TWENTY FIRST EUROPEAN ROTORCRAFT FORUM

Paper No VII-7

IDENTIFICATION OF EXTENDED MODELS FROM BO 105 FLIGHT TEST DATA FOR HOVER FLIGHT CONDITION

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August 30 - September 1, 1995
SAINT-PETERSBURG, RUSSIA

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Abstract

Mathematical models for the dynamics of the DLR BO 105 helicopter are extracted from hover flight test data using system identification approaches. The flight tests are characterized. Using a common data base CERT/ONERA and DLR jointly evaluated the flight tests, applying their individual techniques. Data consistency analyses showed that velocity measurements were not suited and the required data reconstruction is discussed in detail. Identification results obtained for conventional 6 degrees of freedom (DOF) rigid body models and 9 DOF higher order models with rotor DOF are presented and compared, and the favourable agreement of the individual results with the flight data is shown. The suitability of the identified higher order model for applications like the design of high bandwidth control systems is demonstrated.

Introduction

In the past, the DLR Institute of Flight Mechanics spent much effort on the development of accurate flight mechanics models using system identification techniques. To support the control system design for the DLR BO 105 In-Flight Simulator ATTHeS, main emphasis has been placed on the medium speed range of about 80 knots. The reliability of the identified models was convincingly demonstrated by the high accuracy of the model following control system of the in-flight simulation.

For the extension of the ATTHeS simulation range, reliable models for the low speed and hover flight condition were needed. In addition, these models are also required to improve the analytical simulation and to support handling qualities assessment. Therefore, flight tests particularly designed for system identification purposes were conducted. A major part of the data evaluation and the definition and determination of the flight mechanical models was performed as a joint effort from the DLR Institut für Flugmechanik in Braunschweig, Germany and the CERT Département d'Etudes et de Recherches en Automatique in Toulouse, France (Refs. 1,2). This common work is based on the ONERA/DLR cooperation *Smart Helicopter Concept, Helicopter Handling Qualities in Hover/Low Speed*, which was started by midst of 1992. Its overall objective is to provide contributions to helicopter operations close to the ground in adverse weather conditions for a variety of helicopter operations. To approach this complex objective, two subsequent phases with different areas of main emphasis were defined. In Phase 1: Determine and evaluate vehicle characteristics by concentrating on helicopter handling qualities and then, in Phase 2: include pilot behaviour to investigate pilot-helicopter interfaces. During the last two years, activities were mainly related to the Phase 1 and concentrated on two major tasks:

- Development of mathematical models for control law design and piloted simulation purposes by 1) comparison and improvement of analytical nonlinear helicopter models (simulation codes) and 2) application of system identification techniques for the extraction of derivative models from flight test data.
- Specification of handling qualities requirements as design guide for control law development.

The paper concentrates on the common efforts under the system identification subtask. It first introduces the system identification principle and the applied approaches. Then, flight tests, data processing, and data reliability analyses are addressed. For the identification, models with different complexity were determined. Starting with conventional 6 DOF rigid body models, the model order was increased by including rotor degrees of freedom for a more suitable representation of the main rotor characteristics. The obtained results are presented and discussed in detail. Finally, main conclusions are summarized and an outlook for the continuation of the French/German cooperation is given.

Principle of System Identification

The general approach used in aircraft system identification is shown in Figure 1. In flight tests, specific control input signals are used to excite the aircraft modes of interest. The control inputs and the aircraft response are measured and recorded. To check the quality of the measurements, compatibility analyses are applied. They make use of data redundancies and range from comparisons of similar variables up to the evaluation of the kinematic relationship between measured variables. The obtained results are needed for correcting the measurements by removing scale factor and offset errors (data de-trending) and/or for reconstructing time histories of non-measured or inaccurately measured variables. For the identification step, the aircraft dynamics are modelled by a set of differential equations describing the external forces and moments in terms of accelerations, state and control variables, where the coefficients are the stability and control derivatives. The objective of the identification is to determine these coefficients and to provide an accurate mathematical model for the aircraft dynamics. Using the measured pilot control inputs, the response of the mathematical model is calculated and compared to the measured aircraft response. The response differences are then minimized by the identification algorithm that iteratively adjusts the model parameters. For the definition of the minimum or the best 'curve fit' several criteria can be applied. For aircraft identification, the Maximum Likelihood criterion is often used and seems to be best suited for the application. Generally, the parameter estimation can be formulated in the time-domain format, where the time history differences between the measured and the model response are minimized or in the frequency domain format, where FFT transformed variables are used instead of time histories. Both approaches have their own characteristics. They have both successfully been applied for rotorcraft identification and various factors determine, which one is more suited for a particular evaluation.

