3 Modeling and Simulation—Basics and Benefits

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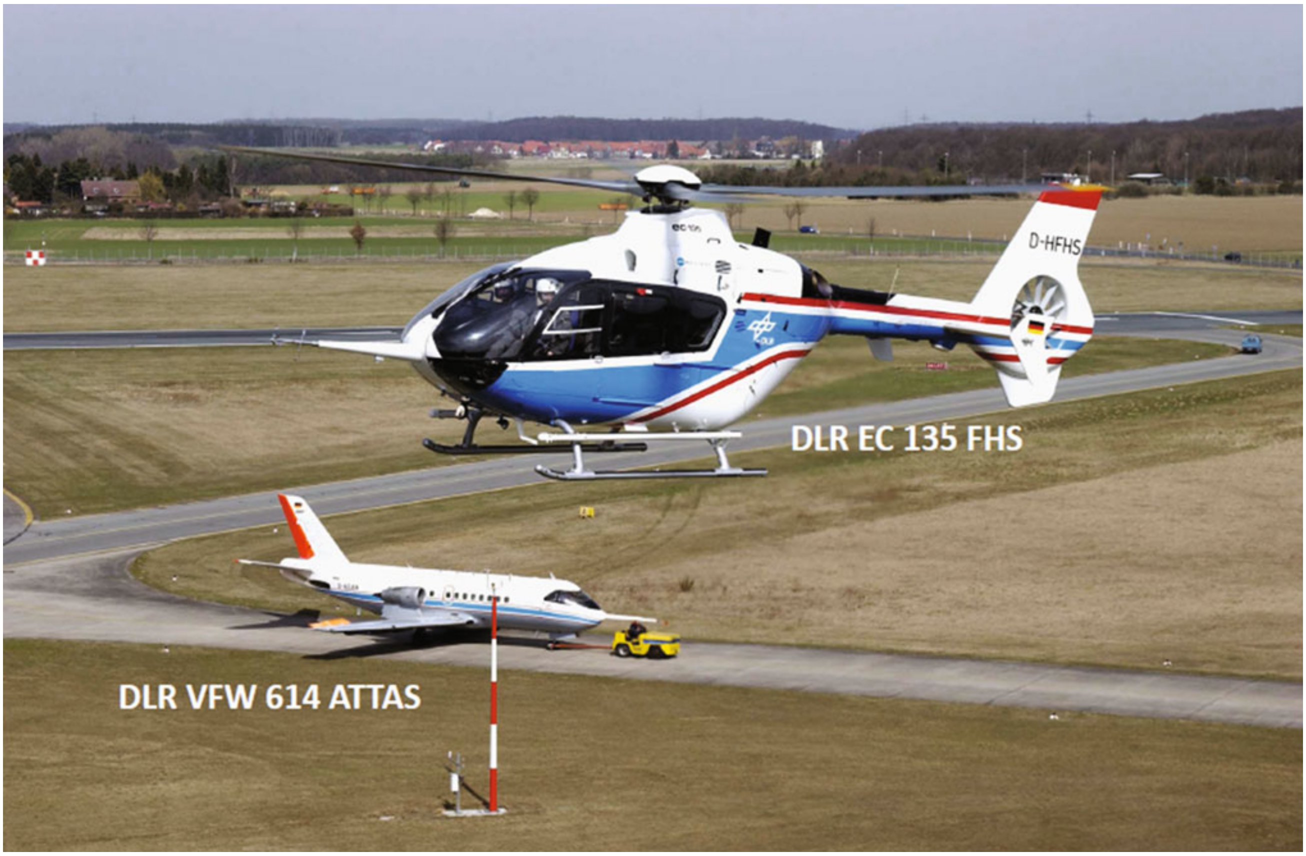

