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PARAMETRIC MODELING APPROACH TO INCREASE NONLINEAR FAN-IN-FIN DYNAMIC RESPONSE SIMULATION FIDELITY

Philipp Krämer

Institute of Flight Research / Rotorcraft
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)

Abstract

Sophisticated research projects and demanding standards require increased fidelity in rotorcraft flight dynamics simulation.

The Eurocopter EC 135 helicopter will serve as the future *Flying Helicopter Simulator* (FHS) research flight test vehicle at DLR. Simulation for flight test support, hardware-in-the-loop simulation and flight control system design are particularly demanding in terms of flight dynamics modeling for the entire aircraft and its components.

In addition to its improved performance and augmented safety, the Fan-in-Fin anti-torque concept features aerodynamic enhancements that exclude the utilization of coarsely adapted models for *classical* tail rotors.

This paper reviews a modeling approach developed at the DLR Institute of Flight Research for high fidelity rotorcraft simulation. It consists of a combination of generic nonlinear modeling with parametric modeling that proved to substantially increase the accuracy of complex aerodynamic models.

After an introductory overview on the technique and concept of helicopter anti-torque generation, a thorough investigation of the EC 135 Fenestron physics and aerodynamic behavior is presented.

The approach to improve existing models or respectively to generate new formulations is presented and reviewed in detail for the improved Fenestron dynamics modeling.

Results of the initial investigations are presented that clarify the considerations to be taken into account for the integrated application of the combined approach.

Finally a brief introduction to the simulation and system identification software is given since the successful realization of the described modeling approach is directly depending on powerful and specialized tools.

Symbols and Abbreviations

$\underline{c}$	rotor load coefficients ($[c_T, c_l, c_m]^T$), $-$
t	time, sec
u, v, w	translational velocities in body axis directions, m/sec
v_0, v_1, v_2	flow velocities *far upstream*, at the rotor, and *far downstream*, m/sec
v_i	Induced rotor velocity, m/sec
v_v	vertical free stream velocity, m/sec
p, q, r	roll, pitch, yaw rate with respect to body axes, rad/sec
K_p, K_q	wake distortion parameter roll, pitch, $-$
K_C	wake contraction parameter (A_1/A_2), $-$
K_T	Fenestron thrust damping parameter, $N sec/rad$
$\hat{\underline{L}}$	gain matrix, sec/m
$\underline{M}$	apparent mass matrix, $-$
S_0, S_1, S_2	flow cross section *far upstream*, at the rotor, and *far downstream*, m^2
T_{FEN}	thrust generated by the Fenestron, N
β	blade flapping angle, rad
$\underline{\lambda}$	inflow ratio ($[\lambda_0, \lambda_s, \lambda_c]^T$), $-$
δ_x, δ_y, δ_0, δ_P	pilot cyclic longitudinal, cyclic lateral, collective, pedal control input, $\%$

Presented at the 27th European Rotorcraft Forum, Moscow, Russia, 11-14 September 2001.

θ_{1s}, θ_{1c}	longitudinal cyclic, lateral cyclic blade pitch, rad
θ_{FEN}	Fenestron collective control angle, rad
Ω	main rotor rotational velocity, rad/sec
$\cdots_{0,c,s}$	mean, cosine and sine component
$\cdots_{T,l,m}$	thrust, lateral, longitudinal component
$AFCS$	Automatic Flight Control System
BE	Blade Element
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
FCS	Flight Control System
FHS	Flying Helicopter Simulator
$HOST$	Helicopter Overall Simulation Tool
$MFCS$	Model Following Control System
$ONERA$	Office National d'Etudes et de Recherches Aérospatiales (French National Aerospace Research Establishment)
PID	Parameter Identification

Figure 1: EC 135 Fenestron.

1 Introduction

Among the state of the art rotorcraft in service today are a variety of anti-torque systems, each of which have their special advantages.

The classical tail rotor is still the most widely used system which has the advantages of requiring relatively low power while contributing positively to the helicopter's yaw damping and directional stability in forward flight [1]. Among the disadvantages of the tail rotor concept are the fact that its exposed design may be dangerous for persons on the ground and for the helicopter and the crew itself when interfering with wires, trees etc.

Besides concepts like tandem or coaxial main rotors two out of several advanced shaft driven anti-torque concepts developed during the last decades made their way into production. The *NOTAR* technology — introduced by MD Helicopters on the MD500, MD600 and MD900 rotorcraft series — features no externally rotating rotor. A variable pitch fan inside the root of the tail boom generates thrust that is led into the tail boom [2]. The anti-torque momentum is obtained by exploitation of the so called *Coanda Effect* and a controllable nozzle at the end of the tail boom. This system satisfies the safety considerations and proved to be superior to conventional tail rotors in terms of reduced noise emissions.

A third system, that proved its capabilities from the 1970ies onwards and which has been continuously improved since its introduction, is the *Fan-in-Fin* technology. Besides the Russian Kamov Ka-60 series, the Boeing/Sikorsky Comanche from the US and the Japanese Kawasaki OH-X (each presently under development), the Franco-German company Eurocopter offers the largest variety of rotorcraft equipped with their *Fenestron* system (see figure 1).

A remarkable step in the development of the Fenestron was the introduction of the EC 135 helicopter (see section 2). In addition to its closed design, the Fan-in-Fin concept offers a large variety of noise reduction opportunities. Additionally, this technology proved to have essential advantages in performance compared to the open tail rotor. This results mainly from the exploitation of the effects that are provided by the aerodynamically ducted shroud but also from the vertical fin and/or the tail boom being no longer directly in the flow.

Both, the NOTAR as well as the Fenestron, represent a significant increase in complexity compared to the (already not trivial) tail rotor system. The mechanical complexity as well as the one resulting from the complex aerodynamics involved lead to challenging problems and questions for the design and research engineers.

In the era of extensive numerical analysis in each phase of the product design cycle, mathematical modeling of the helicopter aerodynamics and flight dynamics has become a key discipline. The numerical description of the anti-torque device is a central part of this effort. Two exemplary areas where high model fidelity is essential are the development of training simulation, where a certain level of fidelity is required to qualify the simulator according to international standards [3, 4], and Flight Control System (FCS) design, where the computer needs to have an accurate description of the plant in order to provide satisfactory and safe control.

The EC 135 will serve as basic helicopter for the Flying Helicopter Simulator (FHS) which currently finishes its development at DLR and industry [5]. For the FHS a flight dynamics model is needed which shall be used for evaluating integrated system hardware and software prior to the flight tests in ground based piloted simulation as well as serving for the design of the Model Following Control System (MFCS) for which exceptional accuracy is crucial [6].

The aerodynamic models for the Fan-in-Fin technology appear to still have deficiencies mainly in the correct prediction of the thrust response to dynamic control inputs. With sophisticated projects like the FHS under development and the introduction and support of new high performance helicopters, an improvement of the Fan-in-Fin dynamic response prediction becomes a high priority.

This paper deals with an approach to face these challenges with techniques that combine nonlinear analytical modeling with parametric optimization. This approach already proved to be effective in improving the model fidelity inside a complex nonlinear aerodynamics model environment [7]. For the Fenestron modeling this approach is being further extended.

Promising initial results encourage to proceed as they already show significant improvements in the prediction of on-axis yaw response and additionally improvements in the coupled axis behavior simulation.

2 Relevant Design Features and Physical Effects

Especially in performance and the reduction of noise emission the revised EC 135 Fenestron (see figure 2) contains major improvements compared to older models such as those installed on the SA 341 ”Gazelle” or the AS 365 ”Dauphin” types.

