

Prediction and Simulator Verification of State–Space Rotor Modelling of Helicopter Manoeuvring Flight

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Abstract

Among the many fundamental components of a flight simulator, the mathematical representation of the vehicle dynamics stands out for complexity and importance. This is especially true for helicopters, for which the complex dynamics involved prevents simple models to be sufficiently accurate without the need of a certain amount of artificial tuning. In this work, a methodology to obtain a computationally efficient, finite-state representation of the aeroelastic response of helicopter main rotors suitable for real-time flight simulation is proposed. It is capable of introducing rotor dynamics effects usually neglected in models commonly applied to flight simulations. This rotor model has been implemented in the SIMONA Research Simulator at the Delft University of Technology, and the results obtained from dedicated flight tests carried out by two experienced pilots are presented and discussed.

1. INTRODUCTION

The scope and usefulness of a flight simulator goes well beyond its pilot training capabilities; indeed, simulators play an important role during the design process of vehicles and control systems. The ability of a simulator to accurately predict the behaviour of a helicopter using as information only its physical characteristics would be highly desirable as it would allow manufacturers to get an early feedback from pilots on any design decision (concerning, for instance, handling qualities, rotorcraft-pilot coupling proneness, etc.). However, despite the complexity and the use of state-of-the-art components in modern simulators, they are not yet able to provide a fully coherent representation of reality.^[1] Moreover, with the aim of correcting some sub-optimal behaviour in specific flight conditions and to respect the tolerances needed for the validation of a flight model, a certain amount of artificial tuning is often applied on top of the physical model. These modifications are often not justified from an engineering standpoint and, while improving simulations for particular operating conditions, they may have an adverse effect on other parts of the flight envelope.^[1]

The need to tune the model can often be related to the deficiencies of the mathematical model describing the helicopter dynamics. The physics involved is indeed the result of the coupling of complex phenomena like

the nonlinear structural dynamics of the slender main rotor blades, the complex rotor aerodynamic environment resulting from the combination of blade motion and inflow induced by wake vorticity remaining in close proximity of the rotor disk, the interaction of the air flow with the fuselage, the main and tail rotors and mutual interactions, the interaction with the ground, the dynamics of engine and actuators, the effects of control systems. Real-time simulation of these phenomena requires a suitable trade-off between modelling accuracy and computational efficiency.

In this work, the focus is on the mathematical modelling of the main rotor aeroelastic behaviour suitable for simulators. Modelling and simulation of the complete aerodynamic/aeroelastic response of a helicopter rotor during arbitrary manoeuvring flight conditions is yet far from being predicted with suitable accuracy. Research in the 1990's and 2000's in the USA^[2–9] pointed out the deficiencies in current rotor wake modelling for simulator applications and suggested that inaccurate and incomplete modelling of transient dynamics of the rotor wake results in deficiencies in simulator behaviour to pilot control inputs. In addition, concerning rotorcraft pilot couplings (RPC), recent research^[10–12] highlighted the effects that aeroelastic and wake modelling may have on pilots biodynamic response. For these reasons the ability to include wake and aeroelastic effect in simulator models is fundamental.

Here, the methodology presented in Refs. [13, 14] for deriving computationally efficient, reduced-order models, from complex aeroelastic solvers is employed to obtain a state-space main rotor model to be used for flight simulation tasks. Considering the hub rigid-body motion as input (given in terms of linear and angular velocities components), it provides the loads (force and moment component) transmitted by the rotor to the airframe, as resulting from rotor blade aeroelastic response.^[13] The specific model developed for this paper purposes concerns the aeroelastic behaviour of the Bo105 helicopter main rotor. The Bo-105 is a light, twin-engine, multi-purpose helicopter developed by Bölkow of West Germany. It pioneered the rigid/hingeless rotorhead when it was introduced into service in 1970. Unless otherwise stated, the blades are modelled including one lag, two flapping and one torsional mode, and a complex wake inflow model derived by a free-wake potential-flow solver^[15] is employed. This model is included and operated in SIMONA (Simulation, Motion and Navigation) Research Simulator (SRS), which is a six-degree-of-freedom simulator located at the Delft University of Technology (TU Delft), specifically designed for human-machine interaction and handling qualities research projects.^[16] Among the available models included in SIMONA, a simple helicopter fuselage flight dynamics model is selected to be coupled with the introduced state-space main rotor model. It considers a tail rotor model based on the blade element theory with a quasi-dynamic inflow, a rigid-body model for the fuselage and includes the aerodynamic forces produced by fuselage and empennages.

