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Modification of a Helicopter Inverse Simulation to Include an Enhanced Rotor Model

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Nomenclature

h	maximum manoeuvre height	(m)
I_R	effective inertia of the main rotor	(kg m^2)
k	current solution time point	
K_3	engine model gain	
n_{pts}	number of points in inverse simulation / manoeuvre	
r	fuselage yaw rate	(rad / s)
Q_E	engine torque	(N m)
Q_R	main rotor torque	(N m)
Q_{TR}	tail rotor torque	(N m)
Q_{tr}	transmission torque	(N m)
t	time	(sec)
t_k	time point in inverse simulation / manoeuvre definition	
t_m	time taken to complete a manoeuvre	(sec)
$\mathbf{u}$	control vector	
x_e, y_e, z_e	displacements relative to an earth fixed inertial frame	(m)
$\mathbf{y}$	output vector	(units vary)
$\mathbf{y}_{des}$	desired output vector	(units vary)
Δt	inverse simulation / manoeuvre discretisation interval	(sec)
θ_0	main rotor collective pitch angle	(rad)
θ_{1s}, θ_{1c}	main rotor longitudinal and lateral cyclic pitch angles	(rad)
θ_{0tr}	tail rotor collective pitch angle	(rad)
τ_{e1}, τ_{e2}, τ_{e3}	engine time constants	(sec)
Ω	main rotorspeed	(rad / s)
Ω_i	idling rotorspeed	(rad / s)
ψ_{azi}	blade azimuth angle	(rad)
ψ	heading	(rad)
V_f	aircraft flight velocity	(m / s)

I. Introduction

An individual blade rotor model has been developed at the University of Glasgow by Rutherford and Thomson[1] for use in helicopter inverse simulation. In the context of helicopter flight dynamics an inverse simulation generates the control displacement time histories for the modelled helicopter performing a defined task. In order to implement such a model in an inverse sense, it is necessary to adopt a numerical integration technique similar to that proposed by Hess et al[2]. The inverse algorithm used by Rutherford and Thomson, known as Genisa (GENeric Inverse Simulation Algorithm), is described in detail in [1] where the problem of numerical stability is also addressed.

The helicopter individual blade rotor model, Hibrom, represents the state-of-the-art in helicopter inverse simulation. Some simplifying assumptions were made in its development, most significantly the assumption of constant rotorspeed (conclusions, [1]). In reality, changes in blade pitch and hence blade aerodynamic drag will lead to changes in demanded torque and hence a continuous variation in rotorspeed. It is important to model this degree of freedom, since it has a direct influence on the dynamic behaviour of the main rotor. In addition, the inclusion of rotorspeed degree of freedom must be achieved before other modelling features, such as lead/lag freedom, can be incorporated.

This technical note describes modifications made to the inverse algorithm Genisa which allow the rotorspeed degree of freedom to be incorporated within Hibrom.

II. Generic Inverse Simulation Algorithm: Genisa

The integration-based inverse solver, Genisa, is essentially a modification of that documented by Hess et al[2] and is driven by specified manoeuvre constraints. The starting point is therefore a mathematical definition of the desired flight path to be followed by the subject vehicle. Genisa operates by constraining the helicopter's earth-referenced accelerations along with one attitude (heading in the case of a longitudinal manoeuvre) and so the desired output vector $\boldsymbol{y}_{des}$ is evaluated for a series of n_{pts} discrete time points:

$$y_{des}(t_k) = \{\ddot{x}_e(t_k) \quad \ddot{y}_e(t_k) \quad \ddot{z}_e(t_k) \quad \dot{\psi}(t_k)\}^T; \qquad (1)$$
$$0 \le t_k \le t_m, \quad k = 1, n_{pts},$$

where t_m is the time taken to complete the manoeuvre.