The newly introduced noise reduction measures and performance improvements include [8]:

- a larger diameter to decrease the required power and thus the Fenestron rotor blade tip speeds,
- unequal rotor blade spacing to modulate the harmonic noise peaks over a larger bandwidth,

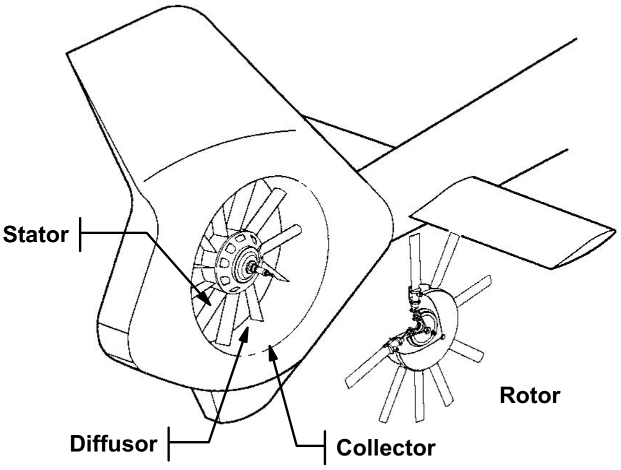

Figure 2: The Fenestron in Detail [8].

- an equally spaced stator stage behind the rotor in the flow to convert the energy of the swirl flow into thrust by pressure recovery and thus allow to further reduce blade tip speeds,
- inclined stator radial orientation to prevent pressure peaks caused by bypassing rotor blades,
- revised and more efficient airfoils with spanwise variable relative thickness,
- revised collector and diffusor profiles, and
- optimized drive shaft design and position.

The unequally spaced 10-blade rotor and the stator in the flow are the most visible contributions to the improvements of the already advantageous characteristics of the Fenestron. These improvements, making it more sophisticated and more complex, also renders more difficult the task of a mathematical description of the system.

The rotor features as one of its particularities a relatively high blade twist compared to conventional tail rotors. Considering low blade root angles in forward flight it occurs that the inner part of the Fenestron rotor blades generates positive inflow while the outer parts of the blades generate negative inflow.

Figure 6 shows the computation of the induced velocities v_i of an isolated, fixed EC 135 Fenestron rotor (without shroud and stator). The results are given for a steady state sweep of the control angle θ_{FEN} for each of the assumed five Blade Elements (BE). It can be seen that e.g. for a control angle of $\theta_{FEN} = 0\ deg$ (which corresponds to a positive effective blade root angle of incidence) the innermost BE ring still generates a positive inflow of approximately $6\ m/sec$ while the outermost BE ring accounts already for a negative inflow of $-8\ m/sec$. This generates a complex flow field to be considered.

In addition, the high number of blades and the decreased diameter of the Fenestron leads to a particularly high solidity which needs to be considered as suggested by [9].

The stator replaces the (formerly cylindrical) attachment struts as mechanical component of the Fenestron. Its aerodynamic benefit is the energy recovery that results from the conversion of the rotating flow coming from the rotor into an axial flow while the energy is converted into additional thrust. It proved to straighten the swirl flow almost entirely by 15 to $20\ deg$ for a typical working state [8].

The collector is shape optimized for maximum suction. In this configuration it approximately doubles the thrust the unshrouded rotor would generate (in hover). In sideways flight this ratio increases or decreases according to flight direction while in forward flight the collector was found to generally increase the rotor thrust by a factor greater than 2 [10]. Additional design constraints are the avoidance of flow separation at the innermost point which is achieved by maintaining a minimum depth and radius of the collector. For the entire arrangement this demand is contra productive to the forward flight aerodynamics optimization since a slim cross section is more favorable in terms of drag minimization.

The diffusor is designed to expand the flow exiting the stator. Deviating from the classical subsonic diffusor theory that indicates an ideal opening angle of roughly $20\ deg$ the opening angle is limited to about $10\ deg$ for constructive reasons. This is to prevent the flow through the Fenestron from turning instable in the presence of main rotor wake at low horizontal speeds [8].

The entire arrangement of yaw control and anti-torque generation comprises the comparably large vertical fin and the vertical end plates at the horizontal stabilizer. The fin and the end plates are inclined (see figure 3) in a way to develop a side force in forward flight that takes over the anti-torque generation from the Fenestron. Measurements presented in [11] show that beginning from a forward speed of approximately $80\ kts$ the fin generates all the necessary side force. In that flight regime the Fenestron is exclusively used for directional flight control.

Other forward flight considerations are concerned with the surrounding flow field the Fenestron (or any other tail rotor device) operates in. So it gets into the zone of main rotor downwash as horizontal speed increases. Furthermore it turns out of the fuselage wake and into the free stream when the helicopter reacts to pedal or longitudinal cyclic control input.

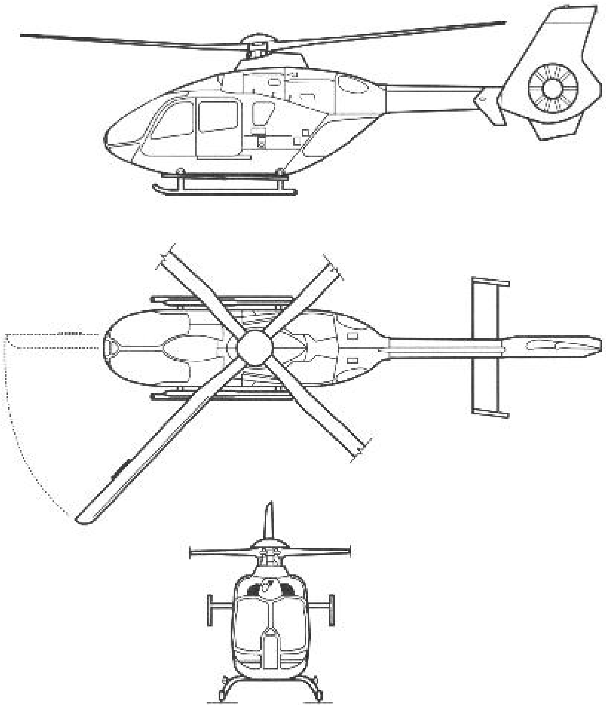

Figure 3: General helicopter layout.

Investigations and modeling is an ongoing challenge since the introduction of Fan-in-Fin anti-torque systems. Thorough knowledge has been developed and published for Fan-in-Fin performance and steady state operation (e.g. in [12]). However, even when validated and optimized with wind tunnel data, the steady state approaches develop significant deficiencies when operated in dynamic simulations. Besides the theories applied in [9], Kothmann [13] approaches the dynamics formulation by introducing an adapted dynamic inflow model.

Although these improvements are promising first steps, further improvements are necessary to improve flight control and AFCS design that critically depend on precise yaw control models.

