ANALYSIS AND FLIGHT TEST COMPARISON FOR HOVER PERFORMANCE

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Abstract

This study presents a comprehensive comparison of power predictions for a hovering helicopter derived from experimental test results with Momentum Theory, and Peters&He Finite State Analysis. The objective is to identify and quantify the discrepancies between theoretical models and empirical data. The Momentum Theory, a classical approach, provides a first-order estimate of induced power but often lacks accuracy in complex aerodynamic scenarios. Conversely, the Peters&He Finite State Analysis offers a more detailed modeling of unsteady aerodynamics and blade dynamics. By comparing the power predictions from these analytical methods with actual test results, this research highlights the limitations and strengths of each approach. The findings reveal critical insights into the applicability of Momentum Theory and Finite State Analysis for predicting hover performance, with implications for the design and analysis of rotorcraft systems. Ultimately, this work contributes to a deeper understanding of the predictive capabilities of these theories in the context of helicopter hover performance, guiding improvements in both theoretical and empirical methods.

1. NOTATION

A	Rotor Disc Area
C_{D0}	Zero Lift Drag Coefficient
C_T	Thrust Coefficient
$C_{Pprofile}$	Profile Power Coefficient
$L_{TailArm}$	Tail Arm Distance
P	Power
$P_{aux. loss}$	Auxiliary Systems Power
P_{calc}	Calculated Total Power
P_{eng}	Engine Exit Total Power
P_i	Induced Power
P_{ideal}	Ideal Induced Power
P_{MR}	Main Rotor Shaft Power
P_{TR}	Tail Rotor Shaft Power
$P_{profile}$	Profile Power
R	Rotor Radius
T	Thrust
v_i	Induced Velocity
v_{ideal}	Ideal Velocity
ρ	Air Density
κ	Induced Power Factor
σ^*	Solidity
σ	Density Ratio
λ_h	Hover Inflow Ratio
μ	Advance Ratio
Ω	Angular Velocity
AC	Advisory Circular
CS	Certification Specification
ECU	Electronic Control Unit
FLB	Flightlab
GW	Gross Weight
HOGE	Hover Out-of-Ground Effect
HIGE	Hover In-Ground Effect
IFR	Instrument Flight Rules
MT	Momentum Theory
MR	Main Rotor
MTOW	Maximum Take-off Weight
NDARC	NASA Design & Analysis of Rotorcraft
VFR	Visual Flight Rules
FPDA	Flat Plate Drag Area

2. INTRODUCTION

Helicopter design is shaped by performance requirements, which are specifed by mission needs. Estimation of helicopter performance at design stage is crucial due to sizing of major components of helicopter, such as rotor sizing, fuselage shaping and engine selection. Therefore, it is crucial to have an accurate helicopter performance mathematical model in order to correctly satisfy needs of designed helicopter. Due to core purpose of helicopter, hover performance may be the most important caracteristic of any utility helicpoter design. Therefore, studies on increasing the consistency of analysis methods at hover is very important. Due to complicated flow field nature of hover, the estimation of required power become a challenge. This paper adresses the issue of hover power prediction accuracy with different analysis methods and compares them with flight test results.

T625 Gökbey is a utility helicopter with 6050 kg maximum take-off weight powered by twin CTS800-4AT turbo-shaft engines. T625 is equipped for VIP transportations, medical missions, and search & rescue operations with VFR, IFR, day and night operations. The first flight of T625 was made in 2018 and flight tests have been performed since then.

Figure 1: T625 Gökbey in Operation

T625 is classified as a large rotorcraft and its certification is subject to CS 29 because MTOW of the rotorcraft is larger than 3175 kg [1]. On the other hand, AC 29.45 states that, flight data of tests can be interpolated or extrapolated for specific temperatures and altitudes [2]. Since the T625 is in the civil certification process, the tests are carried out under different conditions in order to interpolate/extrapolate results throughout the flight envelope. For this paper, data from three test sites in different altitudes are utilized. Location of the test sites can be seen from the Figure *2* and the altitudes of these bases are given as Table 1

Figure 2: Test Site Locations (Kocaeli, Ankara, and Erzurum Left-to-Right Respectively)

