maneuver MTE and a Hover Maneuver MTE with turbulence. Level One HQRs indicate that no vehicle improvement is needed, Level Two HQRs indicate that vehicle deficiencies warrant improvement, and Level Three HQRs indicate that vehicle deficiencies require improvement (Ref. 10). The spread of HQRs displays a pattern of degraded vehicle configurations generally having worse HQRs (higher ratings) than a nominal healthy vehicle configuration.

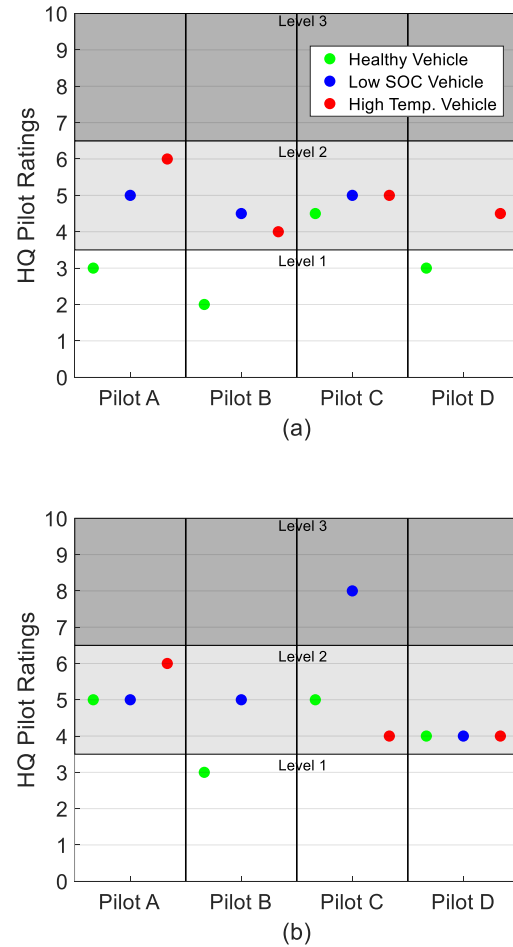


Figure 15. Handling Qualities Ratings: (a) Vertical Maneuver MTE; and (b) Hover Maneuver MTE with Turbulence.

Pilot stick commands and comments indicate that HQs for the LPC vehicle were worse for the degraded vehicle configurations due to higher pilot workload, axis coupling, and sluggish vehicle response. The HQRs between the low SOC and high temperature degradation do not yield major differences even though pilots commented on feeling a difference in vehicle response between the two configurations.

A biproduct of voltage saturation was pilots having to deviate from their preferred piloting technique. A large grouping of pilot ratings and comments indicated the need to alter their input aggressiveness and duty cycle. Figure 16 compares the differences in aggressiveness and duty cycle techniques that were used between the different vehicle configurations. Aggressiveness is defined in the context of this paper as the measure of dynamic control deflection which is recorded as a time-averaged summation of pilot inceptor inputs during the maneuver. Duty cycle is defined as the frequency with which the pilot is making significant adjustment to their inputs. More information on the definition and computation of aggressiveness and duty cycle is found in Ref. 11. The calculated values in Figure 16 for aggressiveness use a low-pass filter frequency of 0.001 rad/s for both the vertical and the lateral/longitudinal axes. The duty cycle calculation for the same axes uses a sensitivity value of 0.01 to determine the threshold for defining a significant adjustment to an input.

The measurement of aggressiveness and duty cycle for the Vertical Maneuver MTE in Figure 16(a) illustrates that pilots generally reduced their stick aggressiveness for degraded vehicle configurations in the vertical axis commands. When flying degraded vehicles prone to voltage saturation, Pilots A, B, and C all generally reduced their aggressiveness from what they had exhibited with a healthy configuration. Pilot B and Pilot D generally did not reduce their vertical axis stick aggressiveness for the high temperature powertrain configuration. The result is that the corresponding lateral axis stick aggressiveness appears to increase as a product of axis cross-coupling due to voltage saturation. This correlation matches what was recorded from pilot comments.

