COMANCHE VERTICAL RATE OF CLIMB GUARANTEE METHODOLOGY

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Abstract

The RAH-66 helicopter was in the Engineering and Manufacturing Development (EMD) phase of the program. During this phase nine aircraft were to be built for developmental and operational tests. One of the Key Performance Parameters was the Vertical Rate of Climb (VROC) at 4000 feet pressure altitude and 95 degrees Fahrenheit in its primary mission configuration. The VROC performance goal was 750 feet/minute (fpm) with a threshold value of 500 fpm.

Since test day conditions will not allow collection of guarantee data efficiently, a generalized engineering approach with referred data is necessary to satisfy the contractual guarantee points. The methodology requires a generalized hover performance baseline. From this starting point a generalized climb correction curve is generated using empirical data as a basis to determine a climb correction factor. From the generalized climb correction curves a referred guarantee point is identified. The value of the assessment is only as good as the assumptions and test conditions.

In this paper, a full description of all equations, test methodologies, analyses and pilotage techniques will be discussed as they relate to insuring the VROC guarantee points are accurately determined.

Nomenclature

A/C : Aircraft
AGL : Above Ground Level
C_P : Power coefficient,

$$C_P = \frac{SHP \times 550}{\rho \pi R^2 (\Omega R)^3}$$

C_W : Weight coefficient,

$$C_W = \frac{W}{\rho \pi R^2 (\Omega R)^2}$$

CTT : Combined Test Team
EMD : Engineering and Manufacturing Development
GPS : Global Positioning System
GPV : Generalized Power Variation
GW : Gross weight
H_p : Ambient pressure altitude
MRP : Maximum Rated Power
M_T : Rotational tip Mach number,

$$M_T = \frac{\Omega R}{1116.4\sqrt{\theta}}$$

N_p : Engine output shaft rotational speed
N_R : Main rotor rotational speed
$N_{R,ref}$ Referred main rotor rotational speed,

$$N_{R,ref} = \left(\frac{N_R}{\sqrt{\theta}}\right)$$

OAT : Outside Air Temperature
OGE : Out-of-Ground-Effect
R : Main rotor radius
RADS : Rotating Air Data System
SHP : Sum of Shaft HorsePowe output of engine(s)
VROC : Vertical rate of climb
VVR : Vertical Velocity Ratio
W : Weight (engine start GW + cable tension – total fuel burn off)

Ω : Main rotor rotational speed
δ : Ambient pressure ratio,

$$\delta = \left(1 - \frac{H_p}{145442}\right)^{5.255876}$$

θ : Ambient temperature ratio,

$$\theta = \frac{OAT + 273.15}{288.15}$$

π : Mathematical constant, 3.14159…

ρ : Air density, $\rho = 0.00237688\sigma$

σ : Air density ratio ,

$$\sigma = \frac{\delta}{\theta}$$

Introduction

The Comanche Vertical Rate of Climb (VROC) exit criterion is specified in the May 2000 Performance Weapon System Specification (PWSS-2000-310-901-4) par. 3.2.1.2.2.2. It is required therein to demonstrate vertical rate of climb performance of 500 fpm using 100% maximum rated power (MRP) of the T800-LHT-802 growth engine at a 4000 foot pressure altitude and 95 degree Fahrenheit (35 degrees Celsius) atmospheric conditions.

The helicopter configuration is specified to be configured with the Comanche Radar installed. Hereafter this configuration is referred to as the production aircraft. The VROC exit criterion compliance shall be based on the determination of out-of-ground-effect (OGE) hover performance, climb power increment, testing errors and the proper accounting of instrumentation on external drag and power required. The following paragraphs describe the procedures for obtaining the components and analysis needed to determine compliance.

Testing Techniques

To determine *VROC* exit criteria compliance, the data collection effort involves a two-part process.

- The first part is determination of out-of-ground-effect (OGE) hover power required. Data are gathered using free-flight, air-referenced hover and tethered hover techniques. The measured data is subsequently nondimensionalized using ambient air density, rotor tip speed, and disk area (see Data Analysis/Reduction section).

