10th ANKARA INTERNATIONAL AEROSPACE CONFERENCE   **AIAC-2019-000**
18-20 September 2019 - METU, Ankara TURKEY

TRIM ALGORITHM DEVELOPMENT FOR HELICOPTER FLIGHT DYNAMICS SIMULATION

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ABSTRACT

The flight training simulators are widely used in pilot training programs. For manned helicopters, flight simulators are used not only to reduce time and cost of training activities, but also to prevent possible loss of pilot or aircraft during training. Flight simulators give an invaluable chance to pilot for effective training in different flight conditions including circumstances that can't be trained live. Starting the simulation at desired initial conditions capability has an important role for training quality. At the same time, it is critical for verification and validation efforts. Obtaining trim positions that make the aircraft stabilized in a desired condition without the need for the operator to constantly apply a control force is necessary to achieve this capability. In the meantime, required time to get trim values should remain reasonable. For these purposes, proper trim algorithm should be developed. In this context trim algorithm is developed for HELIX (Generic Helicopter Model). HELIX is a high fidelity generic helicopter model simulating all major components of a helicopter. This paper introduces the highlights of trim algorithm development studies. Trim algorithms include many equations and variables. The selected set of these elements directly affects accuracy of trim positions. Especially main rotor parameters have a critical role on helicopter flight dynamics. The effects of main rotor parameters on trim algorithm are presented in this study. The obtained trim positions are compared for validation with both the ones attained with the help of autopilot and real flight test trim values. The flight tests are selected from Qualification Test Guide (QTG) defined by certification standards for helicopter flight simulation training devices. The trim algorithm developed at the end of this study is applied to HELIX. Thus, proper trim points are obtained quickly

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INTRODUCTION

Helicopter pilot training programs include intense usage of flight training simulators. They can radically decrease the cost of flight training and consumed time for effective training. There is no risk for losing aircraft itself and pilot life. Flight simulators can give an invaluable opportunity to the pilots for fully concentrated training session. Pilots can face different adverse weather conditions and various malfunctions including the ones that can't be trained live in the simulator environment.

Starting the helicopter in a trimmed position from the desired point and reposing the helicopter to the intended conditions are significant for providing training at targeted level. Helicopter trim computation is quite an important work for also analyzing helicopter flight dynamics and stability. Better trim result is the foundation for analyzing and evaluating the helicopter's flight quality correctly and exactly. But the helicopter is a highly coupled multi-body vehicle, so the trim equations are quite complex, higher-order, nonlinear equations with lots of variables. Considering the helicopter's flight state varies constantly, it's hard to give the suitable initial value for the trim equations, instead we can only determine the range of the variables by experience. According to these characteristics, we need to search for a highly efficient algorithm which can converge to the accurate value in full span to get the correct trim results. The prediction of trim settings has been vigorously pursued since the 1980s and still is a demanding exercise because of the divergence of iterative schemes and excessive machine time [J. McVicar and R. Bradley, 1997]. Most of trim algorithms given in the literature contain so many assumptions. For higher quality training, obtaining more precise trim points in a short time period is very critical and important.

The outline of this paper is as follows: Next section gives brief information about HELIX. We then emphasize important parts of our trim theory and describe trim algorithm development methodology. Finally, we evaluate our results and present concluding remarks.

HELIX – A GENERIC HELICOPTER MODEL

The major design objective of HELIX is to develop a high fidelity generic helicopter model simulating all major components of a helicopter, including main rotors and engine components. Main rotor modeling extends the reputable GENHEL model [Howlett, 1981]. Another remarkable design objective of HELIX is higher capability of representing different type of helicopters. A novel adaptive and flexible structure is designed to implement all design parameters reflecting the flight characteristics of a helicopter. By using this structure, the model is adapted to the target helicopter. The main framework is developed in MATLAB & Simulink environment. Certain models are developed in C++ and used as a library in MATLAB & Simulink.

The main blocks of HELIX are Environmental Model, Flight Control System (FCS) and Automatic Flight Control System (AFCS), Weight and Balance, Ground Handling, Aerodynamics and 6-DOF (Degree of Freedom) Equations of Motion. The environment block calculates temperature, air pressure and air density parameter values affecting helicopter performance. The aerodynamics block includes main rotor, tail rotor, fuselage and empennage sub-models. The general structure is based on GENHEL model. Flight control system functionalities including mixing unit are handled out, stability augmentation system (SAS) and autopilot modes such as altitude hold, air speed hold are developed in the FCS and AFCS blocks. The weight and balance block includes moments of inertia, total weight calculations taking into account fuel, payload and determination of center of gravity location. Translational

and rotational accelerations are calculated from total forces and moments affecting on the helicopter in different flight regimes by the equations of motion block. [Demirel, Ayci 2016]

