
Time domain System Identification of Longitudinal Dynamics of Single Rotor Model Helicopter using SIDPAC

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ABSTRACT

This paper presents a time-domain approach for identification of longitudinal dynamics of single rotor model helicopter. A frequency sweep excitation input signal is applied for hover flying mode using widely used for space state linearized model. A fully automated programmed flight test method provides high quality flight data for system identification using the computer controlled flight simulator X-plane[®]. The flight test data were recorded, analyzed and reduced using the SIDPAC (System Identification Programs for Air Craft) toolbox for MATLAB resulting in an aerodynamic model of single rotor helicopter. Finally, the identified model of helicopter is validated on Raptor 30-class model helicopter at hovering showing the reliability of the proposed approach.

Key Words: Small Model Helicopter, System Identification, X-Plane, SIDPAC, Flight Data.

1. INTRODUCTION

An UAV (Unmanned Aerial Vehicle) is some kind of aircraft or helicopter, which is capable of flying without an on-board human pilot. It may be operated manually from a ground station or it may be autonomous to accomplish the different task without human interaction by means of advanced feedback control systems [1-2]. Unmanned helicopters are well known type of UAVs; and more successful in surveillance, navigations and battle ground application. The helicopter is typical a LTI MIMO (Linear Time Invariant Multi-Input-Multi-Output) nonlinear system having 6DoF (Six Degrees of Freedom) and four control input variables. Accurate dynamical model of helicopter is required for design of stable controller for different flight modes. Generally, two modeling approaches first-principle and system identification

modeling are widely used for helicopters [3-4]. The development of reliable model of a small unmanned helicopter using the first principle approach has been noted to be a challenging task since many unknown parameters are required to be estimate; therefore this method is suitable for full scale helicopters rather than small scale helicopters [5]. System identification modeling divides into time domain and frequency domain techniques. This approach relies on real flight data for obtaining the actual helicopter dynamics. This technique involves the combination of physical insight with system identification technique and readily yields a suitable model for LTI controller synthesis of autonomous helicopter applications [6-7]. In time-domain system identification, a model helicopter can be treated as a SISO (Single Input and Single Output)

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with three independent SISOs system. Among various system identification techniques reported in literatures, the most widely used tools for time-domain system identification are the PEM (Prediction Error Method) and CIPHER (Comprehensive Identification from Frequency Responses) [8-9]. Both methods can be categorized as a parametric estimation problem, where the values of unknown model parameters are required to find in a mathematically derived helicopter model. Both methods used cost function and start with minimizing it using model parameter initial values. The literature did not show the details of obtaining the initial values used to start the parameter estimation problem [10-11]. Ultimately, frequent measurements and experiments are required to obtain these unknown parameters and it is also too weighty and time taking process.

In this paper, an alternative time domain system identification toolbox SIDPAC, is used to identify a model for small rotary wing helicopter comes from X-plane flight simulator. A toolbox SIDPAC is used to estimate the unknown parameters of a model helicopter in combination with OEM (Output Error Method) and EEM (Equation Error Method) for obtaining the initial values. A nonlinear model for small helicopter is used and longitudinal dynamics are obtained using nonlinear equation of motion. The frequency sweep input excitation signal is applied as input because of its adequate acceptance in flight vehicle identification process. The X-plane simulator is used to obtain the experimental flight data and to verify the modeling results because this commercially available simulator gives a better indication of the approach applicability in real-time flight applications. The verification result shows the successful potential of proposed approach in terms of simple and accurate identification methodology.

The organization of paper as follows: Section 2 describes the single rotor model helicopter and the development of the helicopter's longitudinal dynamical model. Section 3 discusses the simulation platform consisting of flight simulator X-Plane and SIDPAC. Section 4 deals with the creation of input frequency sweep signals. Section 5 describes identification strategy using SIDPAC toolbox and lastly identification results and model validation are demonstrated. Finally Section 6 states the conclusion remarks.