In order to assess the suitability and level of fidelity of the proposed helicopter modelling for real-time helicopter flight simulations, it has been tested by two experienced test pilots who performed a wide range of manoeuvres in the SRS. Pilots' feedback and data obtained from the simulations carried out are presented and discussed in Section 3, along with the identification of limits and required improvements of the simulation approach examined, after an outline of the main rotor aeroelastic finite-state modelling given in Section 2.

2. FINITE-STATE MAIN ROTOR AEROELASTIC MODEL

The flight simulation model developed in this work consists of coupling a finite-state model for rotor aeroelasticity^[13, 14] with the flight dynamics model already present in the SRS at TU Delft..

The reduced-order modelling employed in this work for

the real-time simulation of the main rotor aeroelasticity relates hub forces and moments, \mathbf{f}_H , transmitted to the airframe to hub motion and blade controls, \mathbf{x} .^[13, 14] It relies on the availability of a database of linear time invariant (LTI) finite-state perturbation models computed off-line, each obtained through the methodology introduced by some of the authors in Ref. [13], which is based on the perturbation of steady flight conditions. The LTI finite-state perturbation model is provided in the following differential form

$$(1) \quad \begin{cases} \dot{\mathbf{f}}_H = \mathbf{f}_{H_0} + \mathbf{A}_2 \delta \ddot{\mathbf{x}} + \mathbf{A}_1 \delta \dot{\mathbf{x}} + \mathbf{A}_0 \delta \mathbf{x} + \mathbf{C} \dot{\mathbf{r}} \\ \dot{\mathbf{r}} = \mathbf{A} \mathbf{r} + \mathbf{B} \delta \mathbf{x} \end{cases}$$

where $\delta \mathbf{x}$ denotes hub motion and blade control perturbation with respect to the reference flight condition state variables, \mathbf{x}_0 , for which hub loads, \mathbf{f}_{H_0} , hold. In addition, \mathbf{A}_2 , \mathbf{A}_1 , \mathbf{A}_0 , \mathbf{B} , \mathbf{C} are real, fully populated matrices, whereas \mathbf{A} is a block diagonal matrix containing the poles related to the dynamics of the additional states, \mathbf{r} . These additional states describe the internal rotor dynamics, including blade structural modes and wake vorticity dynamics: their number is the result of a trade-off between level of accuracy and computational efficiency required for the state-space model (the latter being a crucial aspect considering the purpose of real-time simulations). The model identification process is independent on the aeroelastic solver applied, but of course the accuracy of the identified model depends on it.

Since the rotor aeroelastic behaviour is intrinsically nonlinear, all the coefficients appearing in Eq. 1 are dependent on the reference state, \mathbf{x}_0 . Thus, the simulation of arbitrary manoeuvring flights requires the updating of the model as the operating conditions significantly differ from the reference ones. This is carried out by exploiting the database of LTI finite-state perturbation models mentioned above (each identified through suitable flight condition parameters), and recasting Eq. 1 in the following equivalent convenient form

$$(2) \quad \begin{cases} \dot{\mathbf{f}}_H = \mathbf{f}_{H_0} + \mathbf{A}_2 \delta \ddot{\mathbf{x}} + \mathbf{A}_1 \delta \dot{\mathbf{x}} + \mathbf{A}_0 \delta \mathbf{x} + \mathbf{C} (\mathbf{r} - \mathbf{r}_0) \\ \dot{\mathbf{r}} = \mathbf{A} \mathbf{r} + \mathbf{B} \mathbf{x} \end{cases}$$

where \mathbf{r}_0 is determined as

$$(3) \quad \mathbf{r}_0 = -\mathbf{A}^{-1} \mathbf{B} \mathbf{x}_0$$

that coincides with the asymptotic steady state solution of the additional states dynamics forced by the current reference flight condition, \mathbf{x}_0 , where hub loads, \mathbf{f}_{H_0} , hold (in turn determined from a suitable database of reference hub loads).