TRIM THEORY

The helicopter's size and shapes vary, but major components are common. The lift is produced by the main rotor. The main rotor has the most important role on the helicopter dynamics since directional controlling, propulsive and lifting forces are mostly generated by the main rotor. Tail rotor is required for anti-torque effect cause of main rotor. The vertical stabilizer produces force in lateral directions to stabilize the helicopter. The horizontal stabilizer produces lift and helps stabilize the helicopter in forward direction.
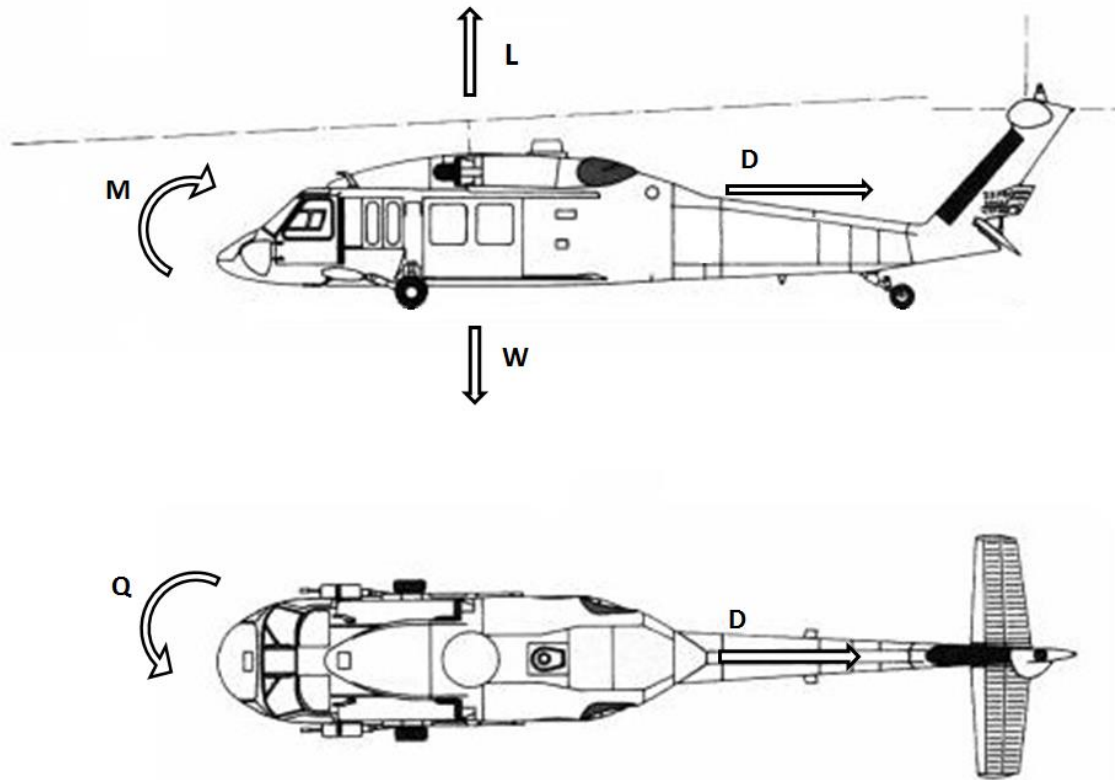

Figure 1: Forces and moments acting on a helicopter.

In Figure 1, the forces and moments are given which are acting on a helicopter in trim position. L and M denote the total lift and pitching moment vectors. The drag forces on all of the components of the helicopter are shown as one vector D, which is against to motion. Gross weight is shown as W. The torque (Q) produced by the main rotor is shown in order to state the anti-torque effect of the tail rotor. The direction of torque vector depends on direction of main rotor rotation (counter-clockwise or clockwise).

When all forces and moments (i.e. the aerodynamic, inertial and gravitational) about three mutually perpendicular axes are equal, the aircraft is in a state of equilibrium. That equilibrium state is called as trim. When propulsive force is greater than drag the aircraft will accelerate; when lift is greater than the weight the aircraft will climb.

When considering the flapping and feathering of the blades of both main rotor and the tail rotor, the motion of the main rotor with respect to the fuselage, the swash plate mechanism, and the moving horizontal stabilizer in some of the helicopters, there are many equations of motion that one should solve for analysis.

Because of the fact that a helicopter has so many degrees of freedom, it is much more difficult to analyze with respect to fixed-wing aircraft. The fuselage has 6 degrees of freedom (DOF), the main rotor has 4 DOF (3 for rotor flapping and one for the rotation of the rotor (throttle)), tail rotor has also 4 DOF, etc. However, with some feasible assumptions, the helicopter system can be reduced to 6 DOF like a fixed-wing aircraft, three for translation and three for rotation. A helicopter with a main rotor and a tail rotor, assuming it as having a rigid structure, has more than 20 differential equations, which makes the problem highly non-linear and very difficult to solve. The following general simplifications are implemented in order to make the problem easier:

– The helicopter structure is considered to be absolutely rigid;
– The blades are assumed as uniform and the lag bending, elastic twist, and axial deflections are disregarded, except the flapping motion;
– The blades have homogeneous mass distribution;
– Empirical downwash, sidewash, L&D of empennage relations are used;

On the basis of these simplifications, the system describing the helicopter motion can be reduced to 11 equations. These equations are based mainly on main rotor and tail rotor characteristics.

