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## **Identification Of A Nonlinear Grey-Box Helicopter UAV Model**

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## Executive summary

# Identification Of A Nonlinear Grey-Box Helicopter UAV Model

### **Problem area**

We present a flight dynamics nonlinear model for a flybarless helicopter UAV, valid for a range of flight conditions, including the Vortex-Ring-State (VRS) and autorotation.

### **Description of work**

To allow for computational efficiency, while maintaining a high-level of model fidelity, a grey-box modeling framework has been adopted, in which model uncertainty such as parameter uncertainties, unmodeled higher-order dynamics, and unmodeled static nonlinearities have been replaced by empirical coefficients. The

derivation of these coefficients has been based upon a novel identification approach, anchored in the combined paradigms of nonlinear optimal control and neural networks.

### **Results and conclusions**

Preliminary simulation results show that our model strategy is in good agreement with an equivalent FLIGHTLAB simulation model.

### **Applicability**

Development of flight control systems for small-scale UAV helicopters.

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# Identification Of A Nonlinear Grey-Box Helicopter UAV Model

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We present a flight dynamics nonlinear model for a flybarless helicopter UAV, valid for a range of flight conditions, including the Vortex-Ring-State (VRS) and autorotation. To allow for computational efficiency, while maintaining a high-level of model fidelity, a grey-box modeling framework has been adopted, in which model uncertainty such as parameter uncertainties, unmodeled higher-order dynamics, and unmodeled static nonlinearities have been replaced by empirical coefficients. The derivation of these coefficients has been based upon a novel identification approach, anchored in the combined paradigms of nonlinear optimal control and neural networks. Preliminary simulation results show that our model is in good agreement with an equivalent FLIGHTLAB model.

## I. Introduction

In the past twenty years, scientific progress related to sensors technology and computational hardware has allowed for sustained research in the field of robotics. In particular, when considering flying robots, the availability of increasingly reliable, high performance, and miniaturized sensors, combined with advances in computing power on miniaturized hardware, has yielded impressive developments in the area of Unmanned Aerial Vehicles (UAVs)<sup>a</sup>. These unmanned vehicles have been developed for both civilian and military missions<sup>b</sup>, while their *raison d'être* stems from the need for (real-time) information<sup>c</sup>. Further, UAV deployment and recovery from unprepared or confined sites may often be necessary, such as when operating from or above urban and natural canyons, forests, or naval ships. Hence, for these situations, a helicopter UAV capable of flying in and out of such restricted areas would represent a particularly attractive solution. Now, the development of such an autonomous helicopter system requires for an elaborate synergy between various engineering fields, including modeling, system identification, estimation and filtering, control, and finally software and hardware avionics integration. In this paper, we elaborate on the first and second items, i.e. the modeling and identification paradigms.

### I.A. The Modeling Framework In Engineering

In the realm of physics and engineering, a wide range of systems may be subsumed as energy handling devices<sup>2</sup> that interact with inputs and outputs via energy ports. Understanding such systems is concomitant to the development of conceptual models, i.e. system models, which define both the system's structure and its associated behavior. Building such models requires selection between fundamentally different design philosophies, namely (i) mechanistic/first-principles, also called White-Box (WB) vs. empirical-based, known as Black-Box (BB), or even a mixture of both resulting in a Grey-Box (GB) representation,<sup>3</sup> and (ii) Linear

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<sup>a</sup>Although industry and the regulators have now adopted Unmanned Aerial System (UAS) as the preferred term for Unmanned Aircraft, as UAS encompasses all aspects of deploying these vehicles and not just the platform itself.

<sup>b</sup>UAVs have typically been associated with the so-called *DDD* tasks:<sup>1</sup> Dull e.g. long duration, Dirty e.g. sampling for hazardous materials, and Dangerous e.g. extreme exposure to hostile action.

<sup>c</sup>Spanning a broad spectrum, i.e. visual, electromagnetic, physical, nuclear, biological, chemical, or meteorological information.

Time-Invariant (LTI) vs. NonLinear and/or Time-Varying (NL-TV), or again a mixture of both resulting in a State-Dependent Riccati Equation (SDRE), Gain Scheduling (GS), or Linear Parameter Varying (LPV) description.

#### *I.A.1. White- vs. Black-Box Modeling*

White-Box models refer to modeling structures based upon detailed understandings of the underlying physical laws governing the system, hence providing substantial contribution towards behavior recognition from a scientific viewpoint. On the other hand, when a thorough understanding of the system's laws is not required or necessary, then BB model structures, derived from specific observations, result in simpler representations, with the additional advantage of shorter design and development cycles.<sup>3</sup> When used independently, both of these approaches may, at times, be unattractive. For instance, in the case of a WB representation, and when the system's first-principles laws are only partially understood, the development of such a WB model may become a challenging task, and further result in a final product with questionable model fidelity. Alternatively, even when the laws of physics happen to be well comprehended, the development and validation of such WB models may turn out to be highly resource demanding, especially in the case of complex and high-order industrial plants, such as helicopters. Next, one also has to consider the intended model application, since this latter may as well impose restrictions on the modeling structure and its complexity. For example, depicting a system with an accurate mathematical representation, in a computationally tractable way for its intended application, may result in conflicting requirements.<sup>4</sup>

On the other hand, for the case of BB models, their development may be impaired by the well-known principle of induction<sup>d</sup> deficiencies. Indeed it is conspicuously accepted that induction has serious endemic limitations, as a finite number of observations is generally not sufficient to envelop the infinite number of model operating regimes<sup>e</sup>.<sup>3,5</sup>

#### *I.A.2. Grey-Box Modeling*

Consequently, and for some practical applications, it is the appropriate mixing of mechanistic with empirical knowledge that allows to leverage, in a reciprocal way, the drawbacks of one method with the benefits of the other. By so doing we create the so-called GB modeling paradigm, also known as hybrid modeling.<sup>6</sup> For instance, in a mainly WB approach, aspects of the system that are not sufficiently well understood, which in general are regrouped under the umbrella of modeling uncertainties (i.e. unmodeled higher-order dynamics, unmodeled static nonlinearities, parametric uncertainties, and delays) may be described by a BB model, this latter being identified through parameter estimation techniques based upon experimental data. Conversely, in a predominantly BB approach, some physical insight may often be instrumental to make certain structural choices, such as the adequate model order and the nature of its nonlinearities.<sup>3</sup> In this context, the GB modeling meets (i) the required end-product accuracy and reliability, (ii) the computational tractability specifications, and (iii) the development cost limits, all of which have resulted in a growing interest towards the GB modeling structure, imbued by the increasing demand for nonlinear models to be applied in intelligent and autonomous systems and vehicles, and various optimization based disciplines.

### **I.B. Our Grey-Box Helicopter Model**

The purpose of this paper is to present a novel, highly accurate, computationally efficient, GB helicopter UAV model, suitable for optimal trajectories computation.<sup>7,8</sup> While the WB model is loosely based on the ideas we presented in Ref. 9, the derivation of the BB model is based upon a novel identification approach, anchored in the combined paradigms of nonlinear optimal control and neural networks.

Now with regard to the WB representation, it has been tailored towards small-scale flybarless<sup>f</sup> helicopter UAVs, and is also valid for a range of flight conditions including the Vortex-Ring-State (VRS) and autorotation. The nonlinear dynamics includes the twelve-states rigid body equations of motion, the single-state

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<sup>d</sup>The principle of induction suggests that it is possible to generalize from a sufficiently large number of consistent observations.<sup>3,5</sup>

<sup>e</sup>The region for which the model is locally valid is called an operating regime.

<sup>f</sup>Without a Bell-Hiller stabilizing bar.

main rotor Revolutions Per Minute (RPM), a static Tip-Path-Plane (TPP) main rotor model, and a static uniform main rotor inflow model. Besides, the model accommodates for flight in the VRS, and for deterministic wind and Dryden stochastic atmospheric turbulence. Further, static ground effect has been accounted for by a correction factor applied to the non-dimensional total velocity at the rotor disk center. The fuselage model is based upon aerodynamic lift and drag coefficients, which are tabulated as a function of airflow angle of attack and sideslip angles. These lookup tables are derived from a scaled-down full-size helicopter fuselage aerodynamic model. The horizontal and vertical tails are based upon flat plate models, whereas the tail rotor has been modeled as a Bailey type rotor. Finally the paper reviews all assumptions made in deriving the model, i.e. structural, aerodynamics, and dynamical simplifications, which are valid for stability and control investigations of helicopters up to an advance ratio limit<sup>g</sup> of about 0.3.<sup>10-12</sup>

## II. White-Box Modeling

### II.A. Rigid Body Equations of Motion

#### II.A.1. Assumptions

- The vehicle has a longitudinal plane of symmetry, and has constant mass, inertia, and Center of Gravity (CG) position, hence fuel consumption and/or payload pickup/release are neglected. The vehicle is also a rigid system, i.e. it does not contain any flexible structures, hence the time derivative of the inertia matrix is zero. Further variations of helicopter CG locations due to main rotor blades position are neglected.
- The vehicle height above ground is very small compared to the earth radius, implying a gravitation independent of height and thus constant. Additionally the center of mass and CG are identical for a constant gravity field.
- The earth is assumed fixed and flat. There is then no longer a distinction between the directions of gravitational force and the force of gravity, hence the external force becomes the force of gravity<sup>h</sup>. Gravity is also a function of latitude, for all practical purpose we will consider the medium latitudes of 52°.
- Finally, we neglect the effect of buoyancy or Archimedes force, which is negligible with respect to all other forces.

#### II.A.2. Modeling

To start, our model is defined by a thirteen-state vector, and a four-control input vector

$$\begin{aligned} \mathbf{x} &= \left( x_N \ x_E \ x_Z \ \phi \ \theta \ \psi \ u \ v \ w \ p \ q \ r \ \Omega_{MR} \right)^T \\ \mathbf{u} &= \left( \theta_0 \ \theta_{TR} \ \theta_{1c} \ \theta_{1s} \right)^T \end{aligned} \quad (1)$$

Then, classical Newtonian mechanics and the fundamental relationship of kinematics provide us with the standard twelve-state rigid body equations of motion, following notations of Ref. 13.

$$\begin{pmatrix} \dot{x}_N \\ \dot{x}_E \\ \dot{x}_Z \end{pmatrix}^o = \begin{pmatrix} V_N \\ V_E \\ V_Z \end{pmatrix}^o \quad \begin{pmatrix} V_N \\ V_E \\ V_Z \end{pmatrix}^o = \mathbb{T}_{ob} \cdot \begin{pmatrix} u \\ v \\ w \end{pmatrix}^b \quad (2)$$

$$\begin{pmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{pmatrix}^b = - \begin{pmatrix} q.w - r.v \\ r.u - p.w \\ p.v - q.u \end{pmatrix}^b + g \cdot \begin{pmatrix} -\sin\theta \\ \cos\theta \sin\phi \\ \cos\theta \cos\phi \end{pmatrix}^b + \frac{\mathbf{F}_{aero,GFus}}{m_{Fus}}^b \quad (3)$$

<sup>g</sup>The flight envelope of small-scale helicopters is well within this limit.

<sup>h</sup>For further details on the geoid earth and gravity see Ref. 13,14.

$$\begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix}^b = \mathbb{I}_{Fus}^{-1} \cdot \left( \mathbf{M}_{G_{Fus}}^b - \begin{pmatrix} p \\ q \\ r \end{pmatrix}^b \times \left( \mathbb{I}_{Fus} \cdot \begin{pmatrix} p \\ q \\ r \end{pmatrix}^b \right) \right) \quad (4)$$

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix}^b = \begin{bmatrix} 1 & \sin \theta \cdot \frac{\sin \phi}{\cos \theta} & \sin \theta \cdot \frac{\cos \phi}{\cos \theta} \\ 0 & \cos \phi & -\sin \phi \\ 0 & \frac{\sin \phi}{\cos \theta} & \frac{\cos \phi}{\cos \theta} \end{bmatrix} \cdot \begin{pmatrix} p \\ q \\ r \end{pmatrix}^b \quad (5)$$

$$\mathbb{T}_{ob} = \begin{bmatrix} \cos \theta \cos \psi & \sin \theta \sin \phi \cos \psi - \sin \psi \cos \phi & \cos \psi \sin \theta \cos \phi + \sin \phi \sin \psi \\ \sin \psi \cos \theta & \sin \theta \sin \phi \sin \psi + \cos \psi \cos \phi & \sin \theta \cos \phi \sin \psi - \sin \phi \cos \psi \\ -\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi \end{bmatrix} \quad (6)$$

With  $\mathbf{F}_{aero, G_{Fus}}^b$  the aerodynamic forces experienced by the fuselage CG in the body frame  $F_b$ , and  $\mathbf{M}_{G_{Fus}}^b$  the moments of all forces expressed at the fuselage<sup>i</sup> CG in frame  $F_b$ .