To define and execute a successful experiment for system identification, the following so-called **'Quad-M'**-requirements must carefully be investigated from a physical standpoint:

- The **M**aneuver of the helicopter must provide as much information as possible about the dynamics of the aircraft. It implies the development of appropriate input signals, optimized in their spectral composition, but still flyable by the pilot.
- Reliable **M**easurements are indispensable as system identification is based on the input/output relationship of the vehicle motion. Measurement inaccuracies, that cannot be corrected or compensated, lead to biased estimation results.
- The definition of the **M**odel structure is a key element. Depending on the intended purpose, often high order rotorcraft models are needed and a practical comprise between model accuracy, flight testing efforts, measurement requirements, data processing, and system identifiability must be found.
- Suitable identification **M**ethods are required for both, data quality analysis and parameter identification. Here, various techniques of different complexity and performance, working in the time or frequency domain are available.

Flight Tests for System Identification

Independently from the actually applied technique, system identification approaches always rely on the information content about the system under test provided by the amplitude and phase relationship between the measured control inputs and the resulting measured system response. Therefore, the test input is one of the major factors influencing the accuracy with which the model parameters can be determined. There are a few standard input signals, which are widely applied for aircraft system identification, like doublets, multi-step '3211' inputs, and frequency sweeps. The 'ideal' approach for pilot flown tests is: (1) establish trim for the selected flight condition, (2) generate a prescribed input in one single control and avoid coupling into other controls, and (3) at the end of the input signal let the aircraft respond without further control activity. Such tests are flown for each control variable and, if possible, they are repeated to provide data redundancy. Each test run should last at least 25 to 30 seconds and the response amplitudes should stay within the small perturbation assumptions of linear derivative models.

Most of the previous BO 105 rotorcraft identification work was concentrated on the medium speed range of about 60 to 80 knots (Refs. 3-5). At this flight condition the helicopter is less unstable and the flight tests could be conducted without any problems. It was relatively easy for the pilot to generate the desired inputs without any further control activity and without larger coupling between the control variables (Figure 2).

In hover and low speed flight condition the BO 105 helicopter has stronger coupled DOF and is highly unstable. Consequently, it was not possible to conduct the flight tests for system identification similarly to the test at 80 knots (Figure 3). It was already difficult to establish trim before beginning the test. Then, a few seconds after the input signal was started a diverging response in the lateral directional motion (roll and pitch) was seen. Although the pilot tried to reduce the roll response by a short pulse in the lateral control, he had to retrim the helicopter after about 14 seconds as the roll attitude had reached about 45 degrees and the yaw rate was more than 20 degrees/second, which exceeds the selected measurement range of the rate gyro. At the end of the test, after about 20 seconds, the BO 105 had almost made a full turn. As such flight test data are not suited for system identification, the pilot was asked to start the input signals as usually, but then to apply additional inputs on his own to keep the response within acceptable amplitudes of about 25 degrees deviation from trim. When the resulting control activity is compared to the desired input signal, it probably does not make sense to design optimized control inputs for the BO 105 in hover. It may be an alternative to ask an experienced pilot to excite the aircraft modes as good as possible taking also into account the constraints on the aircraft response given by system identification requirements.

