Art and Science of System Identification
Through innovative ideas in flight maneuver techniques, parameter estimation methods, and aerodynamic modeling, the Institute has established itself internationally as a major contributor to the field of flight vehicle system identification. The inverse-principle based system identification methodology provides a scientific approach to modeling and estimation. Over the last thirty years, aircraft parameter estimation techniques have been successfully applied to various tasks such as:

- Data correlation for increasing the confidence in flight mechanical prediction techniques,
- Generation of high fidelity aerodynamic databases for training and in-flight simulators,
- Flight envelope expansion through isolation and identification of non-anticipated aerodynamic effects,
- Handling qualities assessment, and
- Rotorcraft modeling with high bandwidth requirements.

Table 1 provides a concise summary of the various applications covering a broad spectrum from simple aircraft to high performance, highly augmented modern flight vehicles and other miscellaneous dynamic systems.

System identification is an interdisciplinary task requiring a coordinated approach encompassing the important aspects of:

- Flight test instrumentation,
- Flight test techniques, and
- Analysis of flight data.

The art and science of these strongly interdependent topics practiced in the Institute have led to a well established Quad-M (Maneuvers, Measurements, Methods, and Models) approach, which has been the key to the highly successful application of system identification methodology to numerous dynamic systems at DLR.

### Flight Measurements and Data Pre-Processing

The accuracy of the parameter estimates is directly dependent on the quality of the flight measured data, and, hence, high accuracy measurements of the control inputs and of the motion variables are a
prerequisite for successful application of the modern methods of system identification. Considerable effort has been spent on this aspect at the Institute. Commercially available sensors, standard signal processors, and in-house developed data processing systems are judiciously combined to optimize this laborious and time-consuming process. Capability to design, fabricate, and install a full-fledged flight test instrumentation, including its flight certification, was successfully demonstrated for a high-fidelity flight simulator data gathering with the C-160 Transall aircraft. A total of 91 physical parameters were measured and recorded, Figs. 1 and 2. A few signals were picked off from the basic aircraft instrumentation, but the bulk of them required additionally installed sensors. The test aircraft was one from the operational fleet of the German Air Force. Due to safety reasons, it was not permitted to drill holes into the aircraft, and, hence, installation of additional sensors and test equipment was ingeniously done using clamps, brackets, etc.

**Optimal Inputs for Dynamic Motion**

The scope of identification is limited by the flight tests, since the physical phenomenon postulated as a cause-effect model cannot be identified, if it is not in the data. Hence, a proper experiment design is important. Moreover, accuracy and reliability of parameter estimates depend heavily on the amount of information available in the vehicle response. In general, an optimal input is that which best excites the frequency range of interest. Purely from this view point, the direct choice may appear to be a frequency sweep. However, sweep testing is mostly restricted to single axis excitation. Moreover, it leads to relatively long maneuver times and thus the vehicle has a tendency to depart from the nominal trim. Based on these practical considerations, several signals, for example, multistep 3211, Mehra, Schulz, and DUT, were designed in the seventies. The doublet input is also often used due to its simplicity. Fig. 3 shows Koehler’s 3211 input developed in the Institute and its power spectrum in comparison to step and doublet inputs. The 3211, Mehra, DUT, and the recently designed Langley inputs are efficient; amongst them the multistep 3211 signal is the easiest to realize and relatively easy to fly manually by pilots. In addition, the frequency contents can be readily adapted to match changing flight conditions. It is for these reasons that the 3211 signal is widely used internationally for system iden-
Table 2: DLR 3211 input signal statistics

<table>
<thead>
<tr>
<th>Period</th>
<th>Flight Vehicle</th>
<th>Institution</th>
<th>Period</th>
<th>Flight Vehicle</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974 – 1983</td>
<td>HFB 320 FLISI</td>
<td>DFVLR</td>
<td>1993</td>
<td>Convair CV 580</td>
<td>NRC</td>
</tr>
<tr>
<td>1981 – 1983</td>
<td>Do TNT-Experimental</td>
<td>Dornier</td>
<td></td>
<td>Rotorcraft</td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>FBW Jaguar</td>
<td>Bae</td>
<td>1977</td>
<td>Bo 105 S3</td>
<td>MBB</td>
</tr>
<tr>
<td>1984</td>
<td>F-8 DBW</td>
<td>NASA</td>
<td>1980 – 1987</td>
<td>Bo 105 ATHE5</td>
<td>DFVLR</td>
</tr>
<tr>
<td>1984</td>
<td>A300-600</td>
<td>AI</td>
<td>1982</td>
<td>UH 60 A</td>
<td>US Army</td>
</tr>
<tr>
<td>1985</td>
<td>Tornado</td>
<td>Bae</td>
<td>1983</td>
<td>RSRA</td>
<td>NASA</td>
</tr>
<tr>
<td>1987</td>
<td>Cessna Citation 500</td>
<td>NLR</td>
<td>1988 – 1990</td>
<td>AH 64 Apache</td>
<td>MDHC</td>
</tr>
<tr>
<td>1990</td>
<td>Dash 8 Series 100</td>
<td>NRC</td>
<td>1988 – 1990</td>
<td>SA 330 PUMA</td>
<td>RAE</td>
</tr>
</tbody>
</table>

