Integration of Dynamic Inflow Model to Helicopter Dynamics Simulator

Internship Report

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Abstract

The report presents the integration of a dynamic inflow model into a helicopter simulation software previously utilizing a static inflow model. In unsteady dynamic conditions, the buildup of inflow is accompanied by a lag caused by the time required to accelerate the mass of air above the rotor. Thorough Analysis of previous literature pertaining to inflow models, especially those considering dynamic inflow, has been carried out. Following that, the Pitt-Peters dynamic inflow model was implemented to numerically solve for the inflow and determine the resulting loads, thus capturing the helicopter's state during transient responses. Simulation results for collective stick-up and collective stick-dump control inputs are also presented.

1 Introduction

Inflow refers to the air that moves through the rotor system of a helicopter or any rotorcraft. It is the airflow generated as the rotor blades rotate and produce lift. Inflow velocity is the speed at which air moves through the rotor disk. It represents the downward or upward movement of air relative to the rotor, which affects the aerodynamic forces acting on the blades. In general, inflow velocity is a result of the rotor's thrust production, where the rotor draws air from above and accelerates it downward (in hover or vertical ascent). It is directly related to the induced velocity and it can vary depending on the flight conditions. Induced velocity is the downward velocity imparted to the air by the rotor blades of a helicopter or propeller, which creates lift. It is a result of the aerodynamic forces generated by the blades as they rotate and push air downward.

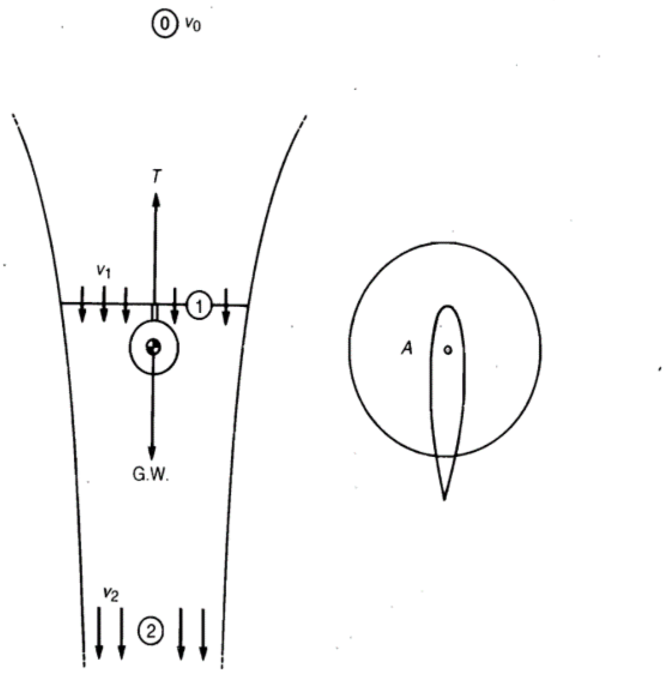


Figure 1: Induced velocities in the vicinity of a hovering rotor

There are two primary categories of inflow, Static and Dynamic:
Static inflow refers to the steady airflow through the rotor disk, typically observed when a helicopter or rotorcraft is in hovering flight or moving at a constant vertical velocity, such as during ascent or descent. Under static inflow conditions, the airflow through the rotor disk does not change with time. The inflow is restricted to only radial and azimuthal variations. This simplifies the aerodynamic

modeling and makes it easier to predict the rotor's performance, as the net forces acting on the blades remain constant with time. However, static inflow models are limited to steady-state conditions and do not account for changes in the airflow when the helicopter is accelerating, decelerating, or responding to dynamic control inputs.
Dynamic inflow, on the other hand, occurs when the airflow through the rotor disk becomes non-uniform and time-dependent, particularly during maneuvering, acceleration, or deceleration. In these cases, the rotor experiences changes in induced velocity across different regions of the rotor disk, leading to a non-steady distribution of airflow. This phenomenon typically arises when the helicopter is transitioning from one flight condition to another or undergoing dynamic changes such as blade flapping, pitch changes, or forward flight. Dynamic inflow is characterized by transient effects where the rotor disk airflow takes time to redistribute, introducing a delay in the rotor's response to control inputs. The non-uniformity of dynamic inflow complicates aerodynamic modeling because the inflow conditions are constantly changing and differ across the rotor disk. This creates variations in the lift and thrust forces generated by the rotor blades, making the helicopter's behavior more difficult to predict.

