From Flight Test to a Simulator Model - System Identification of the ISTAR Research Aircraft

Christian RAAB[1,a *], Anton DILCHER[2,b]
[1]DLR (German Aerospace Center) – Institute for Flight Systems
[2]DLR (German Aerospace Center) – Flight Experiments
Lilienthalplatz 7, D-38108 Braunschweig, Germany
[a]Christian.Raab@dlr.de, [b]Anton.Dilcher@dlr.de

Keywords: Flight Test, Data Analysis, Modelling, System Identification, Simulation

Abstract The German Aerospace Centre (DLR) acquired a Dassault Falcon 2000LX research aircraft, designated ISTAR (In-flight Systems & Technology Airborne Research), to support research in variable stability, advanced flight control concepts, and pilot assistance systems. A high-fidelity flight dynamics model of the ISTAR is essential for the development of these systems and for simulator-based flight control testing. The model is based on an aerodynamic model identified through system identification (SysID) techniques using flight test data. The modular design of the aerodynamic modelling software enabled seamless integration of the identified model into the ISTAR simulator. This paper gives an overview of the model development process and an example for the application of the simulator model for the design and implementation of a yaw controller is presented.

Introduction

The development of a flight dynamics model for a simulator is a complex and time-consuming task, particularly during the design phase of new aircraft. Initially, the model relies heavily on wind tunnel measurements and computational fluid dynamics (CFD) calculations, which are later refined and validated using flight test data. The accuracy of the flight dynamics model is crucial, as it directly impacts the design of flight control functions and performance models. Furthermore, the model is an integral component of flight training devices, which are typically developed in parallel with or subsequent to the aircraft development process.

This paper provides an overview of the flight dynamics model development process for ISTAR, which is being designed as a platform for testing novel guidance, navigation, and control systems. In the forthcoming years, the aircraft's control system will undergo substantial modifications, enabling researchers to integrate and test custom flight control software [1]. To facilitate this development, a cockpit simulator has been established at the DLR AVES (Air Vehicle Simulator) simulation centre, supporting the development and validation of flight control software prototypes. Consequently, an accurate flight dynamic model is essential to demonstrate to regulatory authorities that the implemented modifications and safety measures are based on a realistic model.

A key strategy for accelerating the model development process was the direct reuse of software components created during the system identification (SysID) process in the AVES simulator software. The aerodynamic model was verified through software validation during the SysID process, where model outputs were directly compared to flight data measurements. Additionally, the flight dynamics model was validated using an automated process, which enables rapid updates to the simulator model in response to significant modifications to the aircraft or to new flight test data. This approach ensures that an up-to-date 6-degrees-of-freedom model of the ISTAR flight dynamics can be maintained at all times.

Aircraft and Instrumentation

The ISTAR aircraft is a modified Dassault Falcon 2000LX with a wingspan of 21.38 m and a maximum takeoff weight of 19.4 t. The standard avionic system features two independent Air Data Systems (ADS) that measure atmospheric parameters and calculate airspeed, Mach no. and barometric altitude. To obtain more accurate air data measurements, a nose boom installation is utilized, which enables the collection of data in the relatively undisturbed airflow ahead of the aircraft nose. Three independent and one experimental inertial reference systems measure acceleration along and rotational rates around the body axis. Position sensors installed on the aircraft control surfaces record the deflections of the elevator, ailerons, and rudder. A data acquisition system is integrated into the cabin, enabling the processing and storage of all flight parameters. The aircraft cabin features two stations, allowing the flight test engineer and an experimenter to monitor flight parameters in real-time during flight operations. This configuration facilitates direct communication with the test pilots, permitting the repetition or adaptation of manoeuvres as required by the experimenter.

