A NOVEL WAKE INTERFERENCE MODEL FOR HELICOPTER REAL-TIME SIMULATION

Jan Juraj Đeverlija, Anna Abà, Pierluigi Capone
ZHAW Zurich University of Applied Sciences, Winterthur, Switzerland

Alessandro Masi, Matteo Daniele, Francesco Scorcelletti
Kopter Group AG – Leonardo Company, Wetzikon, Switzerland

ABSTRACT

Aerodynamic mutual interference occurring between rotors' wake, fuselage and aerodynamic surfaces has a notable impact on the flight characteristics of a helicopter. A simple and flexible method for quantifying aerodynamic interaction between the rotor wake and airframe is presented. The model, implemented in the Zurich University of Applied Sciences (ZHAW) simulation framework, has been developed for both off-line and real-time helicopter simulation and was validated by comparison against an existing model already validated with flight test data. The model was also tested on the motion-based, virtual-reality flight simulator ZHAW High-Fidelity Simulator.

Acronyms

AoA	Angle of Attack
AoS	Angle of Sideslip
CFD	Computational Fluid Dynamics
CW	Cowlings
EoM	Equations of Motion
HT	Horizontal Tail
OS	Operating System
TB	Tail Boom
TPP	Tip Path Plane
TR	Tail rotor
VF	Vertical Fin
WHeSI	White-Box Helicopter System Identification
ZHAW	Zurich University of Applied Sciences

Symbols

d	Distance from tip path plane	[m]
p, q, r	Body axis angular velocity components	[rad/s]
R	Main Rotor radius	[m]
u, v, w	Body axis velocity components	[m/s]
v_i	Uniform component of induced velocity	[m/s]
θ	Pitch Angle	[rad]
ϕ	Bank Angle	[rad]
χ	Departure Angle	[rad]

1 Introduction

A complete helicopter model suitable for flight mechanics, control system design and real-time simulation is currently under development in the framework of the funded Innosuisse (Swiss Innovation Agency - www.innosuisse.ch) Project "WHeSI – White-Box Helicopter System Identification" in collaboration with the helicopter manufacturer Kopter (koptergroup.com). Aerodynamic mutual interference occurring between rotor wake, fuselage and aerodynamic surfaces has a notable impact on the flight characteristics of a helicopter. One way to numerically reproduce this interaction is through computational fluid dynamics (CFD) which, however, remains also nowadays highly demanding in terms of computation time [Hoydonck-2009], [Chaffin-1997] and, therefore, not suitable for real-time applications. Classical vortex models such as prescribed wake models, which implement predefined wake geometries, and free wake models, where the wake is allowed to deform under its own influence, are usually coupled with panel methods to obtain wake-airframe interactions in the form of perturbation of the induced velocity at the location of the aerodynamic components. Despite being reliable, accurate and less computationally intensive than CFD, these models are still demanding for real-time simulations [Lorber-1988], [Quackenbush-1994].

Accurate free wake modelling suitable for real-time simulation was implemented in early 2000s where a free-vortex wake model was integrated with the UH-60A helicopter model [Horn-2006]. It was shown that increasing time step of the free wake and simulation brings the simulation to real-time without big accuracy loss. Computational load using free vortex wake model was also assessed recently in [Saetti-2022]. This showed significant improvement in runtime performance for slower than real-time simulation but concluded that by increasing the simulation time step, reducing the order of the system and/or with usage of a faster machine, is possible to achieve real-time simulation. In [Saetti-2023] a XV-15 tiltrotor model was coupled with state-space free-vortex wake code achieving real-time performance. For flight dynamics applications finite-state dynamic wake models, based on generalized velocity potential expanded in terms of Legendre functions, are predominately utilized [Fei-2015].

This paper presents a simple and flexible method for quantifying aerodynamic interaction between the main rotor wake, airframe and tail surfaces. The model, implemented in the ZHAW simulation framework, has been developed for both off-line and real-time helicopter simulation and has been validated by comparison with an existing model already validated against experimental data. The model was also tested on the motion-based, virtual-reality flight simulator HiSim [HiSim] (High-Fidelity Simulator).

2 Wake Interference Model

The wake interference model comprises two parts (see Figure 1):

- The first subsystem, called Wake Building, develops a wake that depends on main rotor inflow and on aircraft relative wind speed.
- The second part, which will be the focus of this paper, calculates the main rotor wake interaction with the fuselage, horizontal stabilizer, vertical fin, and tail rotor. Tail rotor wake influence on the airframe is not considered.

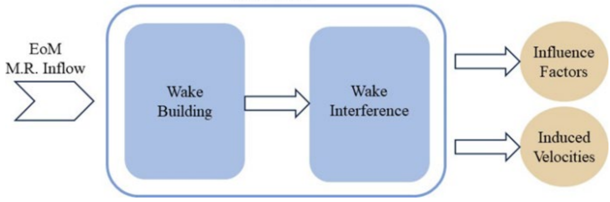

Figure 1: Wake Model Block Scheme

Unlike other interference models, which use Biot-Savart law to calculate induced flow based on vortex segment vorticity, the proposed method uses a very simple approach, based on geometric calculations of the wetted areas of the aerodynamic components. Regarding the development of the wake itself, different methods can be used based on the required level of accuracy.