The more recent emphasis on expanding the design techniques based on additional practical considerations has resulted in new inputs having improved properties. These inputs are, however, difficult to fly manually and can be best realized through onboard computer implementation. Thus, although it may appear that the current trend is towards more complex computerized inputs, the simpler inputs like doublet or 3211 will continue to be as accepted in the future as in the past.

Parameter Estimation Methods

Recognizing early the need for efficient analytical tools for analysis of flight data from flight vehicles of increasing complexity, as a long term perspective the research and developmental work on aircraft parameter estimation methods was initiated at the Institute in the early seventies. This work has gone through various phases of innovations, updates, and consolidations. This process continues even today with the current goal being to meet new demands and project specific requirements. Fig. 4 shows at a glance the evolution of the software tools for parameter estimation in the time domain.

Although the recent focus has been on the time domain methods, parameter estimation methods in the frequency domain have also been developed and used extensively in the Institute, particularly for rotorcraft identification. Similarly, other techniques of frequency analysis based on spectral, coherence, and frequency response functions catering to multi-input/multi-output systems have also been developed.
The two milestones in the development of aircraft parameter estimation methods in the Institute are: i) extension of the widely used output error method to general nonlinear retarded systems and ii) development of filter error algorithms for such systems accounting for atmospheric turbulence and measurement noise. This systematic work on algorithmic development was supported by the Special Research Project SFB-212 of the Technical University of Braunschweig. Today’s comprehensive software package, called ESTIMA, is a modular system of algorithms for aircraft parameter estimation in the time domain and is a unique tool of the Institute, see Table 3.

Aerodynamic Model Identification – Last Decade’s Highlights

Since it would be a mammoth task to provide a complete description of the various applications listed in Table 1, only a few highlights of the last decade are presented here. It does not in anyway imply that the other cases were less important or simple.

High Fidelity Databases for Training and In-Flight Simulators

With the evolution of modern high performance aircraft, spiraling developmental and experimental costs, and increasing flight safety issues, the importance of ground-based flight and in-flight simulators has increased significantly in the recent past. Simulators are increasingly used not only for pilot training, but also for other applications such as flight planning, envelope expansion, design and analysis of control laws, handling qualities investigations, and pilot-in-the-loop studies. The majority of these cases demand high-fidelity aerodynamic databases of the flight vehicle and the importance of flight validation of such a database is well recognized. Applying system iden-

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**Table 3:** Scope of application and main features of estimation package ESTIMA

<table>
<thead>
<tr>
<th>Scope of application:</th>
<th>Main features:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESTIMA is optimized to meet the heavy demands of:</td>
<td>Modes:</td>
</tr>
<tr>
<td>- processing large amount of flight data (up to 80000 data points from 80 flight maneuvers)</td>
<td>- Output: Output error method</td>
</tr>
<tr>
<td>- estimation of large number of parameters (up to 1200)</td>
<td>- Filter: Filter error method</td>
</tr>
<tr>
<td>- complex dynamical systems with large number of state, observation, and control input variables (up to 30, 60, and 60 respectively)</td>
<td>- EKF: Estimation by Extended Kalman Filter</td>
</tr>
<tr>
<td>It caters for and is applicable to:</td>
<td>- TRIM_FV: Trim the model to specified flight measured conditions</td>
</tr>
<tr>
<td>- linear and general nonlinear retarded systems</td>
<td>- SIM_1P: or arbitrarily specified flight conditions</td>
</tr>
<tr>
<td>- unstable aircraft</td>
<td>- UMRECH: Data pre-processing</td>
</tr>
<tr>
<td>- systems with measurement noise and atmospheric turbulence (process noise)</td>
<td>Optimization methods:</td>
</tr>
<tr>
<td>- multi run evaluation concatenating several maneuvers</td>
<td>- Gauss-Newton (Modified Newton-Raphson) method</td>
</tr>
<tr>
<td>- estimation of time delays and hysteresis</td>
<td>- Levenberg- Marquardt method</td>
</tr>
<tr>
<td>- different optimization and integration methods</td>
<td>- Quasi-Newton and Conjugate gradient methods</td>
</tr>
<tr>
<td>- hybridization of integration methods</td>
<td>- Direct search methods of Powell and Jacob</td>
</tr>
<tr>
<td>- special option for proof-of-match computations</td>
<td>- Simplex method of Nelder and Mead</td>
</tr>
<tr>
<td>- classical simulation mode providing possibilities to trim the model and carry out simulation</td>
<td>- Subspace searching Simplex method</td>
</tr>
</tbody>
</table>