Analytical Equations for Static Inflow:
Using actuator disc theory the inflow velocity can be obtained as:

$$v_1 = \sqrt{\frac{1}{2\rho}}\sqrt{D.L}$$

where $D.L = \frac{\text{Thrust}}{\text{Disc Area}}$ is the disc loading and ρ is the density of air.

Using blade element theory we can get a more detailed and general view of the induced velocity; one that takes into account variation of blade twist , chord length and the varying speed of blade element with radius. The most general expression for the induced velocity derived in this manner would be:

$$v_1 = \frac{-\frac{\Omega}{2}acb + \sqrt{\left(\frac{\Omega}{2}acb\right)^2 + 8\pi b\Omega^2 ra\theta c}}{8\pi}$$

where Ω is the angular velocity of blade, r is the radial location of blade element, a is the slope of the C_l vs angle of attack curve, b is the number of blades, c is chord length of blade element and θ is the angle of blade twist.

2 Problem Statement

Static inflow models are those that predict the helicopter dynamics using the static inflow equations mentioned above. They don't account for the transient response to dynamic inputs given to the helicopter. Whereas, the dynamic inflow models do account for the transient characteristics. There are multiple models that provide equations which give us the inflow dynamics during the transient stage of the input response. Such models are discussed in the literature review below. The implementation of a dynamic inflow model helps us improve the helicopter dynamics predictions involving an input. The in-house helicopter simulator used a static inflow model which doesn't account for the transient characteristics or the time-wise variation of the inflow. In the case of collective up and dump inputs, the simulations yielded unsatisfactory results. Hence, it was the task to integrate a dynamic inflow model to the simulator to obtain better simulation results, especially during the transient stage of the input response.
In our work, we are implementing the dynamic inflow model to a flight having an advance ratio, which is the ratio of the forward velocity to the blade tip speed, that is negligible. An elaborate explanation of implementation is given later in the Methodology section.

3 Literature Review

Carpenter and Fridovitch, in 1953(Ref. [1]), noticed a time delay in inflow development following rapid changes in collective pitch. Following this, they formulated an apparent mass term to be included with the time derivative of induced flow to account for the time delay based on simple momentum theory. When the rotor is given a positive pitch angle, the induced velocity starts to build up thereby accelerating the mass of air through the rotor. Since a large mass of air has to be accelerated in order to reach the new inflow state, there will be a dynamic lag associated with the build up of the inflow. The time constant associated with this build up is calculated based on the apparent mass terms. The thrust during the unsteady conditions for a flapping blade can then be written as

$$T = m\dot{v} + 2\pi R^2 \rho v \left(v + V_v + \frac{2}{3}\dot{\beta}R \right)$$

where v is the instantaneous induced velocity, m is the apparent mass, R is the rotor radius, ρ is the density of air flowing, β is the blade flap angle and V_v is the vertical velocity of the rotor hub. The apparent mass term was defined to be 63.7% of the air mass of the circumscribed sphere of the rotor.

Pitt and Peter(Ref. [2]) developed a dynamic inflow model based on unsteady actuator-disc theory. The model relates the transient rotor thrust, pitch and roll moments to the transient response of the rotor inflow. The model in hover is identical to Carpenter and Fridovitch's model with the only exception that the apparent mass is smaller by almost 64%. The model is represented by the following first order, linear differential equation,

$$\begin{bmatrix} M \end{bmatrix} \dot{\begin{bmatrix} \lambda_o \\ \lambda_s \\ \lambda_c \end{bmatrix}} + \begin{bmatrix} L \end{bmatrix}^{-1} \begin{bmatrix} \lambda_o \\ \lambda_s \\ \lambda_c \end{bmatrix} = \begin{bmatrix} \Delta C_T \\ \Delta C_L \\ \Delta C_M \end{bmatrix}$$

where ΔC_T, ΔC_L , ΔC_M are the aerodynamic perturbation in thrust, roll moment and pitch moment coefficients and λ_o, λ_s, λ_c are the magnitudes of uniform, side to side, and fore to aft perturbations in inflow. Note that the thrust, roll moment and pitch moment coefficients refer to aerodynamic components only. $\begin{bmatrix} L \end{bmatrix}$ is the static coupling matrix between the inflow components and the aerodynamic loads. $\begin{bmatrix} M \end{bmatrix}$ is the apparent mass matrix. The total induced flow perturbation($\bar{\lambda}_i$) is given as,

$$\bar{\lambda}_i = \lambda_o + \lambda_s r \sin(\psi) + \lambda_c r \cos(\psi)$$

where r is the non dimensional radial distance and ψ is the azimuth angle as shown in Fig 2. This perturbation value can be added to the previous induced flow value to obtain the value at present.