Fig. 1. *The DLR ISTAR research aircraft with installed nose boom. Source: Uwe Bethke, Braunschweig.*

Flight Manoeuvres and Test Points

A comprehensive flight test campaign was conducted to gather data for the development of a model representing the flight dynamics throughout the operational envelope. The test program comprised 9 flights, performed between February and May 2022, during which a total of 26 test points were completed. These test points spanned various altitudes, speeds, and aircraft configurations, including different slat/flap settings and landing gear states. Details about the test points are shown in Tab. 1. The flight test campaign involved a range of SysID manoeuvrers designed to excite the aircraft's motion modes independently. Longitudinal motion was excited through multi-step elevator inputs, small step inputs, and double step inputs to the thrust lever and horizontal stabilizer. Lateral manoeuvrers included bank-to-bank turns, aileron and rudder doublets, and steady heading sideslip manoeuvrers. Additionally, level accelerations and decelerations were performed at altitudes of 30 000 ft and 45 000 ft. The collected dataset, which spans over 6.5 hours, includes more than 590 manoeuvres. Notably, the flight test campaign was impacted by nose boom vibration issues at speeds above 290 kt indicated airspeed (IAS), which precluded the completion of test points 5, 6, 7, and 9. These test points will be revisited once the vibration issues have been resolved. Overall, the gathered flight data provided a solid foundation for the development of an accurate flight dynamics model of the ISTAR aircraft.

Data Post-Processing and Compatibility Check

Accurate flight data measurements were crucial for developing a high-quality flight dynamics model. To ensure data consistency and accuracy, a data compatibility check (DCC) was performed [2]. The DCC is a higher-level process that detects and corrects measurement errors, and develops sensor models that provide adequate agreement between reference and measured airflow signals. A key component of the DCC is the flight path reconstruction (FPR) method, which uses inertial measurements to calculate reconstructed air data. We applied the DCC method to our flight data measurements to ensure their accuracy and consistency [3]. Another aim of the DCC is to develop

Table 1. *Flight test points used for system identification manoeuvrers.*

TP	Altitude [ft]	IAS [kt]	Ma	TP	Altitude [ft]	IAS [kt]	Ma
1a	11 000	120	0.22	7	27 000	320	0.79
1b	11 000	135	0.25	8	27 000	220	0.56
1c	11 000	145	0.27	9	33 000	300	0.84
1d	11 000	150	0.28	10	37 000	260	0.80
2	11 000	170	0.32	11	37 000	240	0.75
3	11 000	220	0.41	12	37 000	220	0.69
4	11 000	270	0.50	13	37 000	190	0.60
5	11 000	320	0.59	14	37 000	160	0.51
6	20 000	320	0.69	15	45 000	210	0.78

models for the aircraft air data and inertial sensors, representing the dynamic sensor characteristics. Accurate sensor models were essential for the SysID process and simulator model development, as control system designs must account for sensor characteristics such as time delays, bias, and factor errors. In preparation for the SysID process, the flight data were augmented with additional aircraft properties, including current weight, centre of gravity (CG) position, and moments of inertia. These parameters were derived using a manufacturer's weight and balance model, which accounted for the zero-fuel weight and the current fuel content in each tank. Additionally, a manufacturer-provided engine model was employed to compute the thrust force as a function of Mach number, altitude, and engine speed (N1).

System Identification

A crucial component of the flight dynamics simulation is the aerodynamic model, which determines the aerodynamic forces and moments acting on the aircraft. This model typically consists of equations for each aerodynamic force and moment coefficient, with each term comprising a derivative parameter multiplied by an influence variable. To estimate the aerodynamic parameters, the output error method was applied, which operates in the time domain and compares the model outputs with the measured flight data [2]. The procedure is illustrated in Fig. 2: The measured control deflections, engine thrust and current weight and balance properties were used as inputs to the model. Utilizing these inputs and the rigid body model states, the aerodynamic model calculated the forces and moments acting on the aircraft. The necessary state variables, such as flight speed, were determined using the equations of motion. Numerical integration of the equations of motion yielded the resulting model states, which served as inputs for the sensor models. The sensor models, which were previously validated through a DCC, remained fixed, and their outputs were compared with the measured flight data. An iterative process was used to minimize the calculated model error by optimizing the model parameters. This involved adjusting the structure and parameters of the aerodynamic model accordingly. The SysID process was performed using the MATLAB tool FITLAB [4], developed by the DLR Institute for Flight Systems. The kinematic model, aerodynamic model, and sensor model were integrated as modular software components into a C++ library for use with the SysID process. The models and identified parameters, denoted by hatched blocks in Fig. 2, are the software components that are reused for implementing the flight dynamics model in the simulator.