The database of LTI aeroelastic models is evaluated for a number of flight conditions chosen within a given domain of variables, y , that suitably characterize the aeroelastic behaviour of the rotor. Variables y could include, for instance, advancing ratio μ , collective pitch, θ_0 , tip-path-plane angle of attack, α_{TPP} , distance from the ground, h , and/or other parameters useful to define a specific flight condition. Of course, as the set of variables y grows, the number of LTI models to be evaluated grows, along with the computational effort needed to create the database.

Once the LTI model database is computed, an efficient methodology to update the LTI finite-state models as the flight conditions change is required. Indeed, during a flight simulation, in case of discrete changes of LTI aeroelastic models, two main problems would arise: (i) the reference force, f_{H_0} , would be subject to discrete jumps, thus negatively affecting the simulation quality, and (ii) the additional states, \hat{x} could represent different dynamics as the LTI models are updated, thus making their numerical integration meaningless.

In order to overcome this problem, a methodology was developed in Ref. [14], that provides a main rotor aeroelastic model that is continuous with respect to the variables y , and applicable for real-time simulation. Specifically, the variation of the coefficients in Eq. 2 is described using multi-dimensional b -splines, with nodes and coefficients determined by solving (through a gradient based method) a nonlinear least-square problem with separable variables. The advantage in using b -splines functions lies in the possibility of adopting optimal sets of input data locations in the space of parameters, that allows best fitting of matrix coefficients variation (for instance, in our kind of problems, input data are conveniently concentrated near hovering flight condition, where the gradient of transfer functions is expected to be relevant).

For the present work, the rotor aeroelastic model is based on a beam-like blade structural solver, coupled with aerodynamic loads predicted by a quasi-steady, sectional formulation with wake inflow correction provided by a boundary element method tool for free-wake analysis of three-dimensional, unsteady, potential flows, capable of modelling complex phenomena, like wake impingement and blade vortex interaction (BVI). The main advantage of this model over simpler models neglecting blade aeroelasticity is the possibility to capture the effects of interaction between blade aeroelastic modes and flight mechanics.

| Manoeuvre description | Group |
|-------------------------------|----------------------|
| Longitudinal step input | Control step input |
| Lateral step input | |
| Collective step input | |
| Pedal step input | |
| Autorotation | High gain tasks |
| Full collective | |
| Acceleration, deceleration | |
| Steady level flight | Steady manoeuvres |
| Steady climb and descent | |
| Steady level turn | |
| Evolution from 20° | Free evolution |
| Evolution from forward flight | |
| Evolution from steady turn | |
| Spiral mode check | Modes check |
| Fugoid mode check | |
| Hover board | High frequency tasks |
| Longitudinal frequency sweep | |

Table 1: Performed manoeuvres

3. SIMULATION RESULTS

This section presents the results of the piloting simulations performed in the SIMONA Research Simulator at the Technical University of Delft, as driven by the finite-state rotor load model described in Section 2.. The scope of the test activity was twofold: (i) to assess the feasibility of application of the proposed rotor model in a real-time simulation device, and (ii) to collect pilot's feedback on the general perceived quality of simulation and on any issue raising during the tests. Two experienced test pilots have been asked to perform several manoeuvres on the SIMONA Research Simulator driven by a Bo-105 helicopter model obtained by coupling the finite-state main rotor model of Section 2. with the helicopter model already implemented in the SIMONA simulator.

Given the exploratory nature of this work and the type of the investigated manoeuvres, only the advancing ratio, μ , was used to update the flight condition, y . However, it is worth noting that the computational power of SIMONA is estimated capable of working with updating based on more than three parameters.

All the simulations have been performed without any augmentation or control system. This choice is motivated by the intention of letting the pilot interact directly with the helicopter model, avoiding the implementation of tunable filters. For the same reason, the SIMONA motion system has been disabled. It is worth noting that neither of the pilots actually piloted a Bo-105 helicopter.