3 Modeling Approaches

Two classical approaches are common in rotorcraft system modeling. On one hand analytical modeling based on detailed knowledge of the occurring physical phenomena, represented by the right column in figure 4. This leads to precise and widely applicable models if the physics is

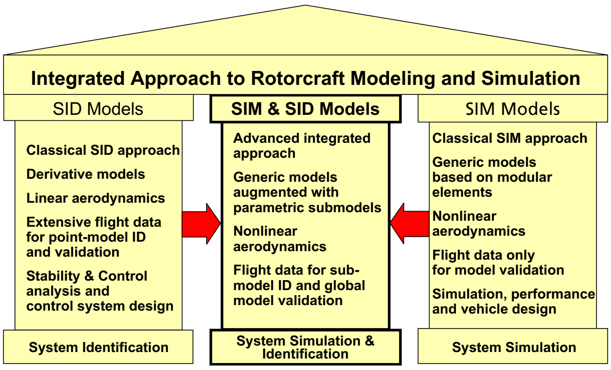

Figure 4: Three columns modeling philosophy.

thoroughly known but also to very complex formulations which degrade the real time capability of the entire model. On the other hand parametric modeling (see the left column in figure 4) combines runtime efficiency with global model structures that do not require that extensive knowledge of the concerned phenomena. These widely linear models are more or less *black boxes* that do not allow an insight into the physics as the analytical modeling provides. Thus, specific improvements of model components from gained knowledge of the physics are hardly possible. Furthermore, limitations to small perturbation assumptions about a stationary point require efforts to open the linear models to the entire envelope of the concerned aircraft.

The DLR Institute of Flight Research is developing a technique to combine the advantages of both approaches described above which is illustrated by the center column in figure 4. It consists of the systematic application of nonlinear models that incorporate parametric terms — either derived during model creation or specific extensions to the nonlinear models — that are being identified by parameter optimization procedures. With this approach it proved to be possible to generate high fidelity models that allow real time application keeping their physical structure transparent [7].

The generically derived models available today for Fan-in-Fin devices mostly consist of adapted models that have originally been developed for classical (tail) rotors. After an examination of the applied theories with respect to the Fenestron architecture and physics, these theories have been tuned by introducing global factors for the thrust generation according to actuator disc theory.

The wake contraction factor K_C adapts the actuator disc theory that derives thrust from the increase in velocity caused by the rotor from *far upstream* to *far downstream* of the rotor disc. As schematically illustrated in figure 7, for a free stream rotor (shown on the left hand side) the velocity at a point far downstream (index 2) equals twice the induced velocity v_i through the rotor (index 1) plus a vertical velocity v_v when the rotor experiences a vertical motion (i.e. a sideways or yaw motion for helicopter tail rotors).

Deviating from this classical rotor theory, the wake of a rotor inside a cylindrical shroud is considered not to contract but to propagate in a parallel way. Thus the velocity far downstream of the rotor equals the total inflow velocity at the rotor being $v_2 = v_1 = v_v + v_i$.

This assumption has been used with some success also for rotors with aerodynamically shaped shroud — sketched on the right hand side of figure 7. However, optimizations using whirl tower tests performed by Eurocopter revealed values for K_C significantly lower than 1 for far downstream velocity assumptions according to equation (1).

$$v_2 = v_v + K_C\, v_i \tag{1}$$

This has been explained not only by flow widening caused by the diffusor but also by the representation of losses at the rotor due to viscosity and flow gyration effects in this parameter. When the flow direction inverts, the contraction parameter is found to be even inferior to the value for positive inflow. This additional decrease is attributed to the poor diffusion provided by the collector.

When working with models derived in the explained manner, a phenomenon occurs that is significant for the deficiencies of present generic Fan-in-Fin models. The dynamic simulation shows an overprediction in the yaw response of the helicopter, i.e. an underestimation of system damping to dynamic yaw control input as shown in figure 8. It shows the simulated response (dash-dotted, red) of the EC 135 to a 3-2-1-1 pedal input at $65\ kts$ forward flight compared to the measured values from the flight test (solid, blue).

It can be clearly seen that beginning with the control input the predicted value of the yaw rate r — shown on the lower right of the figure — shows the correct trends and directions but overshoots the measured value significantly. Only some seconds after the termination of the control input, the predicted signal appears to recapture the measured one where the investigation stops.

On the lower left side of figure 8 the roll rate p is shown to represent the coupling behavior and its prediction of the aircraft. Here as well, the response appears to be overpredicted but not as heavily as for the on-axis yaw response.

Again, the trends appear to be mostly correct.

From analyzing the case depicted in figure 8 it is directly visible that the approaches of adapted tail rotor models do not match satisfactorily the demands of a high quality Fenestron simulation. New approaches for generic modeling of such devices are inevitable.

The parametric derivative models are generally better suited to deal with not precisely known physics which is due to the global character of these approaches [14]. To estimate the values of the used derivatives the application of a system identification procedure is necessary where the parameters are tuned by use of wind tunnel, flight test, or test rig data.

Studies have been undertaken to identify linear derivative models of the EC 135 helicopter. A model structure has been used that proved capable for identification of rotorcraft such as the BO 105. These models were fully linearized 6 DOF formulations with identified coefficients for the impact of the rigid body motion (represented by the translational velocities $[u, v, w]$ and the angular rates $[p, q, r]$) and the pilot control input $[\delta_x, \delta_y, \delta_0, \delta_P]$ on the applied global forces and moments.

It turned out, however, that these models were inadequate to deal with the Fenestron equipped EC 135 as good as with conventional helicopter types.

One effect that shows a typical behavior of an EC 135 simulation with these identified linear models is depicted in figure 9. It shows the simulation of the yaw rate response to a 3-2-1-1 pedal input compared to the same flight test data shown in figure 8.

The most evident impression one get from comparing figure 9 with figure 8 is that no overprediction occurs but that the overall match of the flight test data appears to be relatively good. Still a deviation starting approximately after second 90 indicates an unsymmetrical response prediction that was not captured by the system identification procedure. This is a clear evidence of existing Fenestron specific physical phenomena that are not able to be represented in the utilized parametric helicopter model structure.

Since figure 9 shows the result of a flight case at $65\ kts$ forward flight, the Fenestron can be considered to operate practically idle in the absence of yaw control input (see section 2). So, the flow direction through the Fenestron can be considered *negative* (in the sense *diffusor ⇒ collector*) for the first input after second 85; then *positive* (*collector ⇒ diffusor*) for the input at second 89 — here the response fairly matched the flight test data; then again *negative* for the input starting after second 91. Here a clear disagreement can be observed for the *negative* inflow condition while the next positive step response is matched better again.

This result leads to the conclusion that classical linear derivative models used for rotorcraft system identification and simulation do not qualify entirely for an anti-torque device with as unsymmetrical flow phenomena occurring as at the EC 135 Fenestron. Further investigations executed at DLR obtained improvements in these specific results by utilizing more sophisticated model structures. However, the disadvantage of the derivative models is that they do not lead to the specific model deficiencies in the way an analytical setup would do. While even an improved derivative model structure stays at a global level, a generic model permits the specific improvements of model components considered to be deficient.

The combined parametric/analytical modeling keeps this advantage of detailed model improvements and offers in addition the possibility to do this even if the applied physics are not known thoroughly enough to contribute with entirely generic model improvements.

In [7] an example is given where the cross coupling behavior of a BO 105 helicopter has been significantly improved for hover and level flight conditions. This has been achieved by utilizing an extended dynamic inflow equation for the main rotor aerodynamics. This *Parametric Wake Distortion* formulation (2) based on [15, 16, 17] consists of the basic *Pitt & Peters* equation extended by a parametric term that feeds back the relative roll and pitch motion between the rotor disc and the fuselage to the induced velocity distribution over the rotor.

$$\underline{M}\,\dot{\underline{\lambda}} + \underline{\hat{L}}^{-1}\,\underline{\lambda} = \underline{c} + \frac{1}{\Omega}\,\underline{\hat{L}}^{-1} \begin{bmatrix} 0 \\ K_p\,(p - \dot{\beta}_s) \\ K_q\,(q - \dot{\beta}_c) \end{bmatrix} \qquad (2)$$

Substantial improvements in the axis coupling prediction have been shown by identifying the *wake distortion parameters* K_p and K_q.