Integration methods:

- Euler, Runge-Kutta 2nd, 3rd, and 4th order
- Runge-Kutta-Fehlberg 4th/5th order with step size control
- Backward differentiation formula for stiff systems
Art and Science of System Identification 2000

Identification methods, aerodynamic databases were generated by the Institute for the military transport aircraft C-160 Transall, Fig. 5, and the commuter aircraft Dornier 328, Fig. 6, in both cases meeting the Level D quality criteria, the highest fidelity class specified by FAA [2, 3].

The In-Flight Simulator ATTAS (Advanced Technologies Testing Aircraft System) is a fly-by-wire aircraft, Fig. 7, and has been the testbed for numerous investigations, such as modeling of direct-lift control, separate wing and tail identification, separation of pitch damping derivatives, control surface interference effects, and modeling of actuation systems of primary controls as well as propulsion systems. Extensive tests and identification efforts led to a high fidelity global aerodynamic database [4, 5].

**Unsteady Aerodynamic Modeling**

Although unsteady aerodynamics has been a subject of extensive investigations using computational fluid dynamic methods, wind tunnel tests, and a number of semi-empirical models, flight validation of the postulated models has been difficult in the past. The recent advances in aerodynamic modeling have led to analytical models for complex processes such as ground effects and separated flow including stall hysteresis, making identification and validation from flight data amenable. As a typical example, Fig. 8 shows a comparison of the total lift and pitching moment coefficients derived from flight measurements with those estimated using system identification. Applying Kirchhoff’s theory of flow separation, a parametric model with only three unknown parameters adequately characterizes the quasi-steady stall behavior. This innovative approach was successfully applied in the development of aerodynamic databases for the aforementioned Level D training simulators C-160 Transall and Dornier 328 as well as to the In-Flight Simulator ATTAS [6].

**X-31A System Identification**

The USA/German experimental aircraft X-31A is a highly augmented technology demonstrator with enhanced maneuverability, incorporating advanced technologies such as high angle-of-attack aerodynamics and an integrated flight control system including thrust vectoring, Fig. 9. The X-31A system identification, for which the Institute was primarily responsible, posed special challenges mainly because: i) the basic aircraft is inherently un-
stable leading to error propagation and divergence in the numerical integration during open loop identification and ii) the flight control laws suppress oscillatory and transient motions as well as lead to correlated input and motion variables resulting in identifiability problems. The solution to the first problem of numerical divergence is provided by diligent choice of appropriate estimation algorithms from the wide variety available in the modular system of algorithms ESTIMA. The solution to the second problem of identifiability was provided through separate surface excitation (SSE). In this approach the computer generated standard inputs such as doublet or 3211 are fed directly to the control surfaces. The electronics for single surface excitation were designed and provided by the Institute.

As a typical example, Fig. 10 shows estimates of the canard control effectiveness obtained from X-31A flight data for two cases, namely the pilot input and separate surface excitation maneuvers. As evident from Fig. 10, the pilot input maneuvers yield estimates with large standard deviations shown by vertical bars and, moreover, the scatter is also large. On the other hand, the separate surface excitation maneuvers yield well identifiable estimates.

The results of X-31A system identification have been used to validate and in several cases update the original database. Fig. 11 shows two typical examples of database update. The flight estimates did not confirm the wind-tunnel predicted large negative value of the dihedral effect between 30°-45° of angle of attack. Similarly, considerable discrepancies were observed in the directional stability at higher Mach numbers. System identification provided improved models of aerodynamic characteristics including post stall regime and thrust vector control for flight test planning, flight envelope expansion, and a validated database for simulation and control law modifications and verification [7, 8].