Calculations of aerodynamic forces and moments on the helicopter are described below [Leishman, 2006]:

Main Rotor Forces and Moments

In this study, the main rotor model is based on a Blade Element Rotor Model (BERM). In this method, total rotor forces and moments are calculated from a combination of aerodynamic, mass and inertia loads acting on each blade. This model assumes that each blade element acts as a two-dimensional airfoil section producing aerodynamic forces which are then numerically integrated along the blade span. Virtual blades that are distributed through equal azimuth angle intervals over the rotor disk area are constructed to obtain more realistic solution results. The virtual blades are divided into small sections (segments) from root to the tip. The influences of the rotor wake and inflow characteristics are taken into account by the angle of attack and Mach number at the element section. From these aerodynamic calculations, total lift and drag forces are calculated on each blade. With the help of axis transformations total forces and moments are obtained on the main rotor hub. Finally, these forces and moments are transformed to body axis, and then translated to center of gravity. [Prouty, 2005]

Fuselage Forces and Moments

Fuselages of helicopters have arbitrary geometric shapes generally. Since it is hard to develop high-fidelity generic fuselage mathematical model without aerodynamic coefficient tables, this method is used for UH-60. These aerodynamic coefficients were generated as a lift and drag coefficient with respect to fuselage angle of attack and sideslip angles in wind axis. From these aerodynamic coefficients, total lift and drag forces are calculated on the fuselage of the helicopter. Finally, these forces are transformed to body axis and translated to center of gravity.

Tail Rotor Forces and Moments

For the tail rotor model, simplified and closed-form Bailey's tail rotor model is used. The tail rotor model is similar to the main rotor except flapping dynamics are ignored, which is acceptable since for short blades flapping is very low and can be neglected. The airflow impinging on the tail rotor is developed from the free stream, rotor wash and fuselage side-wash, together with body angular rate effects. Total velocity components are resolved through the cant angle into the tail rotor shaft axes system. Total calculated forces and moments on the tail rotor are transformed about the cant angle and translated to the center of gravity.

Empennage Forces and Moments

The empennage model includes the horizontal and vertical tail model. The horizontal and vertical tail are modeled by using the so-called quadratic aerodynamic form of lift and drag. In this approach, lift and drag force are calculated using aerodynamic coefficients, velocity, density and reference area. For the higher fidelity, these aerodynamic coefficient tables allow for all ranges of angle of attack. Therefore, stall characteristics are included. After calculating the lift and drag forces on the horizontal and vertical tail aerodynamic center, in wind axis, these forces transformed to the body axes using local angle of attack and sideslip angle and translated to center of gravity.

Atmosphere parameters take the altitude effect on air density, pressure and temperature into account. The helicopter is assumed to combine the six degrees of freedom rigid body equations of motion (in body axes) with the lateral & longitudinal flapping dynamics.

In previous studies, the trim values were found to start the simulation at the desired point at initialization phase by using autopilot at the backstage. The starting trim point for autopilot that was obtained for 4000 ft. altitude and 70 knot indicated air speed (IAS) condition was used as default values. The elapsed time for reaching trim points has become more longer with various altitude and velocity selections. For this reason powerful trim algorithm development is required.

TRIM ALGORITHM DEVELOPMENT

Trim Parameters

Before starting trim algorithm development studies, various analyses are performed on dynamic main rotor parameters ($\phi, \theta, \lambda, \theta_0, \theta_{1s}, \theta_{1c}, \ddot{\beta}, \dot{\beta}$ and β) and tail rotor parameters (λ_{TR}, θ_p). They are investigated to determine which parameters are more effective on elapsed time for trim (ETT). For this purpose, a reference autopilot trim point (AP trim point in Figure 2, 3 and 4) is obtained with the help of AFCS. In order to compare with reference trim point, flight data trim point is added to related figures. Firstly, initial value for $\ddot{\beta}$ is equalized to zero and then simulation is run again in order to reach trim condition. For the second condition $\ddot{\beta}$ and $\dot{\beta}$ are set to zero at the same time as initial values. Similarly β is additionally set as zero for next instance. As a final condition, just λ is equalized to zero. All results are presented in figure 2. $\ddot{\beta}$ and $\dot{\beta}$ do not have significant effect on ETT. However λ and β have significant effect on ETT. They double the ETT as compared to the AP trim point.
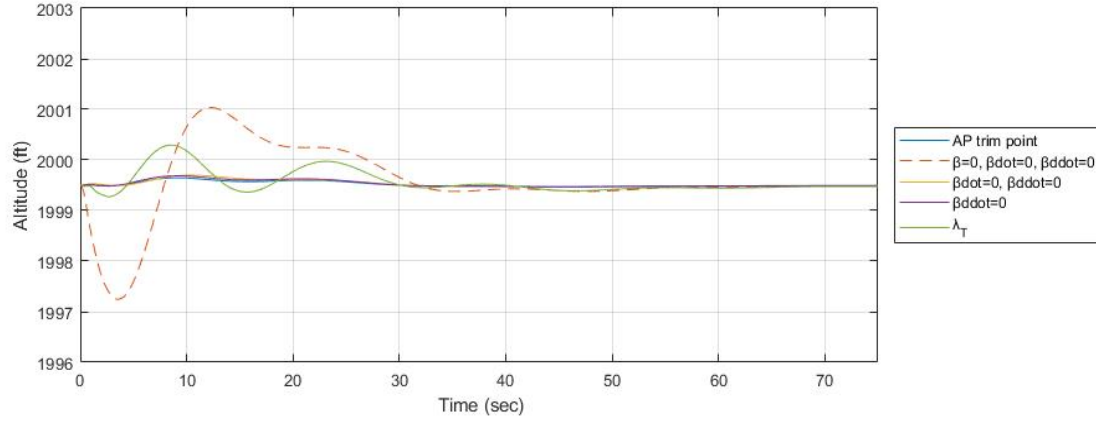
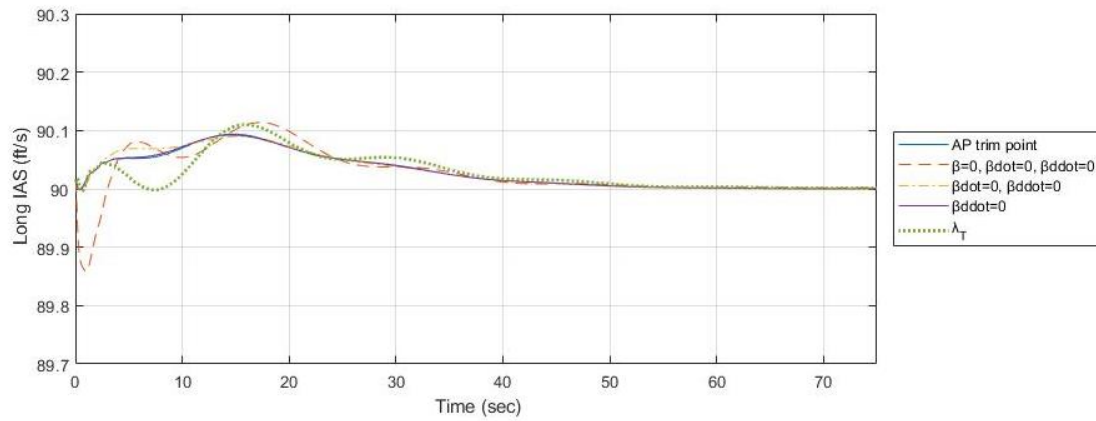Figure 2.a: Altitude vs Time for flap parameters