- The second part involves measuring the vertical climb rate obtained for various power increments above OGE hover power. These data are gathered using the partial power vertical climb technique (Refs. [1-3]).

The following subsections describe these two techniques in detail.

Hover Procedure

Hover power required is determined using the tethered hover technique in winds less than 3 knots. The tether cable shall provide a wheel height of at least 100 feet above the ground. Power will be stabilized incrementally from the minimum required to hold the cable taut to the maximum permissible. Data will be recorded at each stabilized point and at cable angles equal to or less than five degrees. All performance data will be obtained at a referred rotor speed, $N_{R,ref}$, which is defined as

$$N_{R,ref} = \left(\frac{N_R}{\sqrt{\theta}}\right)$$

where N_R, is the rotor speed and θ is the ambient outside temperature ratio. The referred rotor speed corresponds to the rotational tip Mach Number, M_T, at 100% EMD rotor speed at 35 degrees Celsius. At the exit criterion point, the referred rotor speed is 96.7% N_R. Flight test data often equate or refer to C_W as the thrust coefficient (C_T) where the primary difference is the summation of the vertical drag, canted tail fan vertical thrust, and exhaust thrust. The C_W is easily obtained from the aircraft gross weight (GW), but the measured C_P includes the effect of the total vertical force differences. Therefore, it is important to document the configuration of the baseline hover data so that vertical drag changes can be accounted for.

Tethered hover data gathering at the referred rotor speed will emphasize the exit criterion point C_W level by duplicating C_W values approximately 10% above and below the exit criterion C_W value. A statistically sufficient number of data points shall be obtained to determine the hover power required in the following form

$$C_P = A_0 + A_1 C_W^{3/2} + A_2 C_W^3$$

where the coefficients (A_0, A_1 *and* A_2) are determined from a least squares linear regression.

Vertical Climb Procedures

The EMD vertical climb testing should be conducted similarly to the test methods used during the Comanche Milestone II testing and the anhedral tip testing on A/C 1 in September of 2001. The test site ambient wind speeds shall be within the 0-10 knots range up to approximately 1000 ft above the runway with gusts lower than 3 knots. The difference between the balloon anemometers on the lower wind station and the higher wind station shall also not be greater than 5 knots, and the wind direction at each height shall be within 45 deg. The helicopter itself shall have less than 3 knots of relative wind during the vertical climb maneuver. As with hover performance testing the referred rotor speed (96.7% N_R) will be used to duplicate M_T at EMD 100% rotor speed at 35 degrees Celsius. Data will be reduced to non-dimensional form using the equations outlined in the Data Analysis/Reduction section and the Nomenclature section.

In order to conduct a complete vertical climb test point, the initial flight test data point is an approximately 10 second OGE hover record, followed by an incremental fixed collective setting. The helicopter should accelerate vertically while holding 0-3 knots on both longitudinal and lateral airspeeds. A data run of approximately 10 to 20 sec is then taken while maintaining a steady climb condition. This procedure is repeated using incremental increasing collective settings up to maximum power available, and replicated as many times as necessary to achieve a sufficient amount of valid data. The primary vertical rate of climb data shall be determined from a linear least square fit of radar altimeter data over the steady portion of the vertical climb data record.

In addition to a “good” or “no good” assessment, test pilots should independently apply a Cooper–Harper like rating scale reflecting the quality of the data run to each test point to assist in identifying the best test points during the post flight analysis. The balloon weather station wind data, ambient pressure altitude (H_p), outside air temperature (OAT), and relative humidity nearest the rotor height above ground level (AGL) shall also be recorded on each test point.

Sufficient vertical climb performance test runs of 25 to 30 qualified test points should be conducted to statistically validate the derived generalized climb performance curve over the widest vertical velocity range possible. This would require conducting vertical climbs, at a low C_W (lightest practical gross weight) and at the EMD referred rotor speed of 96.7%, incrementally over the full range of available power. Additional vertical climb test data should also be obtained at the exit criteria vertical climb performance guarantee point conditions by targeting the required C_W and 96.7% N_R at the specification conditions. The current projected C_W is approximately 0.01 which would require ballasting the aircraft to about 16000 lbs on a standard day at the West Palm Beach sea level test site.