The wake building process is based on the simple model described in [Dreier-2007]. The following assumptions were made (refer to Figure 2, Figure 3 and Figure 4):

- Induced velocity at the rotor disc $v_i(0)$ is uniform and perpendicular to the tip path plane.
- Wake at distance d is always parallel to the rotor tip path plane.
- Asymptotically, the induced velocity in the far wake is twice the magnitude of the induced velocity at the hub and the contraction of the wake is calculated via momentum theory.
- The wake skew angle is calculated based on the local induced velocity and helicopter motion. Therefore, instead of a straight cone frustum, the wake is shaped as a curved, truncated cone.
- Currently, the propagation of the wake is considered to be instantaneous; while an average dynamics of the wake can be easily introduced, in future development a detailed evaluation of this dynamics is envisaged.

Development of the main rotor wake is done inside *Wake Building* block, using a tip path plane (TPP) reference system with the x- and y-axis lying on the TPP and positive, respectively, to the back and to the right, and the z-axis perpendicular to the TPP and positive up. The wake interference is calculated up to a distance of one rotor radius downstream, along z-axis. The computation is made by discretizing this region in twenty steps. As said, the induced velocity is considered to be uniform and perpendicular to the tip path plane. Therefore, induced velocities Oat each step are obtained using expression (1) developed by McCormick [McCormick-1967], where d is the distance from the rotor hub, R is rotor radius and $v_i(0)$ being the uniform component of induced velocity at the hub.

$$\frac{v_i(d)}{v_i(0)} = 1 + \frac{\left(\frac{d}{R}\right)}{\sqrt{1+\left(\frac{d}{R}\right)^2}} \tag{1}$$

The acceleration of the wake is taken into account, which influences the shape of the wake from a straight cone frustum into a curved cone. Acceleration of the wake changes the curvature of stream tube midline by introducing a departure angle χ from the rotor tip path plane. This is defined as the angle between the normal to the TPP and the wake midline at the ith step, calculated on the plane generated by the TPP normal and the speed vector. Wake longitudinal and lateral skewness is calculated using the departure angle at each increment. The contraction ratio $R(d)/R(0)$ of the wake along the midline is computed as per expression (2), where d is the distance from the rotor hub and $R(0)$ is the rotor radius. Assumption is made that the circle representing the contracted wake at distance d is always perpendicular to the z-axis.

$$\frac{R(d)}{R(0)} = \sqrt{\frac{1+\left(\frac{d}{R}\right)^2}{\left(\frac{d}{R}\right)+\sqrt{1+\left(\frac{d}{R}\right)^2}}} \tag{2}$$

With wake being known, 3D wake-induced velocities are also calculated at the location of each aerodynamic component using expression (1) and transformed back from TPP reference system to body frame axis. Then the wake model interference computation continues to the second part, *Wake interference on surfaces* subsystem, in which aircraft geometry is considered.

For the wake interaction, helicopter fuselage, aerodynamic surfaces, horizontal tail, vertical fin and tail boom, are represented as infinitely thin flat surface meshes composed of triangles, while the tail rotor is represented by a circle. The mesh is calculated only once and initialized prior to simulation start.

Since the aircraft components mesh is constructed in body axes, computation of influence factor for each aerodynamic surface begins with the necessary transformation of triangle coordinates into the TPP reference axes followed by projecting each triangle into the TPP *xy* plane and obtaining its incentre. The contracted wake diameter and midline x and y coordinates are then calculated, for a distance d corresponding to the incenter z-coordinate. These three parameters allow to quantify the amount of triangle area being inside the wake. The process is continued for all the elements of a surface, the influence factors are weighted by the triangle surfaces and summed. If the plane identified by the triangle is perpendicular to the circle representing the wake sheet, the triangle is treated as a line, and the influence factor is obtained in a similar way, by calculating the length of the line immersed in contracted wake diameter. If an element is fully immersed in wake, the factor is equal to one. Being completely outside of the wake gives the element a factor of zero.

Wake induced velocities and influence factors for all aerodynamic surfaces are fed to the helicopter model's *Aerodynamics* block, where aerodynamic loads are computed using lookup tables derived from CFD and/or wind tunnel tests. To account for the effect of the wake, the calculation is done twice: in one case, considering only the freestream flow due to the helicopter motion; in the second case, considering both the freestream flow and the locally induced velocities generated by the main rotor wake. A weighted average of the resulting loads is then calculated, based on the wake influence factors. Clearly, this approach introduces a significant additional computational burden.

The newly developed helicopter model has been continuously compared with an existing one. To compare local forces, moments, aerodynamic angles, and velocities at multiple airframe locations, it was decided to split the airframe of the Flightlab® model into six different segments: cabin front, cabin rear, cowlings, tail boom, skids, and shroud. In order to present clean results, it was decided to activate the wake effect in the Matlab/Simulink® model only those elements that are not shadowed by other airframe components, i.e. cowlings, tail boom, and tail surfaces. Additionally, due to the complexity of shroud aerodynamics, it was decided not to model the main rotor wake interference with it.