The Genisa algorithm then proceeds by making an initial estimate of the applied control inputs which, over a predefined time increment, will move the helicopter to its desired location. These control displacements are applied to the helicopter model and the equations of motion solved by numerical integration to obtain the helicopter's actual states at the next time point. An iterative scheme is then set up whereby control displacements are adjusted until the error between desired and actual outputs is within a prescribed tolerance. This process is repeated for each time interval, yielding a control time history $\boldsymbol{u}(t_k)$ for the complete manoeuvre, where:

$$\boldsymbol{u}(t_k) = \{\theta_0(t_k) \quad \theta_{1s}(t_k) \quad \theta_{1c}(t_k) \quad \theta_{0tr}(t_k)\}^T. \qquad (2)$$

The success of the method outlined above relies on the selection of a suitable time step, Δt, over which the applied controls are to be held constant. The rotor forces and moments are calculated by integrating elemental forces over the span of each blade. As the velocity at each spanwise location varies as the blade rotates, the total force calculated is harmonic with period equal to a complete revolution of the blade (or $1/n$ revolutions of an n-bladed rotor). For the Genisa/Hibrom inverse simulation the time step Δt is therefore chosen to match an integer number of main rotor periods, thereby accommodating the rotor periodicity which is inherent in the individual blade rotor model. Unfortunately, this requires the assumption of constant rotorspeed to be made. In the following section, modifications to the Genisa algorithm will be described which eliminate the necessity to constrain rotorspeed, thereby allowing an engine governor model to be included in Hibrom.

III. Enhanced Genisa/ Hibrom Inverse Simulation

A Description of the Engine Governor Model

Variations in rotorspeed due to changes in torque demand are sensed by an engine governor. The governor then attempts to redress the imbalance by demanding a suitable change in fuel flow, thereby increasing or decreasing the engine torque output as required. Naturally there is a lag between the rotorspeed change and the resulting torque change and hence the rotorspeed is a degree of freedom within the system. Hibrom has been modified to include a simple model of the engine governor which is essentially that given by Padfield[3] and is described briefly here.

Rotorspeed, Ω, is related to the engine torque output, Q_E, by the equation:

$$\dot{\Omega} = \left(\frac{1}{I_R}\right)\left(Q_E - Q_R - Q_{TR} - Q_{tr}\right) + \dot{r}. \tag{3}$$

The overall engine torque response to a change in rotorspeed is then given by the 2nd order, nonlinear differential function:

$$\ddot{Q}_E = \frac{1}{\tau_{e1}\tau_{e3}}\left[-\left(\tau_{e1} + \tau_{e3}\right)\dot{Q}_E - Q_E + K_3\left(\Omega - \Omega_i + \tau_{e2}\dot{\Omega}\right)\right]. \tag{4}$$

The lead and lag time 'constants', τ_{e2} and τ_{e3}, are in fact functions of engine torque, introduced in transfer functions representing the demanded fuel flow change in response to a change in rotorspeed and the resulting engine torque response.

Equations (3) and (4) are now included in the main rotor model, Hibrom, resulting in three additional degrees of freedom corresponding to Ω, Q_E and $\dot{Q}_E$.

B Modifications to the Genisa Algorithm

As discussed in section II, the periodic nature of the rotor forcing requires that the solution time interval matches an integer number of main rotor periods (i.e. a quarter turn for a 4 bladed rotor). Assuming constant rotorspeed, this interval can be conveniently fixed throughout the simulation. The existing Genisa algorithm typically requires a time consistent with one half turn of the main rotor, which Rutherford[4] found to be "sufficiently long to allow the transient dynamics to settle". Once this discretisation interval has been established, the desired output can be calculated at each time point and used as input to Genisa.