2. SINGLE ROTOR MODEL HELICOPTER

The rotor wing unmanned helicopter is a rigid body, therefore using Newton law is used to obtain the 6DoF sub-system. These subsystems can be written and shown in Equations (1-6). These equations of motion for model helicopter are based on dynamics, basic aerodynamics and helicopter theory [12]. Fig. 1 shows the forces and moments of model helicopter.

$$\dot{u} = (vr - wq) - g \sin \theta + \frac{[(x)_{,r} + X_{fus}]}{m} \quad (1)$$

$$\dot{v} = (wp - ur) + g \cos \theta \sin \phi + \frac{[(y)_{mr} + Y_{f,s} + Y_{tr} + Y_{vf}]}{m} \quad (2)$$

$$\dot{w} = (uq - vp) + g \cos \theta \cos \phi + \frac{[(z)_{mr} + Z_{fus} + Z_{ht}]}{m} \quad (3)$$

$$\dot{p} = \frac{qr(I_{yy} - I_{zz}) + ?}{I_{xx}} \quad (4)$$

$$\dot{q} = \frac{rp(I_{zz} - I_{xx}) + ?}{I_{yy}} \quad (5)$$

$$\dot{r} = \frac{pq(I_{xx} - I_{yy}) + ?}{I_{zz}} \quad (6)$$

The main rotor thrust vector, tail rotor thrust vector, fuselage drag, damping forces of the stabilizers and gravitational force are considered as main force production for the helicopter. Four control inputs are observed and defined as $\delta = [\delta_{col}, \delta_{ped}, \delta_{lon}, \delta_{lat}]^T$. The TPP is defined by a and b angles which show the TPP tilt at the longitudinal axis and lateral axis as shown in

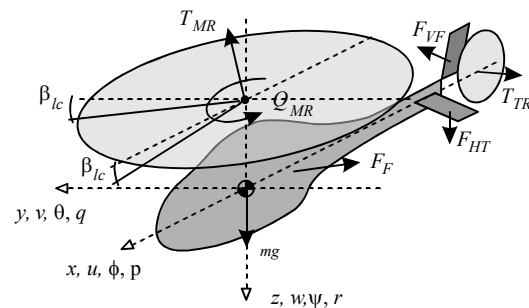


FIG. 1. THE HELICOPTER MODEL SHOWING FORCES AND MOMENTS

Fig. 2. The tip-path-plane model describes the main rotor and the stabilizer bar flapping dynamics as [13]:

$$a = -q - \frac{a}{\tau_f} + \frac{A_{lon}}{\tau_f} \delta_{lon} \quad (7)$$

$$b = -p - \frac{b}{\tau_f} + \frac{B_{lat}}{\tau_f} \delta_{lat} \quad (8)$$

2.1 Longitudinal Dynamics Model

It can be shown that based on rigid body assumption and application of law of conservation of linear and angular momentum, the basic nonlinear Euler-Newton equations of motion describing the longitudinal dynamics of helicopter are given as:

$$\dot{u} = (vr - wq) - F_x^g + \sum \frac{F_x}{m} \quad (9)$$

$$u = (vr - wq) - F_x^g + \sum \frac{F_x}{m} \quad (10)$$

$$\dot{\theta} = q \cos \phi - r \sin \phi \quad (11)$$

And simplified first-order tip-path-plane equation of motion for longitudinal flapping dynamics is given by:

$$\tau_f \dot{a} = -q \tau_f - a + A_b b + A_{lon} \delta_{lon} \quad (12)$$

Where $\tau_f = \frac{16}{\gamma \Omega}$ and $A_b = \frac{16}{\gamma \Omega^2} \frac{k_\beta}{I_\beta}$

Linearization of the model equation is done in order to simplify the analysis about some equilibrium point.