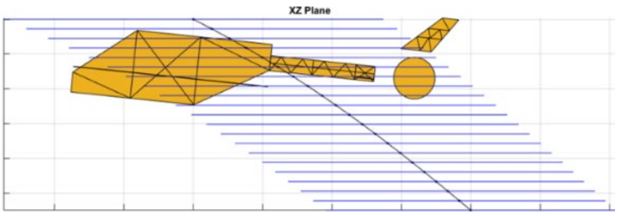

Figure 2: Example of Wake in Tip Path Plane, xz- view

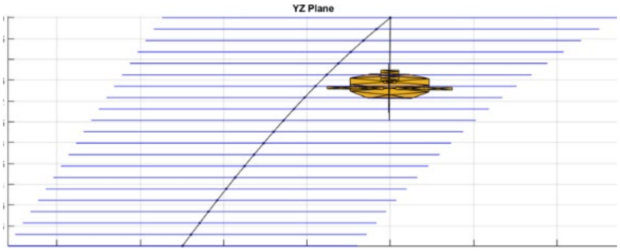

Figure 3: Example of Wake in Tip Path Plane, yz- view

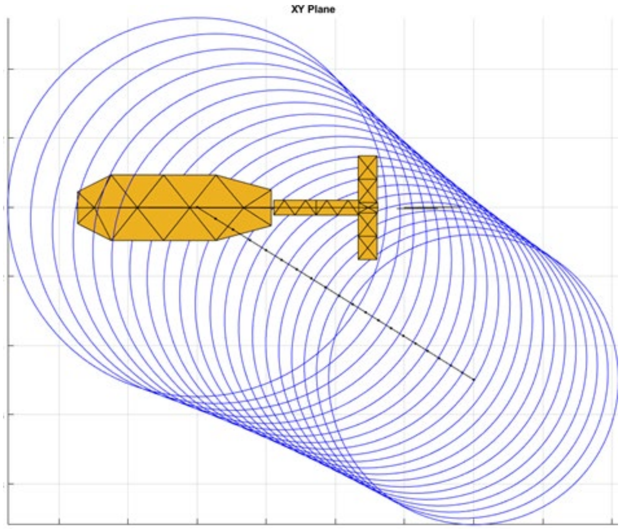

Figure 4: Example of Wake in Tip Path Plane, xy- view

3 Computational Load

The complete helicopter model is implemented in the ZHAW simulation framework. All simulation models in this framework are developed in Matlab/Simulink® and run on a standard Windows® Operating System (OS). Since this is not a real-time OS, the real-time operation is controlled by an ad-hoc routine written in C++ and embedded in the Simulink® model. The resulting simulation setup corresponds to the so-called "soft-real-time". The coherence of the simulation time with the solar time is always monitored during real-time sessions. In practice, this approach has never been a problem provided that a sufficient margin exists between the computational power of the used computer and the computational load of the model.

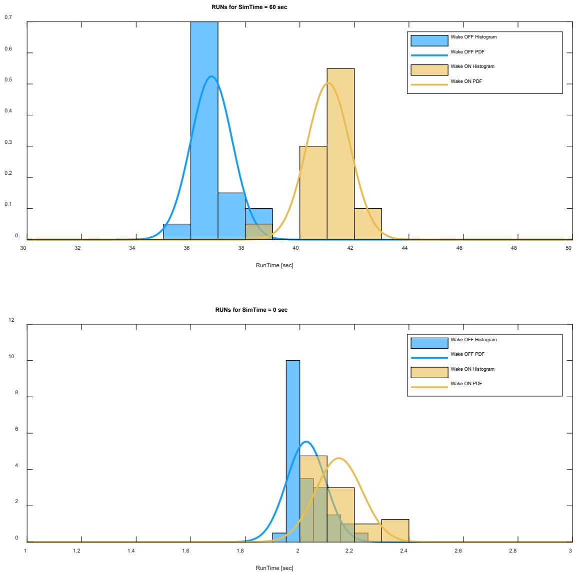

Figure 5: Computational Load of Helicopter Model

On the other hand, the soft-real-time approach makes it a bit more difficult to precisely evaluate the extra computational load introduced by the wake interference model. To evaluate the computational load of the novel method, the complete helicopter simulation model was run for a simulation time of 60 sec for a statistically meaningful number of times, with and without the wake interference model. Additionally, both models, with and without wake interference, were also run for a simulation time of 0 sec to compute the time required by Matlab/Simulink® to initialize the models. The obtained data was fitted with normal distributions (see Figure 5).

The tests were carried out on a standard laptop that is not representative of the more powerful computers dedicated to real-time simulations. It follows that only the evaluated percentual increase in computation load is significant in this analysis. The resulting increase in computational time is reported in Table 1.

Case	Sim Time	Mean Run Time
Wake Off	60 sec	36.8 sec
Wake On	60 sec	41.0 sec
Wake Off	Only Initialization	2.0 sec
Wake On	Only Initialization	2.1 sec
	Δ Run Time	4.1 sec
	Δ Computational Load	12 %

Table 1 – Increase in Computational Load

The increase in computational load is well within the margins still available to run the model in real-time in both ZHAW simulation facilities: the HiSim - High Fidelity Simulator [HiSim] and the ReDSim - Research and Didactics Simulator [ReDSim].

4 Method Verification

As with any tool used to develop an aircraft, also the proposed method needs both verification and validation. *Verification* is the process of evaluating that the method has been implemented as intended. *Validation* is instead the process of evaluating whether the method is correct and complete.

The chosen wake interference approach has been verified in terms of static and dynamic effects on the simulation model. As already mentioned, the wake interference affects the following components: Horizontal Tail (HT), Vertical Fin (VF), Tail Rotor (TR), Tail Boom (TB) and Upper Deck Cowlings (CW).

Figure 6 shows a visualization of the wake in trimmed conditions at different speeds. While the static effect of the wake seems to be evident, the dynamic effects are less evident and depend on factors such as the variation of the induced velocity intensity and direction on each specific component as well as the variation of the area of the component that is affected by the wake.