All hover flight tests were flown with additional stabilizing pilot inputs. From a system identification view it is certainly not the desired way of flight testing, but it was considered as the best practical solution. However, the pilot inputs are now influenced by the aircraft response and it has to be checked very carefully to what extent the pilot is acting like a feedback control system. To avoid any output/input correlation problems and difficulties related to the so called closed loop identification, the pilot was asked to use step and pulse-type control inputs instead of continuous control motions, which can be more correlated to output variables. This approach proved to be very effective as an evaluation of the flight test data did not reveal any data correlation due to feedback influences.

Flight Test Data Reliability and State Reconstruction

Data quality and consistency are critically important to the identification. Excessively noisy or kinematically inconsistent data can lead to the identification of an incorrect model or can prevent convergence of the mostly iterative identification solutions. Preliminary checks of the data quality and consistency help to detect and eliminate error sources and can save much time and effort in the identification process. Unreliable measurements can be replaced by reconstructing data from other measured variables. Therefore, a detailed analysis of the flight test data accuracy was conducted.

As an example, the measured time histories for flapping and control angles of the individual rotor blades were first compared to each other to determine offset and scale factor corrections. Then, the measurements were transferred into the fixed body axis system. To verify the physical consistency of the obtained variables, the longitudinal and lateral flapping and coning angles were compared to the primary (on-axis) helicopter response, and the control variables derived from the blade control angle measurements were compared to the variables measured at the pilot position. The good agreement proved that the blade motions were accurately measured.

An approach, which has become standard in measurement quality checks, is the data consistency analysis. It is based on the kinematic relationship between redundant measured data, like rates and attitude angles or linear accelerations and velocities. For the BO 105 hover flight test data there was a perfect agreement for the calculated attitude angles (derived from measured rates) and the measured ones. However, as typical for helicopters, more difficulties were seen for the translational motion. The corresponding nonlinear differential equations for the relationship between linear accelerations and velocities are given by:

$$\dot{u} = a_x - g \sin\theta + rv - qw$$
$$\dot{v} = a_y + g \cos\theta \sin\phi + pw - ru$$
$$\dot{w} = a_z + g \cos\theta \cos\phi + qu - pv$$

In these equations, the linear accelerations and rates are taken from the measurements and treated as known 'control' inputs. For the attitude angles either measurements or calculated data obtained from the kinematic relationship between rates and attitudes are used. The integration of the differential equation system then yields calculated velocities as state variables, known as *reconstructed data*. They are compared to the measured data to correct for drift effects and initial condition errors in the integration and to determine scaling errors. Then, the analyst can decide to use either the (corrected) measured or the reconstructed data for the further evaluation. However, for the hover flight condition there are no measured velocities, unless the helicopter has a low airspeed system. The DLR BO 105 is equipped with a Helicopter Air Data System (HADS). In hover it is working within the rotor downwash and provides the longitudinal and lateral but not the vertical velocities. Therefore, the vertical velocity has to be calculated. To support this reconstruction and to avoid drifts effects, the measured height and its relation to the velocities was formulated as an additional equation:

$$\dot{h} = u \sin\theta - v \cos\theta \sin\phi - w \cos\theta \cos\phi$$

For the data consistency and reconstruction, both DLR and CERT applied their own time-domain Maximum Likelihood techniques, which allow use of nonlinear differential equations.

The measurements for the steady state forward velocity showed up to 9 meters/second for some tests. Although there was some wind when the tests were flown, the measured values were felt to be too large. During the data consistency checks, the velocity initial conditions were modified, and it was seen that they have a large influence on the time histories of the reconstructed data. For a flight test with a longitudinal control input Figure 4 compares the measurements to the reconstructed velocities for three different initial conditions of the velocities: 1) they were assumed to be zero as for ideal hover, 2) they were fixed at the measured value and 3) the initial conditions and an associated offset in the measurement equations were identified. The figure illustrates that, except for the offsets, the obtained time histories for the forward velocity are similar and in good agreement with the measured variable. However, larger differences are seen for the lateral speed component and particularly for the vertical velocity. For the selection of the 'right' data, the comparison with the measured height proves that the initial conditions and associated time histories obtained from the identification agree best with the flight data. It also demonstrates the need for the height information for the velocity reconstruction when no vertical velocity measurements are available. It was then decided to use the reconstructed data instead of the measured ones, because of the high quality of linear acceleration data and angular measurements. However, it remains an uncertainty on the air data accuracy and the strong conclusion, that more accurate and reliable velocity information is required for future flight tests.