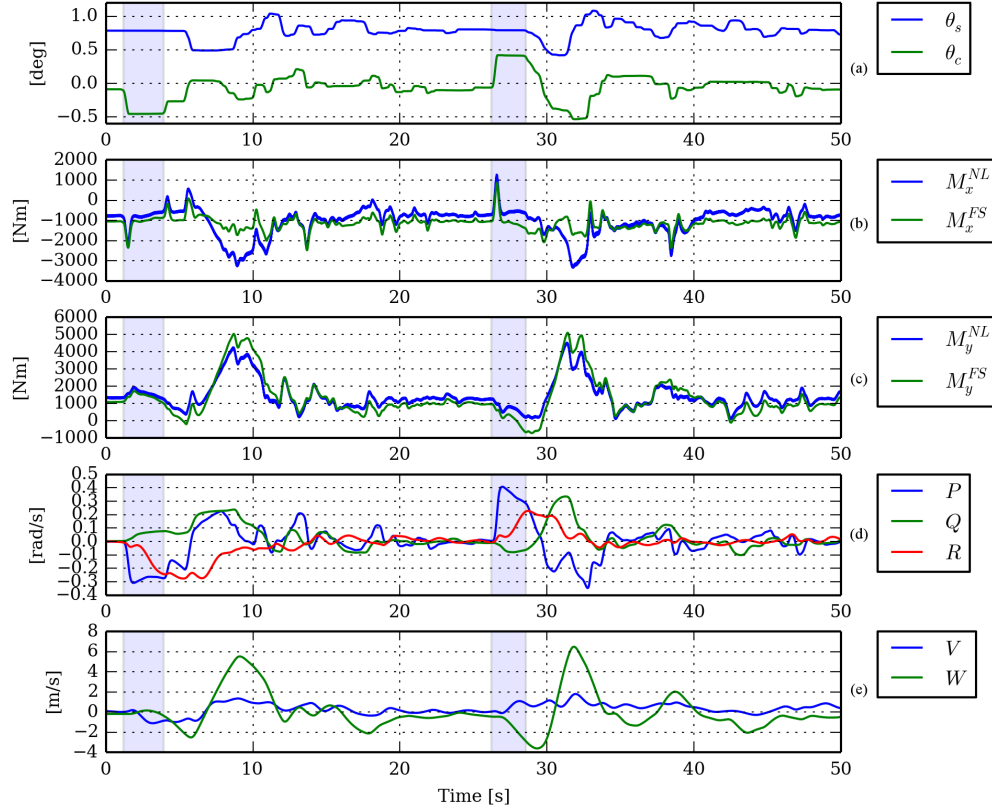


Figure 1: Lateral step input at 50 kt.

The list of the manoeuvres simulated is reported in Table 1.

In the overall, the pilots have asserted that the response to their commands of the simulator driven by the main rotor modelling presented in Section 2 was realistic. However, they have provided specific comments for each manoeuvre flown.

In the following, the outcomes of some of those manoeuvres for which pilots have observed an unusual or unexpected behaviour of the simulator are discussed in detail. In particular, assuming helicopter kinematics and rotor blade controls as those of the considered manoeuvres, the responses driven by the main rotor finite-state model (equal to the real-time ones provided by SIMONA) are compared with the responses evaluated off-line by the complete nonlinear rotor aeroelastic solver. The objective of the comparisons is to assess whether unusual or unexpected simulator responses are due to the intrinsic characteristics of the complete nonlinear aeroelastic model applied or, rather, are produced by the approximations introduced by the finite

state modelling.

3.1. Lateral step input

For the helicopter flying at velocity $U_0 = 50$ kt, the simulator response to a lateral cyclic, θ_c , step input is depicted in Fig. 1. As shown in Fig. 1(a), two θ_c step inputs are commanded by the pilot at the beginning of the observation period and after about 26 s. The pilot feedback on the simulated behaviour has been positive, with a roll-pitch coupling of acceptable magnitude observed. In figure 1(d) the pitch-roll coupling is evidenced by the responses of the rolling, P , and pitching, Q , angular velocity components: the initial left blade cyclic pitch causes a left roll and a comparatively smaller nose up pitching, while a right blade cyclic pitch induces the opposite helicopter response. Soon after the initial cyclic step input, the helicopter starts turning and the pilot perceives a nose-down response: this is confirmed by the combination of the negative rolling with the significant negative yaw angular velocity, R . This behaviour has been deemed normal by both pi-