This model is ideally suited for the combined approach symbolized by the center column in figure 4. The wake distortion of a maneuvering helicopter has been assessed as one of the influences on the deficiencies in the axis cross coupling prediction of rotorcraft in hover. Since a suitable formulation of the aerodynamic effects was not available, a parametric term has been added to the inflow equation in a way that promised to improve the results. Finally, the system identification provided the corresponding values of the parameters that led to the improvement.

This idea is being followed for the improvement of the Fenestron modeling with the considerations and adaptations derived in section 4.

4 Combined Approach for Fenestron Modeling

There are basically two methods to apply the combined parametric/analytical modeling approach.

Existing models can be modified in a way that specific elements are being extended by *error terms* containing parameters that are believed to compensate observed deficiencies when being identified. This method qualifies mainly for cases where the deficiencies are not that substantial that an entirely new model creation is necessary or for cases where it is possible to attribute the deficiencies precisely enough to a model component — i.e. a physical phenomenon — that a specific extension by a parametric term leads to satisfactory results.

Alternatively, if the knowledge of the physical reason of the deficiencies is not thorough enough to directly apply the method described above, a new model structure may be set up. This model then incorporates directly parameters in submodels that are not to be created entirely from the physics or where a possible analytical formulation would lead to unacceptable computational loads. An example for this method could be the exploitation of the *wake contraction factor* K_C explained in section 3 and visualized in figure 7. This would evade a complex aerodynamic description of the flow field in the proximity of the Fan-in-Fin device.

Since the wake contraction is of rather global influence to the Fan-in-Fin model it has to be treated with care. In the presence of parameters more deeply embedded in the model structure, these global factors should be used with reduced weighting. This is to avoid negative interference of parameters in different *model levels* when the system is being identified. For the example of the wake contraction parameter this means that physically more specific parametric models (e.g. models of losses at the rotor due to viscosity effects or of flow swirl mentioned is this context in section 3) may affect the overall response prediction. In that case the priority (i.e. a higher parameter weighting in the identification) should be given to the more *interior* parametric models.

Currently both of these methods are used at DLR to generate improved mathematical models with enhanced fidelity in the prediction of the dynamical behavior of the EC 135 Fenestron. They are considered to lead to the best results when being applied simultaneously, i.e. when the information drawn from an *error model identification* can be useful for the creation of a combined nonlinear parametric model.

To illustrate this principle, again a rather global effort to improve the dynamic Fenestron response prediction is depicted in figure 10. The basic idea is to add damping to the system by extending the Fenestron thrust computation by an error term that feeds back the yaw rate and thus increases the damping in the predicted yaw response according to equation 3.

$$T_{FEN} = T_{FEN} + K_T\ r \tag{3}$$

Again the same flight test shown in the previous figures has been used so that figure 8 can be referred to as the *nominal*, nonoptimized case for $K_T = 0\ Nsec/rad$. For the result shown in figure 10 the extended thrust formulation (3) has been identified leading to an estimated yaw damping factor of $K_T = -3505\ Nsec/rad$ building the goal function with the yaw rate r in order to minimize the error between the measured and predicted value of the yaw rate. It can be observed that the optimization led to the desired effect of an increased damping in the prediction of the yaw rate r (shown on the lower right of the figure). Instead of the overshoot, again an unsymmetrical response is predicted for the respective inflow directions into the Fenestron. For the coupled roll rate p depicted in the lower left graph of figure 10 the slight overshoot seen in figure 8 has been damped as well although it is clearly to be seen that there are deficiencies remaining that are the object of further investigations.

Certainly the model proposed in equation (3) was not believed to compensate all the deficits in the entire Fenestron formulation. Still, this analysis provides useful information for the set-up of a new and more sophisticated model. It showed that the addition of damping to the system is capable to deal with the overshoot in both on and off-axis response predictions. This has to be kept in mind when a newly generated model element shows the characteristics of a damping term so that special attention can be paid to the development of these submodels. This may be done either by enhanced analytical modeling or by the introduction of an additional parametric formulation where considered necessary. So, these observations of the behavior of an identified parametric model can be of benefit to both parametric and generic modeling approaches.

In addition to the observations stated above, figure 10 demonstrates an issue that needs to be taken into account to successfully apply parametric identification in the way proposed in this paper. After the termination of the input signal at second 95 the prediction of the yaw rate shows a considerable discrepancy to the flight test data. In fact, compared to figure 8, the non-optimized case shows a better prediction in this region. This means that if the identification is being executed for the entire time range of the simulation this would lead to a useless and nonoptimal result. Literally seen, the algorithm would improve the prediction for the first ten seconds, then find that with this the prediction of the last five seconds is getting worse and so adapt the parameter to deal with both effects which leads to a paradox situation for the identification. Since it was the goal to improve the damping characteristics for the region of overshoot, i.e. first ten seconds, the identification only leads to satisfying results when being applied only for this time period. For the analysis depicted in figure 10 the identification has been executed for the time period between 85 and $94\ sec$ providing the most adequate result. The parametric model (3) that is expected to improve the result is not intended to deal with other deficiencies and so it does not qualify to deal with other effects encountered in this simulation.

Initial investigations provided the information that an offset in the prediction of the roll rate and thus a drift in roll attitude are the main contributions to these deficiencies in the prediction of the yaw rate. An analysis that used the roll rate p as open loop input from the flight test data provided the result shown in figure 11. It shows that with *ideal* roll rate prediction, the long term response is captured better than shown in figure 10.

The *guided* roll rate naturally results in a nominal simulation ($K_T = 0\ Nsec/rad$ — dash-dotted, red) that differs from the corresponding one shown in figure 8. The identification of equation (3) has been done leading to a Fenestron damping parameter of $K_T = -3020\ Nsec/rad$ and a simulated response depicted by the green, dashed line. Again, the identification was performed for the time period from 85 to $94\ sec$ since the considerations for the damping optimization remain the same as for the previous case. It is obvious that the roll-yaw coupling needs to be regarded as a central factor in the overall simulation fidelity.

This process of analyzing the obtained results of the identification applied according to this approach shows that a thorough knowledge of the physics and the optimization procedure is essential to get to the desired results.

Note that some of the discrepancies for all three, figure 8, figure 10, and 11, result from the flight test data being recorded at a not ideally trimmed state of the helicopter. A slight but noticeable movement in both roll and yaw motion can be observed at the beginning seconds while the controls still have been held fixed in position. This is assumed to be the effect of a small *dutch roll* motion which can not be compensated for the simulation. Even if this effect is small, it shows the importance of high quality flight test data to be used for system identification procedures.

5 Simulation and Optimization

This section is to give a brief overview over the software and algorithms applied for this analysis.

As being described in [7] and [18] the work has been executed using the comprehensive *HOST* (Helicopter Overall Simulation Tool) system. HOST is the standard rotorcraft simulation software used by the industry and public research in Germany and France. Developed by Eurocopter France from the beginning of the 1990ies onwards, it is in use at the entire Eurocopter corporation as well as at ONERA and DLR who jointly improve and extend the system to meet the state of the art modeling, simulation, and post-processing requirements.

HOST consists of a powerful module for nonlinear simulation which serves as the core function for the described work. Furthermore it is capable to provide analysis and evaluation for most disciplines necessary for helicopter and tilt rotor development and research. Among these are rotor dynamics, eigenmode analysis, linearization and linear simulation, real-time code generation and others.