With the introduction of the rotorspeed degree of freedom, the period of the main rotor is no longer fixed and hence the solution interval must vary throughout the simulation. Consequently, the desired flight path can no longer be determined independently of the main program and the time required to complete the manoeuvre will not be known *a priori.*

This problem is overcome by expanding the control vector, $\boldsymbol{u}(t_k)$, to include an estimate of the next time point which will allow sufficient time for the rotor blades to sweep out the desired azimuth. The estimate is based on the value assigned to rotorspeed at the current time point. Similarly, the output vector $\boldsymbol{y}(t_k)$ will now include blade azimuth. The augmented control and output vectors are then given by:

$$\boldsymbol{u}(t_k) = \{\theta_0(t_k) \quad \theta_{1s}(t_k) \quad \theta_{1c}(t_k) \quad \theta_{0tr}(t_k) \quad t_{k+1}\}^T \tag{5}$$

$$\boldsymbol{y}(t_k) = \{\ddot{x}_e(t_k) \quad \ddot{y}_e(t_k) \quad \ddot{z}_e(t_k) \quad \dot{\psi}(t_k) \quad \psi_{azi}(t_k)\}^T \tag{6}$$

The next time point, t_{k+1}, is determined such that the error between the actual and desired blade azimuth is minimised.

An inverse simulation uses a mathematical definition of the task which is to be performed. Effectively equation (6) has to be specified. If we consider the case of a hurdle-hop manoeuvre (employed in terrain following flight), then we can say

$$\begin{aligned} z_e(t) &= 64h\left[\left(\frac{t}{t_m}\right)^3 - 3\left(\frac{t}{t_m}\right)^2 + 3\left(\frac{t}{t_m}\right) - 1\right]\left(\frac{t}{t_m}\right)^3 \\ y_e(t) &= 0 \\ \psi(t) &= 0 \end{aligned} \tag{7}$$

and obtain $x_e(t)$ from

$$\dot{x}_e(t) = \sqrt{V_f(t)^2 - \dot{z}_e(t)^2} \tag{8}$$

where V_f is often simply a constant. The choice of a polynomial function is mainly on the grounds of simplicity, however studies have shown[5] that these simple profiles are sufficient to capture the principal features of the manoeuvre. When the rotorspeed was fixed the manoeuvre time t_m was chosen to coincide with a whole number of rotor periods. With the rotor period no longer held constant, the procedure is to estimate the total manoeuvre time t_m, thereafter evaluating the desired output vector at each time point in turn, until t_m has been exceeded. The rotor model is therefore enhanced by including an engine governor model and hence the rotorspeed degree of freedom, at the expense of a small loss of accuracy in the manoeuvre definition.

IV. Results

The enhanced individual blade rotor model with rotorspeed degree of freedom has been validated against flight data for a quick-hop manoeuvre. The results of this validation exercise are not presented since they are very similar to those previously documented in [1]. In both cases, the simulation successfully captures the overall trend in each variable, although some peak values are significantly underpredicted. A more detailed discussion of the validation process can be found in [1].

To ensure that the new algorithm has been implemented correctly, results can be obtained with the engine equations (3) and (4) disabled. The rotorspeed and engine states $\left(\Omega, \quad Q_E, \quad \dot{Q}_E\right)$ are thus constrained, isolating the operation of the new algorithm from any modifications made to the model. It was confirmed in this way that changes made to the existing Genisa algorithm do not affect the verity of the solution.

With some confidence in the validity of the rotor model and confirmation that the algorithm is operating satisfactorily, it is now possible to examine the effect of including rotorspeed as a degree of freedom within the modelled system. The inverse simulation of a hurdle-hop manoeuvre is considered whereby the pilot's task is to clear a 5m high obstacle and return to the original altitude over a distance of 150m. A constant forward speed of 40 knots is maintained and the obstacle is assumed to be located at the mid-point of the manoeuvre as shown in Fig. 1. The results in Figs. 2 and 3 are compared directly with those obtained using the original Hibrom model without rotorspeed degree of freedom. The two sets of results are qualitatively similar, although the addition of an engine governor model with rotorspeed degree of freedom has clearly influenced the magnitude of the controls. In particular, the trim values calculated by the new model are higher than before. The new Genisa/Hibrom inverse simulation predicts a greater range of control movements necessary to fly the specified manoeuvre and it may be expected that a greater difference between the two sets of results will be observed for more severe manoeuvres.