The results of a successful match between the flight data and the identified flight dynamics model

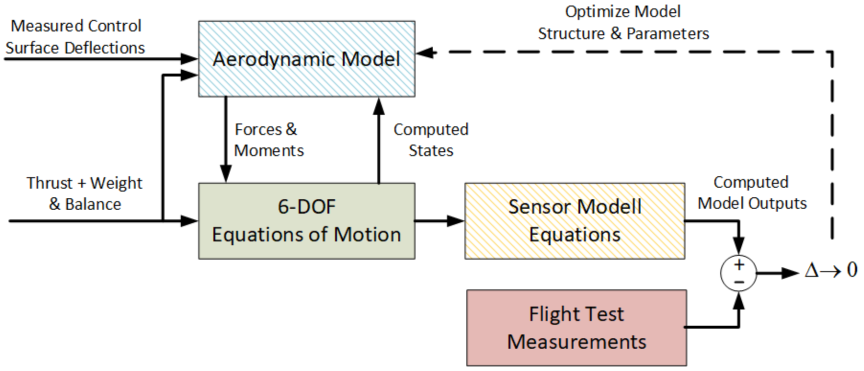

Fig. 2. *System identification process for the aerodynamic model.*

are presented in Fig. 3. This figure displays time series plots of a sequence of lateral manoeuvres, including two bank-to-bank and two rudder doublets, followed by a steady heading sideslip and a rudder release. The input signals of the ailerons and rudder control surfaces are shown in the first two subplots, while the subsequent subplots illustrate the corresponding responses in terms of angle of sideslip, roll rate, yaw rate, bank angle, and yaw angle. A comparison between the measured flight test data (blue lines) and the simulated model responses (red lines) reveals only minor discrepancies, indicating that the model accurately captures the flight dynamics of the ISTAR aircraft. A more detailed description of the system identification procedure and an assessment of the current model quality can be found in a companion technical report [5].

ISTAR Flight Simulator

The ISTAR simulator at the DLR AVES simulation centre is a combination of actual aircraft and reproduced hardware. All software necessary for operating the simulator is being developed completely in-house at the DLR Institute for Flight Systems. A central interface system, based on TCP/UDP communication protocols, connects the different cockpit simulator parts, like pilot control, display, vision and motion systems. The ISTAR simulation model is implemented in /Simulink. The core of the simulation model comprises the equations of motion, supplemented by a set of sub-models for aerodynamics, sensors, weight and balance, landing gear, and engine. Leveraging existing code, the aerodynamics and air data sensor models, previously employed in the SysID process, are integrated into the simulation framework via corresponding C++ S-Functions, promoting code reusability and efficiency. This extensive simulation model is being extended to include the unmodified aircraft's automatic flight control system (AFCS). As ISTAR undergoes modification to its flight control system, these changes will also be reflected in the simulation model. In order to run in real-time within the simulator, the model is compiled using Simulink Coder.

When modifications are complete, the ISTAR simulator will be used to test experimental flight control software prior to flight tests. This also allows the flight test crew to gain experience with the expected flight control behaviour before flying. As the transfer between experimental flight controls and the unmodified aircraft is important from a safety perspective, relevant aircraft systems such as the AFCS must also be sufficiently simulated. Initially basic autoflight functions, such as the yaw damper and the heading and flight path angle modes, have been implemented in the ISTAR simulator, with provisions for the future implementation of more advanced capabilities [6]. As specifics of the Falcon 2000 AFCS, such as system gains or control loop structure, are not known, these needed to be estimated or inferred based on flight test data and limited system descriptions.