A parameter identification (PID) module has been integrated and constantly improved throughout the recent years. It consists of a second order gradient output error minimization technique solved by a modified Newton-Raphson (Gauß-Newton) procedure. Its introduction into the HOST environment represents a remarkable extension of the capabilities that HOST offers. The separation from the *standard* HOST procedures, the GUI based interface (see figure 5), and its intentional handling make it easy to understand and to apply.

It is important to note that this PID procedure is not comparable to the system identification tools used for lin-

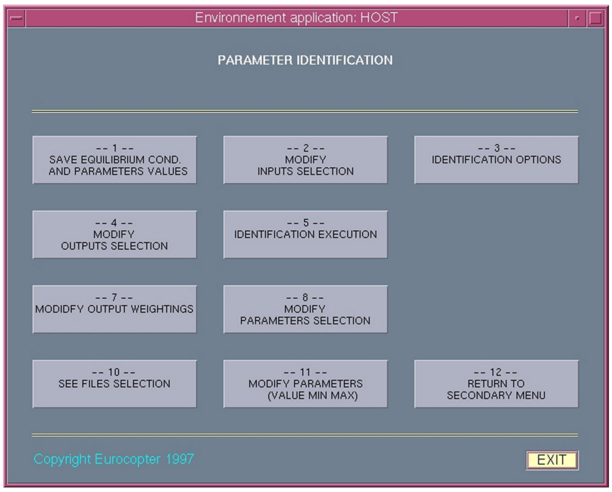

Figure 5: HOST parameter identification menu.

ear derivative model identification with a large number of parameters to be identified simultaneously for the entire system in one attempt. It is intended to deal with specific parameters inside the model environment and to offer the user a large variety of possibilities to influence the procedure depending on the investigated case. These possibilities to adjust the system identification have proved to be of essential importance for the analysis described in sections 3 and 4.

Among other features it allows the user easily by a mostly self explaining menu interface to

- specify the variables for the computation of the goal function,
- allocate a weighting to the chosen parameters and thus balance the influence of the associated effects to the identification,
- choose a certain time range out of the total simulation time for the identification in order to concentrate on an area of specific interest (see section 4),
- use a set of multiple reference data (e.g. from wind tunnel or flight tests) to concatenate which proved necessary for cases of multiple parameter identifications [7], and
- identify dynamic or static (e.g. trim) phenomena or a combination of both if the optimization of a parameter influences both the prediction of the dynamic behavior to control input as well as the trim state.

Since this PID module is directly linked to the nonlinear simulation kernel, it is ideally suited for the combined parametric/analytical approach described above. Its continuous improvement in close dialog between DLR and ONERA allows to tailor it to the current requirements of the HOST user community and makes it to a central element in the Franco-German flight dynamics modeling and simulation research activities.

6 Conclusions and Outlook

The Fan-in-Fin anti-torque system presents special challenges for aerodynamic modeling. Current formulations using classical approaches like a generic analytical modeling or a parametric derivative model set-up do not lead to results as satisfying in dynamic response prediction fidelity as they provide for conventional tail rotors.

The physical phenomena observed at the EC 135 Fenestron have been assessed regarding their influence on the aerodynamics to be considered for Fenestron mathematical formulations and their potential impact on the deficiencies of currently available models. The transition to forward flight requires special attention for the EC 135 tail arrangement since in that condition the anti-torque effect is being obtained entirely by the inclined vertical fin and the end plates at the horizontal stabilizer. This leads to an inflow through the Fenestron in *positive* as well as in *negative* direction on pedal control input.

The DLR Institute of Flight Research is developing an approach combining nonlinear generic model structures with parametric formulations that may be optimized applying system identification techniques. This combined approach is proposed for the generation of improved flight dynamics models of the Fenestron system.

The approach is being analyzed in detail with respect to Fenestron simulation and identification results. Several examples confirm the conclusion that it qualifies for the application in this field of highly sophisticated aerodynamics and flight mechanics modeling.

The entire work is strongly dependent on specialized simulation and system identification codes. These are available to DLR and its partners within the *HOST* rotorcraft simulation software and its integrated parameter identification module. This module is ideally suited to optimize parameters embedded inside the nonlinear rotorcraft model structure.

Next steps will be the creation and successive extension of a new comprehensive formulation of the Fenestron system. These models will be generated directly in an integrated analytical/parametric way by using the system identification iteratively to analyze the effects of certain parametric extensions and revise the model structure.

The preliminary investigations show promising results that encourage to expect substantial improvements for the modeling activities of the EC 135 Fenestron system and in the whole domain flight dynamics and simulation.

References

[1] R. W. Prouty: *”Helicopter Aerodynamics”*, PJS Publications Inc., Peoria, Illinois, 1985.

[2] D. Nyhus, C. Rao: *”Design of the Variable Pitch Fan for the McDonnell Douglas MD 520N Helicopter equipped with the NOTAR System”*, AHS 48th Annual Forum, Washington, DC, 1992.

[3] Joint Aviation Authorities: *”Joint Aviation Requirements — Simulator Training Devices (JAR-STD) 1H: Helicopter Flight Simulators”*, JAA Regulations Division, 1999.

[4] US Department of Transportation, Federal Aviation Administration: *”Advisory Circular, No: 120-63, Subject: Helicopter Simulator Qualification”*, FAA Flight Standards Service, 1994.

[5] H.-J. Pausder, U. Butter, F. Steinmaier: *”ACT/FHS for the Next Generation Technologies Evaluation and Demonstration”*, 25th European Rotorcraft Forum, Rome, Italy, 1999.

[6] W. v. Grünhagen, G. Bouwer, H.-J. Pausder, F. Henschel, J. Kaletka: *”A high bandwidth control system for the helicopter in-flight simulator ATTHeS — modeling, performance and applications”*, Published in the book ”Advances in Aircraft Flight Control”, edited by M. B. Tischler, Taylor & Francis Ltd., UK, 1996.

[7] Ph. Krämer, B. Gimonet: *”Improvement of non-linear Simulation using Parameter Estimation Techniques”*, 26th European Rotorcraft Forum, The Hague, The Netherlands, 2000.

[8] M. Vialle, G. Arnaud: *”A new Generation of Fenestron Fan-in-Fin Tail Rotor on EC 135”*, 19th European Rotorcraft Forum, Cernobbio, Italy, 1993.

[9] M. J. Smith, Y. Li, G. G. Loewy: *”Development of Unsteady Aerodynamic Prediction Techniques for High-Solidity Fans”*, AHS 57th Annual Forum, Washington, DC, 2001.

[10] G. P. Wright, J. T. Driscoll, J. D. Nickerson Jr.: *”Handling Qualities of the H-76 FANTAIL Demonstrator”*, AHS 47th Annual Forum, Phoenix, AZ, 1991.

[11] D. Hamel, A. Humpert: *”Eurocopter EC 135 Initial Flight Test Results”*, 20th European Rotorcraft Forum, Amsterdam, The Netherlands, 1994.

[12] B. N. Bourtsev, S. V. Selemenev: *”Fan-in-Fin Performance at Hover — Computational Method”*, 26th European Rotorcraft Forum, The Hague, The Netherlands, 2000.

[13] B. D. Kothmann, S. J. Ingle: *”RAH-66 Comanche Linear Aeroservoelastic Stability Analysis: Model Improvements and Flight Test Correlation”*, AHS 54th Annual Forum, Washington, DC, 1998.