4.1 Static Verification

The static effect of the wake interference can be evaluated by observing the trimmed control values at different speeds. These are shown in Figure 7.

The main effect on trim comes from the horizontal tail. Very small effects are also produced from the tail boom and cowlings, while the effect on other components is negligible.

4.2 Dynamic Verification

The dynamics of the helicopter has been computed starting from the complete set of equations of motion. The model has been trimmed in the required flight conditions and then linearized with an ad-hoc method aiming at obtaining the most accurate linear model for the given input amplitude region [Capone-2002].

The obtained linear model has been further simplified by removing the high-frequency components such as flapping and inflow dynamics through state condensation. Thereafter, some other "nonessential" states are removed such as: heading and inertial position. The final model contains only the classical 8 flight mechanics states:

$$x = \{\phi, \theta, p, q, r, u, v, w\}$$

The dynamic stability evaluation has been performed for both the complete and reduced linearized models. While the reduction is not necessarily correct, since it eliminates dynamics that may significantly contribute to the response of the helicopter, it provides quite useful information on classical flight mechanics mode eigenvalues. Therefore, the system eigenvalues were evaluated from the reduced model, while time responses were generated from the complete linearized ones.

Figure 8 shows an example of the effects of the different components on the flight mechanics eigenvalues at 40 kts. Is it clear that the root loci do not completely describe the dynamic response of the aircraft because they do not show how the different modes combine together. Nevertheless, some interesting observations can be made, such as the strong effect of the tail boom wake interference on the poles.

Table 1 was compiled by comparing the dynamic responses of the helicopter to collective, lateral cyclic, longitudinal cyclic and pedal to *p*, *q*, *r*, and *w*, respectively.

Speed	HT	VF	TR	TB	CW	All Active
0 kts	-			-		-
20 kts	-			+	+	+
40 kts	-	+		+	+	-
60 kts	+	+		-		-
+ improvement in stability						
- deterioration in stability						

Table 2 – Wake Activation Effect on Stability

For speeds up to 40 kts, the dynamic effects of the wake are confined below 1 rad/sec and are relatively small. This can be also seen by observing the frequency response of the full linear system at 40 kts shown in Figure 9.

Different is the case of 60 kts, where the horizontal tail is just outside the wake (see Figure 10). In this scenario, a small variation of the pitch angle will cause a significant variation in forces generated at the horizontal tail. The strong effect of the HT is visible from the correspondent root locus (Figure 11).

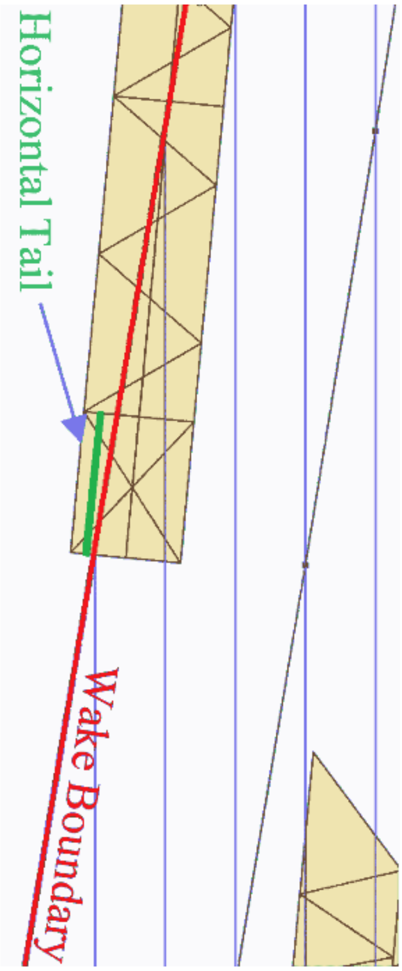

Figure 6: Side view of wake at 60 kts

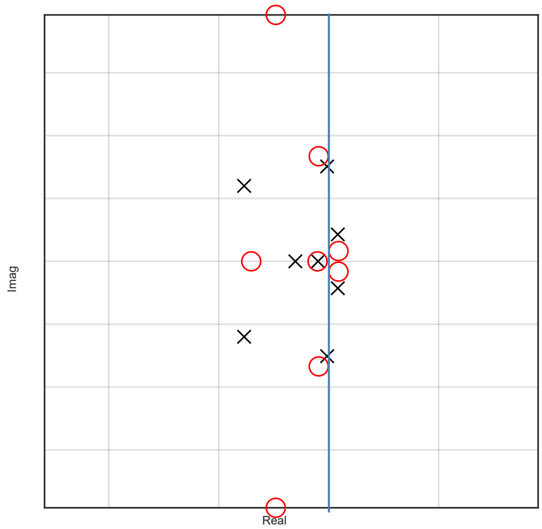

Figure 7: Effect of Horizontal Tail on Root Locus, 60 kts (X=Wake Off / O=Wake Effect on)

5 Method Validation

The model validation has been conducted by comparison against the wake interference model available in the commercial tool Flightlab®, which represents the state-of-the-art for modeling and simulation in the Flight Mechanics industrial frameworks. Furthermore, the Flightlab® model was validated in a preliminary way against data obtained from several flight test campaigns.