In the results shown here a solution time interval corresponding to two turns of the main rotor was used, $\Delta t_k = \dfrac{4\pi}{\Omega_k}$. Physically, a step input is made in each of the four controls which are then held constant over this period. When the frequency of control application is increased to once per revolution of the main rotor the results deteriorate, with unstable oscillations developing in the lateral cyclic control and engine torque derivative, as shown in Figs. 4 and 5. Furthermore, the simulation will not perform with a solution interval corresponding to one half turn of the rotor. The most likely explanation of this behaviour is that a minimum interval corresponding to two turns of the main rotor is required to allow the transient engine dynamics to settle down towards a new steady state following each application of the controls. The time constant associated with a first order approximation to the engine governor model is typically 0.397 seconds. This is more than double the time interval of 0.1755 seconds, which corresponds to one full turn of the main rotor. This explanation can be verified by reducing the engine model time constants τ_{e1}, τ_{e2} and τ_{e3} to 1% of their nominal values. The results improve and a control application interval of once per revolution produces smooth control time histories and engine states.

V. Conclusions

An engine governor model has been successfully incorporated into the individual blade rotor model, Hibrom, for helicopter inverse simulation. Hence the rotorspeed is now a degree of freedom within the modelled system.

A series of modifications have been made to the solution algorithm, Genisa, to accommodate the variation in rotorspeed. In particular, the control application interval is now re-calculated iteratively at each time step. This is necessary in order to match the rotor periodicity which is inherent in the individual blade rotor model. In addition, the control application interval must be sufficiently long to allow the transient dynamics to settle; otherwise algorithm failure can occur.

The addition of rotorspeed degree of freedom does not significantly affect the predicted control time histories for the manoeuvre considered in this study. However, as the boundaries of the flight envelope are approached, it may be expected that the enhanced rotor model will be closer to predicting actual flight behaviour. Furthermore, with the introduction of rotorspeed degree of freedom it will now be possible to improve simulation fidelity by including other blade degrees of freedom.

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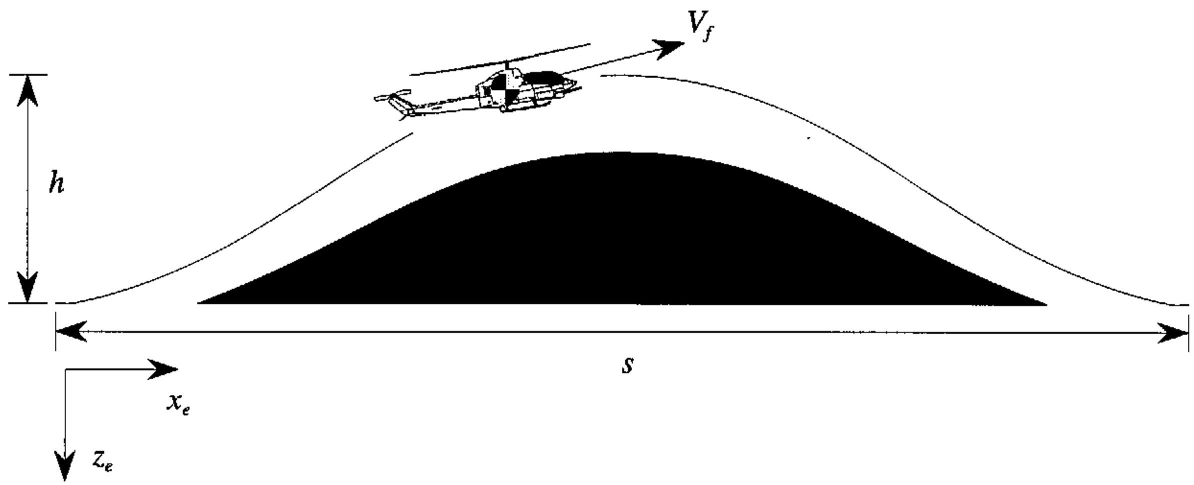