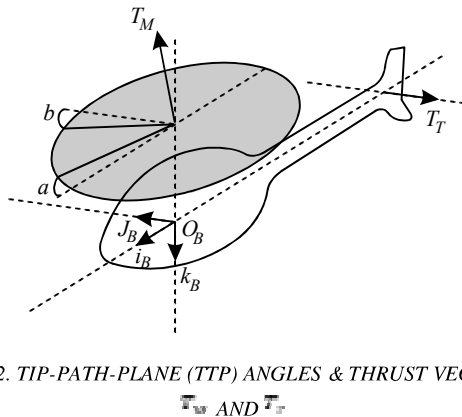


FIG. 2. TIP-PATH-PLANE (TPP) ANGLES & THRUST VECTORS τ_{sw} AND τ_r

Small perturbation theory is used for model equation linearization. The small perturbation theory can be used with sufficient accuracy for response calculations where the disturbances are not infinitesimal [14]. Since for the system identification procedure, hovering flight condition is assumed, therefore the equilibrium values will be:

$$u_0 = q_0 = \theta_0 = 0$$

Assumed all perturbation quantities along with their derivatives are to be small, therefore their squares and products are negligible. Finally linearization of Equations (9-12) yields the parameterized state-space model of the longitudinal dynamics in compact form as:

$$\dot{x} = Ax + B\delta_{lon} \quad (13)$$

And in expanded form as:

$$\begin{bmatrix} \dot{u} \\ \dot{q} \\ \dot{\theta} \\ \dot{a} \end{bmatrix} = \begin{bmatrix} X_u & 0 & -g & -g \\ M_u & 0 & 0 & M_a \\ 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & -\frac{1}{\tau_f} \end{bmatrix} \begin{bmatrix} u \\ q \\ \theta \\ a \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ A'_{lon} \end{bmatrix} \delta_{lon} \quad (14)$$

3. SIMULATION PLATFORM FOR IDENTIFICATION

The simulation platform is implemented using SIDPAC/MATLAB and X-Plane flight simulator developed by Laminar Research. X-plane[®] provides the model of small unmanned helicopter for identification of longitudinal dynamics. Two computers are used for this simulation platform and communication is done through a UDP (User Datagram Protocol) data communication bus.

3.1 X-Plane Flight Simulator

X-plane flight simulator was chosen because it is certified by the FAA (Federal Aviation Administration) to train pilots [15] and its aircraft are extremely accurate which ensures the simulation with high degree of accuracy as an actual flight. It is considered as realistic flight simulator because it incorporates additional features which make it useful for experimenting and validating fixed/rotor wing craft. X-

Plane is not working on stability derivatives to define the flying characteristic of an fixed/rotary wing aircraft as other simulation engines did; instead, it uses actual flow calculations to figure out how the given fixed/rotor wing craft flies in the simulated environment. Raptor-30 V2 model helicopter from X-Plane is used for this work as shown in Fig. 3. The Calibration of this helicopter model is done so that its flight behavior will exactly be similar to the actual flight. However, the yaw rate shows significant sensitivity, this is because of absence of a gyro feedback system.

3.2 SIDPAC

SIDPAC toolbox, [16], written in MATLAB, has been used by Langley Research Center, NASA. Here, it is used to identify state space model of rotor wing helicopter. SIDPAC includes GUI (Graphical User Interfaces) that aid the researcher/analyst in routine tasks such as unit conversion, signal definition, and data compatibility analysis. Fig. 4 represents the GUI in SIDPAC toolbox.