These total forces include contributions from the main rotor, tail rotor, fuselage, vertical tail, and horizontal tail, and are given by

$$\mathbf{F}_{aero, G_{Fus}}^b = \begin{pmatrix} F_{Xaero, G_{Fus}} \\ F_{Yaero, G_{Fus}} \\ F_{Zaero, G_{Fus}} \end{pmatrix}^b = \dots \\ \begin{pmatrix} F_{xMR} \\ F_{yMR} \\ F_{zMR} \end{pmatrix}^b + \begin{pmatrix} F_{xTR} \\ F_{yTR} \\ F_{zTR} \end{pmatrix}^b + \begin{pmatrix} F_{xF} \\ F_{yF} \\ F_{zF} \end{pmatrix}^b + \begin{pmatrix} F_{xVT} \\ F_{yVT} \\ F_{zVT} \end{pmatrix}^b + \begin{pmatrix} F_{xHT} \\ F_{yHT} \\ F_{zHT} \end{pmatrix}^b + \begin{pmatrix} \Theta_{Fx} \\ \Theta_{Fy} \\ \Theta_{Fz} \end{pmatrix} \quad (7)$$

with  $(\Theta_{Fx} \ \Theta_{Fy} \ \Theta_{Fz})^T$  a vector of empirical coefficients, which will be addressed in Section III. The total moments, which also include the components due to the non-collocation of the vehicle CG and fuselage CG, are given by

$$\mathbf{M}_{G_{Fus}}^b = \begin{pmatrix} M_{X, G_{Fus}} \\ M_{Y, G_{Fus}} \\ M_{Z, G_{Fus}} \end{pmatrix}^b = \begin{pmatrix} M_{xMR} \\ M_{yMR} \\ M_{zMR} \end{pmatrix}^b + \begin{pmatrix} M_{xTR} \\ M_{yTR} \\ M_{zTR} \end{pmatrix}^b + \begin{pmatrix} M_{xF} \\ M_{yF} \\ M_{zF} \end{pmatrix}^b + \begin{pmatrix} M_{xVT} \\ M_{yVT} \\ M_{zVT} \end{pmatrix}^b + \begin{pmatrix} M_{xHT} \\ M_{yHT} \\ M_{zHT} \end{pmatrix}^b \\ + \begin{pmatrix} -y_F \cdot F_{Zaero, G_{Fus}} + z_F \cdot F_{Yaero, G_{Fus}} \\ -z_F \cdot F_{Xaero, G_{Fus}} + x_F \cdot F_{Zaero, G_{Fus}} \\ -x_F \cdot F_{Yaero, G_{Fus}} + y_F \cdot F_{Xaero, G_{Fus}} \end{pmatrix}^b + \begin{pmatrix} \Theta_{Mx} \\ \Theta_{My} \\ \Theta_{Mz} \end{pmatrix} \quad (8)$$

with again  $(\Theta_{Mx} \ \Theta_{My} \ \Theta_{Mz})^T$  a vector of empirical coefficients, which will be addressed in Section III. The derivation of the here-above presented forces and moments is given in the next sections.

<sup>i</sup>Note that fuselage inertia and fuselage CG are used here rather than vehicle inertia and vehicle CG, since in the moments term  $\mathbf{M}_{G_{Fus}}^b$  we have already accounted for rotor moments due to main rotor inertial loads.

## II.B. Main Rotor Modeling

### II.B.1. Assumptions

#### Structural Simplifications

- Rotor shaft forward and lateral tilt-angles are zero. The blade has zero twist, constant chord, zero sweep, constant thickness ratio, and a uniform mass distribution.
- Rigid rotor blade in bending. Neglecting higher modes (harmonics), since higher modes are only pronounced at high speed.<sup>15,16</sup> Further, blade torsion is neglected since small-scale helicopter blades are generally relatively stiff.
- Rotor inertia inboard of the flap hinge is assumed small and thus neglected.

#### Aerodynamics Simplifications

- Vehicle flies at a low altitude, hence neglecting air density and temperature variations. Blade element theory<sup>j</sup> is used to compute rotor lift and drag forces. Radial flow along blade span is ignored. Pitch, lag, and flap angles are assumed to be small.
- Momentum theory<sup>k</sup> is used to compute the uniform inflow component.
- Compressibility effects are disregarded, which is a reasonable assumption considering small-scale helicopter flight characteristics. Viscous flow effects are also disregarded, which is a valid assumption for low angle of attacks and un-separated flow.<sup>19,20</sup>
- Aerodynamic interference effects between the main rotor and other helicopter modules, e.g. fuselage or tail rotor, are neglected.
- When deriving an expression for the main rotor torque (i.e. yaw moment), only a vertical flight inflow and power component is considered, hence omitting forward flight contributions.
- The presence of the fuselage just under the main rotor acts as a so-called pseudo-ground effect, resulting in some thrust recovery. This phenomenon is neglected in our paper, although an estimate of its effect may be obtained from Ref. 21.

#### Dynamical Simplifications

- Dynamic twist<sup>l</sup> is neglected. Hence blade CG is assumed to be located on the blade section quarter chord line.
- Unsteady (frequency dependent) effect for time-dependent development of blade lift and pitching moment, due to changes in local incidence are ignored. For example dynamic stall, due to rapid pitch changes, is ignored.
- A balanced rotor is assumed. In general most of the inertial terms, contributing to main rotor moments, vanish<sup>m</sup> when integrated around  $2\pi$  azimuth.

<sup>j</sup>Calculates the forces on the blade due to its motion through the air. It is assumed that each blade section acts as a 2-D airfoil to produce aerodynamic forces, with the influence of the wake contained in an induced angle of attack at the blade section.<sup>17</sup>

<sup>k</sup>States that the total force acting on a control volume is equal to the rate of change of momentum, i.e. mass flow entering and leaving this control volume.<sup>17,18</sup>

<sup>l</sup>Any offset in blade chordwise CG or aerodynamic center position will result in a coupling of the flap and torsion Degrees Of Freedom (DOF) in blade elastic modes.<sup>15</sup>

<sup>m</sup>These terms should be retained when evaluating rotor out-of-balance loads.<sup>22</sup>

## II.B.2. Modeling

VELOCITIES The main rotor hub aerodynamic velocity in the body frame  $F_b$  is given by

$$\mathbf{V}_{a,MR}^b = \begin{pmatrix} V_{a,MR_u} \\ V_{a,MR_v} \\ V_{a,MR_w} \end{pmatrix}^b = \begin{pmatrix} u + (q - q_w) \cdot z_H - (r - r_w) \cdot y_H \\ v - (p - p_w) \cdot z_H + (r - r_w) \cdot x_H \\ w + (p - p_w) \cdot y_H - (q - q_w) \cdot x_H \end{pmatrix}^b - \begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix}^b \quad (9)$$

With

$$\begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix}^b = \mathbb{T}_{bo} \cdot \begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix}^o \quad \text{and} \quad \mathbb{T}_{bo} = \mathbb{T}_{ob}^{-1} \quad (10)$$

And the non-dimensional velocities are expressed as follows

$$\mu_x = -V_{a,MR_u} / V_{MRref} \quad (11a)$$

$$\mu_y = -V_{a,MR_v} / V_{MRref} \quad (11b)$$

$$\mu_z = -V_{a,MR_w} / V_{MRref} \quad (11c)$$

$$\mu_{xy} = \sqrt{\mu_x^2 + \mu_y^2} \quad \text{and} \quad V_{MRref} = \Omega_{MR} \cdot R_{rot} \quad (11d)$$

INFLOW As for the inflow, we consider only the uniform component and we neglect inflow dynamics. Our model is a simplified implementation of the expressions presented in Ref. 23, 24, with the inclusion of the VRS correction from Ref. 25. The momentum theory induced flow  $\lambda_m$  is given from Ref. 17

$$\lambda_m^2 \cdot [(\lambda_m + \mu_z)^2 + \mu_{xy}^2] = \left( \frac{v_h}{V_{MRref}} \right)^4 \quad \text{if} \quad \mu_z \geq 0 \quad \text{or} \quad \mu_z \cdot \frac{V_{MRref}}{v_h} \leq -2 \quad (12)$$

In the VRS, it is given from Ref. 25

$$\lambda_m^2 \cdot [(\lambda_m + \mu_z)^2 + \mu_{xy}^2 + \left( \frac{v_h}{V_{MRref}} \right)^2 \cdot f(\mu_{xy}) \cdot g(\bar{\lambda})] = \left( \frac{v_h}{V_{MRref}} \right)^4 \quad \text{if} \quad \mu_z \cdot \frac{V_{MRref}}{v_h} \in [-2, 0] \quad (13)$$

In the static case, also from Ref. 23, 24, the rotor uniform induced velocity, normal to the TPP, is given by

$$v_{i_o} = G_{eff} / (2V_T) \cdot (-C_T^{TPP}) \cdot V_{MRref} \quad (14)$$

Where  $C_T^{TPP}$  is the main rotor thrust coefficient in the TPP frame. Since the TPP angles are assumed small, we conjecture that it is also valid in the Hub-Body frame, i.e.  $C_T^{HB} \simeq C_T^{TPP}$ . Now, from Ref. 17 we get, after rearranging terms, the thrust coefficient in the Hub-Body frame

$$\begin{aligned} C_T^{HB} &= A + B \cdot v_{i_o} \quad \text{with} \\ A &= -0.5 \cdot \sigma_{MR} \cdot CL_{MR\alpha} \cdot \theta_0 / 3 \cdot (B^3 + 1.5B \cdot \mu_{xy}^2) \\ &\quad - 0.25 \cdot \sigma_{MR} \cdot CL_{MR\alpha} \cdot B^2 \cdot \left( V_{a,MR_w} / V_{MRref} + \mu_{xy} \cdot (\beta_{1c} + \theta_{1s}) \right) \\ B &= 0.25 \cdot \sigma_{MR} \cdot CL_{MR\alpha} \cdot B^2 / V_{MRref} \end{aligned} \quad (15)$$

And  $V_T$  gives the total flow,<sup>25</sup> through the rotor disk, as

$$V_T = \sqrt{(\lambda_m + \mu_z)^2 + \mu_{xy}^2 + (v_h/V_{MRref})^2} \cdot f(\mu_{xy}) \cdot g(\bar{\lambda}) \quad (16)$$

With the following correction factors

$$\begin{aligned} f(\mu_{xy}) &= 1 - 2 \cdot \mu_{xy}^2 \quad \text{if } \mu_{xy} \in [0, 0.707] \\ f(\mu_{xy}) &= 0 \quad \text{otherwise} \\ g(\bar{\lambda}) &= \frac{1}{(2+\bar{\lambda})^2} - \bar{\lambda}^2 + (1 + \bar{\lambda}) \cdot [0.109 + 0.217(\bar{\lambda} - 0.15)^2] \quad \text{if } \bar{\lambda} \in [-1, 0.6378] \\ g(\bar{\lambda}) &= 0 \quad \text{otherwise} \\ \bar{\lambda} &= (\lambda_m + \mu_z)/(v_h/V_{MRref}) \\ \mu_{xy} &= \mu_{xy}/(v_h/V_{MRref}) \end{aligned} \quad (17)$$

From Eq (14) - Eq (15), we can now derive an approximated and simplified expression for the static uniform inflow, in which we have assumed the longitudinal rotor TPP tilt angle to be small  $\beta_{1c} \simeq 0$ , we get

$$\begin{aligned} v_{i_o} &= A \cdot C / (1 - B \cdot C) \\ C &= -G_{eff} / (2V_T) \cdot V_{MRref} \end{aligned} \quad (18)$$

Finally, the ground effect correction factor is given from Ref. 26 as

$$G_{eff} = \frac{1}{0.9926 + 0.0379(2R_{rot}/h_H)^2} \quad (19)$$

**TIP-PATH-PLANE (TPP) ANGLES** As for the Tip-Path-Plane (TPP) model, here too we assume a static behavior. The model is a simplified<sup>n</sup> implementation of the expressions presented in Ref. 11,12. In particular we neglect the effect of roll, pitch and vertical accelerations on the rotor TPP angles.

$$\begin{pmatrix} \beta_0 \\ -\beta_{1c} \\ -\beta_{1s} \end{pmatrix} = \mathbb{K}^{-1} \cdot \left( \mathbb{F}_\theta \cdot \begin{pmatrix} \theta_0 \\ -\theta_{1c} \\ -\theta_{1s} \end{pmatrix} + \mathbb{F}_{pq} \cdot \begin{pmatrix} p \\ q \end{pmatrix} + \lambda \cdot \mathbb{F}_\lambda + \mathbb{F}_0 \right) \quad (20)$$