3.1 Introduction

When we speak of a “simulation”, it implies replication of a process on a computer using mathematical models. Here, the term ‘Process’ implies everything that can be analyzed nowadays in simulations, for example production procedures in factories, worldwide financial transactions, transport by rail and road, and many more. All simulations are based on a mathematical model of the process being investigated. Simulation allows a detailed study of the object before it is realized. The parameters of the mathematical model can be varied to examine various aspects of the process. Model parameters can also be so adjusted that the simulation yields replication of the reality as accurately as possible. The simulation is also a mechanism by which future

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developments can be predicted or evaluated. Simulation plays a key role in successfully preparing and carrying out a flight test program. The more precisely the mathematical model maps the reality, the more realistic is the simulation and the more meaningful are the results. For this reason it is clear that the development of highly accurate mathematical models is of great importance. “Modeling & Simulation” is and remains a challenge for scientists and engineers.

3.2 Simulation and System Identification

3.2.1 General

Simulation software can be bought nowadays for any and every PC. Who does not know the “Flight Simulator” or “Train Simulator”? These computer games show an amazing realism in the representation of the simulated vehicle and its surroundings. What on the PC is just a game, is a training tool for pilots, captains, train drivers, astronauts, and others in their professional life. But simulators are used not only for training or retention of the professionalism, but also for scientific purposes. Development simulators are employed in aviation research to investigate new flight control laws, displays, control elements, etc. for their usability. Experienced pilots review and evaluate the success of a new measure and decide whether a new device or a control law will be introduced or not.

In ground-based human-in-the-loop simulators mathematical models are used, which describe the behavior of the respective vehicle to control inputs and external disturbances. The simulation quality depends not only on how accurately the reality is represented by the mathematical model, but also on the entire simulation environment. That includes the aircraft cockpit or the locomotive driver cabin together with a complete set of instruments and control devices. Furthermore, the representation of the external view and possibly the reproduction of motion feeling and impressions are added. The mathematical model ensures the correct driving of the instruments, displays and motion systems. For the construction of a simulator it is important to define in advance the intended purpose. In many cases it is simply unnecessary to build a complex and expensive simulator, when they are not required by the training tasks at hand [1]. The greatest possible realism for a specific training task leads to, however, meaningful assessments and good training results.

Together with the development of an aircraft, the mathematical models for simulation are developed. In the case of an aircraft the models for the aerodynamic forces and moments are derived from wind tunnel measurements and/or CFD calculations (CFD = *Computational Fluid Dynamics*). In wind tunnel tests the model of the aircraft is mounted on a measuring balance and exposed to the airflow. For determination of aerodynamic forces and moments resulting from the rotational aircraft motion, either costly wind-tunnel models or corresponding results from CFD computations are needed, or otherwise flight tests are required. Flight tests are also necessary for older aircraft, for which the databases are either unavailable or not accurate enough. For the determination of model parameters from flight tests, methods of system identification are applied. Since aerodynamic forces acting on the aircraft during the flight cannot be measured directly, they need to be determined indirectly from the reaction of the aircraft to control inputs. A prerequisite for a successful system identification is a good measuring equipment and data recording.

3.2.2 System Identification

System identification is based on the comparison between flight test and its simulation with a mathematical model. Aircraft movement is excited through the pilot control inputs. The control inputs and the response of the aircraft are measured and recorded. In the subsequent analysis, the measured control inputs, such as a rudder position, are fed into the simulation model. The free parameters of the model, for example, the aerodynamic derivatives, are determined in such a way that the deviations between measured aircraft response and simulated model response to the same control inputs are minimized. A common method for solving this optimization problem is the so-called. maximum likelihood method (a term from probability theory, detailed explanation of which would go too far here; suffice it to state that, in most cases, the product of the error variances represents the cost function for the optimization [2]). The block diagram in Fig. 3.1 illustrates the entire identification process. The system identification is applied to flight test data for the development and validation of mathematical models having very high simulation fidelity. Also, such precise mathematical models are needed for the model inversion process of