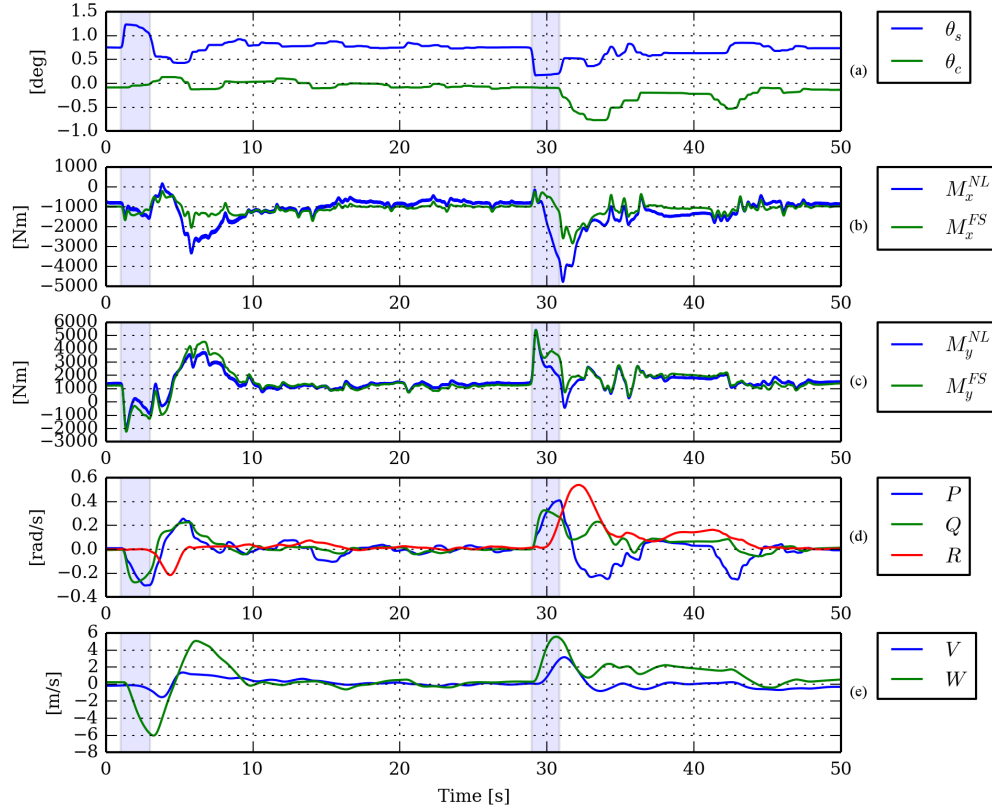


Figure 2: Longitudinal cyclic step input at 50 kt.

lots.

Figures 1(b) and 1(c) depict the rolling and pitching moments as computed by the complete nonlinear solver (NL) and by the finite-state model used in the simulations (FS). The correlation between the two models is very good during the whole manoeuvre, except for two time intervals around 8 s and 30 s, where a considerable discrepancy between rolling moments is observed. This difference can be explained by the results in Fig. 1(e), where the values of the lateral velocity, V and the vertical velocity, W , are shown. Indeed, the load discrepancy is closely correlated with significant perturbations of velocity, W , which were not considered in the finite-state modelling adjournment (as mentioned earlier, the finite-state model is updated only as function of perturbations of the longitudinal helicopter velocity, U).

3.2. Longitudinal step input

Figure 2 shows the simulations resulting from two longitudinal step inputs, applied with the helicopter flying

at velocity $U_0 = 50$ kt. In this case the pilot comments indicated a strong rolling acceleration following the control input. This is confirmed by the results in Fig. 2(d), where comparable variations of the angular velocities P and Q arise because of their remarkable coupling, after the step actuation of the longitudinal cyclic, θ_s . This coupling has been considered very strong by both pilots. Figures 2(b) and 2(c) prove that the rolling and pitching moments predicted by the two numerical models applied similar during the step inputs, and hence it may be concluded that such a behaviour is directly related to the rotor aeroelastic model, rather than to the finite-state approximation. Akin to the lateral step input response, higher discrepancies between the predicted moments appear in combination with remarkable perturbations of vertical velocity W , as depicted in Fig. 2(e).