With the rotor total inflow expressed by

$$\lambda = (-V_{a,MRw} + v_{i_o})/V_{MRref} \quad (21)$$

And the matrices  $\mathbb{K}$ ,  $\mathbb{F}_\theta$ ,  $\mathbb{F}_{pq}$ ,  $\mathbb{F}_\lambda$ , and  $\mathbb{F}_0$  given by

$$\mathbb{K} = \Omega_{MR}^2 \cdot \begin{bmatrix} P^2 & F_1 \cdot \mu_{xy} & 0 \\ F_2 \cdot \mu_{xy} & P^2 - 1 & G_1 \\ 0 & -G_1 & P^2 - 1 \end{bmatrix} \quad (22)$$

<sup>n</sup>We do not use the wind-axis formalism of Ref. 11,12

$$\mathbb{F}_\theta = \Omega_{MR}^2 \cdot \begin{bmatrix} G_2 & 0 & F_2 \cdot \mu_{xy} \\ 0 & G_2 & 0 \\ F_2 \cdot \mu_{xy} & 0 & G_2 \end{bmatrix} \quad (23)$$

Where we modified the element  $\mathbb{F}_\theta(3, 1)$ , in Eq (23) compared to Ref. 11,12, since this gives better results. The remaining matrices are given by

$$\mathbb{F}_{pq} = \Omega_{MR} \cdot \begin{bmatrix} -F_3 \cdot \mu_{xy} & 0 \\ H_1 & -H_2 \\ H_2 & H_1 \end{bmatrix} \quad (24)$$

$$\mathbb{F}_\lambda = \Omega_{MR}^2 \cdot \begin{pmatrix} G_3 \\ 0 \\ F_4 \cdot \mu_{xy} \end{pmatrix} \quad (25)$$

$$\mathbb{F}_0 = \begin{pmatrix} -C_0/I_b \cdot g \\ 0 \\ 0 \end{pmatrix} \quad (26)$$

With

$$P^2 = 1 + K_{S\beta}/(I_b \cdot \Omega_{MR}^2) + \Delta_e/I_b \cdot C_0 \quad (27a)$$

$$F_1 = -\epsilon/8 \cdot \gamma \quad (27b)$$

$$F_2 = -1/2(1/3 - \epsilon/2) \cdot \gamma \quad (27c)$$

$$F_3 = 1/8(2/3 - \epsilon) \cdot \gamma \quad (27d)$$

$$F_4 = -1/2(1/2 - \epsilon) \cdot \gamma \quad (27e)$$

$$G_1 = 1/2(1/4 - 2/3\epsilon) \cdot \gamma \quad (27f)$$

$$G_2 = 1/2(1/4 - 1/3\epsilon) \cdot \gamma \quad (27g)$$

$$G_3 = 1/2(1/3 - 1/2\epsilon) \cdot \gamma \quad (27h)$$

$$H_1 = 2(1 + \Delta_e/I_b \cdot C_0) \quad (27i)$$

$$H_2 = 1/2(1/4 - 1/3\epsilon) \cdot \gamma \quad (27j)$$

**FORCES** The rotor force coefficients, in the Hub-Body wind-axis frame  $F_{HBw}$  are given in Ref. 17. We did not use the side-force coefficient from Ref. 17 since it did not provide satisfactory results (when our model was compared with an equivalent FLIGHTLAB<sup>®</sup> model). For the drag, and thrust coefficients we have

$$C_{HMR}^{HBw} = \frac{\sigma_{MR} \cdot CD_{MR}}{8} \cdot (3\mu_{xy} + 1.98\mu_{xy}^{2.7}) + \frac{\sigma_{MR} \cdot CL_{MR\alpha}}{2} \cdot \left( \frac{\theta_0}{2} \cdot \mu_{xy} \cdot \lambda - \frac{\theta_{1c} \cdot \beta_0}{6} + \frac{\theta_{1s}}{4} \cdot \lambda + \frac{\mu_{xy} \cdot \beta_0^2}{4} \right) \quad (28)$$

$$C_{TMR}^{HBw} = -\frac{\sigma_{MR} \cdot CL_{MR\alpha}}{2} \cdot \left( \frac{\theta_0}{3} \cdot \left[ B^3 + \frac{3}{2} B \cdot \mu_{xy}^2 \right] - \frac{B^2}{2} \cdot \left[ \lambda - \mu_{xy} \cdot (\beta_{1c} + \theta_{1s}) \right] \right) \quad (29)$$

Which gives in the body frame  $F_b$

$$\begin{pmatrix} C_{HMR} \\ C_{YMR} \\ C_{TMR} \end{pmatrix}^b = \mathbb{T}_{b(HBw)} \cdot \begin{pmatrix} C_{HMR} \\ 0 \\ C_{TMR} \end{pmatrix}^{HBw} \quad (30)$$

With

$$\mathbb{T}_{b(HBw)} = \mathbb{T}_{b(HB)} \cdot \mathbb{T}_{HB(HBw)} \quad (31)$$

Now since the main rotor shaft tilt angle is zero, the Hub-Body frame  $F_{HB}$  and the vehicle body frame  $F_b$  are identical, i.e.  $\mathbb{T}_{b(HB)} = \mathbb{I}$ . And

$$\mathbb{T}_{(HB)(HBw)} = \begin{bmatrix} -\cos \beta_{MR} & -\sin \beta_{MR} & 0 \\ -\sin \beta_{MR} & \cos \beta_{MR} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (32)$$

The main rotor sideslip angle is expressed from the fuselage sideslip angle Eq (54) as

$$\beta_{MR} = \text{mod}(\beta_F, 2\pi) \quad (33)$$

Finally expressing the main rotor forces in the body frame we get

$$\begin{pmatrix} F_{xMR} \\ F_{yMR} \\ F_{zMR} \end{pmatrix}^b = \begin{pmatrix} C_{HMR} \\ C_{YMR} \\ C_{TMR} \end{pmatrix}^b \cdot \rho \cdot \pi \cdot R_{rot}^2 \cdot V_{MRref}^2 \quad (34)$$

**MOMENTS** The roll and pitch moments due to the flap hinge spring are given as in Ref. 17

$$L_{(MR,flap)}^b = -\frac{1}{1 - \frac{\Delta_e}{R_{rot}}} \cdot \frac{N_b}{2} \cdot K_{S\beta} \cdot \Gamma \cdot \beta_{1s} \quad (35a)$$

$$M_{(MR,flap)}^b = -\frac{1}{1 - \frac{\Delta_e}{R_{rot}}} \cdot \frac{N_b}{2} \cdot K_{S\beta} \cdot \beta_{1c} \quad (35b)$$

The inertia roll and pitch moments, which arise when the plane of a rotor with offset hinges is tilted relative to the shaft, are given as in Ref. 18

$$L_{(MR,inertial)}^b = -\frac{N_b}{2} \cdot M_{bl} \cdot \Delta_e \cdot y_{Gbl} \cdot \Omega_{MR}^2 \cdot \Gamma \cdot \beta_{1s} \quad (36a)$$

$$M_{(MR,inertial)}^b = -\frac{N_b}{2} \cdot M_{bl} \cdot \Delta_e \cdot y_{Gbl} \cdot \Omega_{MR}^2 \cdot \beta_{1c} \quad (36b)$$

For the main rotor torque (i.e. yaw moment), we simplify the description by only considering the induced and profile components of a rotor in vertical flight,<sup>17</sup> hence omitting forward flight components

$$N_{(MR,aero)}^b = \Gamma \cdot \left( -\lambda \cdot C_{TMR} + \sigma_{MR} \cdot CD_{MR} / 8 \cdot \left[ 1 + 4.6\mu_{xy}^2 \right] \right) \cdot \rho \cdot \pi \cdot R_{rot}^3 \cdot V_{MRref}^2 \quad (37)$$

Next, and by adding the main rotor forces times the respective moment arms, we obtain the total main rotor moments as

$$\begin{pmatrix} M_{xMR} \\ M_{yMR} \\ M_{zMR} \end{pmatrix}^b = \begin{pmatrix} L_{(MR,flap)} + L_{(MR,inertial)} + y_H \cdot F_{zMR} - z_H \cdot F_{yMR} \\ M_{(MR,flap)} + M_{(MR,inertial)} + z_H \cdot F_{xMR} - x_H \cdot F_{zMR} \\ N_{(MR,aero)} + x_H \cdot F_{yMR} - y_H \cdot F_{xMR} \end{pmatrix}^b \quad (38)$$

ROTOR RPM DYNAMICS The main rotor RPM dynamics is related to the available and required power by the following expression<sup>21</sup>

$$N_b \cdot I_b \cdot \Omega_{MR} \cdot \dot{\Omega}_{MR} = P_{shaft} - P_{req} \quad (39)$$

With  $P_{shaft}$  the available shaft power, and  $P_{req}$  the required power to keep the vehicle aloft. This latter is the sum of main rotor induced and profile power, tail rotor induced and profile power, power plant transmission losses, vehicle parasite power (i.e. drag due to fuselage, landing skids, rotor hub, etc), and finally main rotor, tail rotor, and fuselage aerodynamic interference losses.<sup>27</sup>

Considering the case of an engine failure, a first-order response in  $P_{shaft}$  is generally assumed to represent the power decay for turboshaft engines,<sup>28,29</sup> we have

$$\dot{P}_{shaft} = -\frac{P_{shaft}}{\tau_p} \quad (40)$$

With  $\tau_p$  a to-be-identified time constant. For the required power  $P_{req}$ , we simplify the model by only considering the contributions from the main rotor as

$$P_{MR} = \Theta_{MRpwr} \cdot N_{(MR,aero)} \cdot \Omega_{MR} \quad (41)$$

with  $\Theta_{MRpwr}$  an additional empirical coefficient, which will be addressed in Section III.

## II.C. Tail Rotor Modeling

### II.C.1. Assumptions

#### Structural simplifications

- The blade has zero twist, constant chord, zero sweep, and has constant thickness ratio.
- The blade is rigid, hence torsion is neglected.

#### Aerodynamics simplifications

- Linear lift with constant lift curve slope, and uniform induced flow over the rotor.
- Aerodynamic interference effects from the main rotor is neglected, although this may well be an oversimplification, for some flight conditions.<sup>30,31</sup> Similarly, the aerodynamic interference from the vertical tail (due to blockage) is also neglected.
- Compressibility, blade stall and viscous flow effects are disregarded.

#### Dynamical simplifications

- No blade dynamics and simplified inflow dynamics.
- Unsteady effects neglected.

### II.C.2. Modeling

The tail rotor is a powerful design solution for torque balance, directional stability and control of single main rotor helicopters. The theory we apply here is based on the work done by Bailey in Ref. 32. The model represents a standard approach towards tail rotor modeling, as implemented among others in Ref. 22,33,34.

VELOCITIES The tail rotor hub aerodynamic velocity in the body frame is given by

$$\mathbf{V}_{a,TR}^b = \begin{pmatrix} V_{a,TR_u} \\ V_{a,TR_v} \\ V_{a,TR_w} \end{pmatrix}^b = \begin{pmatrix} u + (q - q_w) \cdot z_{TR} - (r - r_w) \cdot y_{TR} \\ v - (p - p_w) \cdot z_{TR} + (r - r_w) \cdot x_{TR} \\ w + (p - p_w) \cdot y_{TR} - (q - q_w) \cdot x_{TR} \end{pmatrix}^b - \begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix}^b \quad (42)$$

In the tail rotor frame  $F_{TR}$  of Ref. 33, we have

$$\mathbf{V}_{a,TR}^{TR} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \cdot \mathbf{V}_{a,TR}^b \quad (43)$$

The non-dimensional velocities in frame  $F_{TR}$  are expressed as follows

$$\mu_{TRx} = V_{a,MR_u}^{TR} / V_{TRref} \quad (44a)$$

$$\mu_{TRy} = V_{a,MR_v}^{TR} / V_{TRref} \quad (44b)$$

$$\mu_{TRz} = \Gamma \cdot V_{a,MR_w}^{TR} / V_{TRref} \quad (44c)$$

$$\mu_{TRxy} = \sqrt{\mu_{TRx}^2 + \mu_{TRy}^2} \quad \text{and} \quad V_{TRref} = \Omega_{TR} \cdot R_{rot_{TR}} \quad (44d)$$

INFLOW The theory we apply here is based on the work done by Bailey in Ref. 32, implemented among others in Ref. 22, 33, 34. The model given in this paper is a simplified approach of the Bailey model. First, the tail rotor blade pitch is given by

$$\theta_{TR} = \theta_{0_{TR}} - T_{TR} \cdot \frac{\partial \beta_{0_{TR}}}{\partial T_{TR}} \cdot \tan \delta_{3_{TR}} + \theta_{bias_{TR}} \quad (45)$$

The Bailey coefficients are given next by

$$t_1 = \frac{B_{TR}^2}{2} + \frac{\mu_{TRxy}^2}{4} \quad (46a)$$

$$t_2 = \frac{B_{TR}^3}{3} + \frac{B_{TR} \cdot \mu_{TRxy}^2}{2} \quad (46b)$$

Assuming zero twist for the tail rotor blades, the inflow is then derived using momentum theory

$$\lambda_{dw} = \frac{CL_{TR\alpha} \cdot \sigma_{TR}}{2} \cdot \left( \frac{\mu_{TRz} \cdot t_1 + \theta_{TR} \cdot t_2}{2 \sqrt{\mu_{TRxy}^2 + \lambda_{TR}^2} + \frac{CL_{TR\alpha} \cdot \sigma_{TR}}{2} \cdot t_1} \right) \quad (47)$$

And the total tail rotor inflow is given by

$$\lambda_{TR} = \lambda_{dw} - \mu_{TRz} \quad (48)$$

Where it is common practice to iterate between Eq (47) and Eq (48) until convergence within a reasonable tolerance.