Figure 1 <u>**The Hurdlehop Manoeuvre**</u>

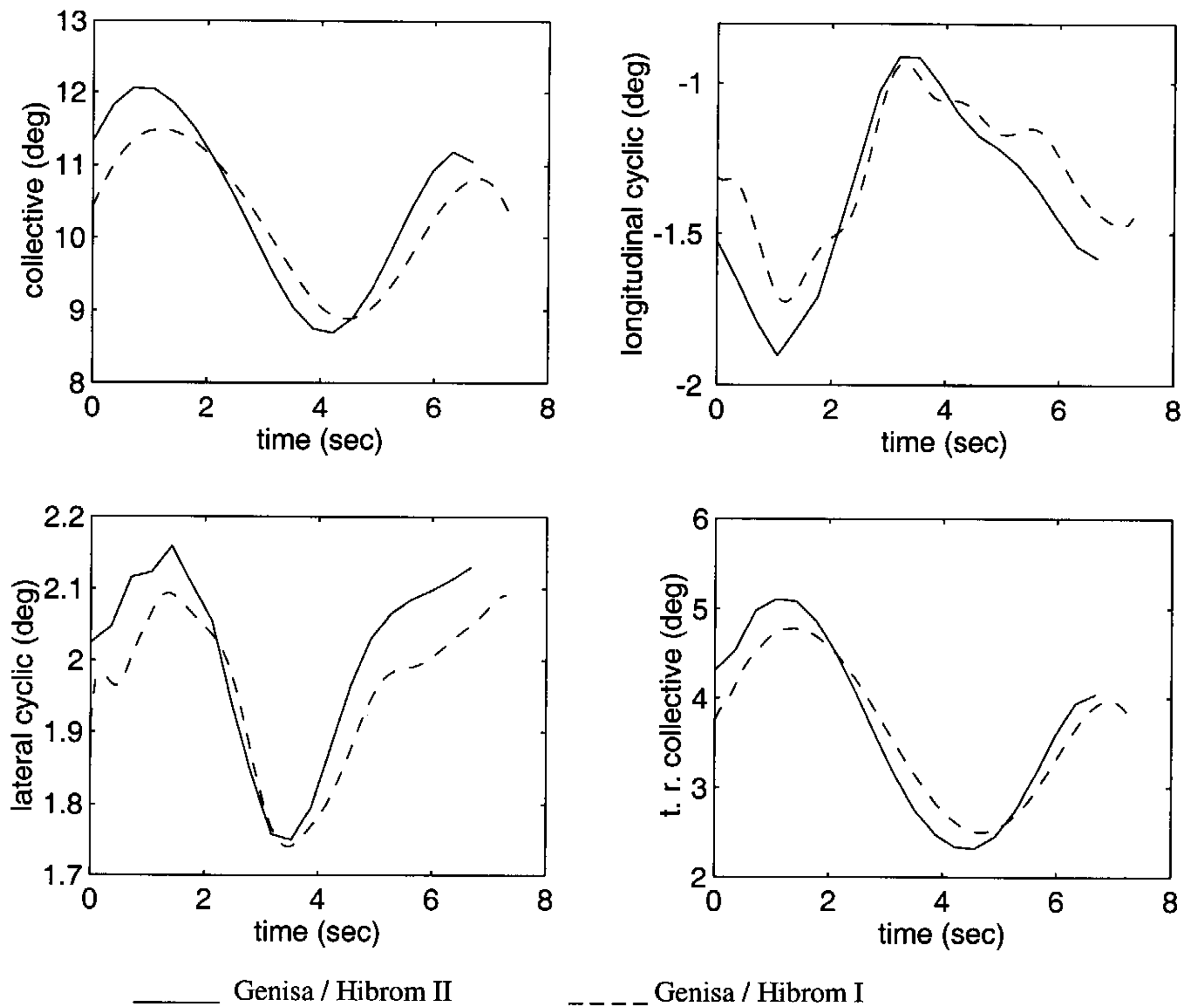

Figure 2 **Comparison between inverse simulation results generated by Genisa / Hibrom I and II (hurdlehop: V_f=40kts, h=5m, s=150m). Time step: 2 turns of main rotor**