3.3. Collective step input

Next, flight simulation corresponding to a step input of the blade collective pitch is presented in Fig. 3. The

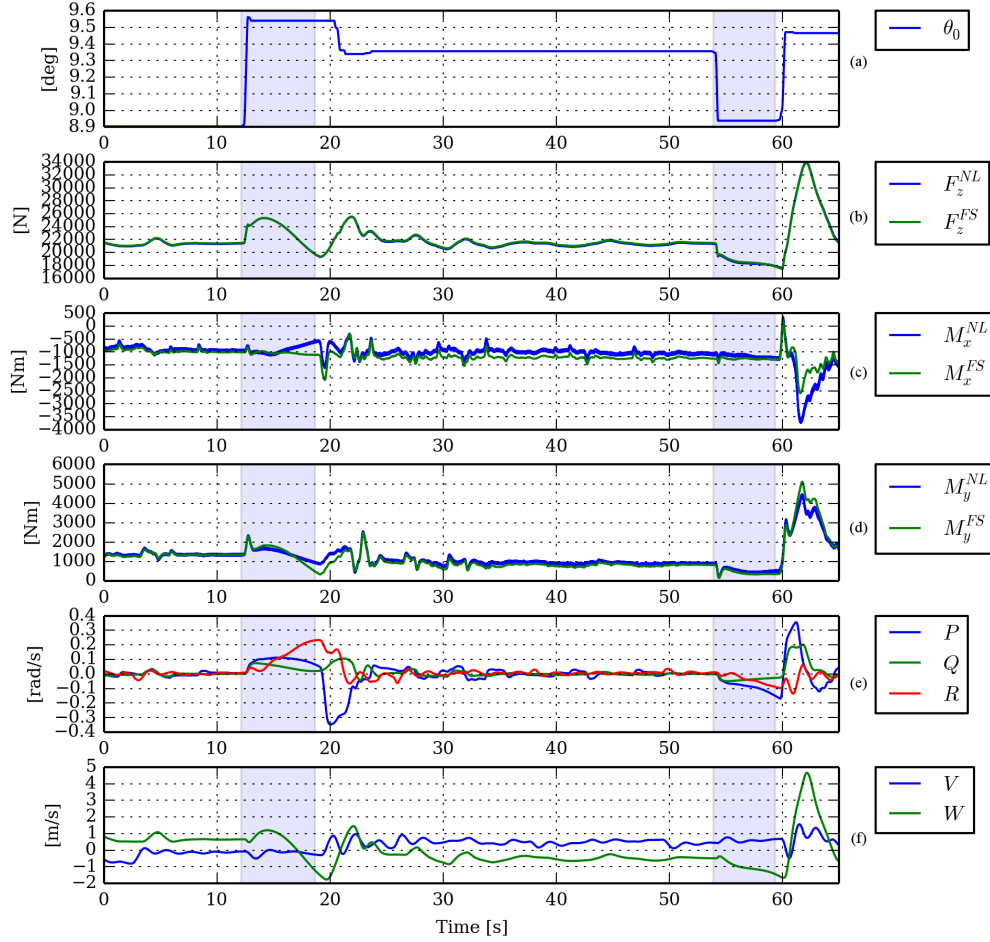


Figure 3: Collective step input at 60 kt.

pilot command has been actuated with the helicopter travelling at a constant velocity $U_0 = 60$ kt. Both pilots noted strong coupling with pitch and roll motions, as shown in Fig. 3(e). The first pilot has deemed the coupling of the collective blade pitch with the helicopter pitch significant but not necessarily unrealistic, while considered the corresponding roll coupling excessively strong. The second pilot noted a qualitative similarity of the overall cross coupling behaviour experienced with that of the helicopter Agusta A109.

In Fig. 3(b) the rotor thrust predicted by the finite-state model is compared with that predicted by the nonlinear solver, while Figs. 3(c) and 3(d) show rolling and pitching moments given by the simulation approaches. The correlation between the two models is excellent, particularly for the vertical forces and the pitching moment. Small discrepancies appear between the rolling

moment predictions. This proves that the cross coupling behaviour observed derives directly from the nonlinear aeroelastic rotor model and is not due to approximations of the finite-state modelling.

3.4. Deceleration manoeuvre

In this section the deceleration manoeuvre performed by the second pilot using two different helicopter models is analysed. The objective of this manoeuvre has been the comparison between simulations based on the model including flap, lag and torsional blade modes (see Fig. 4) and simulations based on the model including only the blade flap mode (see Fig. 5).