[14] P. G. Hamel et al.: *”Rotorcraft System Identification”*, AGARD Lecture Series LS 178, Specialised Printing Services Ltd., UK, 1991.

[15] D. M. Pitt, D. A. Peters: *”Theoretical Prediction of Dynamic Inflow Derivatives”*, 6th European Rotorcraft Forum, Bristol, England, 1980.

[16] J. D. Keller: *”An Investigation of Helicopter Dynamic Coupling using an Analytical Model”*, 21st European Rotorcraft Forum, St. Petersburg, Russia, 1995.

[17] M. Hamers, W. v. Grünhagen: *”System Simulator for the DLR’s Inflight Simulator ACT/FHS — Software and Hardware Realisation”*, AHS 53rd Annual Forum, Virginia Beach, VA, 1997.

[18] Ph. Krämer, B. Gimonet, W. v. Grünhagen: *”Model Parameter Estimation with HOST (Helicopter Overall Simulation Tool)”*, 2nd ONERA-DLR Aerospace Symposium, Berlin, Germany, 2000.

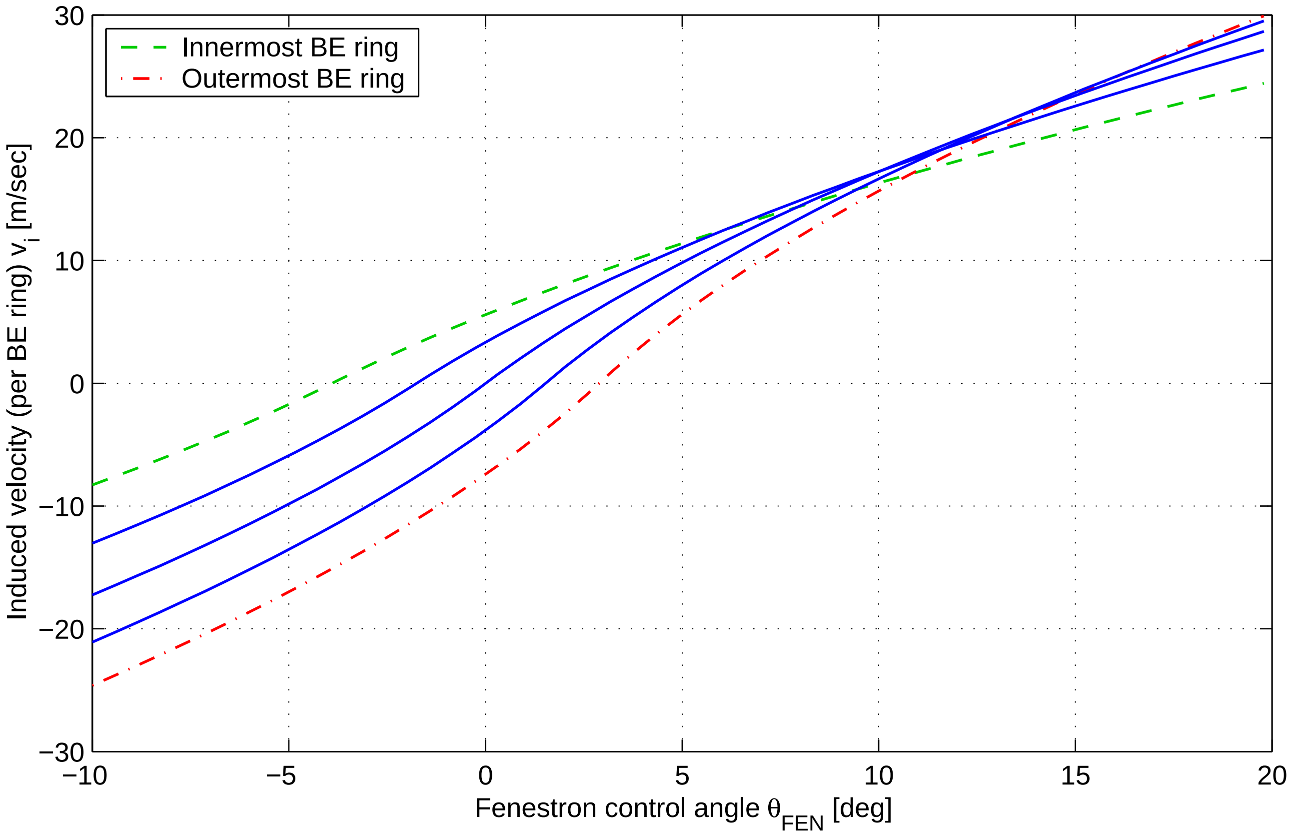

Figure 6: Induced velocity for five Blade Element (BE) rings versus control angle.

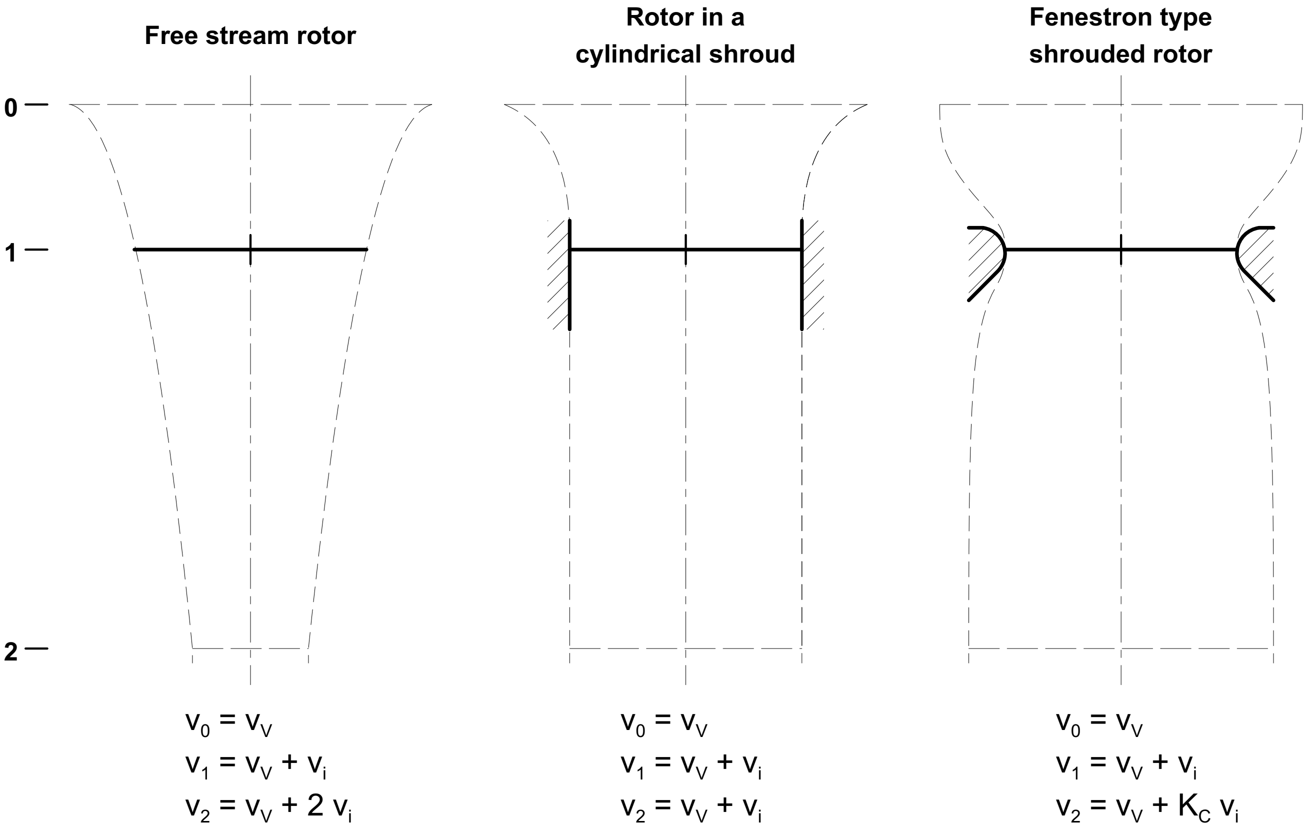

Figure 7: Flow principles for differently shrouded rotors.