FIG. 3. RAPTOR-30 V2 HELICOPTER IN X-PANE

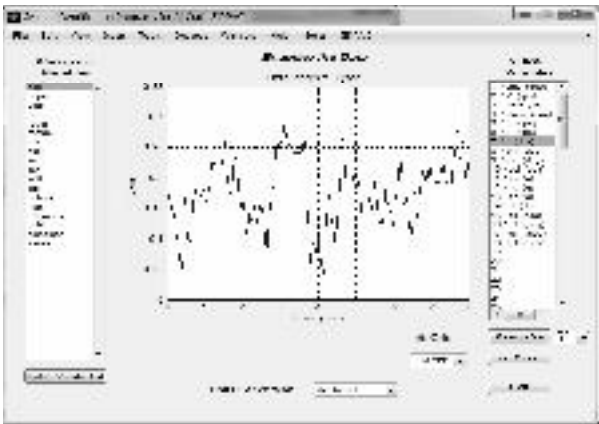


FIG. 4. SIDPAC DATA CHANNEL ASSIGNMENT GUI

4. TIME HISTORY DATA AND FREQUENCY SWEEP INPUTS

The identification process for Raptor-30 V2 starts with the collection of experimental flight data. To ensure the quality of collected flight test data, selection of the input signal is important. A wide variety of frequency excitation signal for aircraft system identification can be found in [9]. A frequency sweep signal is selected in this research for the identification process simply because it is a sinusoidal signal with variable frequency and increases logarithmically with time and due to these characteristics, the desired frequency band can be covered. The amplitude of frequency sweeps are not kept constant due to position sustainability of helicopter around at certain operating flying condition. This frequency signal is applied to one control surface input of helicopter at a time while remaining inputs kept uncorrelated. The frequency sweep input signal requires prior knowledge of frequency bandwidth. According to [15], rotorcraft identification process requires frequency bandwidth lies between 0.3-12 rad/sec. Suppose $[\omega_{min} \omega_{max}]$ are the desired frequency interval, then the maximum will be $T_{max} = 2\pi/\omega_{min}$ and suggested time length equal to $T_{rec} \geq 4 T_{max}$. Then frequency excitation input signal is given by:

$$u = A \sin[\varphi(t)] \quad (15)$$

$$\varphi(t) = \int_0^{T_{rec}} [[\omega]_{min} + K(t)(\omega_{max} - \omega_{min})] dt \quad (16)$$

$$K(t) = C_2 \left[\exp\left\{ \frac{C_1 t}{T_{rec}} \right\} - 1 \right] \quad (17)$$

The suggested value for $C_1=40.0$ and $C_2=0.0187$ are found in [15]. A typical computer simulated frequency sweep input having amplitude equal to one is shown in Fig. 5. The computerized frequency sweeps inputs applied to Raptor-30 V2 are based on Equations (15-17).

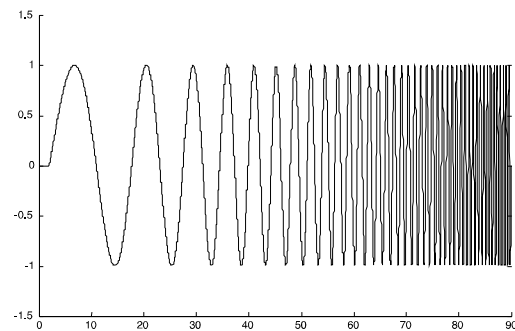


FIG. 5. AUTOMATED FREQUENCY SWEEP INPUT SIGNAL

5. IDENTIFICATION PROCEDURE USING SIDPAC

OEM is applied to estimate the unknown parameters of a space state model helicopter. Initial values can be obtained by EEM. In the longitudinal space state model u, q and δ_{lon} are used to estimate the unknown parameters.

5.1 Output Error Method

OEM is widely used as a parameter estimation method for LTI MIMO aircraft dynamic system. In OEM, cost function is minimized by tuning the model parameter (λ).

$$J(\lambda) = \frac{1}{n} \sum_{i=1}^N \rho(i) \hat{R}^{-1} \rho^T(i) \quad (18)$$

where $\rho(i)$ represents the output error between the model output and measured output and \hat{R} shows covariance matrix of output error. Here in this study, cost function defined as an error between in-flight measured data and simulated data obtained from the identified helicopter model. Further it defined as a function of the parameters such as helicopter aerodynamic stability and control derivatives, sensor bias and sensitivities of the helicopter model. Let ρ is the cost function and Θ represents the vector of parameters to be estimated with L elements, x shows input vector of the system, y represents observations sensor measurement vector. Let $y_{sim}(x_i, \Theta_1, \dots, \Theta_L)$, where $i=1, \dots, N$. Now, next step is to determine the adjustable parameters vector (Θ) such that it minimizes the cost function which is represented by $f=f(y_{sim}(x_i, \Theta_1, \dots, \Theta_L), y)$. The cost function is calculated by least square method using the minimization of sum of the squared error.