An alternate test method for obtaining demonstration vertical climb data at the primary mission GW, is by conducting free flight hover at the pressure altitude and N_R required to duplicate the required C_W and 96.7% referred rotor speed. Then conduct the vertical climb performance test at the equivalent maximum rated power (MRP) power available at 4K/35C conditions by use of the rotating air data system (RADS) low airspeed system to hover and record vertical climb (0-3 kts airspeed) data at higher altitudes above the test site. However, this method would require a dependence on the calibration of the low airspeed indicating system and that the test is conducted within a smooth and stable air mass.

Instrumentation Package

The selected demonstration EMD aircraft will be instrumented, maintained, flown and the data analyzed by a combined test team (CTT) consisting of U.S. Army representatives, industry contractors, designated flight test engineers and pilots. The instrumentation package weight, nose boom, and external test equipment vertical drag, and power losses will be agreed to by the CTT prior to exit criterion testing. The exit criterion value will be adjusted to account for the instrumentation package effect on performance.

<u>Recorded Data Parameters:</u> Data parameters to be recorded (as a minimum) are as follows:

- Pressure altitude
- Free air temperature
- Radar altitude
- T802 engine torque (2)
- Main rotor torque
- Fantail™ torque
- Engine inlet temperature

- Fuel quantity
- Fuel temperature
- Fuel totalizers
- Rotor speed
- Gas generator speed (2)
- Turbine inlet temperature (2)
- Tether cable tension (Tethered Hover)
- Tether cable angle (2) (Tethered Hover)
- Flight control positions
- Vertical rate of climb
- Acceleration (all three axes)
- Ground meteorological conditions
- Aircraft heading
- Aircraft attitude
- Fuel Flow
- GPS (inertial) longitudinal and lateral velocity data
- GPS (inertial) longitudinal and lateral position data

Engine Calibration: The government shall furnish engines for the test aircraft, which have had test cell torque meter calibrations performed over the full power range and a minimum of three engine output shaft rotational speeds, N_P, (95, 100 and 105% N_R). The overall torque meter accuracy shall be certified by the engine manufacturer to be within 0.5% after the torque meter calibrations are applied. The N_R and N_P speeds in this memo are based on the 100% EMD indicated rotor speed of 729.2 rpm which was equivalent to 98% N_R on the aircraft tested during the previous phase of the program.

Engine Power Available: For the purpose of determining performance, the engine power available at the 100% N_R specification MRP shall be determined from the manufacturer provided engine computer program (also called the “engine deck”). Estimates shall account for installed inlet pressure losses as defined in the engine deck, adjusted for inlet and exhaust modifications as defined for the production aircraft, and hover inlet temperature rise as determined in the flight demonstration.

Total Shaft Horsepower: Total Shaft horsepower required shall be derived from the calibrated engine torque meter data. The flight test data system or other test unique electrical, hydraulic or pneumatic loads will be measured, converted to shaft horsepower using a suitable efficiency and deducted from total shaft horsepower required. Shaft horsepower required shall also be derived from the summation of main rotor torque, fantail torque, and drive system fixed and variable power losses for comparison to the measured engine total SHP.

Low Airspeed System: Vertical climb performance testing requires the determination of low relative wind speeds on the helicopter particularly during the measured steady portion of the vertical climb. The best method is to install and utilize a low airspeed system that measures and displays airspeed and relative direction to the pilots during hover and the climb portion of the maneuver. Since the RADS developed by the Comanche program is designed to displays low speed forward and lateral true airspeed to the pilots, it was planned to be used to hold the 0-3 knots relative airspeed during the vertical climb testing. The display presents longitudinal and lateral true airspeed on a crosshair indicator where a 3 knots circle can be drawn for guidance. However, an applicable low airspeed system calibration based on the weather balloon anemometers and GPS ground speed should be conducted prior to vertical climb testing to determine any system errors and overall accuracy.