**EF 2000 Model Validation**

During the development of Eurofighter, a joint venture between England, Germany, Italy, and Spain, validation of wind tunnel predictions played an important role, particularly to confirm the nonlinear rudder effectiveness and power reversal, Fig. 12. Flight investigations and the subsequent system identification using the specially tailored methods of DLR confirmed these predictions. Besides the specialized task, the Institute also provided project support to the Dasa flight test center.

**Rotorcraft High Bandwidth Modeling**

The philosophy of model-following control based on feedforward regulation provides safer and more accurate mode control; the performance, however, depends
strongly on the quality of the mathematical model of the host vehicle. For such an application, the rotorcraft flight control has to meet high bandwidth requirements, which demand augmentation of the lower to medium frequency range rigid-body model through higher-order rotor dynamics. In the specific case of the DLR In-Flight Helicopter Simulator ATTHeS, Fig. 13, the application of the flight validated higher order models for the model-following control was a major prerequisite for the achieved excellent fidelity. The frequency response of roll rate to lateral stick input shown in Fig. 14 clearly brings out that the high frequency helicopter rotor characteristics cannot be adequately described by rigid-body model alone, but that a 9 degree-of-freedom model combining the rigid-body and rotor dynamics is necessary [9].

**XV-15 Tilt-Rotor Model Validation**

The tilt-rotor aircraft configurations ideally combine the aerodynamic characteristics and the advantages of both helicopter rotors and aircraft performance. Identification of tilt-rotor flight vehicle in hovering flight is, however, particularly difficult because of the highly nonlinear and coupled dynamics, and also because of the open-loop instabilities at such flight conditions. As a part of a USA/FRG Memorandum of Understanding on helicopter flight control, an extensive joint study was conducted to analyze XV-15 flight data, Fig. 15. Parameter estimation techniques in the time and frequency domain were applied to develop a unified approach for rotorcraft identification. The results were used for database validation and for improving model fidelity [10].

**Dissemination of Expertise**

Promulgation of the expertise acquired in the Institute has been consistently one of the focal points over the last three decades. Besides the numerous technical papers in the reputed international journals, key contributions through AGARD activities are noteworthy, for example, Conference Proceedings CP-172 in 1975, CP-235 in 1978, Lecture Series LS-104 in 1979, LS-114 in 1981, LS-178 in 1991, and RTO MP-11 in 1998. The activities of the AGARD Advisory Report AR-280 in 1991 were also coordinated by the Institute. The invited survey paper in the AIAA Journal of Aircraft on “Evolution of Flight Vehicle System Identification” [11] giving a historical perspective and a consolidated account of various contributions and the overview paper on “Advances in Rotorcraft System Identification” [12] have become standard reference material on the subject and are examples of outstanding contributions to the field.
Software Systems and Dedicated Codes

Modeling, analysis, and simulation are the main thrust areas of the Institute. A considerable expertise has been developed in the application of system identification methodology to model flight vehicles, be it a conventional civil or military aircraft, a highly augmented aircraft flying at high angles of attack, a rotorcraft or a missile. Similarly, data analysis and simulations incorporating wind tunnel predicted, flight identified or generic databases are integral parts of the research work. The powerful and validated software tools developed in the Institute for each of these tasks form the backbone of the various applications.

ESTIMA – A Modular System of Algorithms for Parameter Estimation

System identification involves analyzing complex multiple input/multiple output (MIMO) dynamic systems and a large amount of flight data. The advanced methods of parameter estimation, like filter error method and extended Kalman filter, are necessary besides the classical output error and Least Squares methods. Efficient implementation of computational aspects such as state estimation, optimization, and gradients is important, see Fig. 16. Flexibility to handle general nonlinear retarded systems and a wide variety of algorithms is a pre-requisite to cover the broad spectrum of applications, see chapter 5.

The dedicated software tool ESTIMA, a modular system of algorithms for parameter estimation, has evolved over the time and caters for:

- Linear and general nonlinear retarded systems,
- Optimized processing of large amount of flight data (up to 80000 data points from 80 flight maneuvers),
- Complex dynamic systems with large number of state, control input, and output variables,
- Wide variety of gradient and non gradient optimization methods (Gauss-Newton, Levenberg-Marquardt, Simplex, Subplex, Extrem, Quasi-Newton, Conjugate gradient etc.),
- Various integration methods to suit different types of non stiff and stiff dynamic systems, and
- Hybridization of integration and optimization methods.