In Flightlab®, the rotor interference on the other elements of the aircraft is implemented using the Peters-He finite state inflow theory [He-1989], [Peters-1991]. The induced velocity components are calculated at each element location and summed to the asymptotic flow, resulting in a variation of local dynamic pressure, AoA and AoS. The aerodynamic forces and moments of each component of the aircraft are then evaluated via lookup tables depending on Mach number, AoA and AoS.

It must be noted that, while the general approach used in Flightlab® is known, the implementation details are not disclosed to the final user. Therefore, given the lack of proper experimental data allowing a dedicated validation of the Flightlab® model, and the latter being a closed-source code, only a partial validation of the proposed new approach could be performed.

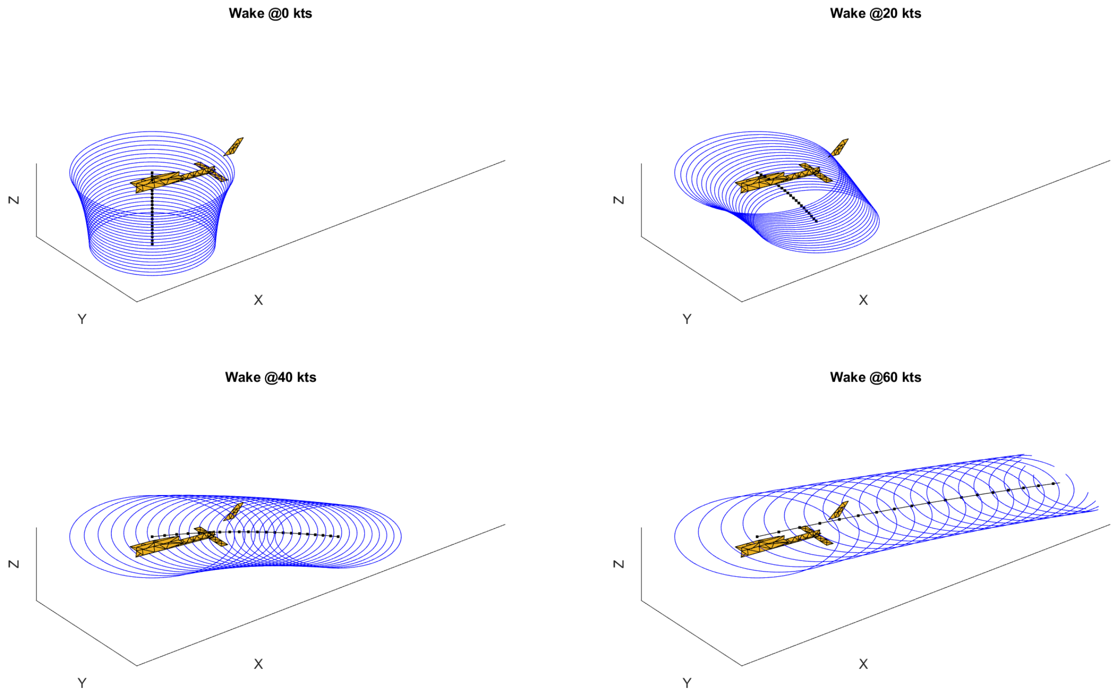

Figure 8: Wake Visualization at different Speeds

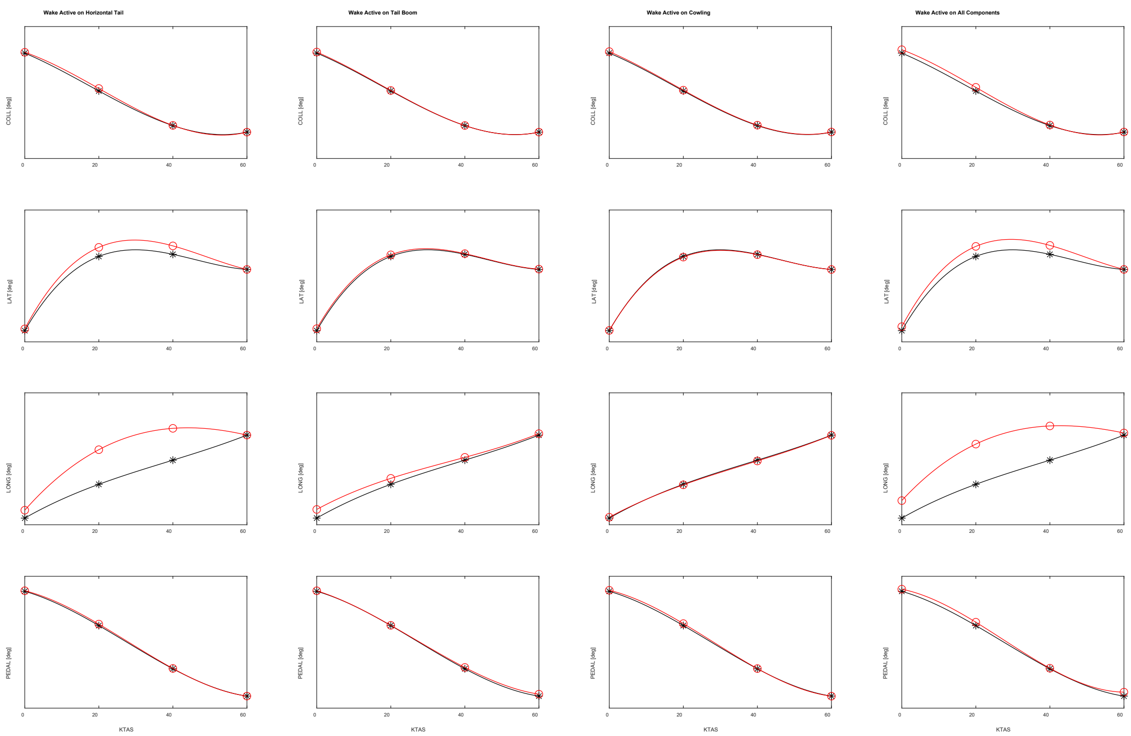

Figure 9: Static Effect of Wake Interference on Trimmed Controls
(X=Wake Off / O=Wake Effect on)