Figure 2.b: IAS vs Time for flap parameters

In the second phase of the study, simulation is run for each control channel. The positions of control channels have an important role on obtaining trim point. Reference trim point value is increased individually by 10%. Collective, lateral cyclic, longitudinal cyclic and pedal test results are presented in Figure 3 respectively. All control channels have considerable effect on ETT and it is observed that the most influential parameter is longitudinal cyclic input. It extends ETT approximately 20 seconds.
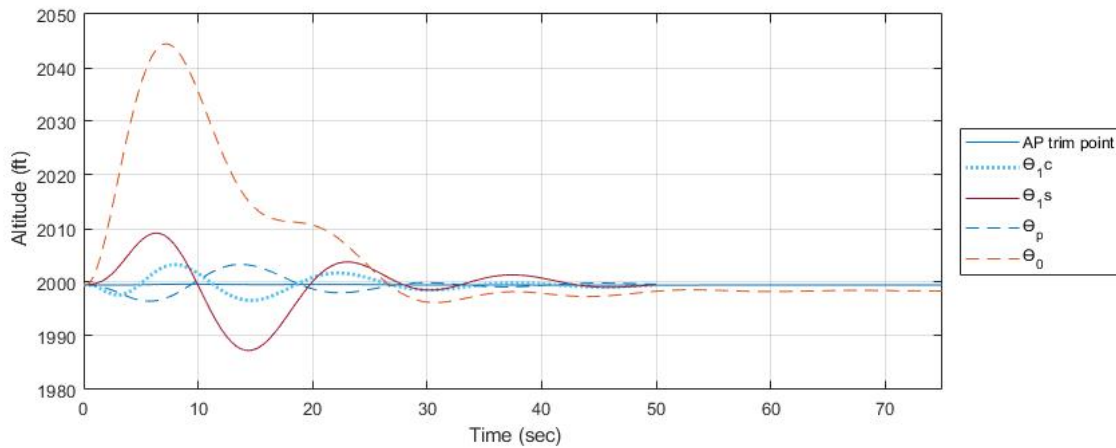

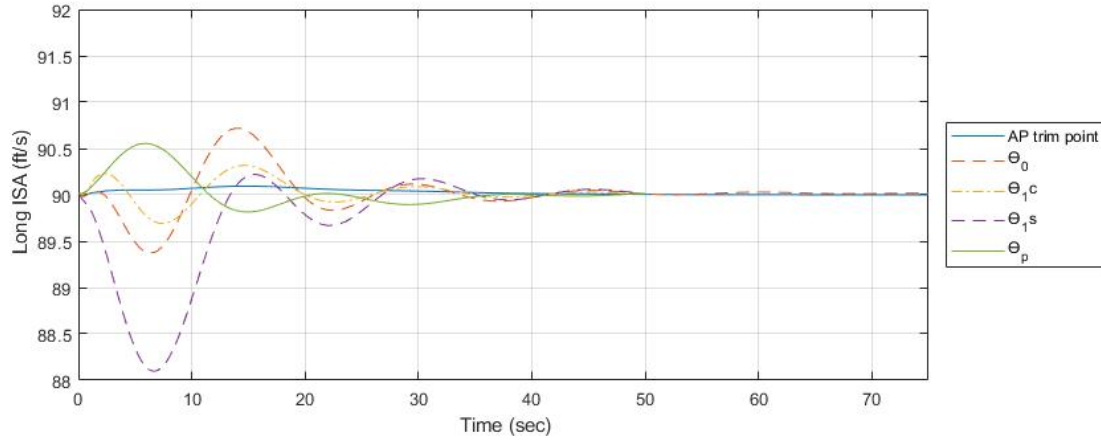Figure 3.a: Altitude vs Time for control channel parameters