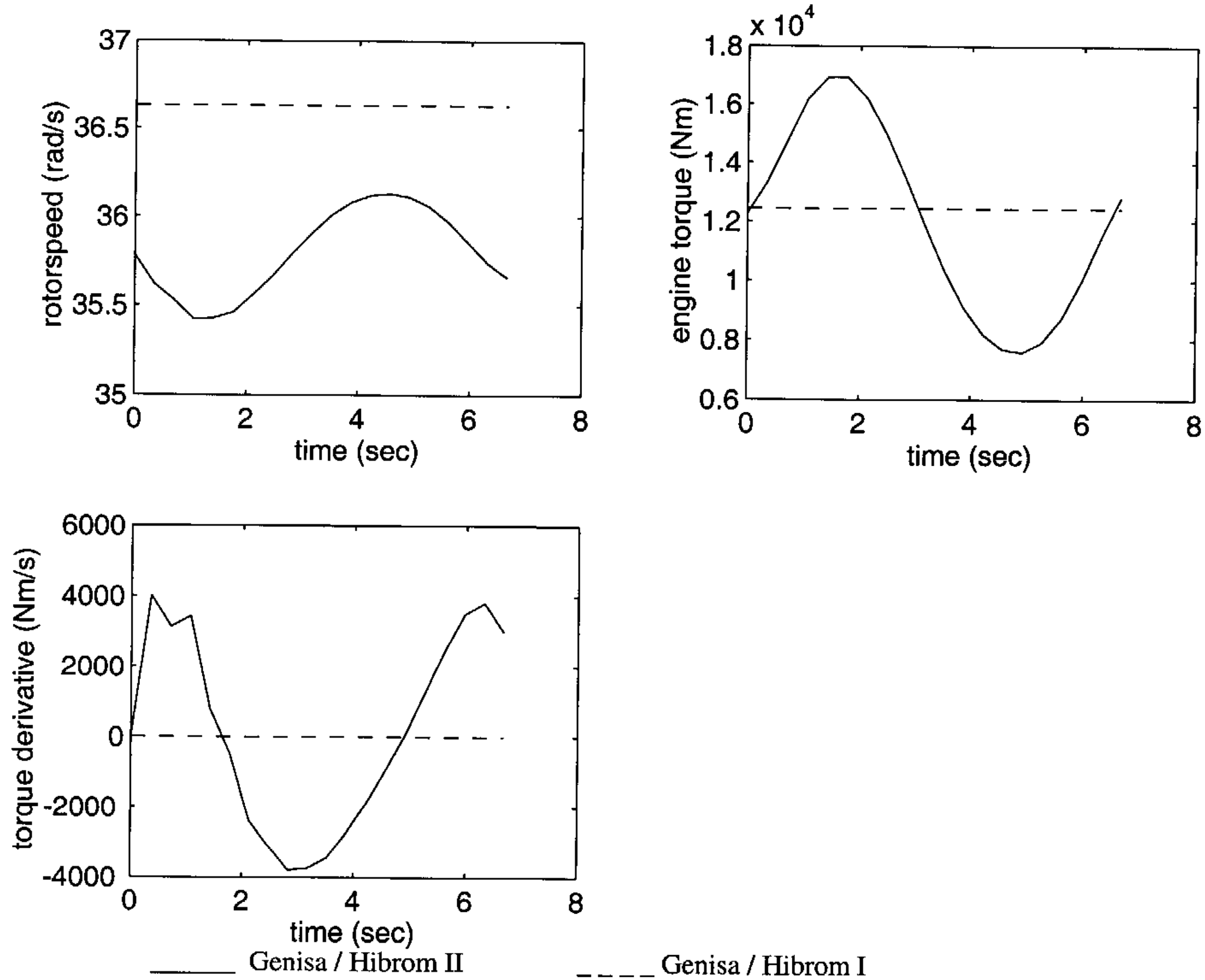

Figure 3 **Comparison between inverse simulation results generated by Genisa / Hibrom I and II (hurdlehop: V_f=40kts, h=5m, s=150m). Time step: 2 turns of main rotor**