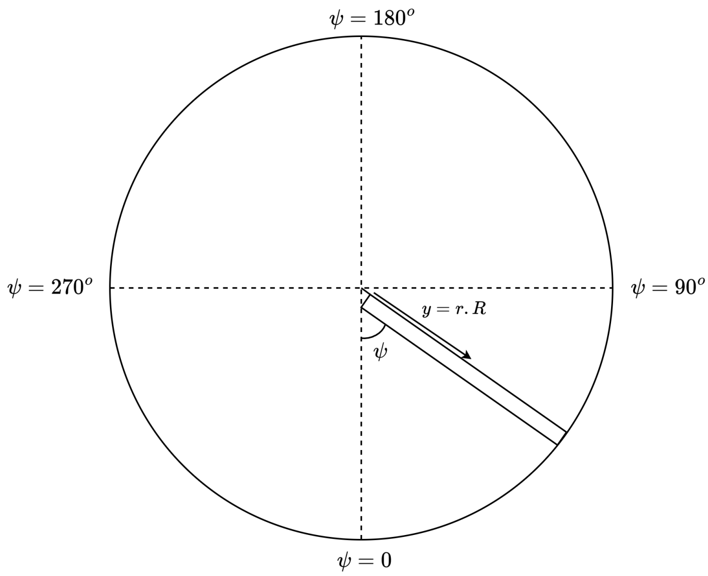


Figure 2: Diagram of Rotor Disc Plane

The $\left[L\right]$ and $\left[M\right]$ matrix are given as follows:

$$\left[L\right] = \frac{1}{V}\begin{bmatrix} \frac{1}{2} & 0 & \frac{15\pi}{64}\sqrt{\frac{1-\sin(\alpha)}{1+\sin(\alpha)}} \\ 0 & \frac{-4}{1+\sin(\alpha)} & 0 \\ \frac{15\pi}{64}\sqrt{\frac{1-\sin(\alpha)}{1+\sin(\alpha)}} & 0 & \frac{-4\sin(\alpha)}{1+\sin(\alpha)} \end{bmatrix}$$

$$\left[M\right] = \begin{bmatrix} \frac{128}{75\pi} & 0 & 0 \\ 0 & -\frac{16}{45\pi} & 0 \\ 0 & 0 & -\frac{16}{45\pi} \end{bmatrix}$$

α is defined as the wake skew angle at the rotor and is given by

$$\alpha = \tan^{-1}\left(\frac{\lambda}{\mu}\right)$$

where μ is the advance ratio and λ is the non dimensional vertical flow velocity at the rotor hub (note that V_∞ is normalized with tip speed), ie,

$$\lambda = \lambda_i(\text{total induced velocity}) + V_\infty \sin(\alpha)$$

and V is the total non dimensional velocity at the rotor hub given by

$$V = \sqrt{\mu^2 + \lambda^2}$$

$[\tau] = [L][M]$ is the matrix of time constants associated with the build up of induced flow following changes in rotor state.

4 Methodology

We intend to integrate the Pitt-Peter inflow model into the indigenously developed helicopter dynamics software. The implementation will be on flying scenarios with the advance ratio close to zero. As a result, we may consider $\alpha = 0$ and $\mu = 0$ which gives the $[L]$ matrix for vertical flight as,

$$\left[L\right] = \frac{1}{V}\begin{bmatrix} \frac{1}{2} & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & -2 \end{bmatrix}$$

The $[M]$ matrix is considered as given in the previous section. The inflow perturbations are calculated using the Pitt-Peter model at each time step and is added to the total induced velocity obtained for the previous time step. When entering the control response loop, the states along with inflow and load values are intitialized with results from the static model at hover. Once the loop is entered, thrust and moment coefficient values are calculated based on the previous states, inflow and current control input values. The calculated coefficients are used to determine the perturbation values that are input to the Pitt-Peter model. The model outputs the inflow derivative which is then used to obtain the current induced flow velocity thereby allowing to determine the rotorcraft loads and states at the current time step. There is an inner loop which continues corresponding the calculation of loads and states until the next time step of the control response is encountered. Once the time corresponds to the next time step of the control input, its value is updated and the loop is repeated.