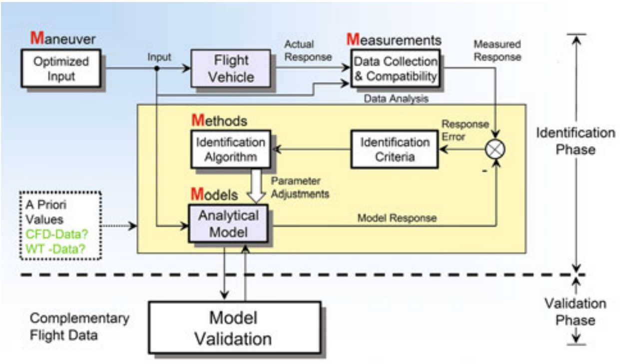

Fig. 3.1 The *quad-M*-principle of system identification (*Credit* Peter Hamel)

the so-called host aircraft of an in-flight simulator (see Sect. 3.3).

To successfully apply the so-called Quad-M-principle (Maneuvers, Measurements, Methods and Models) of system identification solid experience is required, such as that accumulated at the DLR Institute of Flight Systems over the past 50 years (see Figs. 3.2 and 3.3) [3, 4].

3.2.3 Ground-Based Simulation

It was a long way from the very first ground-based human-in-the-loop simulators to today's Level D training simulator (highest fidelity simulation), as utilized nowadays by the airlines. The first simulators ever were built for the training of pilots. Many aircraft from the pioneer generation

Flight Vehicle	Period	Type
Civil Aircraft	1970-1973	Dornier Do 27
	1975-1988	HFB 320-S1 FLISI
	1976	CASA C-212
	1978-1983	DHC-2 Beaver
	1981	A300-600
	1982-1985	Do 28 TNT OLGA
	1984	A310
	1986-1996	VFW 614 ATTAS
	1990	Dassault Falcon E
	1995	Grob G 850 Strato 2C
	1997-1998	Dornier 328-110
	1997	A300-600ST Beluga
	1997-1998	A330-200
	1999-2000	IPTN N250-PA1
	1999-2003	Dornier Do 128
	2000	VFW-614 ATD-EFCS
	2001	A340-600
	2002	Cessna Citation II
	2002, 2006	A318-121
	2004	Pitts S-2B
	2006	G180
	2007	A320
	2007	A380-800
	2010	Diamond DA42NG
	2010-2011	Falcon 20E
	2011-2012	Glider SB 10
	2013-2014	A350
	2013 ==>	A320 ATRA
	2014 ==>	Embraer Phenom 300
Military Aircraft and **Technology Demonstrators**	1976-1983	MRCA - Tornado
	1977	CCV F 104 - G
	1981	Do Alpha-Jet TST
	1984	Do Alpha-Jet DSFC
	1989-1997	C-160 Transall
	1993-1998	Dasa/Rockwell X-31A
	1997	EF 2000 Eurofighter
	2001	X-31A VECTOR
	2009-2010	A400M

Flight Vehicle	Period	Type
Aircraft Models	1978-1980	ATA free flight model
	1980	Do 28 TNT wind tunnel model
	1982-1983	Do 28 TNT free flight model
	2013 ==>	NumEx DLR F18
Helicopter and **Tilt Rotor Aircraft**	1975	Bo 105 S123
	1986-1989	Bell XV-15 tilt rotor
	1989-1990	AH 64 Apache
	1989-1990	SA 330 Puma
	1989-1995	Bo 105 S3-ATTHeS
	1998	SA 365 Dauphin
	1999 ==>	EC 135 FHS
	2007-2008	CH 53
Reentry Models	1989	OHB Falke
	1998	USERS
	2004	Astrium Phoenix RLV
Unmanned Aerial Vehicles	2008 ==>	ARTIS
	2010	UCAV (SACCON)
Rockets and **Projectiles**	1986	EPHAG
	1987-1988	EPHRAM
Aircraft Propulsion Systems	1992	Rolls Royce Tyne R.Ty.20 in C-160 Transall
	1997	Pratt & Whitney PW 119A in Dornier 328-110
	1997	Rolls Royce M45H MK501 in VFW 614 ATTAS
	1999	F404-GE-400 in X-31A
Aircraft Landing Gears	1996-1997	C-160 Transall
	1997	Do 328-100
	1997	VFW 614 ATTAS
	1998	Dasa/Rockwell X-31A
Miscellaneous	1985	Submarine, Class 206 U13
	1997	Aircraft pilot coupling
	1998	CombustionPlant RWE-VVA
	2000-2005	ALEX, Parafoil 252-7 Lite
	2002-2005	FASTWing
	2004-2007	Audi A8ABC
	2012-2013	Tragschrauber MTOsport