FORCES The tail rotor thrust is given by

$$T_{TR} = 2/K_{TR_{corr}} \cdot \lambda_{dw} \cdot \sqrt{\mu_{TRxy}^2 + \lambda_{TR}^2} \cdot \rho \cdot \pi \cdot \left( \Omega_{TR} \cdot R_{rot_{TR}}^2 \right)^2 \quad (49)$$

Finally in the body frame we have

$$\begin{pmatrix} F_{x_{TR}} \\ F_{y_{TR}} \\ F_{z_{TR}} \end{pmatrix}^b = \begin{pmatrix} 0 \\ \Gamma \cdot T_{TR} \\ 0 \end{pmatrix} \quad (50)$$

Where we have neglected any aerodynamic interference effects with the main rotor and vertical tail (e.g. blockage effect).

MOMENTS The tail rotor moments are primarily due to the tail rotor force times the respective moment arms. For completeness we also add the rotor torque acting on the pitch axis,<sup>17</sup> we get

$$\begin{pmatrix} M_{x_{TR}} \\ M_{y_{TR}} \\ M_{z_{TR}} \end{pmatrix}^b = \begin{pmatrix} -z_{TR} \cdot T_{TR} \\ \sigma_{TR} \cdot CD_{TR} / 8 \cdot (1 + 4.6 \mu_{TRxy}^2) \cdot \rho \cdot \pi \cdot \Omega_{TR}^2 \cdot R_{rot_{TR}}^5 \\ x_{TR} \cdot T_{TR} \end{pmatrix} \quad (51)$$

## II.D. Fuselage Modeling

The flow around the fuselage is characterized by strong nonlinearities, and is further distorted by the influence of the main rotor wake. Hence, the associated forces and moments, due to the surface pressures and skin friction, are complex functions of flight speed and direction.<sup>15</sup> Indeed, it is well-known that important unsteady separation effects exist, but are rather complex to model.<sup>15</sup>

### II.D.1. Assumptions

#### Aerodynamics Simplifications

- Fuselage aerodynamic center collocated with vehicle CG.
- Effect of rotor downwash on fuselage is neglected. It can however be modeled as in Ref. 35, using a polynomial in wake skew angle, where the polynomial coefficients need to be fit from flight data.<sup>36</sup>
- Only steady airloads effects on the fuselage are considered.

### II.D.2. Modeling

The fuselage model is based upon aerodynamic lift and drag coefficients, which are tabulated as a function of airflow angle of attack and sideslip angles. For low speed sideways flight, the important fuselage characteristics are in general, the sideforce, vertical drag, and yawing moment. While in forward flight, the three most important characteristics include drag, and pitching and yawing moments variations with incidence and sideslip.<sup>15</sup> The fuselage rolling moment is usually small, except for configurations with deep hulls where the fuselage aerodynamic center may be significantly below the vehicle CG.<sup>15</sup> For additional information, see also Ref. 37,38.



VELOCITIES AND AIRFLOW ANGLES The fuselage aerodynamic velocity, at its aerodynamic center, in the body frame is given by

$$\mathbf{V}_{a,F}^b = \begin{pmatrix} V_{a,F_u} \\ V_{a,F_v} \\ V_{a,F_w} \end{pmatrix}^b = \begin{pmatrix} u + (q - q_w).z_F - (r - r_w).y_F \\ v - (p - p_w).z_F + (r - r_w).x_F \\ w + (p - p_w).y_F - (q - q_w).x_F \end{pmatrix}^b - \begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix}^b \quad (52)$$

The fuselage angle of attack is given by

$$\alpha_F = \arctan(V_{a,F_w}/|V_{a,F_u}|) \quad (53)$$

And the fuselage sideslip angle is given as in Ref. 13 by

$$\begin{aligned} \beta_F &= \arcsin(V_{a,F_v}/V_{a,F}) \quad \text{if } V_{a,F_u} \geq 0 \\ \beta_F &= \pi/2 + \arccos(V_{a,F_v}/V_{a,F}) \quad \text{if } V_{a,F_u} < 0 \quad \text{and } V_{a,F_v} \geq 0 \\ \beta_F &= -\pi/2 - \arccos(-V_{a,F_v}/V_{a,F}) \quad \text{if } V_{a,F_u} < 0 \quad \text{and } V_{a,F_v} < 0 \end{aligned} \quad (54)$$

$$\text{With } V_{a,F} = \sqrt{V_{a,F_u}^2 + V_{a,F_v}^2 + V_{a,F_w}^2}.$$

FORCES In the body frame  $F_b$  we have

$$\begin{aligned} F_{x_F}^b &= q_{dp} \cdot Cx_F^b(\alpha_F, \beta_F) \\ F_{y_F}^b &= q_{dp} \cdot Cy_F^b(\alpha_F, \beta_F) \\ F_{z_F}^b &= q_{dp} \cdot Cz_F^b(\alpha_F, \beta_F) \\ q_{dp} &= 1/2 \cdot \rho \cdot S_{ref_F} \cdot V_{a,F}^2 \end{aligned} \quad (55)$$

The aerodynamic coefficients  $Cx_F(\cdot)$ ,  $Cy_F(\cdot)$ , and  $Cz_F(\cdot)$  are tabulated as a function of airflow angle of attack  $\alpha_F$ , and sideslip angle  $\beta_F$ . These lookup tables have been derived from a scaled-down full-size helicopter fuselage aerodynamic model.

MOMENTS In the body frame  $F_b$  we have

$$\begin{aligned} M_{x_F}^b &= q_{dp} \cdot Mx_F(\alpha_F, \beta_F) \cdot L_{ref_F} \\ M_{y_F}^b &= q_{dp} \cdot My_F(\alpha_F, \beta_F) \cdot L_{ref_F} \\ M_{z_F}^b &= q_{dp} \cdot Mz_F(\alpha_F, \beta_F) \cdot L_{ref_F} \\ q_{dp} &= 1/2 \cdot \rho \cdot S_{ref_F} \cdot V_{a,F}^2 \end{aligned} \quad (56)$$

Here too, the aerodynamic coefficients  $Mx_F(\cdot)$ ,  $My_F(\cdot)$ , and  $Mz_F(\cdot)$  are tabulated as a function of airflow angle of attack  $\alpha_F$ , and sideslip angle  $\beta_F$ . These lookup tables have also been derived from a scaled-down full-size helicopter fuselage aerodynamic model.

## II.E. Vertical Tail Modeling

The role of the vertical tail is twofold: (i) in forward flight, it generates a sideforce and yawing moment, hence reducing the tail rotor thrust requirement, in order to increase the fatigue life of the tail rotor,<sup>15,21</sup> and (ii) during maneuvers, and during wind gusts, it provides yaw damping and stiffness, enhancing directional stability.<sup>15</sup>

### II.E.1. Assumptions

#### Aerodynamics Simplifications

- Effect of main rotor downwash on vertical tail is neglected. It can however be modeled by using flat vortex wake theory<sup>39</sup> (valid for small sideslip angles), as presented in Ref. 40,41, or it may be modeled as a polynomial in wake skew angle as in Ref. 35.
- As an aside, the effect of the main rotor downwash on the tail boom is neglected, but ought to be considered at low speed, since it may influence yaw damping.<sup>15</sup>

### II.E.2. Modeling

The vertical tail is basically a wing,<sup>19,20</sup> several modeling approaches can be found in Ref. 22, 35, 37, 38. Here, we use a flat plate representation.

VELOCITIES AND AIRFLOW ANGLES The vertical tail aerodynamic velocity, at its aerodynamic center, in the body frame is given by

$$\mathbf{V}_{a,VT}^b = \begin{pmatrix} V_{a,VT_u} \\ V_{a,VT_v} \\ V_{a,VT_w} \end{pmatrix}^b = \begin{pmatrix} u + (q - q_w).z_{VT} - (r - r_w).y_{VT} \\ v - (p - p_w).z_{VT} + (r - r_w).x_{VT} \\ w + (p - p_w).y_{VT} - (q - q_w).x_{VT} \end{pmatrix}^b - \begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix}^b \quad (57)$$

Since in the sequel we will neglect the spanwise flow (along the z-axis), we have  $V_{a,VT} = \sqrt{V_{a,VT_u}^2 + V_{a,VT_v}^2}$ .

And the vertical tail angle of attack is given by

$$\begin{aligned} \alpha_{VT} &= -\arctan(V_{a,VT_v}/V_{a,VT_u}) \quad \text{if } V_{a,VT_u} \geq 0 \\ \alpha_{VT} &= -\pi/2 + \arctan(V_{a,VT_u}/V_{a,VT_v}) \quad \text{if } V_{a,VT_u} < 0 \quad \text{and } V_{a,VT_v} \geq 0 \\ \alpha_{VT} &= \pi/2 + \arctan(V_{a,VT_u}/V_{a,VT_v}) \quad \text{if } V_{a,VT_u} < 0 \quad \text{and } V_{a,VT_v} < 0 \end{aligned} \quad (58)$$

FORCES In the body frame  $F_b$  we have

$$\begin{aligned} F_{x_{VT}}^b &= q_{dp}.C_{x_{VT}}(CL, CD, \alpha_{VT}) \\ F_{y_{VT}}^b &= q_{dp}.C_{y_{VT}}(CL, CD, \alpha_{VT}) \\ F_{z_{VT}}^b &= 0 \\ q_{dp} &= 1/2.\rho.S_{ref_{VT}}.V_{a,VT}^2 \end{aligned} \quad (59)$$

The aerodynamic coefficients  $C_{x_{VT}}(\cdot)$  and  $C_{y_{VT}}(\cdot)$  are first functions of the lift  $CL(\cdot)$  and drag  $CD(\cdot)$  aerodynamic coefficients of a flat plate. Additionally the  $C_{x_{VT}}(\cdot)$  and  $C_{y_{VT}}(\cdot)$  coefficients are also functions of the airflow angle of attack  $\alpha_{VT}$ , through the aerodynamic forces projection on the body frame  $F_b$ . Further the  $CL(\cdot)$  and drag  $CD(\cdot)$  coefficients are also tabulated as a function of airflow angle of attack and Mach number.

MOMENTS The vertical tail moments are due to the tail forces times the respective moment arms, and to the aerodynamic pitch moment of a flat plate. This aerodynamic moment produces a yaw moment about the vehicle CG. In the body frame  $F_b$  we have

$$\begin{aligned} M_{x_{VT}}^b &= -z_{VT}.F_{y_{VT}} \\ M_{y_{VT}}^b &= z_{VT}.F_{x_{VT}} \\ M_{z_{VT}}^b &= x_{VT}.F_{y_{VT}} - y_{VT}.F_{x_{VT}} + q_{dp}.M_{z_{VT}}.L_{ref_{VT}} \\ q_{dp} &= 1/2.\rho.S_{ref_{VT}}.V_{a,VT}^2 \end{aligned} \quad (60)$$

Here the aerodynamic coefficient  $M_{z_{VT}}(\cdot)$  represents the pitch aerodynamic coefficient of a flat plate. This latter coefficient is tabulated as a function of airflow angle of attack and Mach number.