The flowchart for the algorithm implemented for obtaining the response to control input is shown in Fig 3. The control input(denoted as θ) is provided as values at discrete time intervals with the time step size denoted as dt_θ. The Runge-Kutta 4th order method is used in solving for dynamic inflow numerically. The time step size(denoted as dt_λ) chosen is at least an order of magnitude lesser than dt_θ for accurate dynamic modelling of the transient state. n is time step count for the control input and θ_n denotes the control input value at the n^{th} time step of the control input. i is the time step count of the numerical method used. The subscript i(in case of induced velocity λ_i, the sub-subscript) therefore denotes the corresponding value at the i^{th} time step, ie, at time idt_λ.

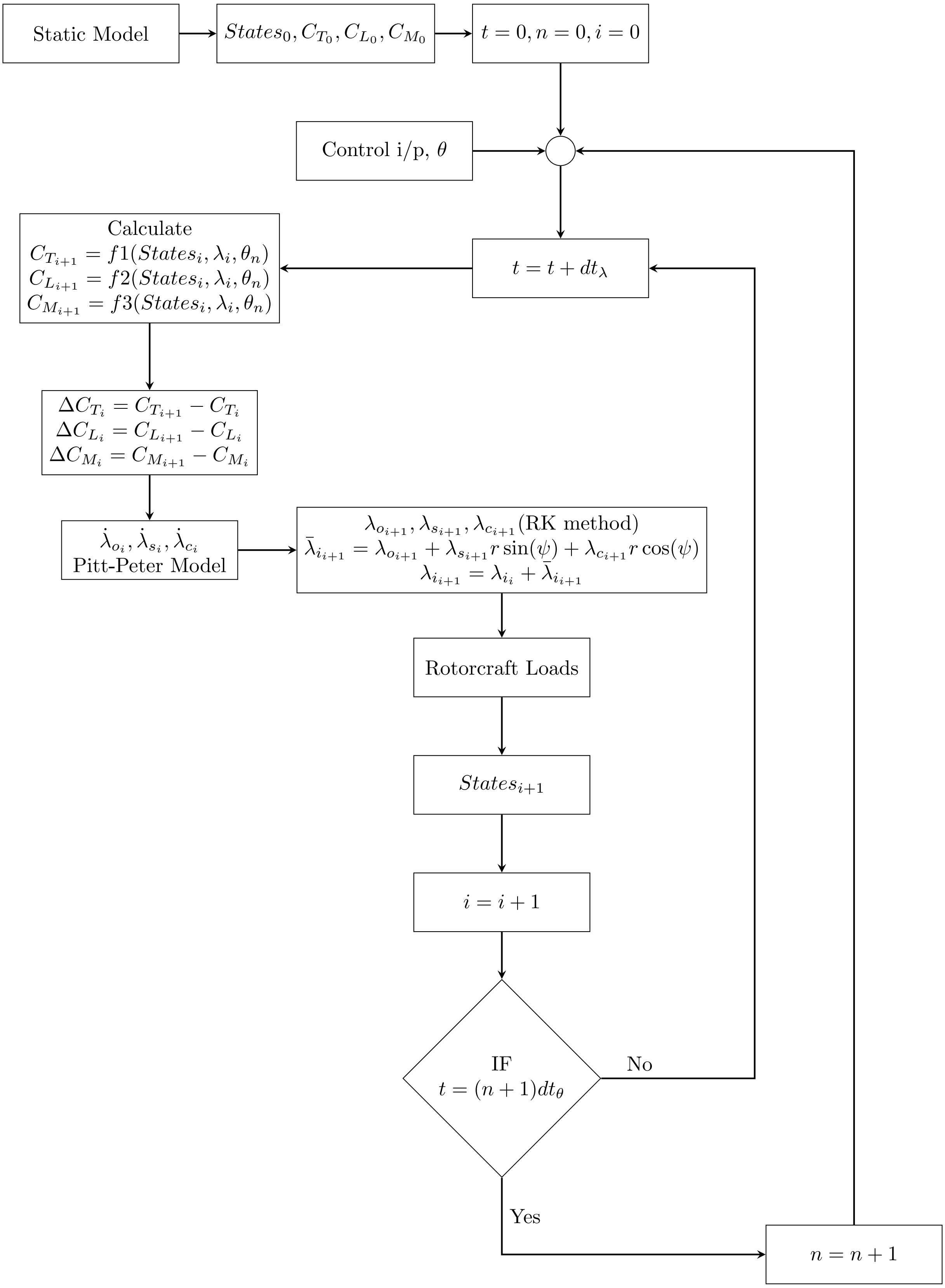
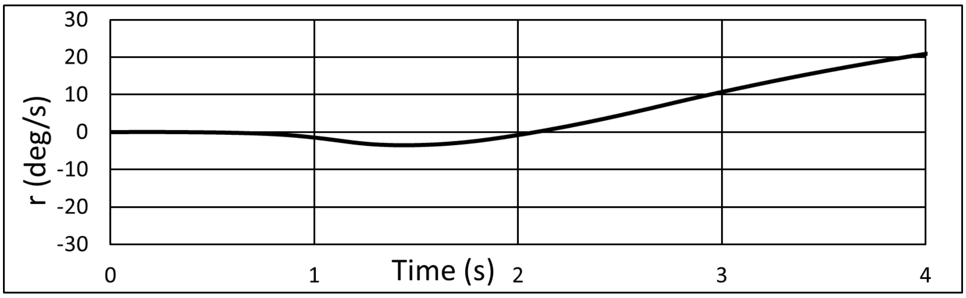