As shown in Figs. 4(a) and 5(a) the manoeuvre starts at $U_0 = 100$ kt and is composed of segments where the velocity decays of 20 kt followed by helicopter re-

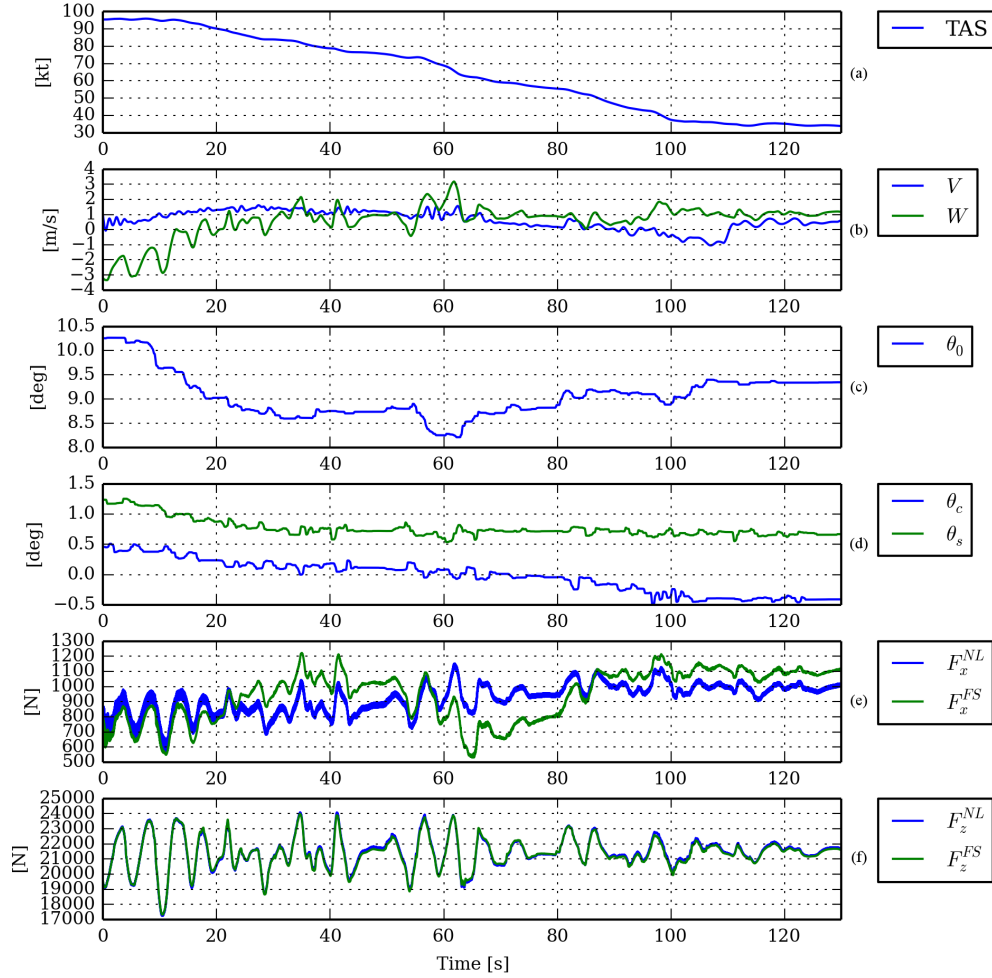


Figure 4: Deceleration with blade flap, lag and torsional modes.

trimming. The pilot did not notice significant differences between the responses from the two models, highlighting just a slightly decreased capability of the helicopter to maintain the trimmed speed around $U_0 = 100$ kt.

It is interesting to note that the rotor thrust predicted by both finite-state models (see Figs. 4(f) and 5(f)) is in good agreement with that computed by the corresponding nonlinear solver, while some differences appear between the x -axis forces determined by the three-mode model (see Figs. 4(e) and 5(e)). Indeed, Fig. 4(e) shows that the high frequency characteristics of the forces are predicted with good accuracy, but a relevant discrepancy is present on the low frequency load content during the whole manoeuvre.

For both blade models, 4/rev oscillations are present in

the x -axis forces computed by the nonlinear solver, with a larger amplitude for the only-flap-mode case. These oscillations are not present in the finite-state model results, in that filtered out by the process of identification of the coefficients of the differential form describing the hub loads as functions of the hub motion.^[13, 14] The spectral analysis reveals also the presence of 80 rad/s oscillations in the three-mode case x -axis forces, corresponding to the frequency of the aeroelastic progressive lag mode.