The measurement of aggressiveness and duty cycle for the Hover Maneuver MTE in Figure 16(b) illustrates that pilots generally reduced their stick aggressiveness for degraded vehicle configurations in the lateral and longitudinal axis commands. Pilots A, B, and C all make pilot comments mentioning the need for additional lateral and longitudinal correction inputs to perform the MTE. In addition, pilots B and C who exhibited higher duty cycle in the vertical axes also exhibited higher duty cycle in the vertical axis. Pilot inceptor workload in the vertical axis should be minimal for the Hover Maneuver MTE, making increased duty cycle in this axis additionally consequential to the vehicle handling qualities.

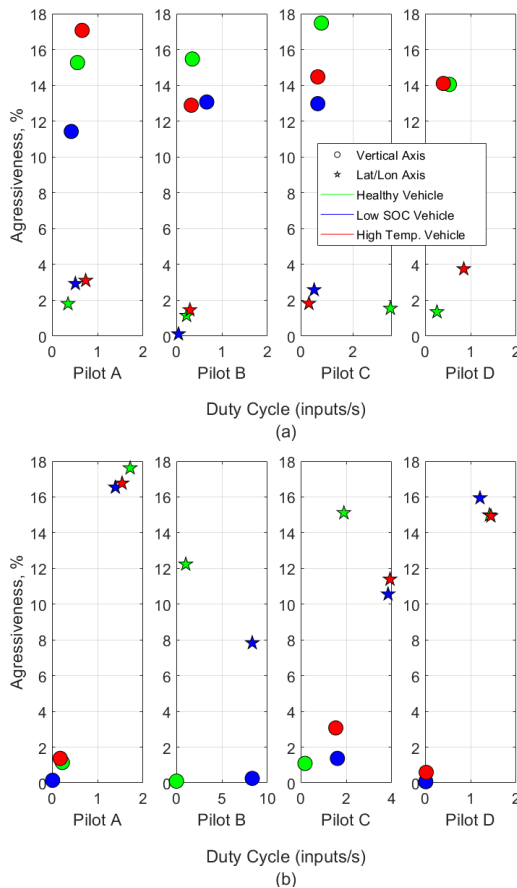


Figure 16. Pilot Aggressiveness vs. Duty Cycle: (a) Vertical Maneuver MTE; and (b) Hover Maneuver MTE with Turbulence.

Pilot A	"Attitude was less controllable with high temperature; it kept wanting to fly through the hover point." (High Temp. / Hover MTE / Turb.)
Pilot B	"Fairly frequent inputs longitudinally and laterally." (Low SOC / Hover MTE / Turb.)
Pilot C	"Tried to focus corrections on both pitch and roll, but that did not work to stabilize the aircraft in time." (Low SOC / Hover MTE / Turb.)
Pilot D	"Consistently got desired but had to compensate... compensation was constant stick inputs to correct after capture." (High Temp. / Hover MTE / Turb.)

Aggressiveness ratings were collected from pilots to quantify whether the needed adjustments to piloting technique due to vehicle configuration were acceptable. Table 3 aggressiveness ratings were collected using a NASA internal aggressiveness rating scale shown in Figure 17. The rating scale is also referenced in the VMS Test 1 Test Plan (Ref. 6). Ratings revealed that the vehicle was less likely to tolerate the preferred level of control aggressiveness when the vehicle was in a degraded configuration. The configurations that were desirable are rated as ones and shown in red in Table 3. The collected aggressiveness ratings for the degradation configurations consistently fell between ratings of three to five, which indicate that the vehicle was either "tolerable," "deficient," or "unacceptable" for the preferred level of aggressiveness. A healthy configuration proves to be generally improved in the aggressiveness ratings.

Aggressiveness

Ability to increase gain while attempting to meet task requirements.