The current weather balloon system in West Palm Beach, Florida can measure wind speed and direction at up to 4 heights between approximately 100 and 1000 ft AGL, at one location on the airport. Therefore, an approximation must be made from the measured wind data at the balloon site for the wind actually prevailing along the aircraft flight path. This procedure is more accurate if the wind stations can be located up-wind of the test site and placed at approximately between 200 and 800 ft AGL where the steady portion of the vertical climb usually occurs.

While the airmass relative velocity was to be maintained using the RADS, the RADS system was unable to accurately measure the airspeed at high angles of attack. During level flight the accuracy was sufficient to perform the mission of the aircraft, however due to the location and shape of the RADS inlet, high angles of attack were problematic. Testing revealed the best resolution available using the RADS in vertical climb was approximately 8 KTAS, however, when the wind and GPS data calibration factors were applied, the overall RADS measurement error was reduced to be within approximately 4 KTAS. This resolution was insufficient for accurate performance data associated with a guarantee point. At termination, the program was investigating utilizing a laser interferometer for airmass reference to meet the required 3 knot constraint of the test. This instrumentation is expensive and flight test unique. This issue highlights the difficulty in meeting the test criteria for low relative winds, especially during high rates of climb through large altitude bands.

Aircraft Weight: The test aircraft will be weighed by a roll-on weighing procedure prior to all performance flight tests and immediately upon completion of testing. The actual test pilots for each test flight and all carry on flight gear will also be weighed and added to the roll-on weight to determine engine start gross weight for each test flight. The roll-on weighing will take precedence in determining the engine start gross weight if there is a difference between the official aircraft weight and balance tracking sheet engine start gross weight, unless it is determined that there was a roll-on scale error or out of calibration date tag. The helicopter longitudinal and lateral center of gravity position will be obtained from the official aircraft weight-tracking sheet. The aircraft ballast and useful load elements will also be weighed in accordance with current accepted weighing practices when shown on the weight sheet.

Pre- and Post- Flight Checks: Pre- and post-flight checks shall include:

- Document test aircraft configuration including an inventory of aircraft equipment, ballast and useful load items.
- Conduct roll on weighing.
- Obtain fuel specific gravity, quantity and temperature on pre flight.
- Check instrumentation operability and calibration currency.

Data Analysis/Reduction

Data points gathered during the exit criterion demonstration test shall be subject to disqualification if: conditions were not stabilized; atmospheric conditions were not suitable; the instrumentation malfunctioned; the aircraft malfunctioned; or other circumstances which in good engineering judgment would disqualify the point.

During data reduction, the CTT flight test engineers should review the time history data obtained for each steady vertical climb record and edit data as required to eliminate any oscillations in the primary parameters like engine torque, radar altimeter, and any data where the RADS airspeed exceeds the 3 knots limit. The vectorally combined GPS and averaged weather balloon relative wind data should also be presented on the time history data for direct comparison to the RADS low airspeed data. Any differences found between the two methods of determining relative wind should also fall within the 3 knots criteria for obtaining valid data. The resulting edited steady vertical climb data segment should have approximately 10 seconds of continuous data, but may have be shorter for the higher rates of climb to stay within the measured wind heights. Data records meeting these criteria will be considered to be qualified data and shall be included in the final data analysis. Any data outside the criteria could also be correlated as additional data, but not utilized to develop the generalized climb performance curve.

Hover OGE

A hover OGE C_P versus C_W curve will be obtained from data run at the referred rotor speed corresponding to the compliance conditions (4000 ft. pressure alititude and 35 degree Celsius). Using a statistically sufficient number of data points, the power required to hover shall be determined from

$$C_P = A_0 + A_1 C_W^{3/2} + A_2 C_W^3$$

where the coefficients (A_0, A_1 *and* A_2) are determined from a least squares linear regression.

GPV and VVR Parameters

Once the OGE hover performance curve is established, the climb power ($C_P|_{Climb}$) data obtained from each qualified data point will be used to determine the Generalized Power Variation (*GPV*) which is given by

$$GPV = \frac{C_P\big|_{Climb} - C_P\big|_{Hover}}{0.707 \times C_W^{3/2}}$$

where $C_P|_{Hover}$ is determined from the hover power required equation using the test C_W for each data point.