Table 1: Test Base Pressure Altitudes

TEST SITE	PRESSURE ALTITUDE [FT]
KOCAELİ	Sea Level
ANKARA	2750
ERZURUM	5700

3. Analysis Methods

Rotor power consists of profile power and induced power components, where profile power is result of airfoil drag and induced power comes from lift component. Majority of power requirement originates from induced power for most of the flight conditions. Generally, analysis methods suffer from low accuracy of induced power prediction and a correction is needed to accurately predict rotor power requirement. In order to enhance the accuracy of the analysis methods, first of all, the appropriate induced power correction factor (κ) should be examined. Moreover, the comparison of hover performance tests with different analysis methods and the examination of consistency should be researched. The methods investigated in this paper are Momentum Theory and Peters&He dynamic wake model.

3.1. Momentum Theory

Hover is a state where the rotor has no velocity with respect to air in any direction. The velocities and loads on the rotor blades are independent of the azimuth position, since the rotor flow field is axisymmetric. In principle, hover flight flow regime is easiest to analyze, however, even with modern mathematical models, accurate prediction of hover performance is not a straightforward process. The rotor’s performance can be examined utilizing a simpler method known as momentum theory even though the airflow around the rotor forms a complex vortical wake. An essential premise of classical momentum theory is that the rotor can be accepted as an extremely thin actuator disk where a pressure discrepancy occurs. This actuator disk generates the thrust force which is produced by the rotation of the rotor. The power needed to create this thrust is provided as torque to the rotor shaft. The implementation of work to the rotor results in an increase in the kinetic energy of the rotor's slipstream, which results in an inevitable loss of energy that is known as induced power. The analysis aims to ascertain how the actuator disk affects the flow, and especially to evaluate the induced velocity and power for a specific thrust. This problem is solved with Momentum Theory by applying the simple fluid dynamic conservation laws. Distribution of the load on rotor blades across an actuator disk leads to the assumption of there are infinite number of blades. The precise flow of the actuator disk differs significantly from that of an actual rotor with a finite number of blades. In practice, the effective induced power exceeds the prediction of momentum theory, since the induced velocity is not uniform and steady. The primary purpose of employing the actuator disk model is to provide an initial approximation of the wake-induced flow and, consequently the ideal induced power. With the utilization of induced power factor, which is an empirical-evaluated coefficient, more consistent estimation of induced power can be done for a rotorcraft. [3][4]

Momentum Theory is the simplest approach to predict rotor thrust and power. For hover condition, induced power can be found as follows:

(1) $P = Tv_i = T\sqrt{\frac{T}{2\rho A}}$

This equation underestimates power to some extent, so an inflow correction factor, κ is multiplied by found induced power value. Leishman states that κ is between 1.15 and 1.25 for main rotors in hover condition [3]. The issue of finding the ideal κ value will be investigated throughout this paper. Inflow ratio of the rotor in hover condition can be calculated as folows:

(2) $\lambda_h = \sqrt{C_T/2}$

3.1.1. Profile Power

Profile power is the power component comes from rotor airfoil drag coefficient. Equation of profile power is given in Eq. 3 and 4 [3] as follows:

(3) $C_{P_{profile}} = \frac{\sigma^* C_{D_0}}{8}(1 + K\mu^2)$

(4) $P_{profile} = C_{P_{profile}} \rho A (\Omega R)^3$

3.1.2. Tail Rotor Power

Tail rotor is used to counteract the moment generated from main rotor. Tail rotor thrust requirement is calculated as follows:

(5) $T_{TailRotor} = \left(\frac{P_{MR}}{\Omega_{MR}}\right)/L_{TailArm}$

From known tail rotor thrust, tail rotor power can be calculated just as main rotor power, but only with a slight difference. Since function of tail rotor is compensating main rotor torque, there is no need to tilt its disk forward or backward, so, its disk angle of attack, (α) must be taken as zero regardless of flight velocity.

3.1.3. Total Power Calculation

Helicopter main rotor and tail rotor power can be calculated via given equations above. Then, total required power can be calculated adding power losses to the rotor power required.