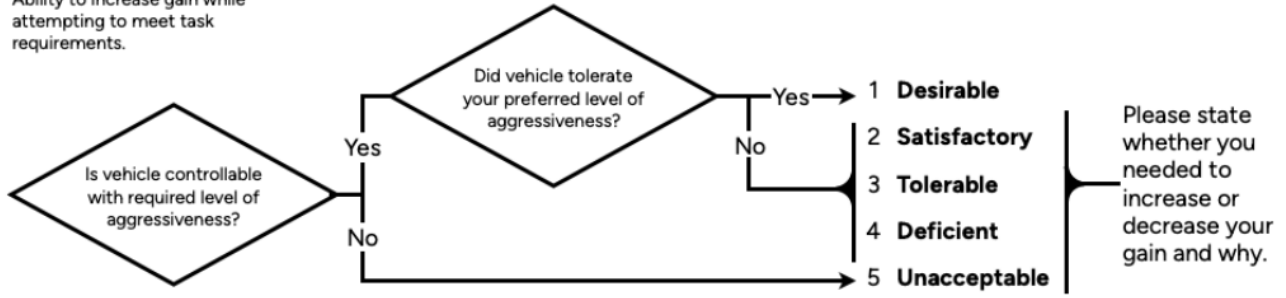


Figure 17. Aggressiveness Scale for VMS Test 1 (Ref. 6).

Table 3. Aggressiveness Ratings for MTEs.

Vehicle Configuration	MTE Ratings: (Vertical/Hover with Turb.)			
	Pilot A	Pilot B	Pilot C	Pilot D
Healthy/Nominal	(1/4)	(1/2)	(3/3)	(x/x)
Low SOC	(3/4)	(x/4)	(3/5)	(x/x)
High Temp.	(4/4)	(3/x)	(3/4)	(x/x)

Note: x indicates that no rating was collected.

Aggressiveness exhibited a large range of change as pilots were forced to change their technique to perform both the Vertical and Hover Maneuver MTEs. Part of the question phrasing used when collecting HQRs was: does desired or adequate performance require “moderate” or “considerate” pilot compensation? Changing aggressiveness to adapt for potential voltage saturation fell within these categories of compensation, resulting in higher HQRs.

Extended duration of voltage saturation increases pilot inceptor aggressiveness in all axes. This correlation during the Vertical Maneuver MTE is illustrated in Figure 18. The aggressiveness metric in Figure 18 is defined according to Ref. 11 and uses the same low-pass filter frequency as in Figure 16. The “Flux Weakening Engaged” percentage measures the extended duration of time that FW control was forced to mitigate voltage saturation during a simulation run. Estimates of the aggressiveness measurement corresponding to the FW engaged percentage are provided in Figure 18. The 95-percent confidence bounds are estimated for the familiarization and evaluation simulation runs of all degraded configurations for the four rotorcraft test pilots mentioned in this paper. These estimates were provided using equations from Ref. 12.

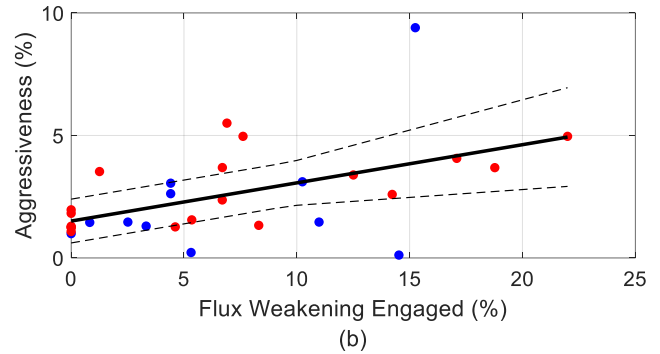
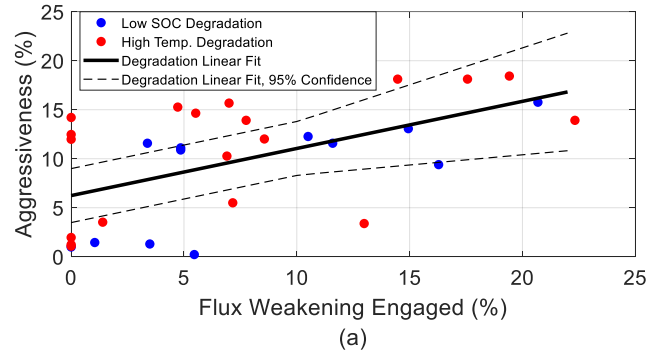


Figure 18. Pilot Aggressiveness vs. Flux Weakening Control Engagement for Vertical Maneuver: (a) Vertical Axis; and (b) Lateral/Longitudinal Axes.