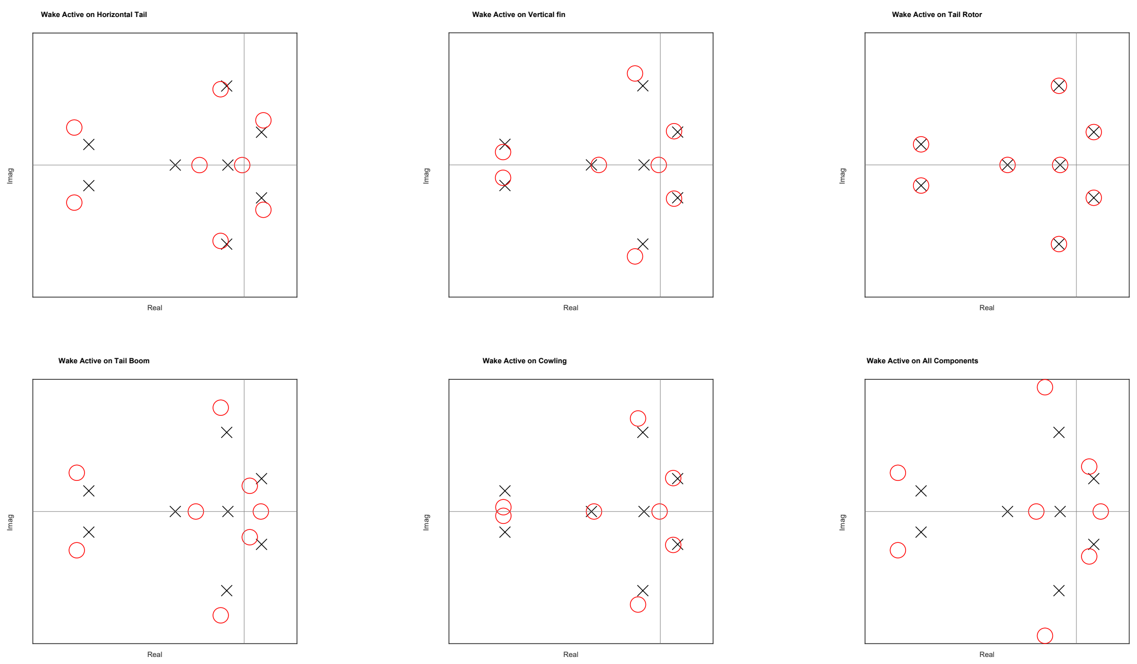

Figure 10: Effect of Components on System Poles (40 kts)
(X=Wake Off / O=Wake Effect on)