## II.F. Horizontal Tail Modeling

The role of the horizontal tail is also twofold: (i) in forward flight, it generates a trim load that reduces the main rotor fore-aft flapping, and (ii) during maneuvers, and during wind gusts, it provides pitch damping and stiffness, enhancing pitch stability.<sup>15</sup>

### II.F.1. Assumptions

#### Aerodynamics Simplifications

- Effect of main rotor downwash on horizontal tail is neglected. Again it can be modeled by using flat vortex wake theory<sup>39</sup> (valid for small sideslip angles), as presented in Ref. 40,41, or it may be modeled as a polynomial in wake skew angle as in Ref. 35.

### II.F.2. Modeling

Here too, we use a flat plate representation. Again, more sophisticated models exist,<sup>19,20</sup> and several approaches can be found in Ref. 22,35,37,38. It is also well-known that, depending on the longitudinal and vertical position of the horizontal tail with respect to the main rotor, erratic longitudinal trim shifts may happen when the helicopter is transitioning from hover to forward flight,<sup>21</sup> as the main rotor wake impinges on the tail surface.<sup>15</sup>

**VELOCITIES AND AIRFLOW ANGLES** The horizontal tail aerodynamic velocity, at its aerodynamic center, in the body frame is given by

$$\mathbf{V}_{a,HT}^b = \begin{pmatrix} V_{a,HT_u} \\ V_{a,HT_v} \\ V_{a,HT_w} \end{pmatrix}^b = \begin{pmatrix} u + (q - q_w).z_{HT} - (r - r_w).y_{HT} \\ v - (p - p_w).z_{HT} + (r - r_w).x_{HT} \\ w + (p - p_w).y_{HT} - (q - q_w).x_{HT} \end{pmatrix}^b - \begin{pmatrix} u_w \\ v_w \\ w_w \end{pmatrix}^b \quad (61)$$

Since in the sequel we will neglect the spanwise flow (along the y-axis), we have  $V_{a,HT} = \sqrt{V_{a,HT_u}^2 + V_{a,HT_w}^2}$ .

And the horizontal tail angle of attack is given by

$$\begin{aligned} \alpha_{HT} &= \arctan(V_{a,HT_w}/V_{a,HT_u}) \quad \text{if } V_{a,HT_u} \geq 0 \\ \alpha_{HT} &= \pi/2 + \arctan(-V_{a,HT_u}/V_{a,HT_w}) \quad \text{if } V_{a,HT_u} < 0 \quad \text{and } V_{a,HT_w} \geq 0 \\ \alpha_{HT} &= -\pi/2 - \arctan(V_{a,HT_u}/V_{a,HT_w}) \quad \text{if } V_{a,HT_u} < 0 \quad \text{and } V_{a,HT_w} < 0 \end{aligned} \quad (62)$$

**FORCES** In the body frame  $F_b$  we have

$$\begin{aligned} F_{x_{HT}}^b &= q_{dp}.C_{x_{HT}}(CL, CD, \alpha_{HT}) \\ F_{y_{HT}}^b &= 0 \\ F_{z_{HT}}^b &= q_{dp}.C_{z_{HT}}(CL, CD, \alpha_{HT}) \\ q_{dp} &= 1/2.\rho.S_{ref_{HT}}.V_{a,HT}^2 \end{aligned} \quad (63)$$

Again, the aerodynamic coefficients  $C_{x_{HT}}(\cdot)$  and  $C_{z_{HT}}(\cdot)$  are first functions of the lift  $CL(\cdot)$  and drag  $CD(\cdot)$  aerodynamic coefficients of a flat plate. Additionally the  $C_{x_{HT}}(\cdot)$  and  $C_{z_{HT}}(\cdot)$  coefficients are also functions of the airflow angle of attack  $\alpha_{HT}$ , through the aerodynamic forces projection on the body frame  $F_b$ . Further the  $CL(\cdot)$  and drag  $CD(\cdot)$  coefficients are also tabulated as a function of airflow angle of attack and Mach number.

**MOMENTS** The horizontal tail moments are first due to the tail forces times the respective moment arms, and further are also due to the aerodynamic pitch moment of a flat plate. This aerodynamic moment produces a pitch moment about the vehicle CG. In the body frame  $F_b$  we have

$$\begin{aligned}
 M_{x_{HT}}^b &= y_{HT} \cdot F_{z_{HT}} \\
 M_{y_{HT}}^b &= z_{HT} \cdot F_{x_{HT}} - x_{HT} \cdot F_{z_{HT}} + q_{dp} \cdot M y_{HT} \cdot L_{ref_{HT}} \\
 M_{z_{HT}}^b &= -y_{HT} \cdot F_{x_{HT}} \\
 q_{dp} &= 1/2 \cdot \rho \cdot S_{ref_{HT}} \cdot V_{a,HT}^2
 \end{aligned} \tag{64}$$

Here too the aerodynamic coefficient  $M y_{HT}(\cdot)$  represents the pitch aerodynamic coefficient of a flat plate. This latter coefficient is tabulated as a function of airflow angle of attack and Mach number.

### III. Black-Box Modeling

A BB model may often be viewed as an empirical, yet simple, system representation, and its purpose is generally threefold, namely (i) to compensate for inaccuracies in model parameters (e.g. CG position, vehicle inertia, flap stiffness, flap hinge offset), (ii) to compensate for not sufficiently well understood areas of a WB model (unmodeled high-order dynamics and/or unmodeled nonlinearities), and (iii) to replace computationally intensive WB sub-systems.

Now since attitude angles and inertial position are readily derived from the linear and rotational velocities, see Eq (2) and Eq (5), it is clear that the crucial states in our model are  $(u, v, w)$ ,  $(p, q, r)$ , and the MR RPM  $\Omega_{MR}$ . Hence, the goal of the BB model is to enhance the overall helicopter model accuracy, by improving the behavior of these seven states. This BB model is thus based on seven empirical coefficients, see also Appendix A, defined as

- Three force coefficients  $(\Theta_{Fx} \ \Theta_{Fy} \ \Theta_{Fz})^T$  to better fit the body linear velocities  $(u, v, w)$ , see Eq (7).
- Three moment coefficients  $(\Theta_{Mx} \ \Theta_{My} \ \Theta_{Mz})^T$  to better fit the body rotational velocities  $(p, q, r)$ , see Eq (8).
- One MR power coefficient  $\Theta_{MRpwr}$  to better fit the MR RPM  $\Omega_{MR}$  dynamics, since we omitted the contributions due to forward flight when deriving an expression for the main rotor torque, see Eq (41).

The presence of these coefficients allows for a versatile enough modeling framework, which permits us to conjecture that the true system is believed to lie inside the representation capacity of our GB modeling structure. We present next the identification method that is used to estimate these empirical coefficients.

#### III.A. Identification Through Nonlinear Optimal Control

The aim here is to identify the seven empirical coefficients, regrouped in  $\Theta(t)$

$$\forall t \geq 0 \quad \Theta(t) = \left( \Theta_{Fx}(t) \ \Theta_{Fy}(t) \ \Theta_{Fz}(t) \ \Theta_{Mx}(t) \ \Theta_{My}(t) \ \Theta_{Mz}(t) \ \Theta_{MRpwr}(t) \right)^T \tag{65}$$

We use a time-domain identification method, formulated as a continuous-time, nonlinear, constrained, optimal control problem. Note that since flight data is not available at this stage, the FLIGHTLAB nonlinear simulation model is used as a proxy, albeit in a noise-free setting, for experimental data. In the sequel, the given thirteen-state vector originating from FLIGHTLAB is denoted as  $\mathbf{x}_{FL}$ , and the corresponding four-control input vector as  $\mathbf{u}_{FL}$ . Note that this thirteen-state vector corresponds to rigid body and RPM parameters (either measured or estimated through extended/unscented Kalman filtering), which are delivered by any standard helicopter UAV avionics unit. We assume also that an observed Input-Output signal sequence  $\mathcal{Z}^N := \{(\mathbf{u}_{FL}(t_i), \mathbf{x}_{FL}(t_i))\}_{i=1}^N$ , collected under the desired operating conditions<sup>o</sup>, is available for

<sup>o</sup>Basically a set of trajectories spanning the vehicle's flight envelope.



the identification.

We consider the following problem, consisting in minimizing the Bolza cost functional  $J(\mathbf{x}(t), \Theta(t), T_o, T_f)$ , with the state-vector  $\mathbf{x}(t)$ , and control input-vector  $\Theta(t)$ , both defined on compact sets  $\mathbf{x}(t) \in \mathcal{P}_x \subseteq \mathbb{R}^{n_x}$ ,  $\Theta(t) \in \mathcal{P}_\Theta \subseteq \mathbb{R}^{n_\Theta}$ , denoting the feasible state and control spaces respectively, with  $n_x = 13$  and  $n_\Theta = 7$  in our case. Further, the independent time variable  $t$  is defined over the time domain  $\Omega = (T_o, T_f)$ , where the final time  $T_f$  may be free or fixed. Note that  $T_o$  and  $T_f$  do not necessarily represent the initial and final time in set  $\mathcal{Z}^N$ , since it is generally not computationally tractable to estimate  $\Theta(t)$ , for a large set  $\mathcal{Z}^N$ , in one shot. Rather, the time domain  $\Omega$  may equally refer to a sub-set of the data present in  $\mathcal{Z}^N$ , implying that the optimization procedure outlined hereunder may need to be repeated for each new  $\Omega$ , in which case the result of any optimization problem will serve as an initial value for the subsequent one.

We define next the cost functional

$$J(\mathbf{x}(t), \Theta(t), T_o, T_f) := \Phi(\mathbf{x}(T_o), T_o, \mathbf{x}(T_f), T_f) + \int_{\Omega} \Psi(\mathbf{x}(t), \Theta(t), t) dt \quad (66)$$

In the general problem formulation, the cost functional  $J(\cdot)$  has contributions from a fixed cost  $\Phi(\cdot)$ , and a running cost over time  $\int_{\Omega} \Psi(\cdot) dt$ . Additionally, this cost functional  $J(\cdot)$  is subject to the system dynamic constraints (see Section II), where the usual representation is given by a set of Ordinary Differential Equations (ODEs), of the form

$$\dot{\mathbf{x}} = f(\mathbf{x}(t), \Theta(t), t) \quad t \in \Omega \quad (67)$$

The initial and final-time boundary inequality conditions are given by

$$\begin{aligned} B_o(\mathbf{x}(T_o), \Theta(T_o), T_o) &\leq 0 \\ B_f(\mathbf{x}(T_f), \Theta(T_f), T_f) &\leq 0 \end{aligned} \quad (68)$$

which may describe the initial and final trimmed flight conditions. Conjointly any algebraic trajectory inequality constraints are given by

$$T(\mathbf{x}(t), \Theta(t), t) \leq 0 \quad t \in \Omega \quad (69)$$

having a fourfold objective: (i) account for vehicle's inherent physical and flight envelope limitations (bounds on speeds, attitude, and main rotor RPM), (ii) account for environmental constraints (the helicopter cannot descend below ground), (iii) prescribe the actuator control inputs  $\mathbf{u}(t) = \mathbf{u}_{FL}(t)$ , and (iv) bound any modeling misfits by  $\|\mathbf{x}(t) - \mathbf{x}_{FL}(t)\|_2 \leq \epsilon$ , with  $\epsilon$  small. For generality, the boundary and trajectory constraints Eq (68)-Eq (69) have been expressed as inequality constraints, equality constraints can simply be enforced by equating upper and lower bounds. Further, in Eq (66)-Eq (69) the functions  $\Phi(\cdot)$ ,  $\Psi(\cdot)$ ,  $f(\cdot)$ ,  $B_o(\cdot)$ ,  $B_f(\cdot)$ , and  $T(\cdot)$  are assumed to be sufficiently smooth, i.e. at least  $C^2$ . Finally, the solution to the trajectory planning gives the optimal empirical coefficients, which minimize the cost functional  $J(\cdot)$ , while enforcing the here-above predefined constraints

$$\hat{\Theta}(t) := \arg \min_{\Theta(t) \in \mathcal{P}_\Theta} J(\mathbf{x}(t), \Theta(t), T_o, T_f) \quad (70)$$

### III.B. Direct Optimal Control and The Pseudospectral Discretization

We chose to solve our problem through a direct optimal control method. In this context, the continuous-time optimal control problem is first discretized in some manner and the problem is transcribed to a NonLinear Programming problem (NLP),<sup>42-44</sup> without formulating an alternate set of optimality conditions as done through indirect methods.<sup>45-48</sup> The resulting NLP can be solved numerically, by well known and efficient optimization techniques, such as Sequential Quadratic Programming (SQP) methods<sup>49-51</sup> or Interior Point (IP) methods.<sup>52-56</sup> These methods in turn attempt to satisfy a set of conditions called the Karush-Kuhn-Tucker (KKT) conditions.<sup>42</sup> Now regarding the discretization of the continuous-time optimal control problem, the three most common discretization approaches to solve an indirect or direct method are: (i) Single-Shooting (SS),<sup>57</sup> (ii) Multiple-Shooting (MS),<sup>58,59</sup> and (iii) State and Control Parameterization (SCP) methods;<sup>60-64</sup> this latter is sometimes also known as transcription in the aerospace community, or as simultaneous strategy



in the chemical and process community. Here SS and MS approaches are so-called control parameterization techniques where the control signals alone are discretized,<sup>65</sup> whereas in SCP as indicated by its name, both state and control are parameterized.<sup>66</sup>