3.1.4. Kappa (κ) Correction

This chapter is dedicated to application of kappa correction. Kappa correction is applied in order to correct induced power calculated from momentum theory, as stated in NDARC [5]. It is stated that induced power correction factor, κ is applied as follows:

(6) $P_i = \kappa P_{ideal}$

Kappa correction ratio defined in Ref.[5] for different advance ratio is given in Figure 3.

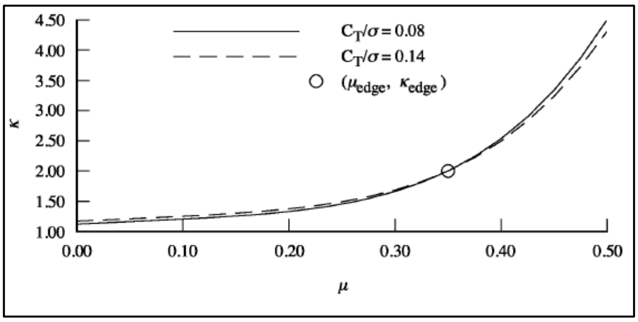

Figure 3: Induced Power Correction Factor with the Changing Advance Ratio [5]

Another kappa correction for induced power also exists in literature, where kappa is also dependent on rotor twist and airframe FPDA. Kappa correction for different advance ratio, twist and FPDA is given [4] where f/A is the ratio between total FPDA and rotor disk area.

Kappa correction ratio defined in Ref.[4] for different advance ratio is given in Figure 4

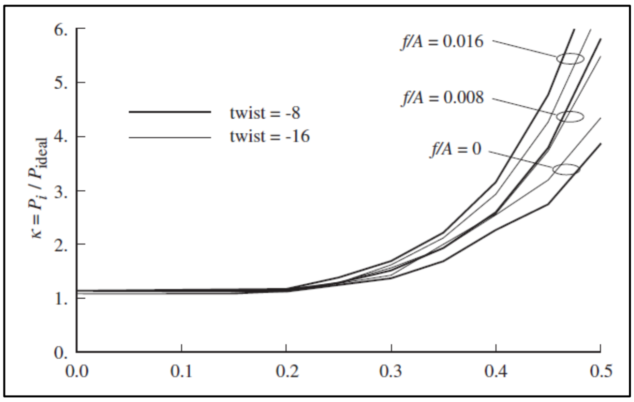

Figure 4: Induced Power Correction Factor for Different Advance Ratios, FPDA and Twist [4]

3.2. Generalized Dynamic Wake Model by Peters & He

Generalized dynamic wake model is based on the unsteady potential flow theory of Peters and He by using Laplace's equation and actuator disk theory. However, it is modified to be unsteady and have finite number of blades. The induced flow distribution is represented in terms of a Fourier series and Legendre functions in the azimuth (harmonic) and radial shape, respectively, where inflow states are expressed as expansion coefficients. The model is based on the incompressible, small disturbance theory and conservation laws. In this method, flow is three dimensional and unsteady acceleration-potential theory with arbitrary lift distribution is used. This model is characterized as representation of induced inflow as dynamic degrees of freedom in a system of first order differential equations in the time domain.

All Peters&He Finite State solutions are performed with Flightlab which is a commercial rotorcraft/aircraft modeling and analysis software that is widely used in aerospace industry. In order to add the κ values into the model, the following equation must be examined theoretically [6]:

(7) $\kappa T = \rho \pi R^3 K_m \frac{dv_i}{dt} + 2\rho \pi R^2 V_T v_i$

Whereas differential term can be eliminated with acceptance of steady-state solution. The V_T can be expanded as follows:

(8) $V_T = \sqrt{(V_z - v_i)^2 + V_x^2 + V_y^2}$

In specific condition of hover, all of the velocity components should be equal to zero. Hence, from the basic derivation, induced power factor, affects the induced velocity via its square-root.

3.3. Performance Mathematical Model

Mathematical models are used for prediction of helicopter behavior at different flight conditions. Performance mathematical model is constructed in order to predict helicopter flight performance, such as power requirement at desired flight envelope of helicopter.