Fig. 3.2 System identification—experience at DLR (*Credit* Ravindra Jategaonkar)

Fig. 3.3 System identification—some recent contributions from DLR (*Credit* Ravindra Jategaonkar)

before the First World War were all but stable and good-natured (see Chap. 2). They demanded the constant attention of the pilot. There were numerous accidents caused by the lack of training. The opportunity to work with an experienced pilot to learn together in an airplane was rather the exception. Therefore, the importance of pilot training on ground, before the bold "Aviator" sat in an airplane, was recognized early. As such it is not surprising that just a few years after the historic flight of the *Wright* brothers, a few aircraft designers built training devices to protect both the pilots and the valuable aircraft.

The first viable ground-based simulator was offered in the year 1909 by the French aircraft company Société Antoinette. This apparatus (see Fig. 3.4), the *Antoinette Learning Barrel* ("Learning Drum") helped the pilots to fly the Antoinette VII monoplane. Student pilots at the flight school in Mourmelon-le-Grand found it necessary to use a training device with which the students could develop those reflexes which were needed to activate the control devices at the right moment in the right direction [5]. The apparatus consisted of two half barrels put over each other. A pilot's seat with the control wheels was mounted on the top. The entire assembly was unstable about all three axes and had to be constantly held in balance by the students. Thereby the simulation task was clearly defined for this trainee. Using the *Antoinette Learning Barrel* it was not yet possible for students to learn to fly, nevertheless they developed a feel for the aircraft reactions to control inputs.

Fig. 3.4 Antoinette "Learning Barrel" (*Credit* North American Museum of Flight Simulation)

Without going any further into the details of the history of development of ground-based human-in-the-loop flight simulators, it can be stated that with the development of new aircraft the need for corresponding training devices also grew. With the introduction of instrument flying during the late nineteen twenties, an appropriate training simulator was also at disposal. In the year 1929, *Ed Link* developed a simulator that provided the pilots a safe way to learn instrument flying. During the years from 1930 to 1950, the famous Link Trainer was built in large numbers and was used for pilot training in many countries around the world. The Link Trainer consisted of a cabin similar to that in an aircraft, but without outside view (see Fig. 3.5). The cabin could yaw up to 360°. It was supported on air-filled bellows which limited rolling and pitching motions. In any case the pilot sensed a reaction of the simulator on activating the control inceptors. More important were the instruments for the blind flight, following them, the pilot should "fly" on a predetermined course. On an evaluation table, the instructor could follow the course of the trainee pilot and over his microphone give instructions. The Link Trainer is considered to be a milestone on the road to the modern training simulator.

Modern training simulators for transport aircraft have achieved a simulation fidelity, which allows to retrain a pilot on a new aircraft type without further training flights (*Zero Flight Time Simulator*). In these ground-based simulators not only the cockpit environment is faithfully recreated, but the external view, the movement and the noise are generated too. The effort for the construction of such a simulator is indeed significant. The acquisition of high-fidelity training simulators is, however, worthwhile for airline operators, because the aircraft can be deployed to generate more revenue, while the pilot can be trained on the simulator day and night.