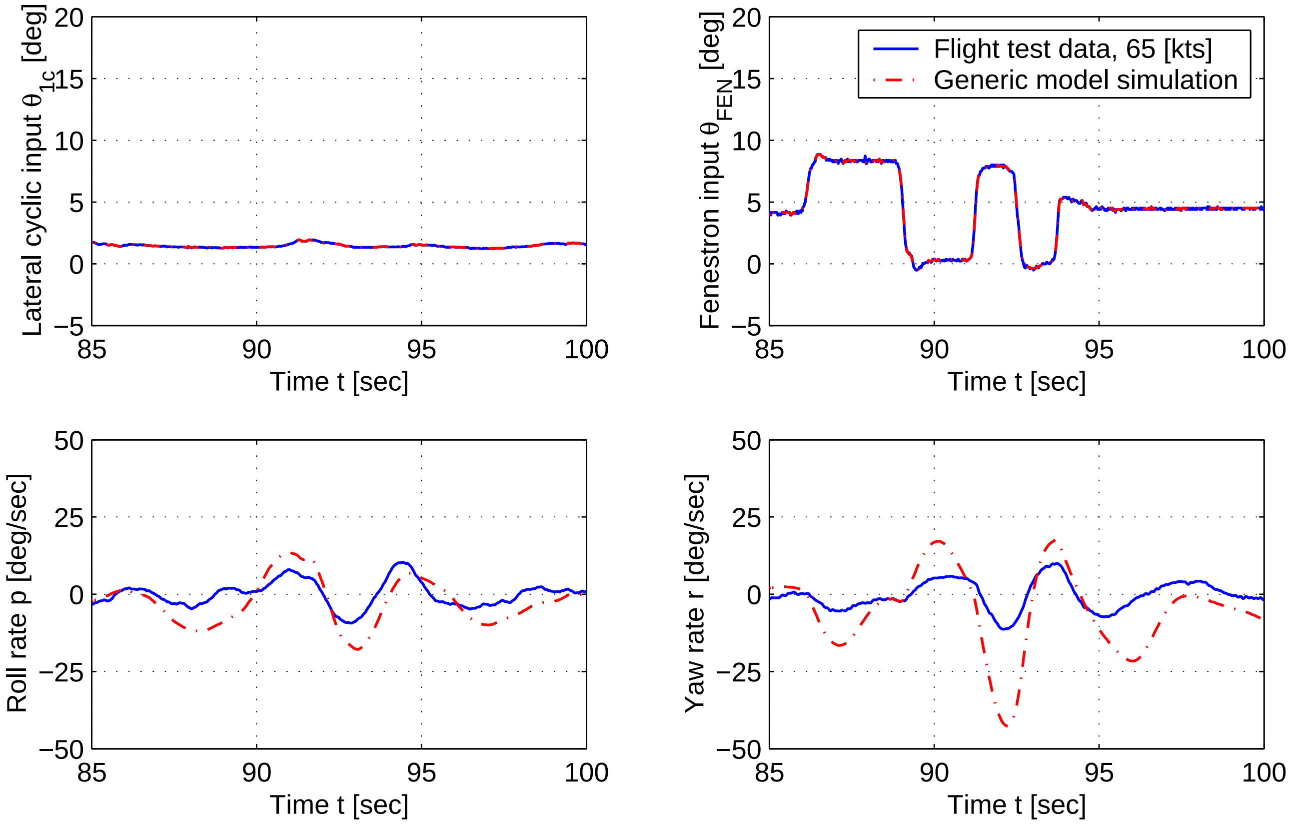

Figure 8: Simulation with standard generic Fenestron model.

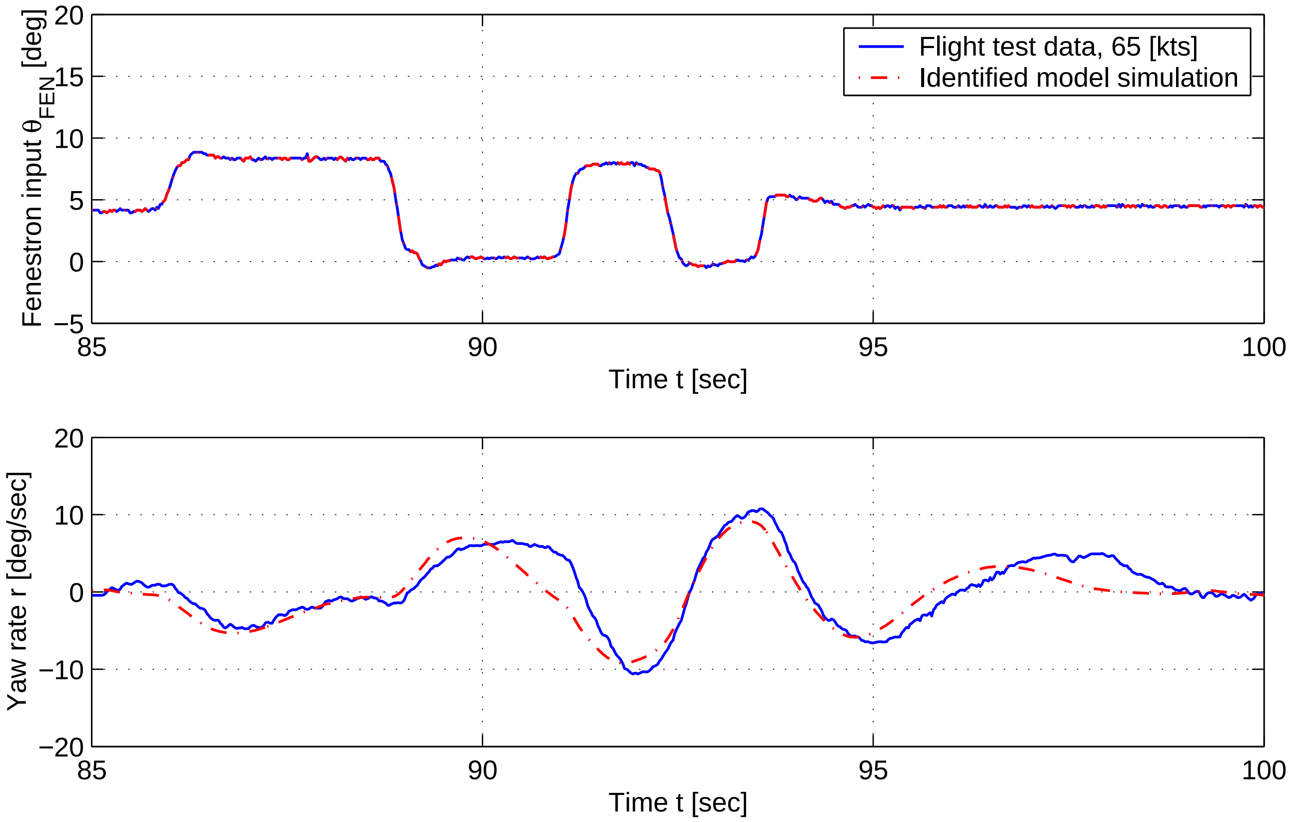

Figure 9: Identified linear derivative model simulation.