Identification Techniques

Both, DLR and ONERA/CERT have developed and applied their own identification software, relying mainly on two extensive identification methods:

- A Maximum Likelihood output error method, working in the time-domain.

  The linear aircraft model is given by:

  $$\dot{x}(t) = A * x(t) + B * u(t) + b_x$$
  $$y(t) = C * x(t) + D * u(t) + b_y$$

  with state vector x, control vector u, and measurement vector y.

  The identification method minimizes the differences between the measured time histories and the model response by adjusting the model parameters in the state and control matrices A and B and the measurement matrices C and D. The Maximum Likelihood criterion is used as cost function. It is possible to identify nonlinear models. This approach has been used frequently and successfully in aircraft system identification, in particular for fixed-wing aircraft. However, in contrast to conventional fixed-wing aircraft, helicopters have strongly coupled degrees of freedom and are unstable in many flight conditions. It complicates the application of time-domain methods for two reasons: 1) in addition to the model parameters, the so-called bias vectors b_x and b_y have to be estimated to compensate for drift, offset, and initial condition errors due to measurement inaccuracies. When higher order models and concatenated runs are used, it drastically increases the numbers of unknowns, 2) after each iteration the time histories of the model response are calculated by numerical integration techniques. For an unstable system the integration can diverge and may even not be possible at all for the required run length.

- A Maximum Likelihood output error method, working in the frequency-domain.

  The above given model is transferred to the frequency domain:

  $$j\omega * x(\omega) = A * x(\omega) + B * u(\omega)$$
  $$y(\omega) = C * x(\omega) + D * u(\omega)$$

  Here, $x(\omega)$, $u(\omega)$, and $y(\omega)$ are the Fourier transformed variables. The transformation assumes periodic signals, i.e. $x(0)=x(T)$. As this is mostly not true for flight test data, correction terms are applied. The estimation algorithm adjusts the unknown coefficients in the matrices A, B, C, and D to determine the best possible agreement between the model response frequency spectra and the measured ones. It should be noted that the coefficients still have the same physical definition as in the time-domain formulation. In this sense, the frequency-domain identification approach can be considered as a transformation of the time-domain identification procedure into the frequency domain. However, there are several distinct advantages for rotorcraft identification. The two most important ones are: 1) only the model parameters are estimated, there are no bias terms. (corrections terms for non periodic signals are extracted from the data and treated as known parameters), 2) as no numerical integration is needed the estimation is not affected by model instabilities. Time histories can be obtained by an inverse Fourier Transformation.

For the evaluation of the hover flight test data both CERT and DLR applied their time-domain techniques for the data consistency analysis. For this task they are ideally suited as 1) nonlinear equations can be evaluated, 2) no small perturbation assumptions have to be met and 3) the actual measurements are used without subtracting steady state condition. For the identification of the helicopter derivative models the time-domain methods was successfully applied for 6 DOF rigid body models. However, when higher order models with rotor DOF had to be determined, these techniques showed an increasing sensitivity with respect to the number of unknowns and the dynamic instability of the helicopter mathematical model. As consequence, it was hard and time consuming to reach convergence of the estimation process. Therefore, most results were generated by the frequency-domain methods. Some comparisons with results from the time-domain approach showed similar identified parameter values.

Discussion of Identification Results

Based on the results from the data consistency checks four runs were selected as common data base for the identification. The time histories of the control inputs are given in Figure 5.