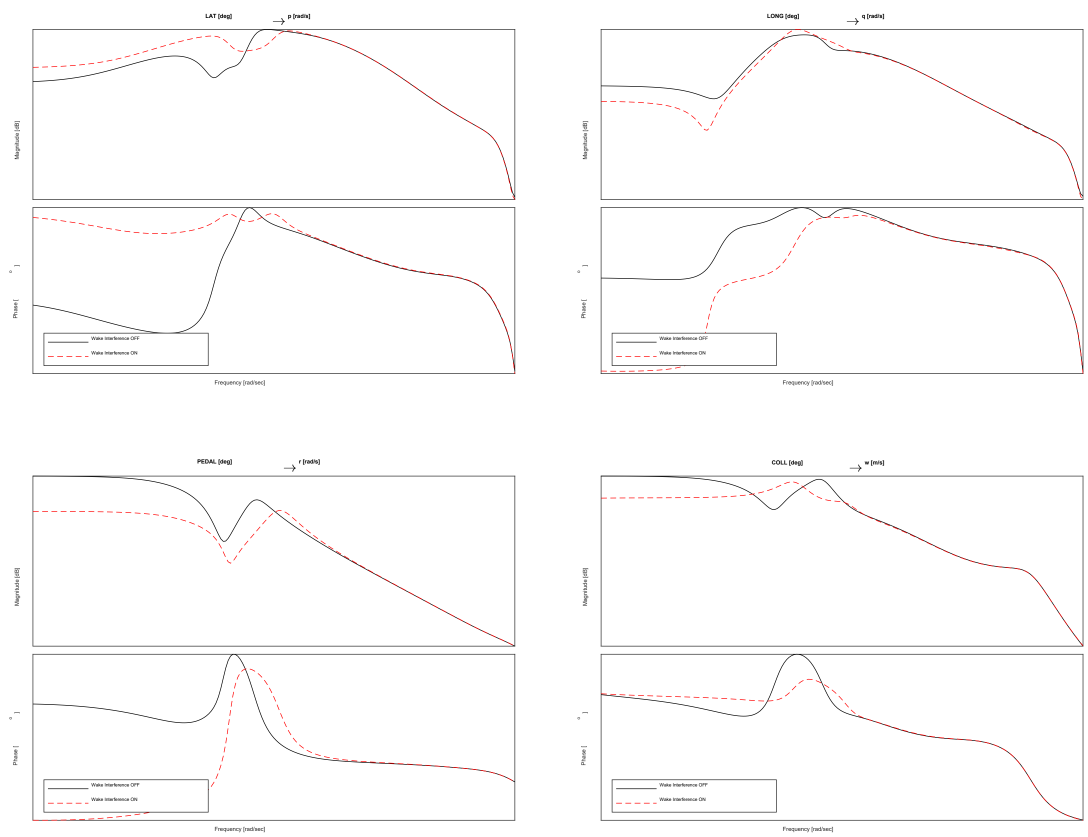

Figure 11: Wake Interference Effect on Frequency Response (40 kts)

5.1 Trim Comparison

The general agreement in trim conditions between the Flightlab® and Matlab/Simulink® models is quite good. Thus, the next step was to verify the effect of the wake interference activation on both models and compare the obtained variation in terms of significant parameters.

Figure 12 shows the comparison of the forces and moments variation at the horizontal tail due to the wake interference activation. The agreement is quite good.

Figure 13 shows a comparison of the forces and moments variation at the tail boom due to the wake interference activation. With the exception of the forces at 0 kts, the models are well correlated.

Figure 14 shows a comparison of the forces and moments variation at the vertical fin due to the wake interference activation. Here the matching is not really good. One reason for this can reside in the chosen flight conditions, which are always at very small AoS. This may result in rather small forces and moments at the fin, for which a meaningful comparison is difficult.

Figure 15 shows the comparison of the forces and moments variation at the cowlings due to the wake interference activation. The matching in this case is not excellent. One possible explanation for this could be the mentioned different implementation of the interference on the various fuselage elements between the two models.