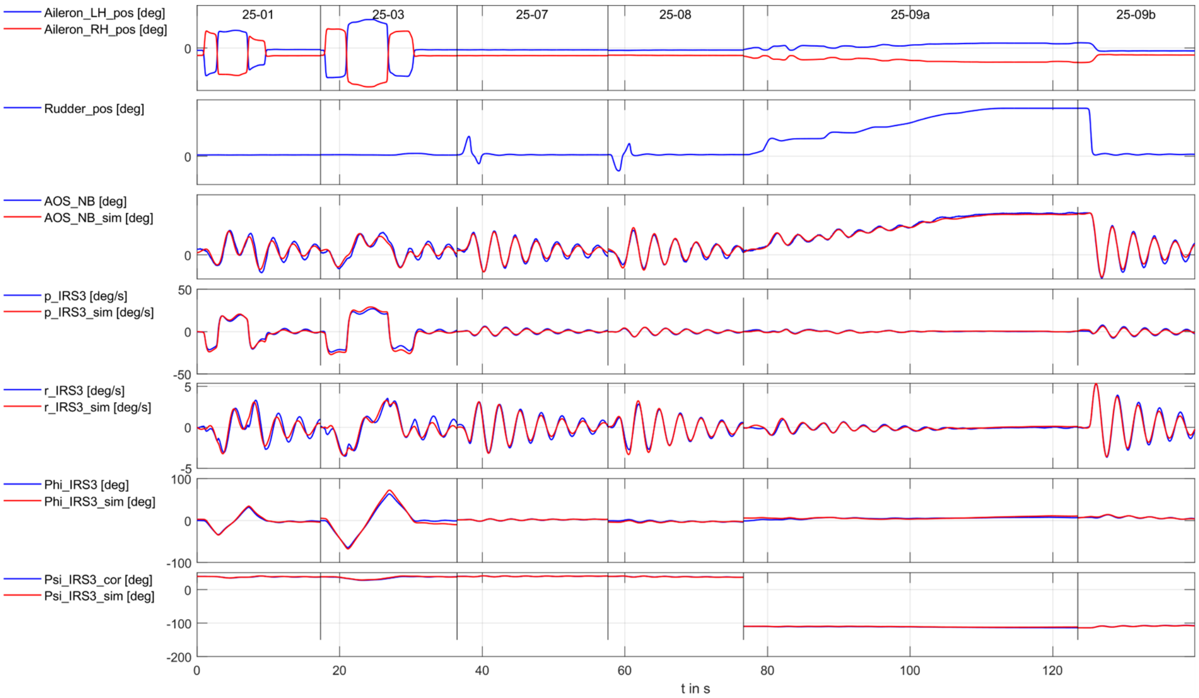

Fig. 3. Time series plots for excitation manoeuvres in the lateral motion with measured flight data (blue) and model response (red).

Yaw Damper Implementation

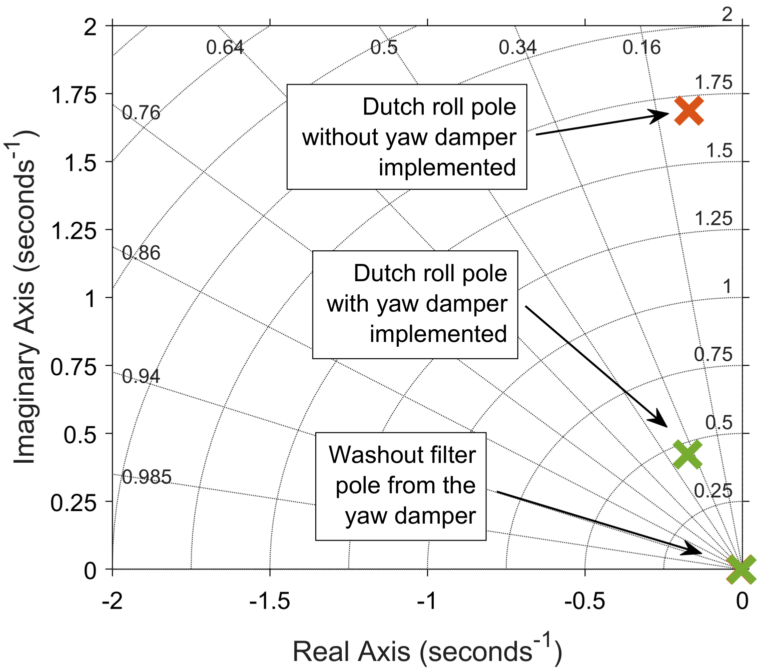

Fig. 4. Location of the dutch roll poles with (green) and without (red) the yaw damper implemented.