5.2 Equation Error Method

The state derivatives are estimated by two ways; either calculated or can be found using numerical differentiation in the space state model of helicopter. In this situation, model unknown parameters is calculated by EEM without considering starting value. Following equation shows this generalization as:

$$\dot{x} = \sum_{j=1}^n \lambda_j^a x_j + \sum_{j=1}^n \lambda_j^b u_j \quad (19)$$

And cost function is representing as:

$$J(\lambda^{a,b}) = \frac{1}{2} \sum_{i=1}^N \delta(i)^T R^{-1} \delta(i) \quad (20)$$

R shows the output error covariance matrix and equation error is given as:

$$\varepsilon(i) = \dot{x} - \sum_{j=1}^n \hat{\lambda}_j^a x_j - \sum_{j=1}^n \hat{\lambda}_j^b u_j \quad i = 1, 2, \dots, N \quad (21)$$

5.3 Identification Results

The data for identification process should cover all the important modes of helicopter's flight dynamics; therefore it is collected from a real-time flight experiment using the Raptor-30 V2 helicopter at hovering as shown in Fig. 6.

The sample input processed data as shown in Fig. 7 for a longitudinal excitation is applied to model helicopter. This data is then used to estimate the unknown parameters of the model. Table 1 shows the identified parameters for longitudinal motion and these are stability derivatives usually expressed in terms of dimensionless aerodynamic coefficient derivatives. Fig. 8 illustrated the comparison results between the predicted and measured outputs for longitudinal velocity motion, rate and angle using the verification data.