The Vertical Velocity Ratio (*VVR*) parameter *VVR* is derived using

$$VVR = \frac{V_{climb} \times 60}{\Omega R \sqrt{C_W / 2}}$$

where V_{climb} is the vertical climb velocity and ΩR is the rotor tip speed.

The *GPV* curve will then be established by performing least squares linear regression of the qualified *GPV* - *VVR* data set in the form:

$$GPV = B_0 + B_1 VVR + B_2 VVR^2 + B_3 VVR^3 + B_4 VVR^4$$

where $B_0 = 0$ is a constraint.

Exit Criterion Compliance Determination

In order to determine *VROC* exit criterion compliance, the data gathered as part of the procedures outlined above must be reduced according to the following common set of ground rules.

The basis for determining Comanche *VROC* performance is defining the generalized climb performance curve, which is the fairing of the Generalized Power Variation - Vertical Velocity Ratio (*GPV* - *VVR*) vertical climb performance data. An example of the *GPV* - *VVR* curve obtained during the anhedral tip testing on A/C 1 in Sept 2001 is provided in Figure 1 (a theoretical curve is shown in Ref. [4]). The *GPV* and *VVR* parameters non-dimensionally relate the incremental climb power required in excess of the hover power required ($C_P|_{Climb}$ - $C_P|_{Hover}$), to the vertical rate of climb capability. As a result, the determination of the *GPV* - *VVR* curve depends on both accurate hover and vertical rate of climb performance flight-testing.

VROC Exit Criteria Gross Weight

The gross weight at which compliance will be determined is currently 13056 lb (5920.3 kg), which corresponds to Aircraft Critical Position 1 (ACP1) of the Primary Mission, with Comanche Radar installed. The *VROC* Exit Criterion ACP1 gross weight in effect at the time of testing shall be used for all calculations to determine compliance.

Exit Criteria Compliance

In order to establish exit criterion compliance, the hover curve is entered at the C_W corresponding to the exit criterion gross weight, ambient conditions and rotor speed. The value obtained for $C_P|_{Hover}$ is then subtracted from the 100% MRP power available ($C_P|_{MRP}$) value determined from the approved engine manufacturer's performance computer program. The resulting power available increment above $C_P|_{Hover}$ is available for vertical climb, and is used to calculate the numerator in the *GPV* equation according to the following equation

$$GPV = \frac{C_P|_{MRP} - C_P|_{Hover}}{0.707 \times C_W^{3/2}}.$$

Using the values for $C_P|_{Hover}$, $C_P|_{Climb}$, and C_W obtained above, the resulting *GPV* - *VVR* curve is entered at the available exit criteria GPV value and the resulting *VVR* calculated from the coefficients obtained for the generalized climb performance equation. The exit criterion *VROC* capability is then calculated as shown below and compared to the criteria of 500 fpm.

$$VROC = VVR\left(\Omega R \sqrt{C_W / 2}\right) / 60$$

Alternatively, the *VVR* required for a *VROC* of 500 fpm at the exit criteria conditions may be calculated as follows:

$$VVR = \frac{VROC \times 60}{\Omega R \sqrt{C_W / 2}}.$$

The *GPV* required would then be calculated from the generalized climb performance equation, and the C_P required to climb at 500 fpm be determined from the following:

$$C_P|_{Climb} = GPV\left(0.707 \times C_W^{3/2}\right) + C_P|_{Hover}$$

Finally the SHP required to achieve the 500 fpm criteria would be calculated from:

$$SHP = \frac{C_P \rho \pi R^2 \left(\Omega R\right)^3}{550}.$$

If the SHP required is lower than the maximum rated power at 4000 ft/35degree C, the exit criteria test data is in compliance.