Figure 3.b: IAS vs Time for control channel parameters

For final step similar effort is performed for attitude angles. Initial values for λ_{TR}, φ and θ are set to zero. As presented in figure 4, all parameters have about two times longer ETT as compared to the AP trim point.
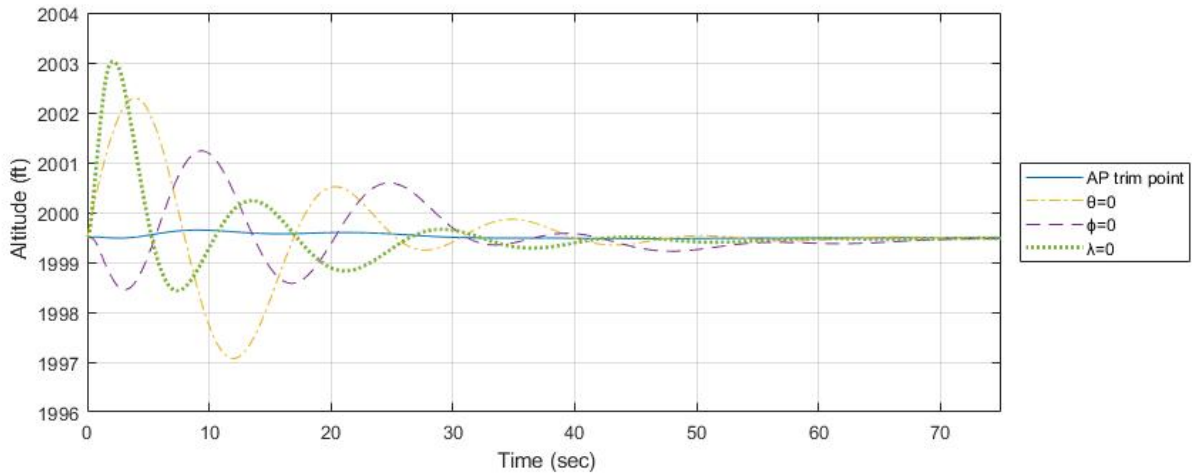

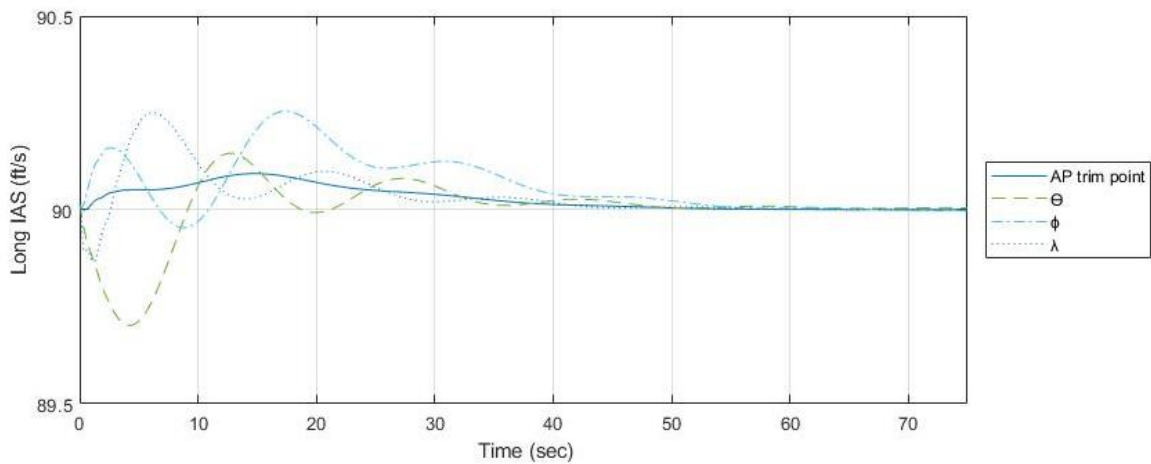Figure 4.a: Altitude vs Time for Attitude parameters

Figure 4.b: IAS vs Time for Attitude parameters

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Trim Equations

Presented Figures 2, 3 and 4 show that ETT is increased two or three times for different conditions. When the default values are given at the same time for cited dynamic main rotor parameters, unacceptable ETT extension is occurred and also for same cases trim point cannot be reached. At the end of this study critical nine parameters $(\phi, \theta, \lambda, \theta_0, \theta_{1S}, \theta_{1C}, \theta_{TR}, \lambda_{TR}, \beta)$ are determined. Instead of calculating β for each blade, the equations of β_0, β_{1S} and β_{1C} can be used. Eventually at least eleven equations are needed to calculate them.