On the other hand, combat aircraft pilots are still predominantly trained in special training aircraft. According to the US Air Force, the training after the introduction of motion systems has even worsened. These motion systems were not able to deliver the acceleration impressions, which a fighter plane pilot is often exposed to. Also, due to a certain neural mismatch between system related time delays of motion and visual cues, training pilots sometimes became dizzy and felt sick (*Simulator Induced Sickness*—SIS). Furthermore, the US Air Force had lost many pilots due to becoming unconscious at high maneuvering loads, because these could not be trained in simulators (*g-Force Induced Loss of Consciousness*—G-LOC [6]). Only through the combination of simulator and centrifuge (*Authentic Tactical Fighting System*—ATFS) it was possible to improve the training success greatly.

3.3 In-Flight Simulation

No matter how good the ground-based human-in-the-loop simulator is, it cannot, however, reproduce the reality. There are always limitations with which one has to live with. To derive maximum benefits from a specific simulation task, the person entrusted with the execution of the task must also possess the necessary professional background (for example, test pilot, flight test engineer).

An aircraft which is converted into an in-flight simulator comes closest to the reality. The complete replica of a hypothetical new aircraft by converting an existing aircraft for the purpose of pilot training is almost impossible and is also not aspired in aeronautics. Depending on the simulation task, only sub-areas will be generally replicated. The special feature of the "in-flight simulation" compared to the ground-based simulation are the authentic vision and motion perceptions, which can be reproduced only by a real aircraft (host aircraft, Fig. 3.6). In addition to these physiological impressions the psychological effect is also important so that serious consequences of pilot actions can also be faced [7]. For the development of flying qualities criteria, aircraft with

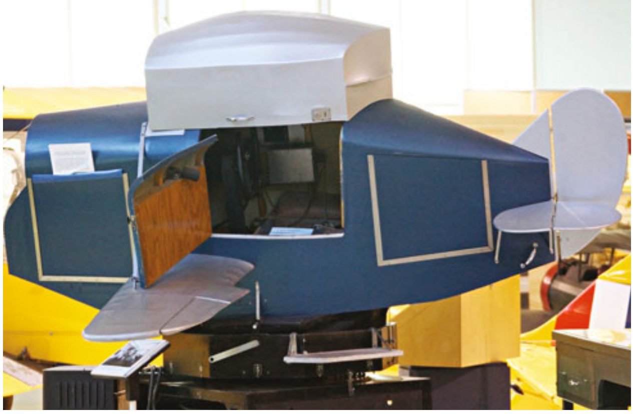

Fig. 3.5 Link trainer (*Credit* Alberta Aviation Museum)

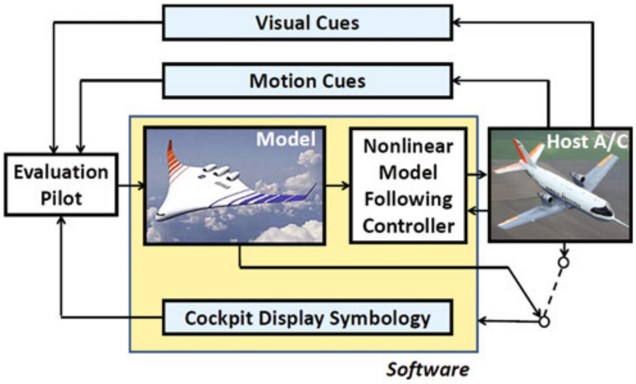

Fig. 3.6 Principles of in-flight simulation

variable stability (*Variable Stability Airplanes*) have proved to be successful (see Chaps. 5 and 7–10).