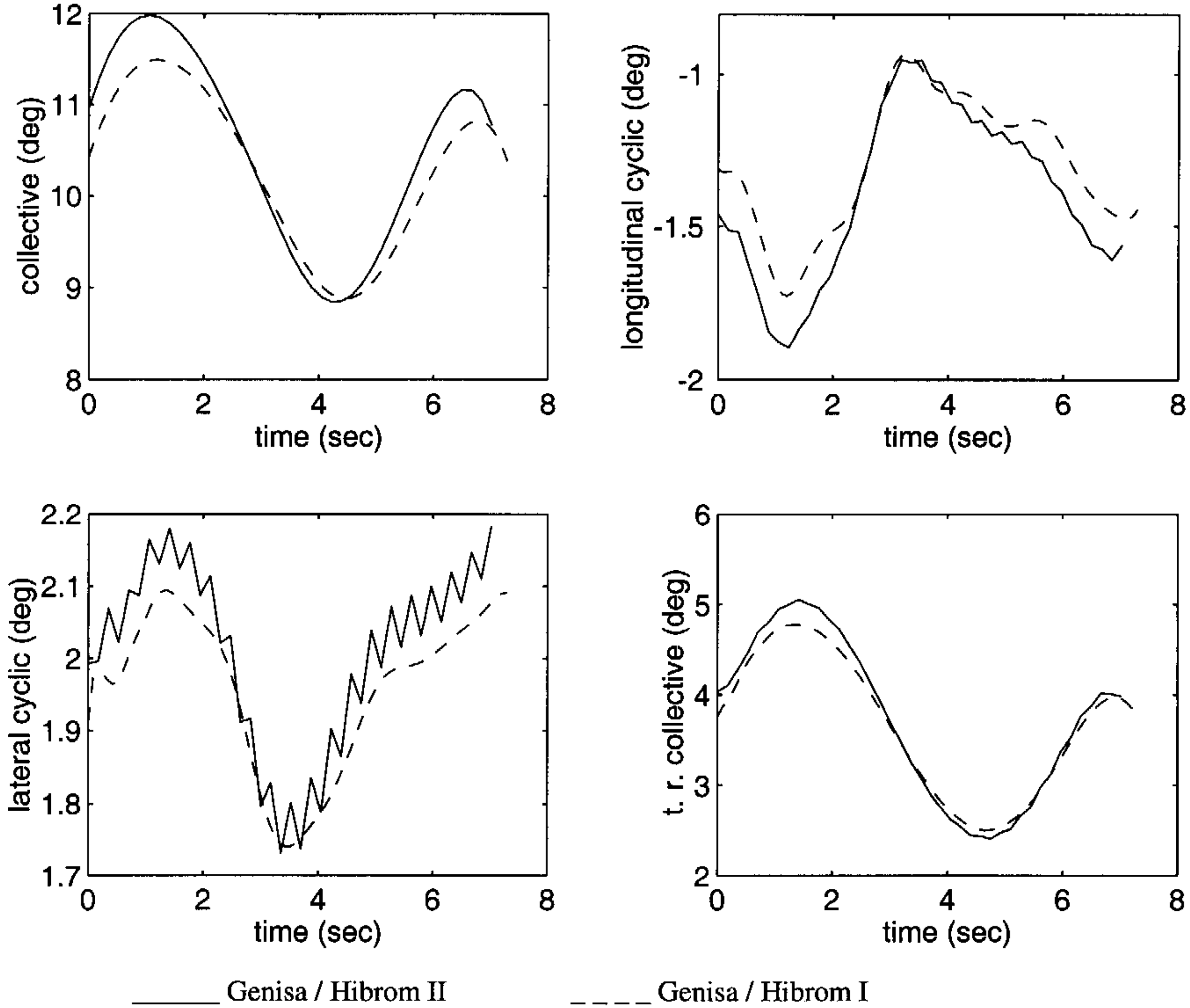

Figure 4 **Comparison between inverse simulation results generated by Genisa / Hibrom I and II (hurdlehop: V_f=40kts, h=5m, s=150m). Time step: 1 turn of main rotor**