For the helicopter model, a set of equations and 11 unknowns are obtained for flight in trim conditions. The trim values of angular velocities (p, q and r) are equal to zero. The helicopter linear velocities can be written as functions of VNED and roll, pitch and yaw angles of the helicopter. Yaw angle is assumed a constant number because it has no effect on trimmed flight. The assumptions made and the equations used in this paper are detailed in [Yavrucuk, 2018].

The calculations are started with predicted values. Therefore, iterations must be performed. It starts with an initial guess.

$$C_T = C_W \qquad (1)$$

For the first step all angle parameters are equal to zero.

$$\theta_0 = \theta_{1S} = \theta_{1C} = \theta_{TR} = \beta_0 = \beta_{1S} = \beta_{1C} = \alpha_S = \emptyset_S = 0 \qquad (2)$$

Inflow ratio:

$$\lambda = \mu\tan\alpha + \frac{C_T}{2\sqrt{\mu^2 + \lambda^2}} \qquad (3)$$

In order to calculate an accurate inflow value, Equation (3) is reiterated within itself with a nonzero initial value of inflow ratio.

Collective:

$$\theta_0 = \frac{3\left[\frac{2C_T}{\sigma a} - \frac{\theta_T}{4}(1 + \mu^2) + \frac{\mu}{2}\theta_{1S} + \frac{\lambda}{2}\right]}{1 + \frac{3}{2}\lambda^2} \qquad (4)$$

Cone angle:

$$\beta_0 = \frac{\vartheta_0^2}{\vartheta^2}\beta_p + \frac{\gamma}{\vartheta^2}\left[\frac{\theta_0}{8}(1 + \mu^2) + \frac{\theta_T}{10}\left(1 + \frac{5}{6}\mu^2\right) - \frac{\mu}{6}\theta_{1S} - \frac{\lambda}{6}\right] \qquad (5)$$

Lateral cyclic:

$$\theta_{1C} = \beta_{1S} - \frac{\frac{4}{3}\mu\beta_0 - \frac{(\vartheta^2 - 1)8}{\gamma}\beta_{1C}}{1 + \frac{1}{2}\mu^2} \qquad (6)$$

Longitudinal cyclic:

$$\theta_{1S} = \frac{\frac{8}{3}\mu\left(\theta_0 + \frac{3}{4}\theta_t - \frac{3}{4}\lambda_{TPP}\right) + \frac{(\vartheta^2 - 1)8}{\gamma}\beta_{1C}}{1 + \frac{3}{2}\mu^2} - \beta_{1C} \qquad (7)$$

Longitudinal cone angle:

$$\beta_{1C} = \frac{\dfrac{X_{cg}}{h} - \dfrac{M_{YF}}{Wh} - \dfrac{C_{HTPP}}{C_T}}{1 + \dfrac{\dfrac{(\vartheta^2 - 1)}{\gamma}}{\dfrac{C_T \; 2h/R}{\sigma a}}} \qquad (8)$$

Lateral cone angle:

$$\beta_{1S} = \frac{\dfrac{-Y_{cg}}{h} + \dfrac{M_{XF}}{Wh} - \dfrac{C_{YTPP}}{C_T}}{1 + \dfrac{\dfrac{(\vartheta^2 - 1)}{\gamma}}{\dfrac{C_T \; 2h/R}{\sigma a}}} \qquad (9)$$

The obtained β_0 , β_{1C} ve β_{1S} values are split again on the azimuth axis, which will fit into 12 equal parts. Thus, it will be convenient to model of input.

Tip path plane tilt angle:

$$\alpha_S = \frac{\dfrac{X_{cg}}{h} - \dfrac{M_{YF}}{Wh} - \dfrac{\dfrac{(\vartheta^2 - 1)}{\gamma}}{\dfrac{C_T \; 2h/R}{\sigma a}} \dfrac{C_{HTPP}}{C_T}}{1 + \dfrac{\dfrac{(\vartheta^2 - 1)}{\gamma}}{\dfrac{C_T \; 2h/R}{\sigma a}}} + \frac{D}{W} \qquad (10)$$

Roll angle:

$$\emptyset_S = \frac{\dfrac{Y_{cg}}{h} - \dfrac{M_{XF}}{Wh} - \dfrac{\dfrac{(\vartheta^2 - 1)}{\gamma}}{\dfrac{C_T \; 2h/R}{\sigma a}} \dfrac{C_{YTPP}}{C_T}}{1 + \dfrac{\dfrac{(\vartheta^2 - 1)}{\gamma}}{\dfrac{C_T \; 2h/R}{\sigma a}}} - \frac{Y_F}{W} \qquad (11)$$

Tail rotor inflow:

$$\lambda_{TR} = \frac{C_{T_{TR}}}{2\sqrt{\mu^2 + \lambda_{TR}^2}} \qquad (12)$$

Pedal:

$$\theta_{TR} = \frac{C_{T_{TR}} * \dfrac{2}{\sigma a} - \dfrac{1}{4}\,\theta_0(1 + \mu^2) + \dfrac{1}{2}\,\lambda_{TR}}{\dfrac{1}{2} + \dfrac{3}{4}\mu^2} \qquad (13)$$

As a result of the iteration, the closer values to trim point are obtained for $\phi, \lambda, \theta_0, \theta_{1s}, \theta_{1c}, \theta_{TR}, \lambda_{TR}$ and β parameters. By means of the results acquired from Fixed Point Iteration method. The cost function of this method is given in the following equation.

$$\text{Cost Function} = (\Delta\phi)^2 + (\Delta\lambda)^2 + (\Delta\theta_0)^2 + (\Delta\theta_{1s})^2 + (\Delta\theta_{1c})^2 + (\Delta\beta_0)^2 + (\Delta\beta_{1s})^2 + (\Delta\beta_{1c})^2 + (\Delta\theta_{TR})^2 + (\Delta\lambda_{TR})^2 \quad (14)$$

The notation ΔX means the difference between old value and new value of X within iteration.