Figure 3: Control Response Flowchart

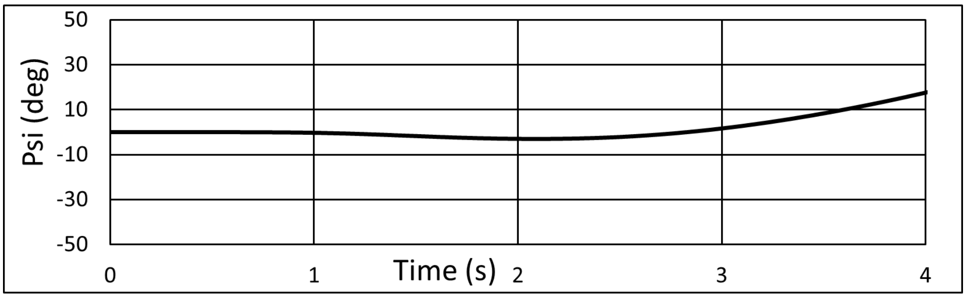
5 Results

Collective-Stick-Up:

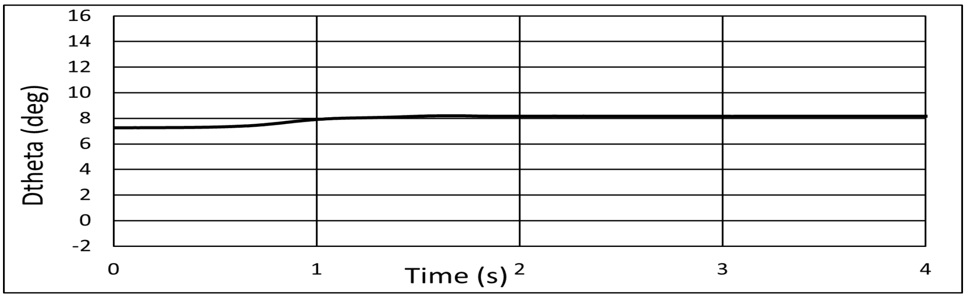
Under a collective-stick-up input, the simulation of the modified software for helicopter dynamics provided the following outputs(refer Fig 4). The time step of the numerical calculation of the dynamic inflow taken here was 0.001 seconds.