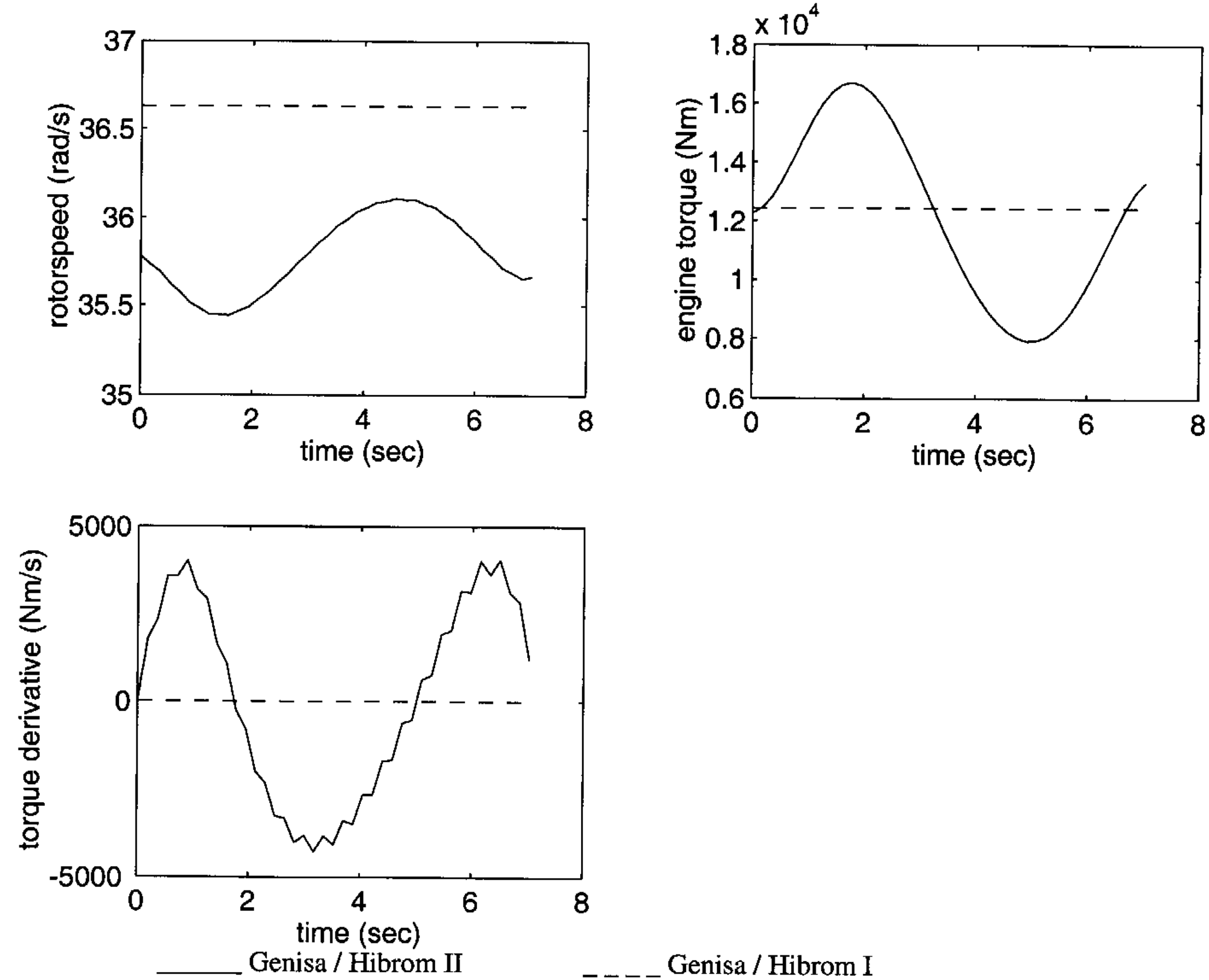

Figure 5 <u>**Comparison between inverse simulation results generated by Genisa / Hibrom I and II (hurdlehop: V_f=40kts, h=5m, s=150m). Time step: 1 turn of main rotor**</u>