An airplane has, considered as a so-called rigid body, six degrees of freedom, namely three rotational (roll, pitch, yaw) and three translational (longitudinal, lateral and vertical). If the in-flight simulator should respond exactly about all the six degrees of freedom (6 DOF) like the aircraft being replicated, then accordingly as many, that is six, independent controls must be available. Normally, this is, however, not the case: an aircraft possesses usually three primary aerodynamic controls, namely elevator, aileron and rudder, and the thrust lever position or the thrust. Corresponding to their main effects, these four so-called control variables are suitable for motion simulation in the three rotational degrees of freedom (that is, the attitude angles and their temporal change) and in the longitudinal direction (that is, the airspeed). The replication of the vertical motion, and thereby also of the vertical load factor, as well as of the lateral motion will be only in limited agreement. If the motion is to be reproduced exactly in these translational degrees of freedom too, then appropriate additional control effectors are needed; for example, fast responding canard control surfaces or trailing edge flaps on the wing, so-called DLC flaps (*Direct Lift Control*), for the vertical motion or direct side force generators, for the lateral motion.

A so-called “model following controller” then ensures that the host aircraft replicates the behavior of the target aircraft in just as many degrees of freedom as the number of independent controls available [8]. In the other degrees of freedom, there are generally, give or take, marked differences in the motion. In the model following control, the procedure adopted is differentiated between the so-called implicit and explicit control.

In the case of implicit control, it is attempted, through static feedforward and feedback, to adapt directly the behavior of the host aircraft such that it behaves like the target aircraft.

In the case of explicit model following control, the model following controller includes in the dynamic feedforward an explicit simulation model (desired model) of the target aircraft (see Fig. 3.7). The signals from the pilot inceptors are connected only to the inputs of this simulation model. The main outcome of this simulation is the accelerations of the target aircraft. Furthermore, when the accelerations are simulated correctly, then automatically their integrals, namely the speeds and positions match too (as long as the initial values of these integrals match). As the relationship between control variables and accelerations is known for the host aircraft, by “inversion” of the simulation equation (from which the accelerations resulting from control deflections are calculated) the necessary control deflections can be calculated from the desired accelerations (which result from the explicit simulation of the target aircraft). Since the accelerations of the host aircraft depend not only on the control variables, but also on the particular flight condition characterized by the so-called state vector, additionally an estimation of this state vector is necessary for the calculation of the required control deflections. This is carried out in general using additional differential equations, which describe the dynamics of the so-called model following observer.

In the case of explicit model following control, the dynamics of the controlled overall system consist of the dynamics of the target aircraft, the dynamics of the model following observer and the so-called error dynamics. The error dynamics describe the temporal behavior of the model following error, no matter how it arises. Ideally, the error is reduced rapidly without overshooting. It can be shown that without additional measures the error dynamics are the same as those of the unregulated dynamics of the host aircraft. Since these dynamics usually exhibit some very slow and/or poorly damped elements such as the Phugoid or the Dutch roll mode, they must be changed through a feedback of the difference between the quantities estimated by the feedforward and the actual, that is measured, variables.

Even in a completely nonlinear case (that is, nonlinear model of the target aircraft, for example, a Level-D simulator model, and nonlinear equations of the host aircraft for the calculation of the control variables and for the model following observer), a very good model following quality can be achieved using this method. However, an iterative numeric inversion of the acceleration equations is necessary for this purpose.

An in-flight simulator is more than an airplane with a variable stability system. The US-literature, however, does not differentiate between the two. The in-flight simulator should convey an impression to the pilot that he/she is virtually flying another type of aircraft. This pertains not only to the visual and motion impressions, but also to the controllability. Despite all these efforts, the in-flight simulation is subject to limitations. One cannot simulate everything. The simulation of a flight at supersonic speed at low altitude using a subsonic aircraft remains problematic and the right cockpit environment cannot easily be realized. Likewise, to simulate a different type of aircraft, the whole database needs to be replaced, not to mention the necessary modifications in the cockpit for the new target aircraft. This is elaborate, time consuming, expensive and also safety critical. This can occasionally be realized more easily in a ground-based simulation. Excluded are then the acceleration impressions, which can hardly be realized realistically with a ground-based simulator. As such it is necessary to tradeoff between deployment of a ground-based simulation, a variable stability aircraft or an in-flight simulator with all the limitations outlined above [9].