Rigid Body Models

First, 6 DOF models were determined. They are based on the assumption that the rotor dynamics are at much higher frequencies than the body modes and can be neglected. In consequence, the model cannot represent the rotor phase delay and predicts an immediate body acceleration response due to control inputs. When compared to flight data it is seen that the model response leads the real helicopter response. A more realistic model response can only be obtained when the rotor dynamic effects are approximated by equivalent time delays for the main rotor control inputs. This approach is usually used for system identification, where the time delays are either given or, with frequency-domain methods, treated as unknowns and estimated. Such conventional 6 DOF models are adequate, when equivalent time delays are applicable and when less accuracy in the high frequency range (from about 2 Hz for the BO 105) can be tolerated, e.g. for handling qualities evaluations.

The model structures and the results for the identification of 6 DOF models were quite similar for DLR and CERT. Figure 6 compares the measured data with the model response. It is clearly seen that in general a good agreement was obtained, although there are still some remaining smaller differences.

Extended Models

When time delays cannot be used or more accuracy is required for the higher frequency range, higher order models with rotor DOF are required. This is particularly true for applications like high bandwidth control-system design. As example, during the development of the model following control system of the DLR In-Flight Simulator BO 105 ATTHeS, it was clearly experienced that 6 DOF models are not appropriate. Therefore, higher order model structures with a realistic representation of the rotor dynamics were defined and the parameters were determined by system identification (Refs. 4 and 5). For the medium speed range, the obtained high simulation quality has confirmed the suitability of the approach (Refs. 6-8). When the operational range for the In-Flight Simulation was extended to hover and low speeds, higher order models were also needed for this speed range.

The principle approach for extending the 6 DOF model is illustrated in Figure 7. In the state vector, rotor states for longitudinal and lateral flapping and for coning are added to the rigid body motion variables, so that 9 DOF are considered. The rotor variables can be modelled as 1st or 2nd order differential equations leading to models between 11th and 14th order. For the identification of the rotor equations, measured rotor states are needed in the measurement vector to match the calculated rotor response of the model with the flight data. Therefore, the BO 105 rotor blades were instrumented with strain gauges at the location of the equivalent hinge offset to measure the blade flapping motion. The sensors were calibrated on the rotating blades under realistic conditions of airloads and centrifugal forces. The data were transferred by a multiblade coordinate transformation from the rotating to the fixed body axis system to obtain the tip plane motion in terms of longitudinal and lateral flapping and coning. As an example for the obtained data accuracy, Figure 8 shows the high correlation between the vertical acceleration and the coning angle (body fixed axis system) for collective inputs. The low noise level on the tip path plane variables also verifies the reliability of the blade flapping calibration.

For the identification of an extended model, both CERT and DLR worked with different model structures, ranging from 11th to 14th order. Based on the obtained results, it was concluded that a model of 12th order is appropriate, with a 1st order rotor longitudinal and lateral flapping and 2nd order rotor coning. Then, the state vector is:

$$x^T = (u,\ v,\ w,\ p,\ q,\ r,\ \Phi,\ \Theta,\ a_1,\ b_1,\ \dot{a}_0,\ a_0)$$

The common data set as already shown in Figures 5 and 6 was used for the identification. As an example for the identification of the rotor dynamics, a 14 seconds data segment with both, longitudinal and lateral control inputs is given in Figure 9. For the flapping variables it presents the time histories of the measured data and the two models identified by CERT and DLR. It is seen that there are only minor differences between the two model responses and that there is a good agreement with the flight data.

The comparison of the rigid body roll and pitch rates is shown by Figures 10 and 11 for two different data runs with mainly a longitudinal or lateral stick control input. Again, flight measurements and the two models responses are given. Like for the above discussed flapping response, the time histories obtained from the CERT and DLR identified models are almost the same. In general they also agree satisfactorily with the flight data. This is in particular true for the roll rate response, whereas for the pitch rate most of the amplitude peaks cannot always fully be matched. A similar result was already seen in the evaluation of flight data from the medium speed range. As the models accurately describe the rotor motion, it seems that the discrepancies are mainly caused by the higher influence of the fuselage on the longitudinal motion than on the lateral response.