The primary difference that a degraded vehicle configuration exhibited from a healthy vehicle configuration was the tendency to hit motor voltage saturations. If a degraded vehicle did not hit these voltage limits, dynamic characteristics were similar to a healthy vehicle. Increasing the aggressiveness in the vertical axis increased the flux weakening engaged percentage (FW_e), which is illustrated in Figure 18(a). The linear fit ($R^2 = 0.31$, $p = 0.0015$) of the vertical axis pilot aggressiveness (A_V) to the FW_e is given by Equation 6.

$$A_V = 6.24 + 0.48(FW_e), 0 \leq A_V \leq 100\% \quad (\text{Eq. 6})$$

Pilot comments indicated that pitch and roll angle correction commands were required often with degraded vehicle

configurations. The longer motor voltage saturation occurred, the more aggressive pilots had to be with their lateral and longitudinal inceptor corrections for the entirety of the simulation run. This relationship is illustrated in Figure 18(b). The linear fit ($R^2 = 0.29$, $p = 0.0028$) of the lateral/longitudinal axes pilot aggressiveness (A_L) to the flux weakening engaged percentage is given by Equation 7.

$$A_L = 1.5 + 0.16(FW_e), 0 \leq A_L \leq 100\% \quad (\text{Eq. 7})$$

The objective in generating the linear fit to the pilot simulation runs is to test whether there is a correlation between inceptor aggressiveness and FW_e measurements by analyzing R^2 and p values. The inceptor aggressiveness calculations for the vertical axis; (see Figure 18(a)); and lateral and longitudinal axis; (see Figure 18(b)) are found to have a statistically significant correlation ($p < 0.05$) with FW_e measurements.

CONCLUSIONS

Four rotorcraft pilots evaluated the handling qualities (HQs) of the Lift-Plus-Cruise (LPC) vehicle simulation within the Vertical Motion Simulator (VMS) during testing conducted in 2022. The pilots flew a simulated LPC concept vehicle through several United States Army Aviation and Missile Command HQs tasks with both healthy and degraded vehicle configurations. A powertrain simulation was critical to addressing the research questions pertaining to low state of charge (SOC) battery and high temperature motor degradations within the vehicle simulation. The data collected from testing yielded insight into the effect of mid-fidelity powertrain degradations on vehicle HQs. Conclusions reached concerning the HQs of a degraded vehicle are:

1. Flux weakening control protected the motor from losing current when the motor voltage saturated due to high back-electromotive force voltage at high motor shaft speeds.
2. Low SOC batteries and high temperature motors pushed motor voltages toward saturation. The sequence leading to saturation in the powertrain occurred differently for the degradation configurations.
3. Voltage saturation resulted in decreased motor torque output. Flux weakening control mitigated this decrease in torque, but the result was still slow vehicle responses to pilot inputs. This condition resulted in pilot-induce-oscillation behavior because pilot command and vehicle response were out of phase with one another.
4. When select motors exhausted their available battery voltage, axis cross-coupling occurred, resulting in uncommanded pitch or roll vehicle responses.
5. Handling qualities ratings collected from the pilots in VMS Test 1 were worse for the degraded vehicle configurations than for the healthy configuration. The handling qualities of a healthy configuration were not dependent on

the voltage saturation because voltage saturation did not occur. The handling qualities of a degraded vehicle, however, were dependent on voltage saturation.

6. Pilots that attempted to avoid voltage saturation had to consider the aggressiveness of their vehicle commands. Aggressiveness techniques changed not only because pilots were attempting to avoid voltage saturation, but also because pilots were forced to make vehicle commands in response to voltage saturation.
7. The adjustment to piloting technique and workload due to degraded vehicle configurations was not preferred by the pilots.

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