Flight Characteristics

The equations set given above are solved by using Fixed Point Iteration method. Thereby the values of 11 unknowns are obtained. The flight characteristics are obtained by using these values and presented graphically below.
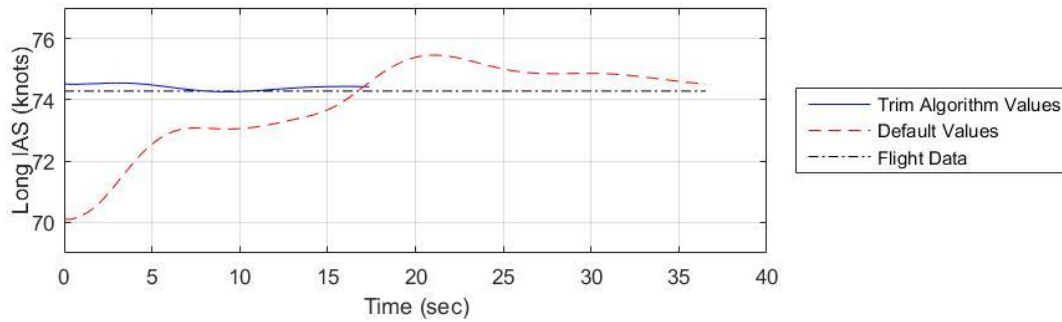

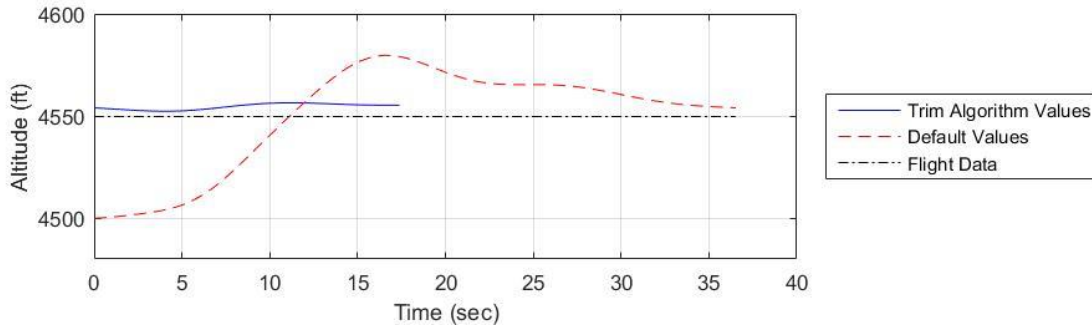Figure 5.a: Long IAS vs Time for trim values

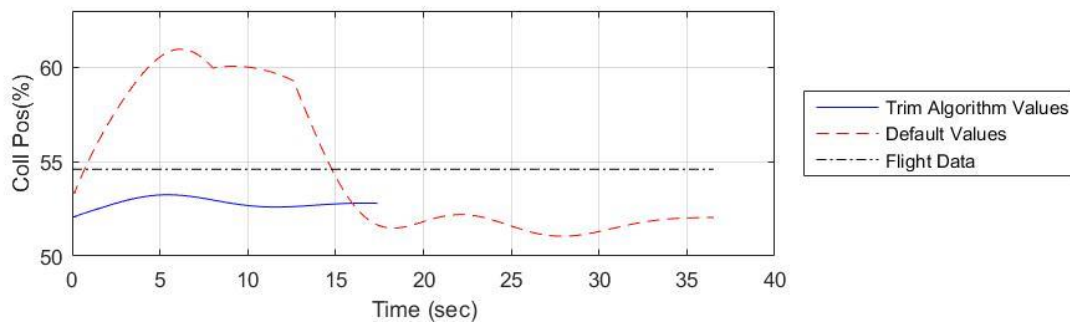Figure 5.b: Altitude vs Time for trim values

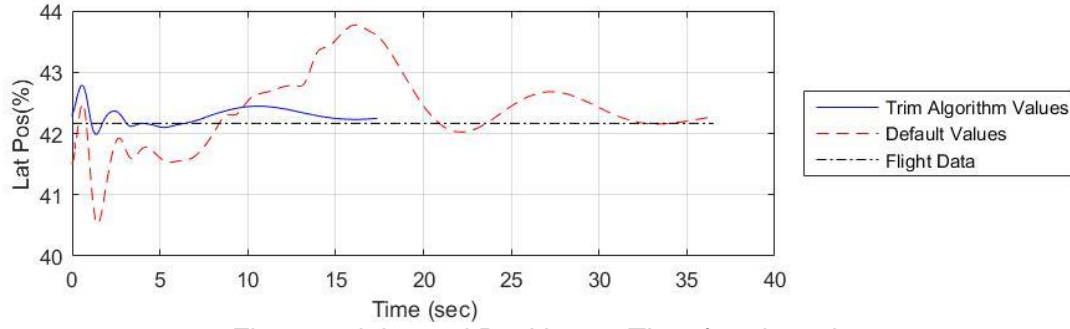Figure 5.c: Collective Position vs Time for trim values