Briefly summarized, in shooting techniques the dynamics are satisfied by integrating the differential equations using a time-marching algorithm. The advantage of direct SS is that it generates a small number of variables, while its main disadvantage is that a small change in the initial condition can produce a very large change in the final conditions.<sup>67</sup> Further, the issue of stability is a major concern. Indeed, time integration over a relatively large shooting segment may lead to catastrophic results for unstable systems, and this is why SS generally fails to get a converged solution for such systems.<sup>68</sup> The SS has been most successful in launch vehicle trajectories and orbit transfer problems, primarily because this class of problem lends itself to parameterization with a relatively small number of variables.<sup>69</sup>

On the other hand, direct MS breaks the problem into shorter steps,<sup>67</sup> greatly enhancing the robustness of the shooting method, at the cost of having a larger number of variables. It is then primordial to exploit matrix sparsity to efficiently solve the NLP equations.<sup>69</sup> Despite the increased size of the problem, the direct MS method is an improvement over the standard direct SS method because the sensitivity to errors in the unknown initial conditions is reduced, since the differential equations are integrated over significantly smaller time intervals. Further, MS have shown to be suited for applications of high complexity, having large number of states.<sup>70</sup> However, an additional difficulty exists with the shooting techniques, namely the necessity of defining constrained and unconstrained subarcs a priori, when solving problems with path inequality constraints.<sup>69</sup> This issue however does not exist with SCP methods,<sup>71</sup> which is one of the reasons why SCP methods have actively being investigated.<sup>69</sup>

In addition, SCP methods are known to be very effective and robust,<sup>70</sup> and SCP techniques have been applied to solve nonlinear optimal control problems, such as in space and launch/reentry applications,<sup>61, 62, 72–76</sup> in aircraft applications,<sup>61, 77–80</sup> in helicopter applications,<sup>81–83</sup> in UAV applications,<sup>84–86</sup> and glider applications.<sup>87</sup> Since SCP methods have been intensively researched in the last decade, we present next a general overview of this concept. In SCP, several discretization procedures have been studied, namely local Runge-Kutta methods in Ref. 65, 66, 88, 89, local orthogonal methods in Ref. 60, 62, 75, 90, 91, Global Orthogonal Approaches (GOA) or spectral methods in Ref. 91–98, and most recently hybrid local/global methods in Ref. 99. Of these four procedures, the GOA have received much attention in the last decade, since they have the advantage of providing spectral convergence, i.e. at an exponential rate, for the approximation of analytic, i.e. sufficiently smooth, functions.<sup>100–102</sup> Thus, for a given error bound, GOA methods generate a significantly smaller scale optimization problem when compared to other methods.<sup>101</sup> This is an important aspect since the efficiency and even convergence of NLPs improves for a problem of smaller size.<sup>103</sup>

In a GOA the system's state-vector is expressed as a truncated series expansion, characterized by Basis (BA) functions, and Expansion Coefficients (EC) determined from test functions, which attempt to ensure that the Ordinary Differential Equations (ODEs), defining the system dynamics, are optimally satisfied. The choice of the BA functions is what distinguishes GOA methods from finite-difference or finite-element methods. In both finite-type methods, the BA is local in character, while for GOA methods the BA consists of infinitely differentiable global functions, such as orthogonal polynomials,<sup>104</sup> trigonometric functions, or constant basis function like Haar<sup>105</sup> or block-pulse. Further, the EC distinguish the three most common types of GOA methods, namely Galerkin, Tau, and collocation. Of these three, the last one, often referred to as the PseudoSpectral (PS) discretization, has received considerable attention in recent years. In PS methods, the BA is described by Lagrange interpolating polynomials,<sup>106</sup> and are expressed using a set of  $N$  support points. The location of these support points is determined by orthogonal polynomials, for example Legendre polynomials,<sup>104</sup> although other choices exist, such as Chebyshev polynomials.<sup>107</sup> Besides the choice of these  $N$  support points, another set of  $K$  points is required for the discretization of the integral within the cost functional, and the system dynamic constraints. These  $K$  points are chosen such that the quadrature approximation of an integral is minimized.<sup>106</sup> Now, it is well known that the highest accuracy quadrature approximation, for a given number of  $K$  points, is the Gauss quadrature.<sup>106</sup> In this case, the location of these  $K$  quadrature points, called Legendre-Gauss (LG) points, is determined by the roots of a  $K$ th-degree Legendre polynomial.<sup>94, 96</sup> It is also worth noting that two additional variations to the LG approach have

extensively been investigated in the last decade, namely the Legendre-Gauss-Lobatto (LGL) method,<sup>92,93</sup> and the Legendre-Gauss-Radau (LGR) method.<sup>91,97,98</sup> It was further reported in Ref. 108 that the LG and LGR methods have been found to be very similar in accuracy, while outperforming the LGL method.

PS methods have been extensively used in solving fluid dynamics problems,<sup>109,110</sup> but only recently have these methods been used for solving a variety of optimal control problems. It is clear that PS methods exhibit a number of advantages when compared to other discretization methods, even when compared to the popular spline parametrization.<sup>67,84,111</sup> Indeed, PS techniques have been widely used in space and launch/reentry applications, see the results of Ref. 112–129. However, they have so far only seen limited use in other aeronautical applications such as: aircrafts,<sup>117,130–133</sup> helicopters,<sup>134</sup> fixed-wing UAVs,<sup>119,135–138</sup> and helicopter UAVs.<sup>139,140</sup> Accordingly, we opt for a PS numerical structure, as the discretization framework for our identification problem.

Once the optimal empirical values  $\hat{\Theta}(t)$  have been obtained, the following step consists in finding a smooth and continuous-time nonlinear mapping,  $g_{\Theta}(\cdot)$  s.t.

$$\hat{\Theta}(t) = g_{\Theta}(\tilde{\mathbf{x}}(t), \tilde{\mathbf{u}}(t)) \quad (71)$$

with  $\tilde{\mathbf{x}} \in \mathbb{R}^{\tilde{n}_x}$ ,  $\tilde{\mathbf{u}} \in \mathbb{R}^{\tilde{n}_u}$ ,  $\tilde{n}_x \leq n_x$ ,  $\tilde{n}_u \leq n_u$  representing either, the full state and control vectors respectively as given in Eq (1), or a subset of these vectors.

### III.C. Neural Networks Model

For physically-intuitive plants, one may select the required states  $\tilde{\mathbf{x}}$  and inputs  $\tilde{\mathbf{u}}$ , based upon engineering judgment, and derive the nonlinear mapping  $g_{\Theta}(\cdot)$  through popular curve-fitting methods. For non-transparent systems, exhibiting significant dependences among variables, one may consider formal/systematic approaches such as principal component analysis, statistical analysis, fuzzy tools, or Neural Networks (NNs). Now, NNs have found a wide range of applications in control theory. Indeed, under mild assumptions on continuity and boundedness, a network of two layers, the first being hidden sigmoid and the second linear, can be trained to approximate any Input-Output (IO) relationship arbitrarily well, provided the number of neurons  $L$  in the hidden layer is high enough.<sup>141,142</sup> Hence, we propose here to anchor the  $g_{\Theta}(\cdot)$  modeling within the NN paradigm.

$$\begin{aligned} \hat{\Theta}(t) &= g_{\Theta}(\tilde{\mathbf{x}}(t), \tilde{\mathbf{u}}(t)) = C_{\Theta} \cdot \mathbf{s}_{\Theta}(t) \\ \mathbf{s}_{\Theta}(t) &= W_{o_{\Theta}} \cdot \kappa(W_{x_{\Theta}} \tilde{\mathbf{x}}(t) + W_{u_{\Theta}} \tilde{\mathbf{u}}(t) + W_{b_{\Theta}}) \end{aligned} \quad (72)$$

where  $W_{o_{\Theta}} \in \mathbb{R}^{n_{\Theta} \times L}$  and  $W_{x_{\Theta}} \in \mathbb{R}^{L \times \tilde{n}_x}$ ,  $W_{u_{\Theta}} \in \mathbb{R}^{L \times \tilde{n}_u}$ , contain the output and hidden layer weights respectively. Further,  $W_{b_{\Theta}} \in \mathbb{R}^L$  contains the sets of biases in the hidden layer,  $C_{\Theta} \in \mathbb{R}^{n_{\Theta} \times n_{\Theta}}$  contains the output linear map, and  $\kappa(\cdot)$  is the activation function, taken as a continuous, diagonal, differentiable, and bounded static sigmoid nonlinearity.

## IV. Simulation Results

We implemented our model in a MATLAB<sup>®</sup> environment.<sup>143</sup> The modeled UAV is an instrumented R/C *Align T-REX* helicopter, belonging to the flybarless two-bladed main rotor class, which physical characteristics as documented in Appendix B. Additionally, for the FLIGHTLAB model, the following options have been selected

- Articulated rotor, and blade element model. Quasi-steady airloads, based on the Peters-He three-state inflow model, with no stall delay effects.
- Bailey tail rotor, and ideal engine.

In this paper, and purely for the sake of illustration, we base the identification on a single trajectory, starting from hover. The applied input corresponds to an 5 s long collective sine-sweep, from 0.1 to 2 Hz,



with an amplitude of  $0.5^\circ$ . Now, the very low vehicle roll inertia, and the low pitch inertia (see Appendix B) have resulted in very noisy roll and pitch rates, due to blade flapping. Indeed, a power spectral density analysis revealed the presence of a high energy component at the  $2/\text{Rev} = 45$  Hz harmonic. Hence, we decided to low-pass the roll and pitch rates, before using them in the identification, with a zero-phase shift, fifth order, digital Butterworth filter, having a cutoff frequency set at 10 Hz.

To solve the nonlinear control problem of Section III.A, the pseudospectral numerical method, as described in Section III.B, is used. This numerical discretization framework is available in a MATLAB environment, through the open-source General Pseudospectral OPTimal control Software GPOPS<sup>®</sup>.<sup>95,144–146</sup> In order to use GPOPS, the optimal control problem must first be reformulated into a GPOPS format, as a set of MATLAB m-files.<sup>146</sup> Second, the helicopter model must also be expressed in a vectorized structure, implying that each model variable and parameter is a vector, which values are time-dependent. This latter aspect is particularly relevant for complex models, where for instance standard matrix-matrix multiplications have to be handled with care, as each matrix element is a vector. Third, (cubic) B-Splines interpolating functions ought to be used, when querying lookup tables, as the spectral convergence of PS methods only holds when the functions under consideration are smooth.<sup>104,147</sup> It is also best practice to non-dimensionalize and scale model variables and quantities, in order to improve conditioning of the numerical problem. With respect to the cost functional of Eq (66), we chose to minimize the variance of  $\Theta(t)$ , on each  $\Omega = (T_o, T_f)$  interval. Next the trajectory constraint  $\|\mathbf{x}(t) - \mathbf{x}_{FL}(t)\|_2 \leq \epsilon$  in Eq (69) has been set to  $\epsilon = 10\%$ . Further, finite differencing has been used to estimate the objective gradient and constraint Jacobian. Once the control problem discretized, it is then transcribed into a static, finite-dimensional NLP optimization problem. An NLP is generally sparse, and many well-known efficient optimization techniques exist to numerically solve large-scale and sparse NLPs. In our case, we use the SNOPT<sup>®</sup> software,<sup>51</sup> which solves finite-dimensional optimization problems through SQP.

From a computational tractability and solvability viewpoint, it is preferable to solve a large number of *small* optimization problems - defined each on a very short  $\Omega = (T_o, T_f)$  interval and having each very few nodes - than to solve a single *large* optimization problem, defined on a large  $\Omega = (T_o, T_f)$  interval with many nodes. Accordingly, we have decided to base the discretization of the optimal problem on just 3 nodes, yielding a NLP problem with 55 variables and 44 constraints. Now since the data provided by FLIGHTLAB is sampled at 540 Hz, we will use a very small  $\Omega = (T_o, T_f)$  interval of 9.26 ms, corresponding to a sampling frequency of  $540/5=108$  Hz. Once the optimal empirical coefficients  $\hat{\Theta}$  have been computed, and before fitting the NN model of Eq (72), we low-pass these coefficients with again a zero-phase shift, fifth order, digital Butterworth filter, having a cutoff frequency set at 2 Hz, in order to remove the unrealistic high-frequency behavior, and any additional outliers. Finally, the NN model of Section III.C is based upon a 5-neurons feedforward network, with a hyperbolic tangent activation transfer function in the hidden layer, and backpropagation training for the weights and biases.