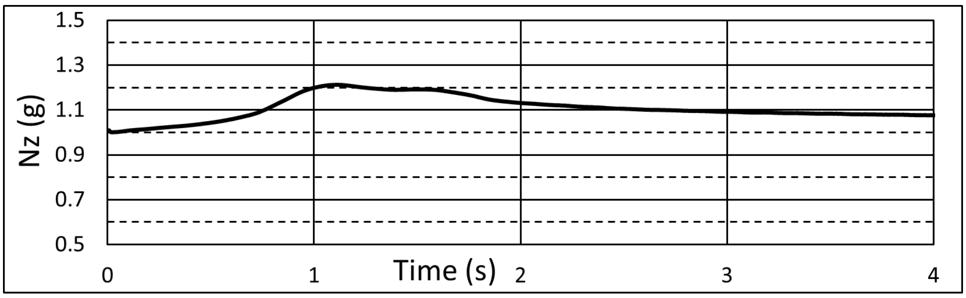
(a) Yaw Rate vs Time



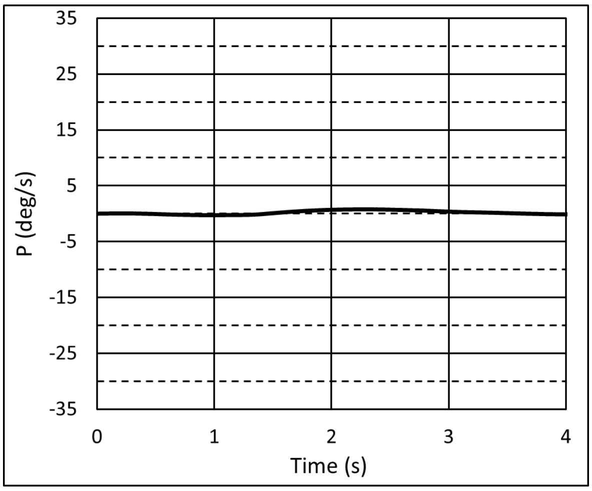
(b) Yaw Angle vs Time



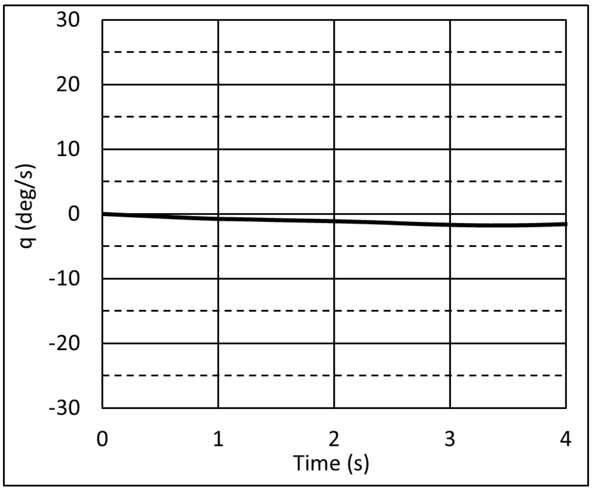
(c) Collective Pitch vs Time



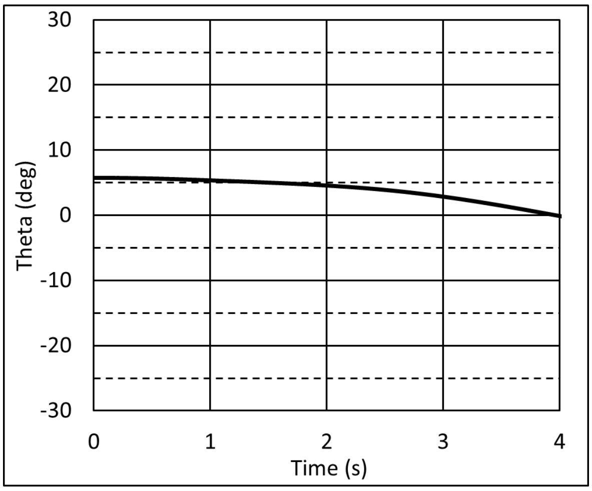
(d) Load Factor vs Time



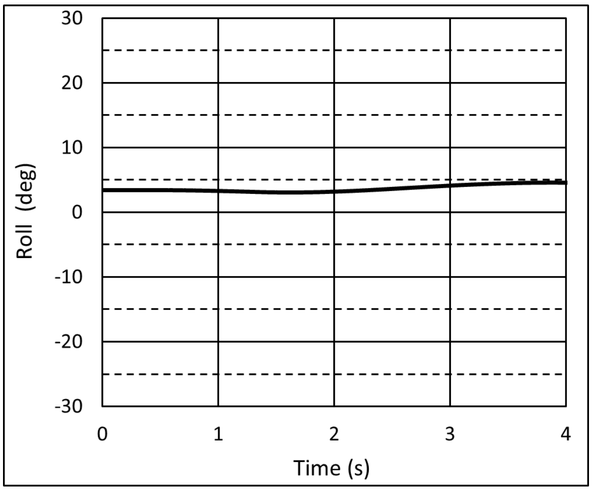
(e) Roll Rate vs Time



(f) Pitch Rate vs Time



(g) Pitch Angle vs Time

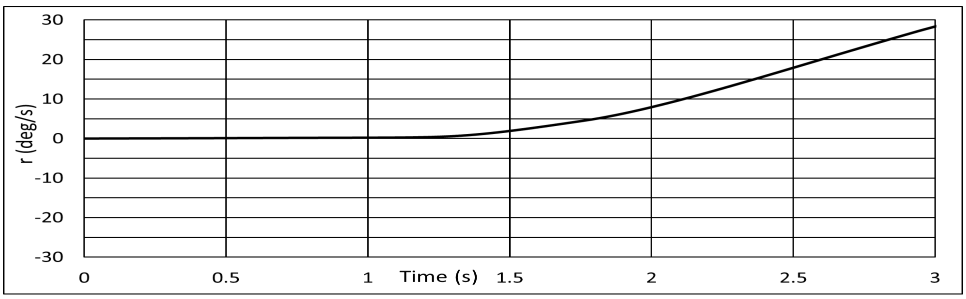