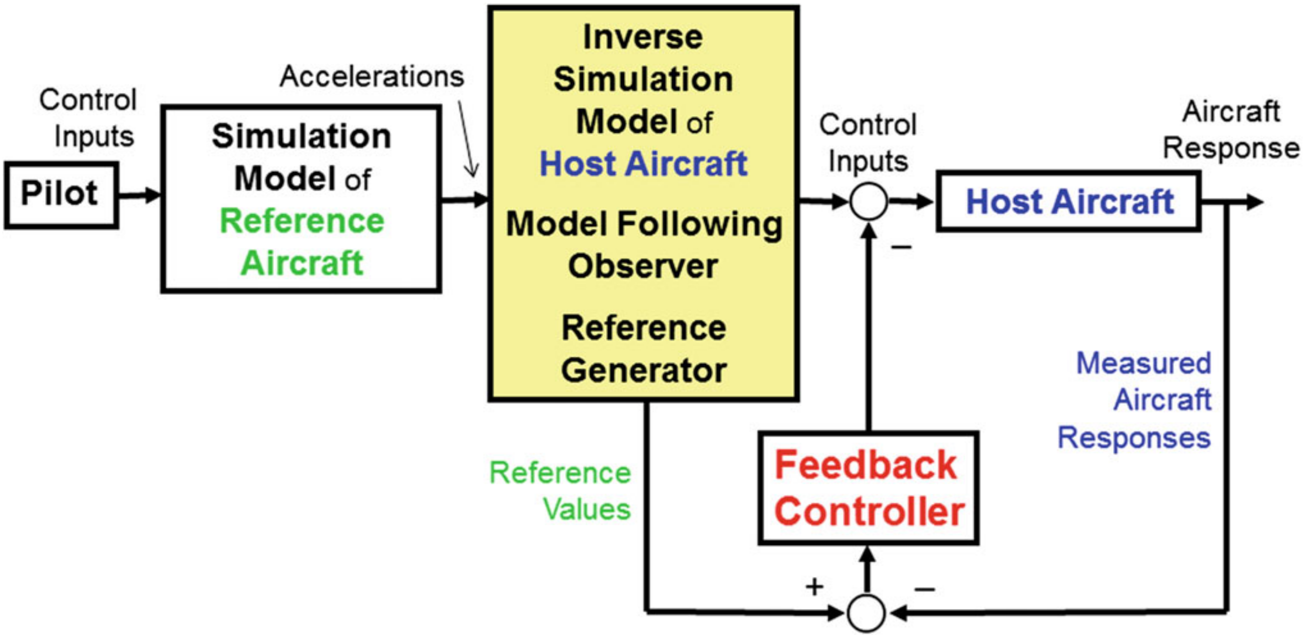

Fig. 3.7 Explicit model following control

Ideally, during the development of a new aircraft, the complete chain of simulation, that is, from of the ground-based simulation to in-flight simulation, is employed to keep the development risks as small as possible (see Fig. 1.2). With the increasing demand for unmanned flight vehicles, a renaissance of in-flight simulation is expected to test and to train flying such unmanned aircraft in civilian airspace with the so-called *Optionally Piloted Flight Vehicles* (aircraft controlled by pilot as needed) or with the so-called *surrogate aircraft* (substitute aircraft) (see Sects. 5.2.1.14 and 9.2.11)

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Author Biography

Bernd Krag was a research scientist at the Institute of Flight Systems of DLR of Braunschweig (1972–2002). From 1993 to 2002 he was head of the Fixed Wing Aircraft department. Prior to joining DLR, he was a research assistant at the Flight Mechanics Branch at the Technical University in Braunschweig (1967–1972). He received his Dipl.-Ing. degree (1967) and Dr.-Ing. degree (1976) in Aerospace Engineering from the Technical University Braunschweig. His main research interests were control configured vehicles (CCV), active control, modeling and system identification, databases for training simulators, and the wake vortex problem. Since retiring from DLR, his interest is in the history of aeronautics research in Braunschweig and aviation history.