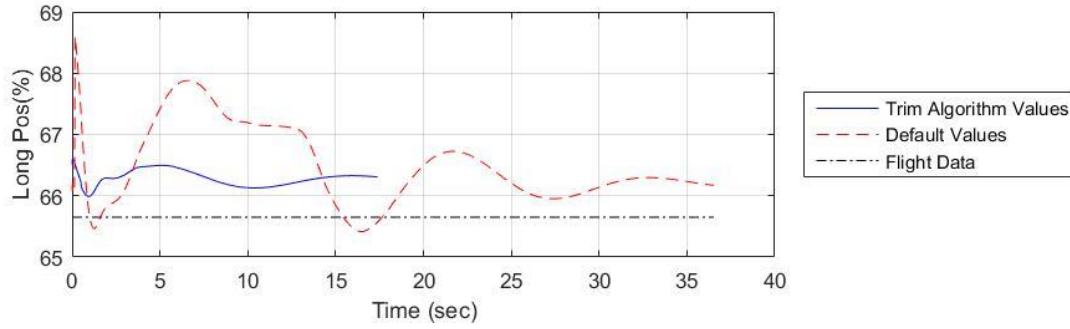Figure 5.d: Lateral Position vs Time for trim values

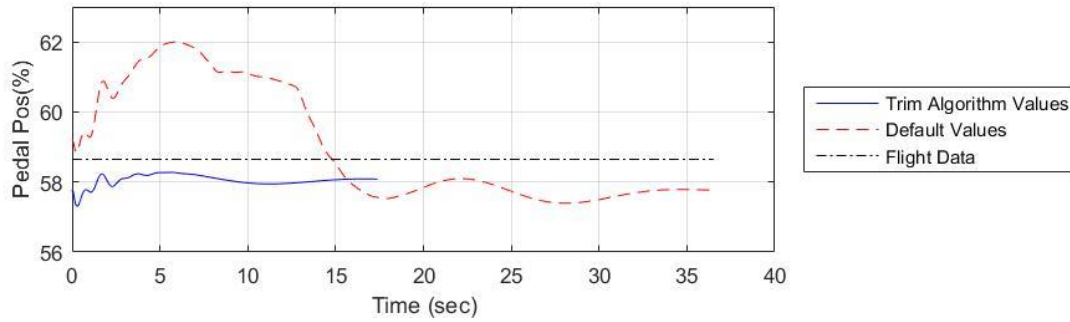Figure 5.e: Longitudinal Position vs Time for trim values

Figure 5.f: Pedal Position vs Time for trim values

Trim algorithm values on the Figure 5 refers to simulation result beginning at the calculated point by using developed trim algorithm. For the rest, autopilot drives the system to obtain exact trim values. Default values refers to trim points which is aimed to be found by autopilot starting with constantly assigned values. Flight data shows trim values of flight test data.

It is easily observed from the presented graphs, using default values take quite more time than using trim algorithm. Due to several assumptions, it is impossible to obtain exact trim points. If trim algorithm values are directly used without tuning by the autopilot, remarkable oscillations are observed in Figures 5.a-f. Especially, Figure 5.e is a good example for the characteristics of the oscillation behavior.

CONCLUSION

The critical main rotor parameters, that are required output for trim algorithm, are determined. Our careful analysis shows there are eleven parameters. In order to obtain parameters, a set of equation is derived. By using this information, the fundamental trim algorithm for a generic helicopter model is developed. This algorithm generates trim values which are used as a starting point for the autopilot to obtain exact trim conditions. Using the autopilot with the

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developed trim algorithm gives invaluable opportunity to obtain trim conditions approximately two times quicker than the case for default values without any remarkable oscillation.

ACKNOWLEDGEMENT

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Appendix

C_D	Drag coefficient
C_T	Thrust coefficient
C_H	Longitudinal force coefficient
C_Y	Lateral force coefficient
Q	Torque
W	Weight
α	Angle of attack
β	Flapping angle, Sideslip angle
$\dot{\beta}$	Flapping rate
$\ddot{\beta}$	Flapping acceleration
β_0	Cone angle
β_{1C}	Longitudinal cone angle

β_{1S}	Lateral cone angle
β_P	Precone angle
μ	Advance ratio
h	Distance between cg and hub plane in z direction
X_{cg}	Distance between cg and hub plane in x direction
Y_{cg}	Distance between cg and hub plane in y direction
Y_F	Lateral force
M_{XF}	Lateral moment
M_{YF}	Longitudinal moment
θ	Blade pitch angle
θ_0	Collective pitch angle
θ_{1C}	Lateral cyclic pitch
θ_{1S}	Longitudinal cyclic pitch
θ_{TR}	Tail rotor blade pitch angle
θ_t	Blade twist
λ	Inflow
ϕ	Roll angle
ψ	Rotor azimuth position
γ	Lock number
σ	Solidity
a	Lift curve slope
ϑ	Flap frequency