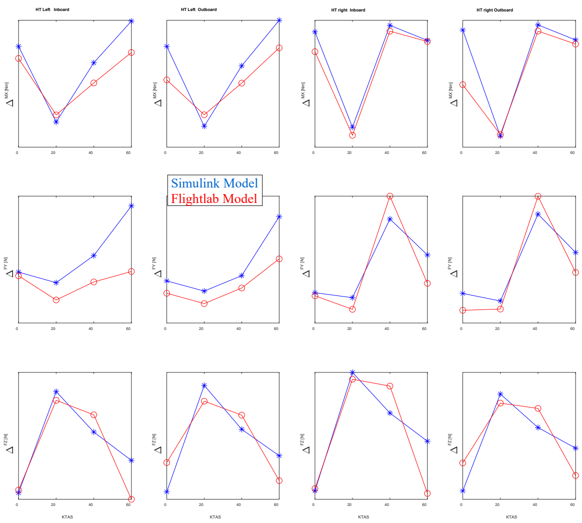

Figure 12: Static comparison, Horizontal Tail

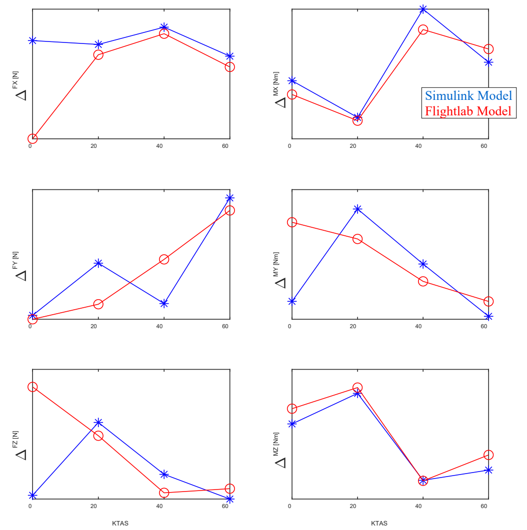

Figure 13: Static comparison, Tail Boom

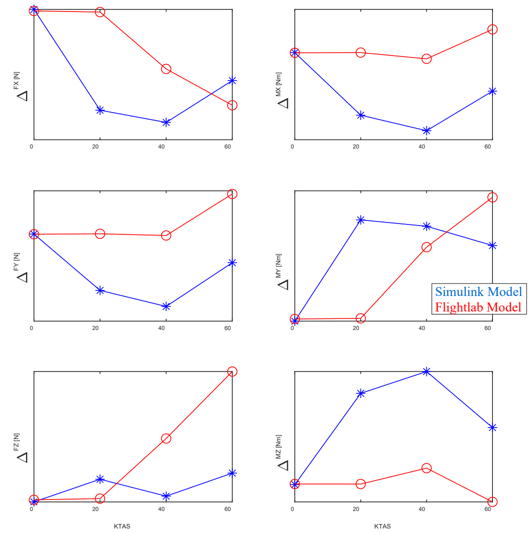

Figure 14: Static comparison, Vertical Fin

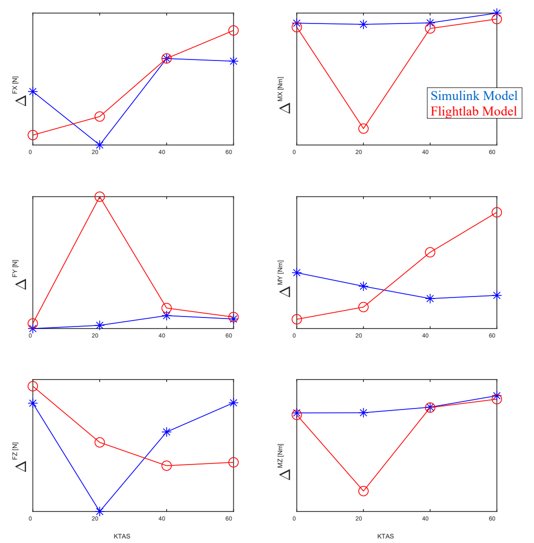

Figure 15: Static comparison, Cowlings

5.2 *Time Response Comparison*

The time-responses of the new Matlab/Simulink® helicopter model to input doublets on collective, lateral and longitudinal cyclic, and pedal were compared to the corresponding ones of the Flightlab® model. The results for the 40 kts case are shown in Figure 16, Figure 17, Figure 18 and Figure 19.

These figures show that, while differences between the two models still exist, the modifications, in terms of dynamic response, caused by the wake interference are comparable. Similar results can be obtained at different speeds (i.e. 0, 20 and 60 kts).

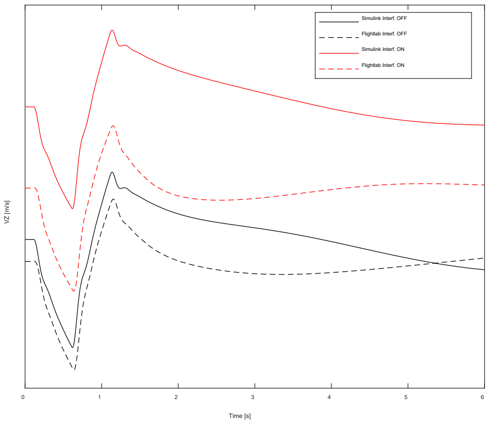

Figure 16: Time response comparison, Collective Input, 40 kts

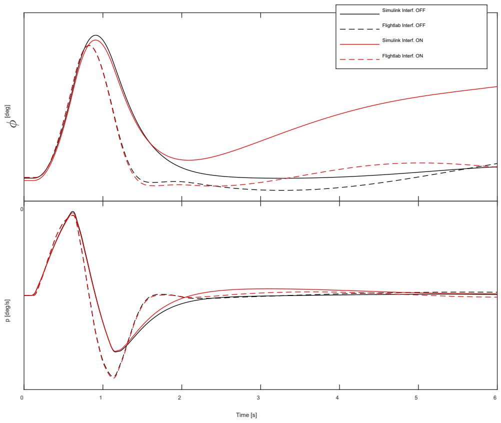

Figure 17: Time response comparison, Lat. Cyclic Input, 40 kts

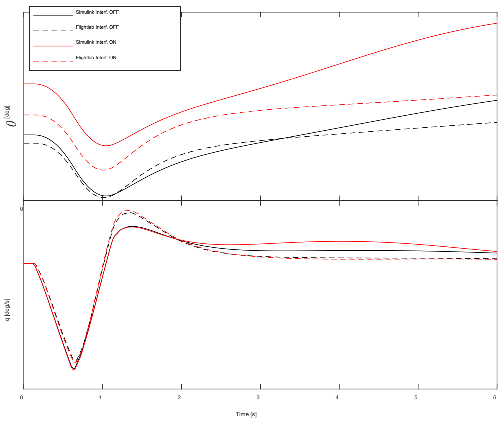

Figure 18: Time response comparison, Long. Cyclic Input, 40 kts

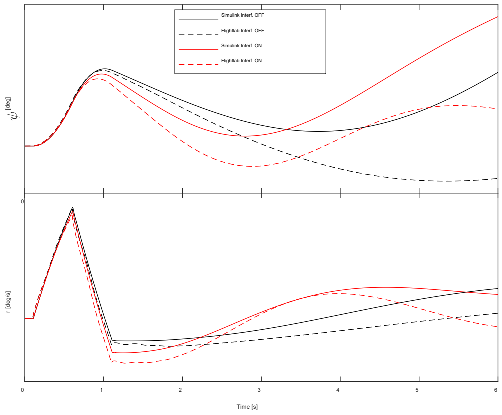

Figure 19: Time response comparison, Pedal Input, 40 kts

6 Conclusion & Outlook

A novel method for the evaluation of the main rotor wake interference with helicopter components has been implemented in the ZHAW simulation framework. The method is sufficiently accurate to guarantee reasonable results even when running in real-time. Another interesting aspect is the relative simplicity of the approach, which should allow straightforward tuning on the basis of experimental data.

The approach allows to model the influence of the wake on different elements of the aircraft and to separately tune each one of them. The method can be easily extended to evaluate the effect of wake interference on additional components for which aerodynamic data is available. Finally, the methodology can be easily adjusted to different wake models with minor changes to the simulation code.

The method has been verified in detail and provides results in line with expectations affecting mainly trim conditions and the low-frequency range of the helicopter dynamics.

The method has been validated against an existing one providing encouraging results but still requiring a more detailed analysis, in particular with regard to flight conditions characterized by significant sideslip angles.

The planned parameter estimation activity under the WHeSI - White-Box Helicopter System Identification project will provide the perfect scenario for a further refinement of the proposed method.

Author contact: Jan Juraj Đeverlija, deve@zhaw.ch.

7 Acknowledgements

The authors want to thank Innosuisse, the Swiss Innovation Agency, for financially supporting the research of which this paper is part.

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