(h) Roll Angle vs Time

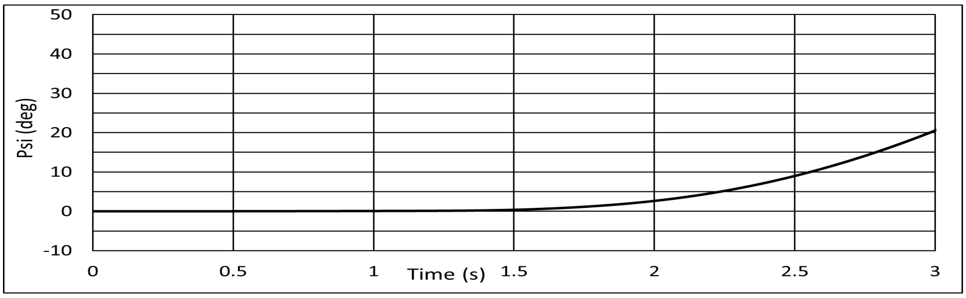
Figure 4: Simulation Results for Collective Stick Up Input

Collective-Stick-Dump:

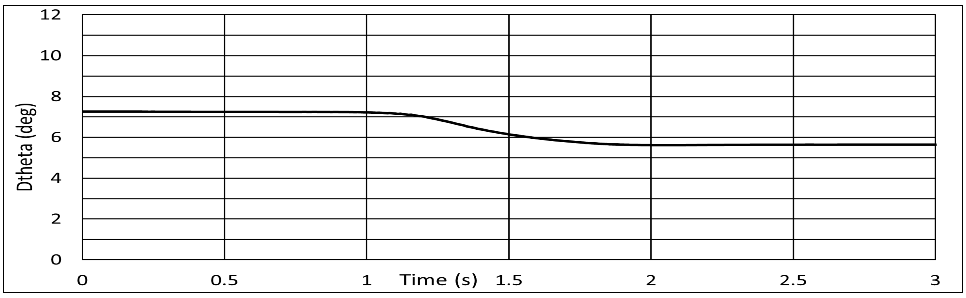
Similarly, under a collective-stick-dump input, the simulation provided the following outputs(refer Fig 5). The time step of the numerical calculation of the dynamic inflow taken here too was 0.001 seconds.