The yaw damper is the most basic form of stability augmentation found in the Falcon 2000 and is used to illustrate how the ISTAR simulation model can be used to develop flight controllers. The yaw damper was implemented using a root locus method and tuned with flight test data. Only very limited information about the yaw damper is available from the aircraft manufacturer. The functioning of the yaw damper was essentially reverse engineered using flight test data. The implementation is conventional using yaw rate feedback to the rudder and a washout filter.

An offline version of the SysID determined flight dynamics model is available in MATLAB/Simulink. With a trimming script a state-space model of the linearized aircraft motion around a trim point of 220 kt IAS at 12 000 ft was computed. This condition was chosen, because SysID test points were performed with and without the yaw damper engaged. Using a state-space model of the lateral-directional motion at this trim point a root-locus analysis of yaw rate feedback to rudder was performed. With the yaw rate feedback and the washout filter implemented in the offline simulation, their effects were tuned to the aircraft motion measured during flight test. Figure 4 shows the effect of the yaw damper implementation on the dutch roll poles. At the trim point, a yaw rate feedback gain of $1.3\,\mathrm{s}$ and a washout filter time constant of $1.5\,\mathrm{s}$, caused the dutch roll damping ratio to increased from 0.1 to apx. 0.4 while the natural frequency decreased (refer to Tab. 2), closely resembling aircraft motion. With the exception of a pole from the washout filter located essentially at the origin, the roll and spiral modes are both stabilized by the yaw damper. Particularly the spiral mode pole moves from very close to the origin further to the left along the real axis. For this yaw damper implementation to be suitable for the entire flight envelope and not just the chosen trim point, gain scheduling will be required.

Conclusion and Outlook

In conclusion, we have successfully developed and implemented a simulation model for the ISTAR research aircraft, utilizing extensive flight test data and system identification techniques. This model has demonstrated its value in flight preparation, testing, and development of control systems, such as the yaw damper controller. Future work will focus on enhancing the ISTAR research aircraft by enabling direct access to the flight control system. Additionally, the simulation model will be refined to capture a broader range of operational conditions, including high- and low-speed regimes, such as stalls, through a series of supplementary flight tests.

Table 2. *Comparison of dutch roll damping and frequency with and without the yaw damper implemented.*

Yaw Damper	Damping	Frequency
Not Implemented	0.10	0.270 Hz
Implemented	0.38	0.073 Hz

References

[1] D. Niedermeier, K. Giese, and D. Leißling, “The new research aircraft ISTAR - experimental flight control system,” *33rd Congress of the International Council of the Aeronautical Sciences, 4. - 9. September 2022, Stockholm*, no. 0439, 2022.

[2] R. V. Jategaonkar, *Flight vehicle system identification*. Reston: American Institute of Aeronautics and Astronautics, Jan. 2015, 1 Online-Ressource (649 pages), ISBN: 978-1-56347-836-9. DOI: 10.2514/4.866852.

[3] C. Raab, “Practical examples for the flight data compatibility check,” *CEAS Aeronautical Journal*, Oktober 2023. [Online]. Available: https://elib.dlr.de/198066/.

[4] S. Seher-Weiss, “Fitlabgui - a versatile tool for data analysis, system identification and helicopter handling qualities analysis,” English, *42nd European Rotorcraft Forum 2016*, vol. Vol. 2, p.1503–1521, 2016.

[5] C. Raab, “Dassault Falcon 2000LX ISTAR System Identification - Part I Process and Aerodynamic Model Description V1.0,” DLR - Institut für Flugsystemtechnik, Tech. Rep., 2024. [Online]. Available: https://elib.dlr.de/206264/.

[6] A. Dilcher, “Development of flight control functions for the simulation model of the Dassault Falcon 2000LX ISTAR,” TU Braunschweig, Tech. Rep., Apr. 2025. [Online]. Available: https://elib.dlr.de/214607/.