Main rotor, tail rotor and fuselage aerodynamic parameters are included in mathematical model in order to calculate required power at desired flight conditions. High fidelity simulation methods and wind tunnel tests are used to obtain required aerodynamic parameters. 2D airfoil aerodynamic tables of rotor airfoils, which are specially designed for T625 GÖKBEY helicopter, comes from high fidelity CFD analyses. Download drag, which originates from interactions between fuselage and rotor downwash, is obtained from CFD analyses where an actuator disk model with fuselage beneath is configured. Also, tail rotor-vertical fin interactions are analyzed with same approach.

Main rotor power has greatest percentage of total required power, and within main rotor power, induced power is most significant contributor. Estimation of main rotor induced power is most important section of power calculation due to share of induced power over total power requirement. Induced power correction factor, κ, is usually used to aid induced power estimation, is used for main and tail rotor induced power estimation. 3x3 Peters-He finite state and momentum theory is used for analyzes this paper, and their accuracy is demonstrated by comparison with flight test result.

Another aspect of aircraft required power comes from transmission loss and auxiliary losses. Auxiliary losses generally refer to the power losses that comes from non-aerodynamic components, such as oil cooling blower fans, and electrical generator. Due to number of different sources of auxiliary losses, it is difficult to measure all of them independently. Next section will present the accuracy of auxiliary loss assumption by comparing flight test and analysis.

3.4. Validation of Helicopter Power Loss Assumption

T625 Flight campaign has been using several prototypes for different testing purposes. Objectives of some tests requires more instrumented helicopters, which does not have clean outer surfaces, thus, not suitable for flight performance test purposes. These instrumented prototypes own torque bridges at main rotor and tail rotor shafts. However, hover testing are solely done with clean prototypes, which does not have necessary sensors to measure main rotor, tail rotor shaft torques, transmission losses and accessory losses. The only power measurement comes from ECU, which is instrumented to gather the torque values at engine shaft. Thus, in order to estimate the total power with the mathematical model and make comparison with respect to the tests, the power losses are needed. These losses were provided by related engineering teams at first. Then, the maturity of the test data created an opportunity for power loss validation.

Over 800 individual test points, corresponding to the instrumented prototypes, which cover most of flight envelope of helicopter are evaluated for determining the power losses. The measured main rotor and tail rotor torque is added to the auxiliary losses coming from the respective teams (9). Figure 5 presents the difference between the engine power (P_{eng}) and calculated power (P_{calc}) for each respective test point.

(9) $P_{calc} = P_{MR} + P_{TR} + P_{aux.loss}$

Obtained results from graph is utilized to correct losses and extract the aerodynamic power more accurately.

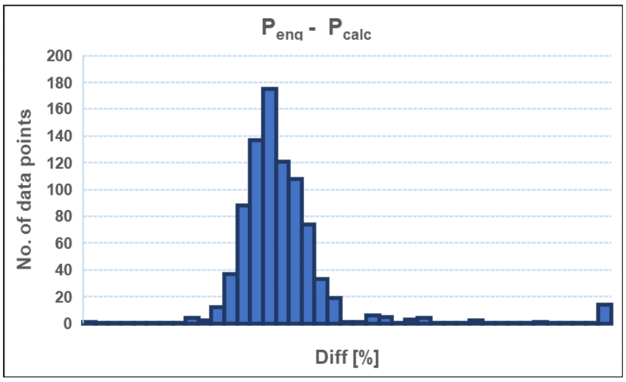

Figure 5: Percentage Difference Between Calculated and Total Power for Test Points

4. Hover Flight Performance Testing

For each gross weight, stable hover data is obtained at different wheel heights to observe ground effect from 5 ft to 100 ft. Each test is done with calm winds, where wind speed tolerance is taken as 3 kts, as stated in AC29.45 [2]. Different gross weight test points are done with ballast and fuel addition, approximately 250kg for each different weight interval. Reference weight and power relation is obtained for each test site. Linear straight fit is applied to the (P/σ) vs $(GW/σ)^{3/2}$[7]. Obtained test results from all test sites are presented in Figure 6.