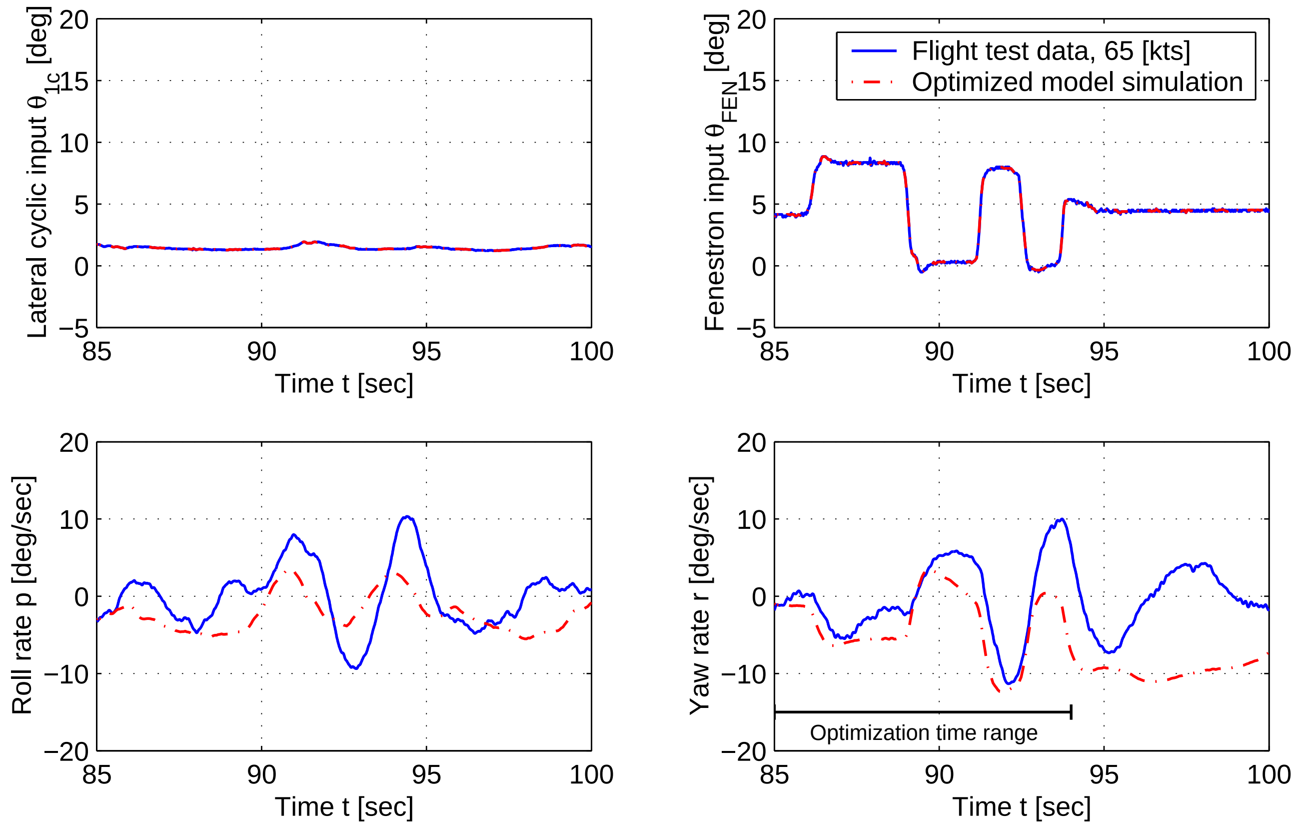

Figure 10: Simulation with yaw damping optimized generic Fenestron model.

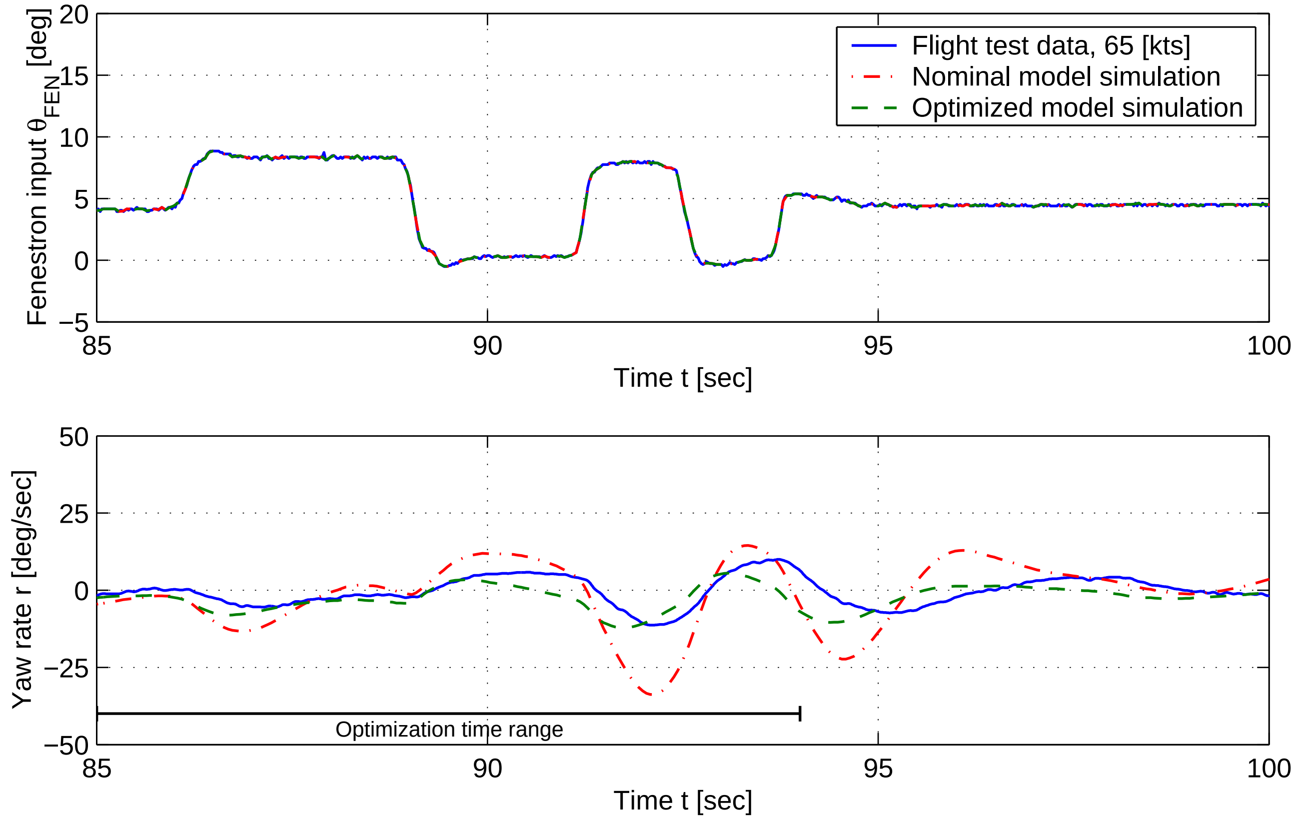

Figure 11: Simulation with nominal/yaw damping optimized generic Fenestron model (roll rate from flight test).