4. CONCLUDING REMARKS

A computationally efficient state-space model for the aeroelasticity of helicopter main rotors has been presented. It has been integrated inside the existing flight

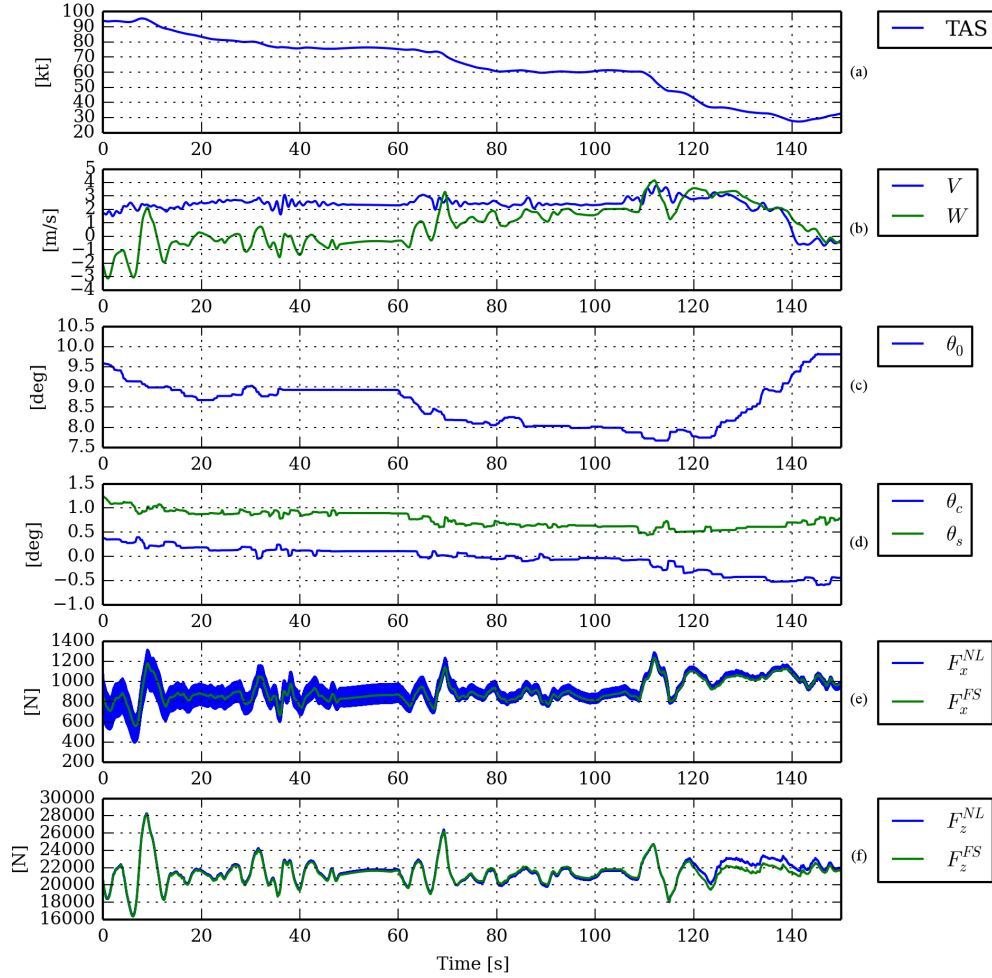


Figure 5: Deceleration with one blade flapping mode.

simulator SIMONA at the Delft University of Technology. The resulting complete helicopter model has been thoroughly tested by two experienced pilots, who performed several manoeuvres with the aim of assessing its limitations and giving a feedback on the overall quality of the simulation. The data obtained from the simulations have been analysed finding out that the finite-state model proposed is well suitable for real-time predictions to be used within flight simulators, and that is capable to reproduce accurately the aeroelastic forces generated by the rotor. In a few cases, some low frequency errors were noticed, usually correlated with the difference between the flown operating condition and that used to build the model. Future tests are needed to investigate if these discrepancies can be alleviated by increasing the size of the database used to update the aeroelastic

reduced-order model during a flown manoeuvre.

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