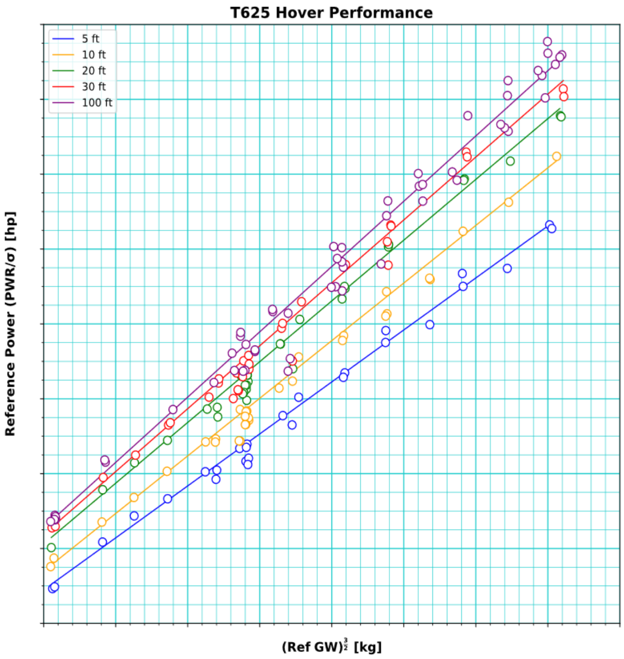

Figure 6: T625 Hover Flight Test Results

5. Test Results and Comparison

Test results obtained from hover flight performance campaign is compared with different analysis methods in this chapter. Obtained losses from test campaign is added to analysis results to accurately compare them with test results, as explained previously. For both methods, different κ values are implemented in order to match analysis results to test results.

5.1. Peters&He Finite State Results

Peters&He finite state analysis results are obtained by using Flightlab simulation software. Developed mathematical model is used for preliminary performance estimations. After test results are obtained and helicopter hover performance characteristic has been materialized, mathematical model parameters are tuned in order to match performance of real aircraft. For this purpose, different kappa values are implemented in mathematical model and results are shown in Figure 7.

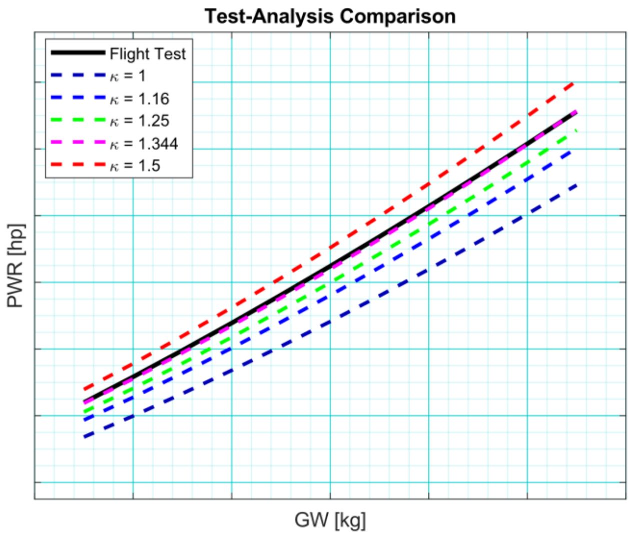

Figure 7: Test and Analysis Comparison for Changing Induced Power Factor

Although all performance test campaign is done with prototypes without MR Torque instrumentation, some test points of other prototypes are taken, which comply with flight performance test requirements. Main rotor power measurements from this test points are compared with analysis results with different κ values to check validity of estimation. As seen in Figure 8, analysis result with selected κ value closely matches with flight test main rotor power measurement.