Conclusions/Recommendations

The Comanche program required the contractor to demonstrate a vertical rate of climb guarantee point. The guarantee point was a Vertical Rate of Climb (VROC) at 4000 ft PA and 95°F in Mission Configuration. This was one of the Comanche Critical Performance Parameters. The VROC performance goal was 750 fpm with a threshold value of 500 fpm. The test methodology was a generalized approach with a derived guarantee value. The method requires an airmass relative airspeed of less than 3 knots. The Comanche RADS was to be used for this reference, but was found to be inadequate at the time this test was conducted. An alternate low airspeed system was being investigated for this purpose. The methodology is sensitive to rounding assumptions. A clearly defined scientific process is required as a part of the statement of work and should specify significant digits for all constants and parameters, especially for C_P and C_T. Any configuration differences between the tethered hover tests and the vertical climb tests would add to the uncertainty and be uncorrectable. Tests for guarantee data should be discussed, understood and clearly defined as a part of the contract.

Acknowledgments

References

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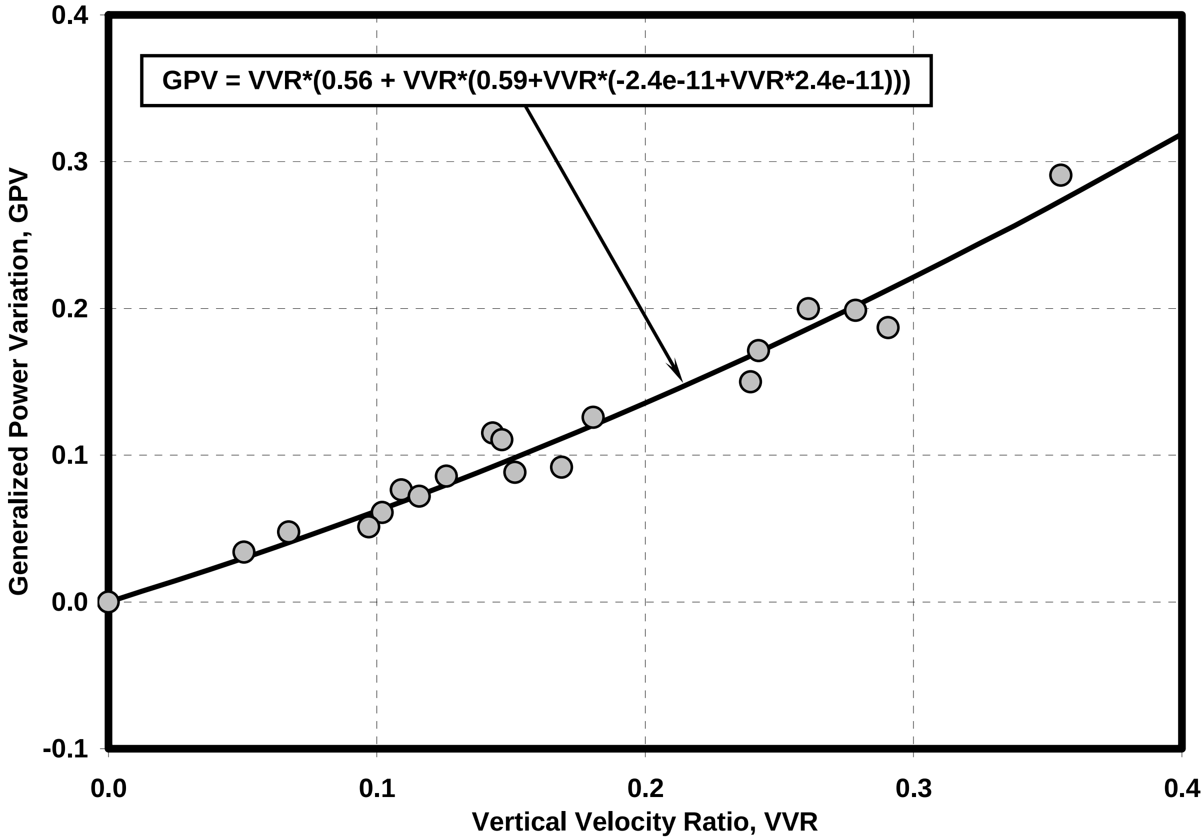

Figure 1: Variation of the Generalized Power Variation (GPV) with Vertical Velocity Ratio (VVR).