Next, we apply a collective sweep input, at a constant main rotor RPM, to both our estimated model and FLIGHTLAB, and briefly compare the open-loop responses. The simulation plots are given in Appendix C. Figure 1 shows the evolution of the body states, whereas Figure 2 displays the inertial positions and velocities. Compared to the FLIGHTLAB benchmark model, we see that the model's preliminary results are encouraging. Note however that the NN model is rather approximate, since trained with only a single trajectory. Hence, future work shall concentrate on NN modeling improvement, since this latter accounts for most of the misfit between our model and FLIGHTLAB.

## V. Conclusion

We have presented a novel methodology, which allows for the formulation of a highly-accurate, yet computationally tractable, grey-box nonlinear helicopter model. The adopted strategy consists in replacing all modeling uncertainty - parameter uncertainties, unmodeled higher-order dynamics, and unmodeled static nonlinearities - by empirical coefficients. Next, the identification of these coefficients has been based upon the combined paradigms of nonlinear optimal control, and Neural Networks (NN). Our preliminary encouraging results invite further application and investigations of the here-presented approach.

## Appendix A: Nomenclature

- Frames
  - $F_I$  Geocentric inertial frame
  - $F_E$  Normal earth fixed frame
  - $F_o$  Vehicle carried normal earth frame
  - $F_b$  Body (vehicle) frame
  - $F_a$  Aerodynamic (air path) frame
  - $F_k$  Kinematic (flight path) frame
  - $F_{HB}$  Hub-Body frame
  - $F_{HB}$  Hub-Body frame
  - $F_{HBw}$  Hub-Body wind-axis frame
  - $F_{TR}$  Tail-Rotor frame
- Frame origins
  - $A$  Origin of frame  $F_I$ , earth center
  - $O$  Origin of frames  $F_E$  and  $F_o$ , an earth surface point
  - $G$  Origin of frames  $F_b$ ,  $F_a$  and  $F_k$ , aircraft center of mass
- Angles between frames
  - $\psi$  Azimuth angle (yaw angle, heading)
  - $\theta$  Inclination angle (pitch angle, or elevation)
  - $\phi$  Bank angle (roll angle)
- Position
  - $x_N, x_E, x_Z$  Coordinates of CG position vector in  $F_E$  frame
  - $x_H, y_H, z_H$  Coordinates of Hub position wrt vehicle CG in  $F_b$  frame
- Altitude
  - $h_H = -x_Z - z_H$  Hub position above ground
- Linear velocities are denoted  $\mathbf{V}$  and their components  $u, v, w$ 
  - $\mathbf{V}_{k,G}$  Kinematic velocity of the vehicle center of mass
  - $\mathbf{V}_{a,G}$  Aerodynamic velocity of the vehicle center of mass
  - $u_k^o = V_N$   $x$  component of  $\mathbf{V}_{k,G}$  on  $F_o$ ,  $V_N$  North velocity
  - $v_k^o = V_E$   $y$  component of  $\mathbf{V}_{k,G}$  on  $F_o$ ,  $V_E$  East velocity
  - $w_k^o = V_Z$   $z$  component of  $\mathbf{V}_{k,G}$  on  $F_o$ ,  $V_Z$  Vertical velocity
  - $u_k^b = u$   $x$  component of  $\mathbf{V}_{k,G}$  on body frame  $F_b$
  - $v_k^b = v$   $y$  component of  $\mathbf{V}_{k,G}$  on body frame  $F_b$
  - $w_k^b = w$   $z$  component of  $\mathbf{V}_{k,G}$  on body frame  $F_b$
- Angular velocities are denoted  $\mathbf{\Omega}$  and their components  $p, q, r$ 
  - $\mathbf{\Omega}_k = \mathbf{\Omega}_{bE}$  Kinematic angular velocity of the vehicle ( $b$ ) relative to the earth ( $E$ )
  - $p_k^b = p$  Roll velocity (roll rate) of the vehicle relative to the earth (frame  $F_E$ )
  - $q_k^b = q$  Pitch velocity (pitch rate) of the vehicle relative to the earth
  - $r_k^b = r$  Yaw velocity (yaw rate) of the vehicle relative to the earth

- Wind

$\mathbf{V}_w$	Wind linear velocity in $F_E$ , of an atmospheric particle which could have been located at the vehicle center of mass
$u_w$	Wind x-velocity in $F_E$
$v_w$	Wind y-velocity in $F_E$
$w_w$	Wind z-velocity in $F_E$
$p_w$	Wind roll-velocity in $F_E$
$q_w$	Wind pitch-velocity in $F_E$
$r_w$	Wind yaw-velocity in $F_E$
$\Psi_w$	Wind azimuthal angular position
$\rho$	Air density

- Mass and Inertia

$m_{Fus}$	Fuselage mass
$\mathbb{I}_{Fus} = \begin{bmatrix} A & -F & -E \\ -F & B & -D \\ -E & -D & C \end{bmatrix}$	Fuselage inertia

- Main Rotor (MR) properties

$\Gamma$	Direction of rotation, $CCW : \Gamma = 1$ $CW : \Gamma = -1$
$N_b$	Number of blades
$M_{bl}$	Blade 0th mass moment (blade mass from flap hinge)
$C_0 = M_{bl} \cdot y_{G_{bl}}$	Blade 1st mass moment
$I_\beta$	Blade 2nd mass moment (inertia about flap hinge)
$I_b$	Blade 2nd mass moment (inertia about rotor shaft)
$R_{rot}$	Rotor radius measured from hub center
$R_{bl}$	Blade radius measured from flap hinge
$\Delta_e$	Distance between hub and flap hinge
$c_{bl}$	Blade chord
$y_{G_{bl}}$	Blade CG radial position from flap hinge
$\sigma_{MR} = \frac{N_b \cdot c_{bl}}{\pi \cdot R_{rot}}$	Solidity
$B$	Tip loss factor, expressed as percentage of blade length $R_{bl}$ no lift is generated outboard of position $B \cdot R_{bl}$
$\gamma = \frac{\rho \cdot c_{bl} \cdot C_{LMR\alpha} \cdot R_{bl}^4}{I_\beta}$	Blade Lock number
$\lambda_m$	Momentum theory induced flow due to rotor thrust (TPP)
$\lambda_h$	Rotor induced inflow in hover $\lambda_h = \sqrt{\frac{C_{TMR}}{2}} = v_h / V_{MRref}$
$\mu$	Advance ratio
$\mu_x$	Non-dimensional forward flight air velocity
$\mu_y$	Non-dimensional sideways flight air velocity
$\mu_{xy} = \sqrt{\mu_x^2 + \mu_y^2}$	Non-dimensional in-plane (rotor disk) air velocity
$\mu_z$	Non-dimensional vertical flight air velocity (normal to the TPP)
$K_{S_\beta}$	Hub spring restraint coefficient (due to flap)
$\bar{\mu} = \frac{\mu}{\lambda_h}$	Normalizing advance ratio
$\bar{\lambda} = \frac{\lambda_m + \mu_z}{\lambda_h}$	Normalizing total inflow
$G_{eff}$	Ground effect corrective factor
$\epsilon = \frac{\Delta_e}{R_{rot}}$	Normalized flap hinge offset

- Main Rotor (MR) properties (Cont'd)
  - $\Theta_{MRpwr}$  Form factor on rotor power
- MR position vector components
  - $x_H, y_H, z_H$  Position of Hub center wrt vehicle CG  $G$
- MR angles
  - $\psi_{bl}$  Azimuthal angular position of blade
  - $\beta_0$  Rotor TPP coning angle
  - $\beta_{1c}$  Longitudinal rotor TPP tilt (positive forward)
  - $\beta_{1s}$  Lateral rotor TPP tilt (positive towards retreating side)
  - $\theta_{bl}$  Blade pitch outboard of flap hinge (feathering) angle
  - $\psi_{PA}$  Swashplate phase angle
  - $\theta_0$  Blade root collective pitch
  - $\theta_{1c}$  Lateral cyclic pitch
  - $\theta_{1s}$  Longitudinal cyclic pitch
  - $\beta_{MR}$  Sideslip angle
- $$\beta_{bl} \simeq \beta_0 + \beta_{1c} \cos \psi_{bl} + \beta_{1s} \sin \psi_{bl}$$

$$\theta_{bl} = \theta_0 + \theta_{1c} \cos(\psi_{bl} + \psi_{PA}) + \theta_{1s} \sin(\psi_{bl} + \psi_{PA})$$
- MR angular velocities
  - $\Omega_{MR100\%}$  Nominal (100%) angular velocity
  - $\Omega_{MR}$  Instantaneous angular velocity
- MR linear velocities
  - $v_{i_o}$  Rotor uniform induced velocity, normal to the TPP and positive when oriented downwards
  - $v_h$  Rotor induced velocity in hover
 
$$v_h = \sqrt{\frac{m \cdot g}{2 \cdot \rho \cdot \pi \cdot R_{rot}^2}}$$
  - $V_{MRref}$  Reference velocity
 
$$V_{MRref} = \Omega_{MR} \cdot R_{rot}$$
- MR forces/moments
  - $F_{xMR}$  x-force
  - $F_{yMR}$  y-force
  - $F_{zMR}$  z-force
  - $M_{xMR}$  Total roll moment
  - $M_{yMR}$  Total pitch moment
  - $M_{zMR}$  Total yaw moment
  - $L_{(MR,inertial)}$  Roll moment due to inertia loads
  - $M_{(MR,inertial)}$  Pitch moment due to inertia loads
  - $L_{(MR,flap)}$  Roll moment due to hub spring restraint (flap)
  - $M_{(MR,flap)}$  Pitch moment due to hub spring restraint (flap)
  - $N_{(MR,aero)} = Q_{MR}$  Yaw moment due to aerodynamic loads
  - $P_{MR}$  Power

- MR aerodynamic and force/moments coefficients
  - $C_{HMR}$  Drag coefficient
  - $C_{YMR}$  Side-force coefficient
  - $C_{TMR}$  Thrust coefficient
  - $CL_{MR\alpha}$  Blade section lift curve slope
  - $CL_{MR}$  Lift coefficient
  - $CD_{MR}$  Mean drag coefficient (profile drag)
- Tail Rotor (TR) properties
  - $N_{bTR}$  Number of blades
  - $R_{rotTR}$  Rotor radius measured from shaft
  - $\frac{\partial \beta_{0TR}}{\partial TTR}$  Partial coning angle wrt thrust
  - $\tan \delta_{3TR}$  Tangent of hinge skew angle for pitch-flap coupling
  - $c_{TR}$  Blade chord
  - $\sigma_{TR} = \frac{N_{bTR} \cdot c_{TR}}{\pi \cdot R_{rotTR}}$  Solidity
  - $\mu_{TRx}$  x-component of advance ratio
  - $\mu_{TRY}$  y-component of advance ratio
  - $\mu_{TRxy}^2 = \mu_{TRx}^2 + \mu_{TRY}^2$
  - $\mu_{TRz}$  z-component of advance ratio
  - $\lambda_{TR}$  Total inflow
  - $\lambda_{dw}$  Inflow
  - $t_1 \ t_2$  Bailey coefficients
  - $CL_{TR\alpha}$  Blade section lift curve slope
  - $CD_{TR}$  Mean drag coefficient (profile drag)
  - $B_{TR}$  Tip loss factor, expressed as percentage of blade length
  - $K_{TRcorr}$  Correction factor
- TR position vector components
  - $x_{TR}, y_{TR}, z_{TR}$  Position wrt vehicle CG (in  $F_{HB}$  frame)
- TR angles
  - $\beta_{0TR}$  Coning angle
  - $\theta_{TR}$  Blade pitch angle
  - $\theta_{0TR}$  Blade root collective pitch
  - $\theta_{biasTR}$  Preset collective pitch bias
- TR angular velocities
  - $\Omega_{TR100\%}$  Nominal (100%) angular velocity
  - $\Omega_{TR}$  Instantaneous angular velocity
- TR linear velocities
  - $\mathbf{V}_{a,TR}$  Aerodynamic velocity of the TR hub
  - $V_{TRref}$  Reference velocity
  - $V_{TRref} = \Omega_{TR} \cdot R_{rotTR}$