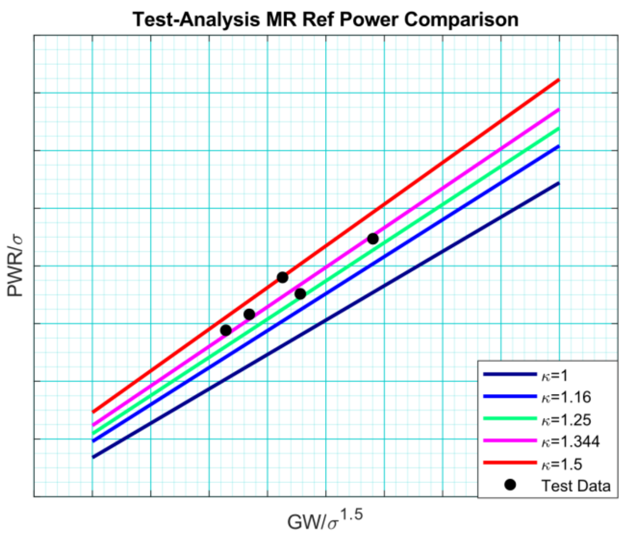

Figure 8: Test and Analysis Comparison for Main Rotor

To further investigate, HIGE analysis results are compared with flight test with selected kappa. Comparison of Peters&He finite state and test results for different wheel heights shows that selected κ, estimates the required power at 5 ft and 30-100 ft wheel heights most successfully, whereas, visible over-estimations can be seen for wheel heights ranging from 10 to 30 ft as shown in Figure 9

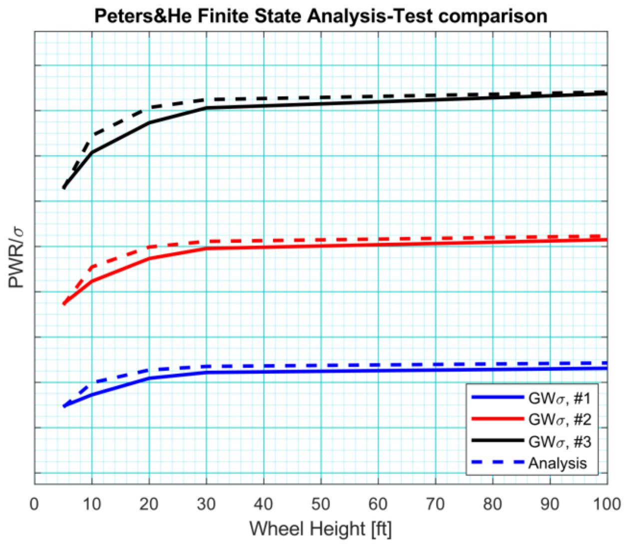

Figure 9: Test Results and Peters&He Finite State Analysis Comparison for Changing Altitudes

5.2. Momentum Theory Results

Analysis result of momentum theory is corrected with empirical inflow correction factor, κ. There are numerous inflow correction methodologies presented in literature, which are defined for various flight regimes, including hover. In this paper, several inflow correction factors are used, including the ones that suggested by Johnson and in NDARC. Comparison of momentum theory, finite state and flight test results are presented in Figure 10. Results shown in the figure indicates that κ values suggested by Johnson and in NDARC yields close results to test. κ value with best matching is also investigated and κ=1.16 has found out to be best match for hover performance test results. From the Figure 10 it can be observed that Peters&He finite state results with selected κ matches best with flight test data compared to the all momentum theory analysis results.

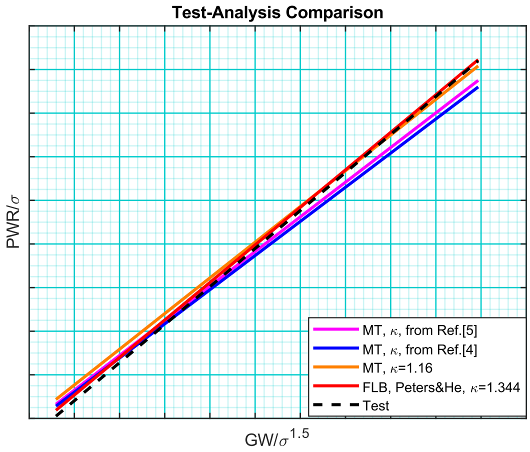

Figure 10: Analysis And Test Comparison

6. CONCLUSIONS

Helicopter transmission and accessory losses are estimated and uncertainties coming from power required data are minimized. Analyses are conducted with different methods as explained in the paper. The corrections required for each analysis method is determined. Peters&He finite state with κ correction is found out to be most accurate compared to other methods investigated in this paper. It is observed that found inflow correction factors are not entirely correct for both IGE and OGE conditions. Small difference observed at IGE can be attributed to complex flowfield happening at IGE and uncertainties about losses. The obtained corrections will be implemented to the mathematical model to enhance the analysis accuracy. This paper also presented performed hovering flight test campaign of T625 helicopter at different altitude, weight and wheel height combinations.

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