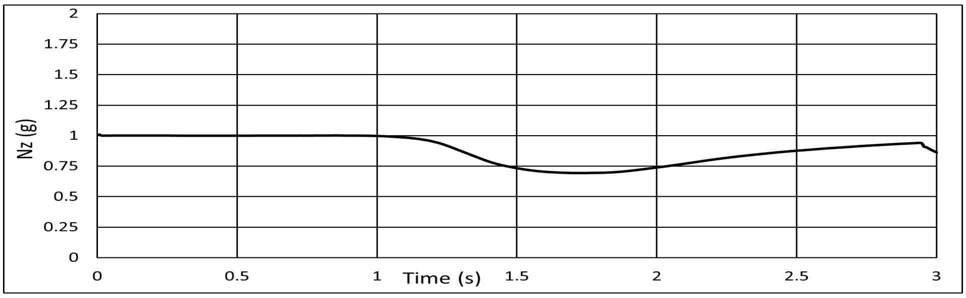
(a) Yaw Rate vs Time



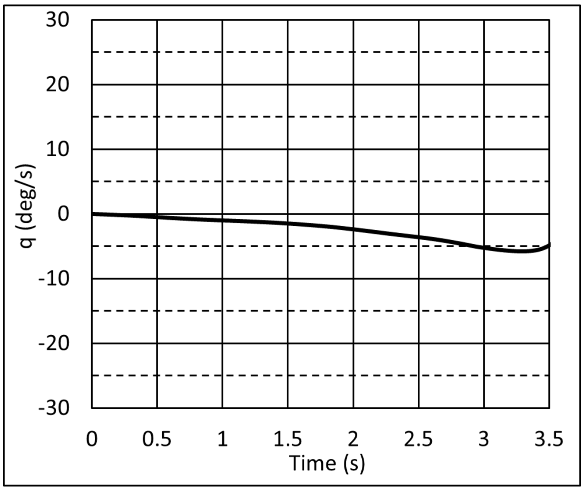
(b) Yaw Angle vs Time



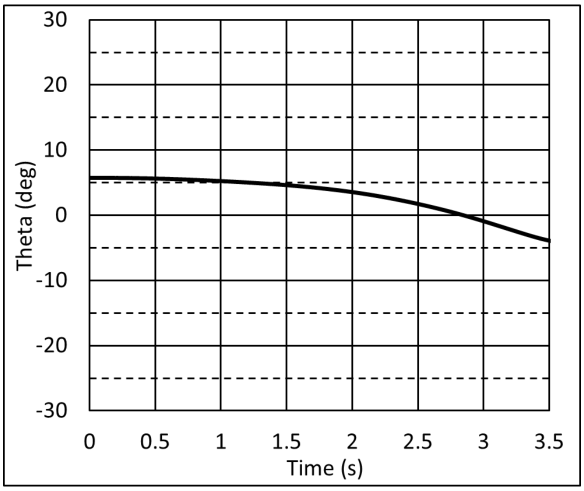
(c) Collective Pitch vs Time



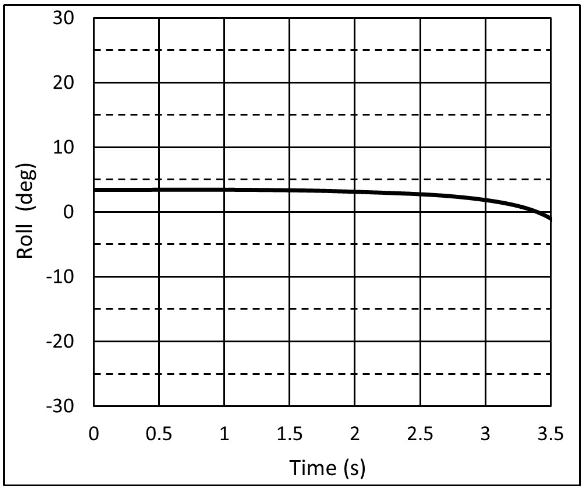
(d) Load Factor vs Time



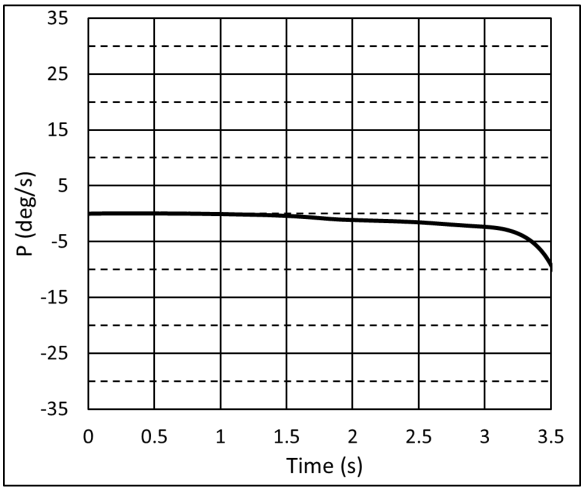
(e) Pitch Rate vs Time



(f) Pitch Angle vs Time



(g) Roll Angle vs Time



(h) Roll Rate vs Time

Figure 5: Simulation Results for Collective Stick Dump Input

6 Conclusion

The Pitt and Peters Dynamic inflow model was incorporated into the indigenous helicopter dynamics simulator. On validation of the simulation results obtained, of that of a collective-stick-up and collective-stick-dump input, with the already existing flight test data, appreciable conformance was not obtained. But, the modified helicopter dynamics simulator would provide a base for future works targeting the betterment of the simulator, considering dynamic inflow, so that it can provide a more acceptable conformance to the flight test data. The project provided meaningful insights into the dynamic modeling of helicopters and the development of simulation software to reflect these dynamics. It introduced advanced concepts of dynamic inflow, deepening our understanding of how a complex machine like a helicopter behaves during transient states caused by control inputs.

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