- TR forces/moments
  - $T_{TR}$  Thrust
  - $F_{xTR}$  x-force
  - $F_{yTR}$  y-force
  - $F_{zTR}$  z-force
  - $M_{xTR}$  Total roll moment
  - $M_{yTR}$  Total pitch moment
  - $M_{zTR}$  Total yaw moment
- Fuselage (Fus) properties
  - $S_{refF}$  Reference area
  - $L_{refF}$  Reference length
- Fuselage angles
  - $\alpha_F$  Angle of attack
  - $\beta_F$  Sideslip angle
- Fuselage position vector components
  - $x_F, y_F, z_F$  Position of fuselage CG wrt
- Fuselage forces/moments
  - $F_{x_F}$  x-force
  - $F_{y_F}$  y-force
  - $F_{z_F}$  z-force
  - $M_{x_F}$  Total roll moment
  - $M_{y_F}$  Total pitch moment
  - $M_{z_F}$  Total yaw moment
- Horizontal/Vertical Tails (HTVT) properties
  - $S_{refHT}$  HT Reference area
  - $L_{refHT}$  HT Reference length
  - $S_{refVT}$  VT Reference area
  - $L_{refVT}$  VT Reference length
- Horizontal/Vertical Tails (HTVT) angles
  - $\alpha_{HT}$  HT angle of attack
  - $\beta_{HT}$  HT sideslip angle
  - $\alpha_{VT}$  VT angle of attack
  - $\beta_{VT}$  VT sideslip angle
- Horizontal/Vertical Tails (HTVT) position vector components
  - $x_{HT}, y_{HT}, z_{HT}$  Position of horizontal tail aerodynamic center
  - $x_{VT}, y_{VT}, z_{VT}$  Position of vertical tail aerodynamic center

- Horizontal/Vertical Tails (HTVT) forces/moments

$F_{xHT}$	HT x-force
$F_{yHT}$	HT y-force
$F_{zHT}$	HT z-force
$F_{xVT}$	VT x-force
$F_{yVT}$	VT y-force
$F_{zVT}$	VT z-force
$M_{xHT}$	Total HT roll moment
$M_{yHT}$	Total HT pitch moment
$M_{zHT}$	Total HT yaw moment
$M_{xVT}$	Total VT roll moment
$M_{yVT}$	Total VT pitch moment
$M_{zVT}$	Total VT yaw moment

- Empirical coefficients (black-box model)

$\Theta_{Fx}$	Added on total x-force
$\Theta_{Fy}$	Added on total y-force
$\Theta_{Fz}$	Added on total z-force
$\Theta_{Mx}$	Added on total x-moment
$\Theta_{My}$	Added on total y-moment
$\Theta_{Mz}$	Added on total z-moment
$\Theta_{MRpower}$	Form factor on MR power

## Appendix B: Align T-REX Physical Parameters

	Name	Parameter	Value	Unit
Environment	Air density	$\rho$	1.2367	$kg/m^3$
	Static temperature	$T$	273.15 + 15	$K$
	Specific heat ratio (air)	$\gamma$	1.4	
	Gas constant (air)	$R$	287.05	$J/kg.K$
	Gravity constant	$g$	9.812	$m/s^2$
Vehicle	Total mass	$m$	7.75	$kg$
	Inertia moment wrt $x_b$	$A$	0.0705	$kg.m^2$
	Inertia moment wrt $y_b$	$B$	0.4760	$kg.m^2$
	Inertia moment wrt $z_b$	$C$	0.2855	$kg.m^2$
	Inertia product wrt $x_b$	$D$	0	$kg.m^2$
	Inertia product wrt $y_b$	$E$	0.0018	$kg.m^2$
Main Rotor	Inertia product wrt $z_b$	$F$	0	$kg.m^2$
	Direction of rotation	$\Gamma$	CW (-1)	
	Number of blades	$N_b$	2	
	Nominal angular velocity	$\Omega_{MR_{100\%}}$	131.37	$rad/s$
	Rotor radius from hub	$R_{rot}$	0.9	$m$
	Blade mass	$M_{bl}$	0.208	$kg$
Tail Rotor	Spring restraint coef. due to flap	$K_{S\beta}$	163.8	$N.m/rad$
	Distance between hub and flap hinge	$\Delta_e$	0.32	$m$
Tail Rotor	Number of blades	2		
	Nominal angular velocity	$\Omega_{TR_{100\%}}$	612.61	$rad/s$
	Rotor radius from rotor hub	$R_{rotTR}$	0.14	$m$
Actuators	MR collective	$\theta_0$	$[-3,10].\pi/180$	$rad$
	TR collective	$\theta_{TR}$	$[-12,18].\pi/180$	$rad$
	MR lateral cyclic	$\theta_{1c}$	$[-7,7].\pi/180$	$rad$
	MR longitudinal cyclic	$\theta_{1s}$	$[-7,7].\pi/180$	$rad$
	MR collective rate	$\dot{\theta}_0$	$[-52,52].\pi/180$	$rad/s$
	TR collective rate	$\dot{\theta}_{TR}$	$[-120,120].\pi/180$	$rad/s$
	MR lateral cyclic rate	$\dot{\theta}_{1c}$	$[-56,56].\pi/180$	$rad/s$
	MR longitudinal cyclic rate	$\dot{\theta}_{1s}$	$[-56,56].\pi/180$	$rad/s$

### Appendix C: Simulation Results

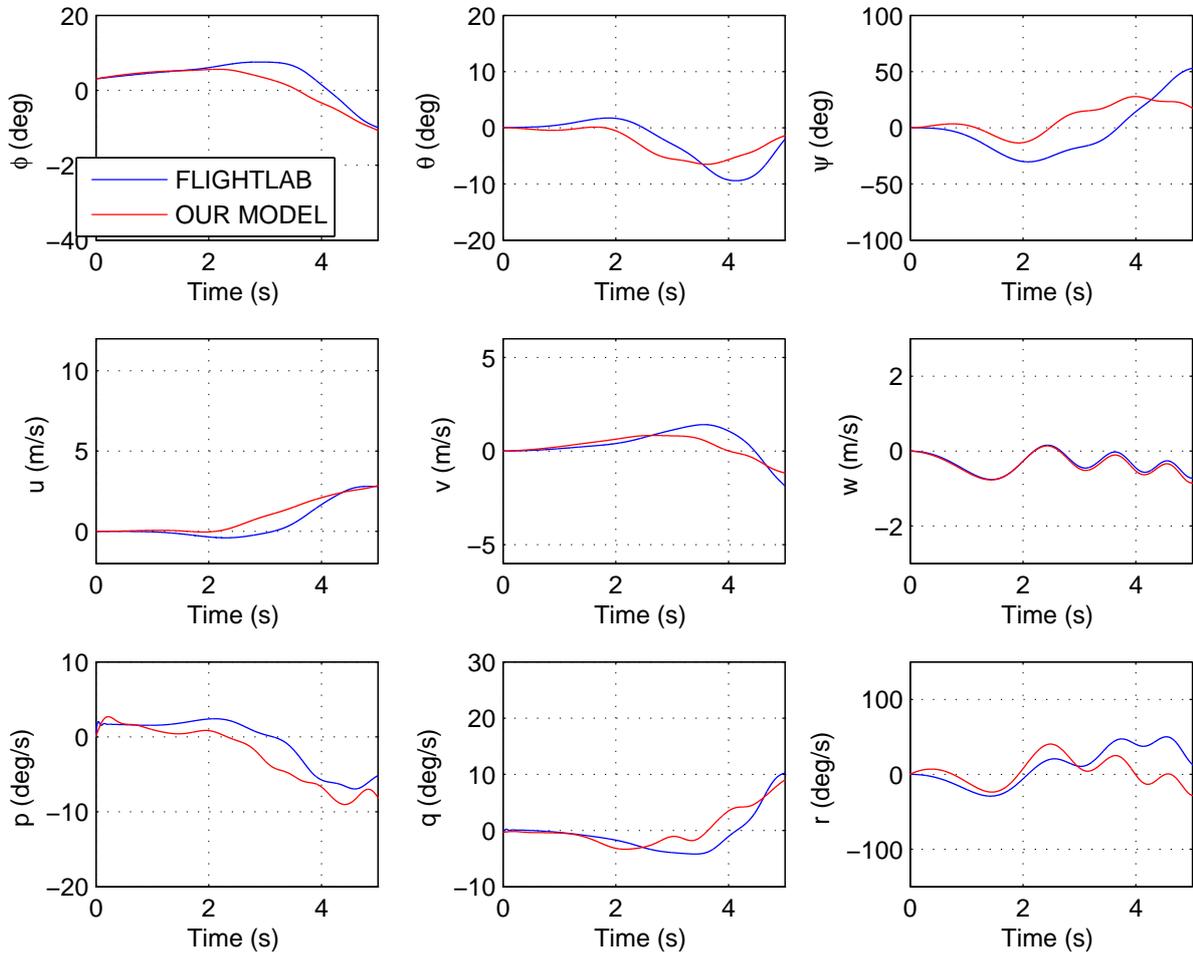


Figure 1. Vehicle response in body frame

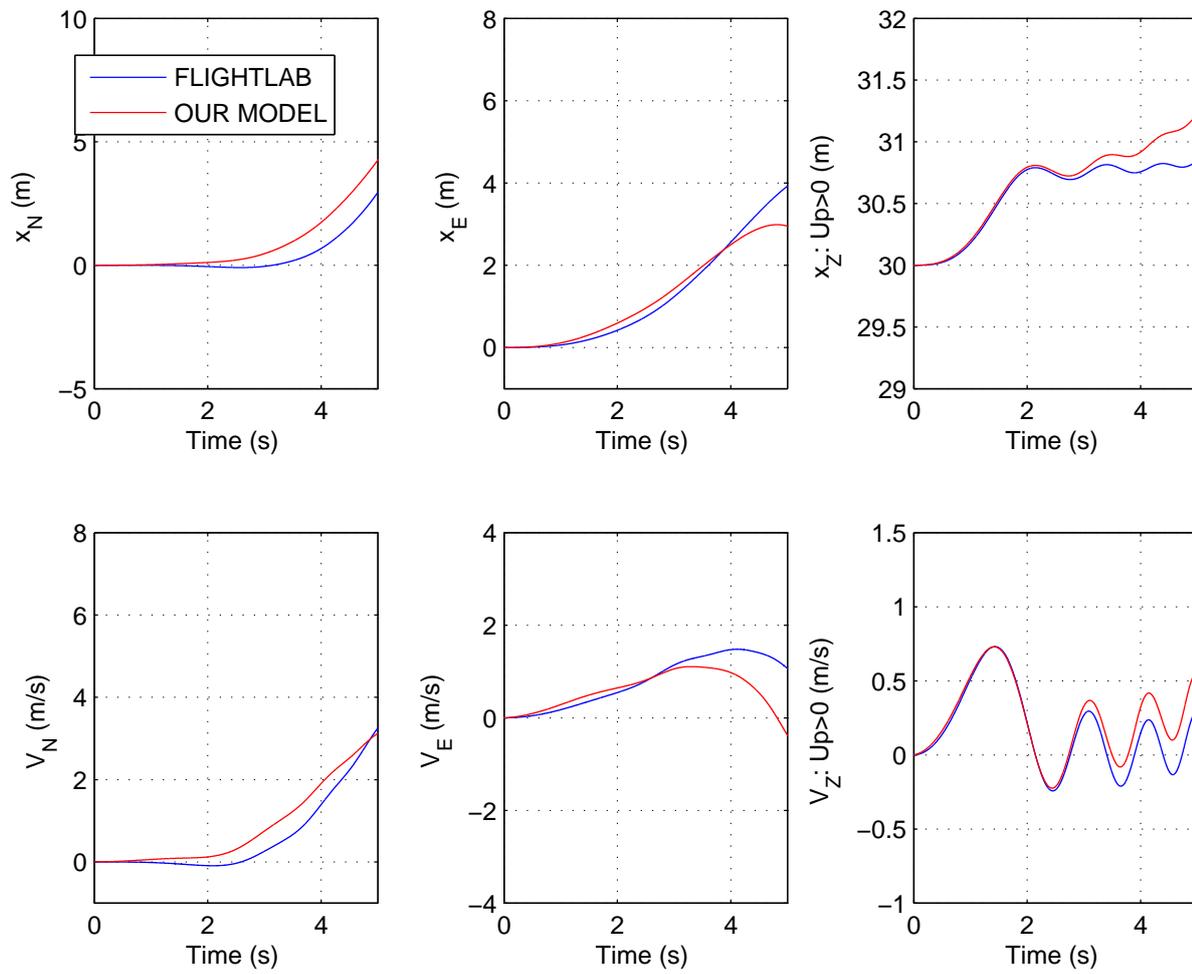


Figure 2. Vehicle response in inertial frame

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