The modular software provides a common environment having a uniform structure and a single set of peripheral support, like reading of flight data, generating outputs from estimation program, plot routines, statistical error analysis etc. for the various modes of operation. ESTIMA has been developed using standard FORTRAN 77 language and is currently implemented under VMS and UNIX operating systems. It is contemplated to extend the scope of this software to optimization with simple bounds and to cater for batch mode operation as well as having a graphical surface for user interaction and display of estimation results [13, 14, 15].

RAPID – Modeling and Analysis with Local Model Networks

Identification of nonlinear physical models presents many problems since both model structure and parameters must be determined. For several applications, like calibration of air data sensing systems or control of combustion plants, it is too costly and time-consuming to deduce possible model structures from engineering knowledge of the system. The software tool RAPID realizes the concept of local model networks by using locally defined partial models to approximate an unknown non-linear function. The structure of the model network is not determined a priori, but results from successive subdivision of the input area into hyper-rectangles. A smooth transition between the local models is achieved by the fuzzy approach of Takagi and Sugeno. For easy user interactions, a OSF/Motif-based graphical user interface and sophisticated visualization modules are designed [16].
PENSUM – Parameter Estimation of Nonlinear Systems Using MATLAB

Recently, more and more research work at the Institute is done using the MATLAB language. In addition, there is renewed interest in frequency domain identification, mainly in the handling qualities research area. Therefore, a toolbox PENSUM was developed which implements Maximum Likelihood parameter estimation method and caters to general nonlinear and linear models written in MATLAB/Simulink. PENSUM works similar to the software package ESTIMA and currently implements the

- Output error method and
- Gauss-Newton optimization.

In addition to handling nonlinear systems in the time domain, PENSUM also allows identification of linear systems in both the time and frequency domain. The linear systems are implemented as MATLAB state space linear time invariant systems and handled using routines from the Control System Toolbox.

DIVA – Dialog Program for Interactive Data Analysis

DIVA is a tool for flight data analysis in the time domain as well as in the frequency domain. The graphical interface OSF/Motif allowed the creation of a common version - XDIVA - for different operating systems. For making it platform independent, a new data format, the so-called Institute’s Standard IS3 was introduced, based on the Common Data Format (CDF) of NASA, and with direct access to the data. The dialogue of XDIVA is written in C, the computing is done with FORTRAN programs called from C, and the graphics system is GINO-F.

The main features of DIVA in the time and frequency domain are:

- Quick look plots,
- Time history plots
- One and two dimensional classification,
- Auto and cross correlation functions,
- Linear regression,
- Spectral analysis,
- Frequency response and coherence functions,
- Transfer function approximation,
- Handling qualities analysis, and
- Multiple input/multiple output (MIMO) analysis.

Besides these main features, DIVA contains Utilities for data pre-processing and generation, and a plot program with free layout. Outside DLR, XDIVA is used by DaimlerChrysler Aerospace and by the integrated team member WTD 61 at Manching [17].

eXpert – A Data Bank for Support of Flight Data Analysis and Parameter Estimation

The program eXpert is a support tool specially developed for the management of large amounts of maneuver related information and the results of system identification. Other additional features such as plotting are also included. It offers various modules to create, manage, and visualize data from the system identification process. The main modules are:

- Database for flight maneuvers (trim conditions, type of inputs, classification of maneuvers, flight data file details, etc.),
- Database for collation of parameter estimation results,
- Automatic generation of input data files compatible with ESTIMA,
- Generation, comparison, and plotting of aerodynamic database in tables from flight identified parameters,
- Convergence plots of parameter estimates to visualize the iteration progress, and
- Online documentation.

eXpert frees the user from routine work. It works under the operating system VMS on an Alpha-station. The data bank uses the DEC-Rdb server and is written in the programming languages C, FORTRAN, and SQL. The graphical user interface is based on the OSF/Motif widget set, plotting is done with GINO-F, and the online documentation is available in HTML.

Outlook

System identification will play an ever-increasing role in the sophisticated complex of modeling and simulation (M&S) during the flight vehicle design and evaluation phases. The integrated utilization of system identification tools and expertise will provide ultimate answers to unmasking the modeling deficiencies, reducing developmental risks, and improving flight safety issues. It appears that the present challenge to flight vehicle system identification may be formulated as to determine a high-fidelity aerodynamic model of high performance, highly augmented vehicles valid over the entire operational envelope.
Such a global model is, in general, of unknown structure, highly nonlinear, and affected by elastic structure, unsteady aerodynamics, and erroneous air data measurements. It is evident from this retrospective that the Institute has been in the forefront of the development in this field and is in a position to face the current and future challenges of flight vehicle system identification.

List of References