FIG. 6. HOVERING STATE OF RAPTOR-30 V2

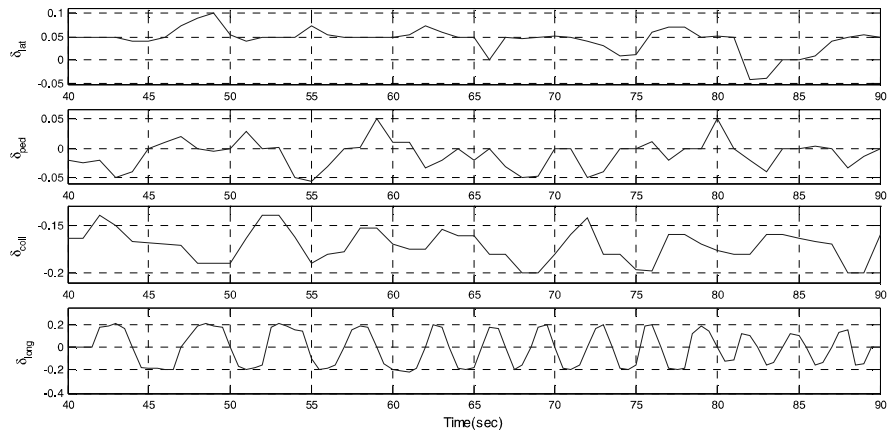


FIG. 7. SAMPLED INPUT SIGNALS FOR THE LONGITUDINAL CHANNEL EXPERIMENT

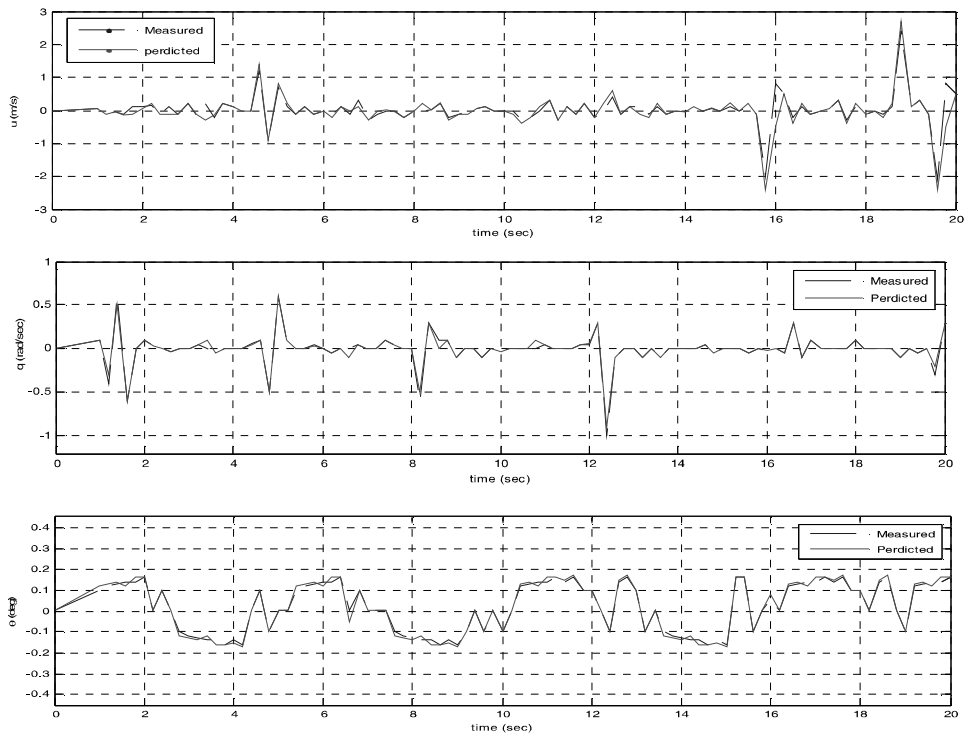


FIG. 8 COMPARISON BETWEEN THE MEASURED (DASHED LINE) AND PREDICTED (SOLID LINE) OUTPUTS FOR LONGITUDINAL VELOCITY MOTION (FIRST) AND RATE (SECOND) AND ANGLE (THIRD) USING THE VERIFICATION DATA

TABLE 1. IDENTIFIED PARAMETERS FOR LONGITUDINAL MOTION

X_u	Force damping derivative caused by longitudinal velocity “ u ”, 1/s	2.38
M_u	Speed stability derivative, rad/ (m s)	-50.8
M_a	Moment “ M ” caused by blade flapping “ a ”	11106
τ_f	main rotor blade constant	-6.57e-4
A'_{ion}	stability derivative to the flapping dynamics	1.20

6. CONCLUSION

The identification of longitudinal dynamics of a single rotor model helicopter using SIDPAC is presented in this study. The frequency sweep input signal was selection for this method which is known as appropriate selection for flight identification. The obtained results show the effectiveness of the proposed identification algorithm. This is expected to simplify the model development stage in the overall

autonomous helicopter development. Because the identification process considers hovering state as a reference flight condition, therefore, the identification is restricted to cover the specific flight envelope. The validation results show the effectiveness and accuracy of the identification method.

7. NOMENCLATURE

O_b, X_b, Y_b, Z_b	BRF (Body Reference Frame)	θ, ϕ, Ψ	Euler Angles
O_g, X_g, Y_g, Z_g	GRF (Ground Reference Frame)	a, b	Tip-Path-Plane flapping angle for longitudinal and lateral
L, M, N	Moments along the BRF	τ_f	main rotor blade constant
F_x	Longitudinal component of external forces	M_y	lateral component of moment
δ_{coll}	collective pitch servo input	δ_{ped}	rudder servo input
δ_{lat}	aileron servo input	δ_{iong}	elevator servo input
A_b	Flapping restraint cross-coupling effect	A_{ion}, B_{lat}	effective steady state lateral and longitudinal gains
p, q, r	Angular helicopter body rates, in Body-Frame	u, v, w	Velocity components relative to air defined in Body-Frame
I_{xx}, I_{yy}, I_{zz}	Moments of inertia about \hat{x}, \hat{y} and \hat{z} - axes.	Ω β	Main/tail rotor rotating speed, Blade flapping angle

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