Comparison of 6 and 9 DOF Models

The comparison of the identification results obtained from the conventional 6 DOF model and the higher order 9 DOF model showed:

- For the 6 DOF model equivalent time delays for the controls were needed to approximate the main rotor dynamics. They are between 40 and 80 milliseconds and cannot be neglected. In the higher order model the rotor dynamics are represented by additional DOF. When equivalent time delays for the controls were also estimated in these models, small values of less then 10 ms were obtained for the main rotor controls. As they can be neglected, such models are appropriate for applications like the control system design for In-Flight Simulation, which will be addressed below.

- A representative comparison of the responses of the two models and the flight test data is illustrated in Figure 12. There is a slightly better agreement between the measurements and the 9 DOF model response, particularly for the higher frequencies. But the improvement is not as significant as expected. Additional evaluations with different complexity in the model order (e.g. with 2nd order blade flapping or with inflow DOF) also showed similar results. A further improvement can probably be obtained, when additional DOF are included in the model, like the dynamics of the engine or the hydraulic system. However, it requires high efforts in instrumentation and measurements, definition of suitable model structures, and the identification itself (Ref. 9). The complexity of the selected approach certainly depends on the objectives and the requirements of the specific application. Presently, the obtained identified models are mainly used at ONERA and DLR for handling qualities investigations and control system design. In particular for in-flight simulation, where accurate high bandwidth models are required, good results were reached with the available models. Consequently, it was concluded, that these models are appropriate and no further extension to more complex models is planned for the near future.

Comparison of Derivatives and Eigenvalues

For comparison, Table 1 gives the major derivatives for the 6 and 9 DOF models, identified by CERT and DLR. Although there are some differences, which mainly result from slightly different models structures, a generally good agreement is seen. The eigenvalues of the models are presented by Figure 13. The results for the 6 DOF models in the right part of the figure confirm again that the two models are quite similar. The small difference for the roll motion is related to different roll damping derivatives L_p. This derivative is generally difficult to determine for the BO 105, as it is very sensitive to the equivalent time delay and, in addition, highly correlated to the control derivative 'roll rate due to lateral stick', $L_{\delta y}$. Both models also show the unstable phugoid mode, which had caused the problems in flight testing.

Considering the eigenvalues for the higher order models, it is clearly seen that the four modes associated with the low frequency rigid body motion are about the same as for the 6 DOF models: phugoid, spiral, pitch-1 and dutch roll. With rotor DOF in the model the remaining modes, roll and pitch-2, become oscillatory, representing the roll/flap and pitch/flap coupling. The coning mode is at higher frequencies with low damping. Again, the similarity of the CERT and DLR models is obvious.

Application of Extended Models

The identified models were mainly needed for the control-system design of the DLR In-Flight Simulators BO 105 ATTHeS. Its operation range was extended to hover and low speed flight conditions. The general concept for the explicit model following control system and a specific application for hover is illustrated in the block diagram in Figure 14. In the forward loop of the control system the pilot 'flies' the model to be simulated. The output of this command model are the desired state variables of the host helicopter response. They are fed to the feedforward controller, which is defined as the inverse model of the host aircraft and therefore, ideally, compensates the host aircraft dynamics. In consequence, the aircraft behaves like the prescribed command model, e.g. like a different helicopter. The feedback system mainly corrects for external disturbances. The performance of the control system highly depends on the accuracy of the host aircraft model used for the feedforward controller. It is obvious that models with time delays cannot be applied as the inverted model requires 'time lead', which is unrealistic for real time processes. Therefore, higher order models with rotor DOF and without time delays are required. They were defined and obtained from system identification results. Numerous flight tests with various command models and different objectives have confirmed the validity of the control system design for the ATTHeS In-Flight Simulator and the high accuracy of its feedforward controller [15].

The extension of the control system for a special task in the hover and low speed regime is given by the additional feedback loop in the upper part of the block diagram in Figure 14. An accurate position hold above a ground fixed or moving object under wind and gust conditions is of special interest, e.g. for rescue missions. Therefore, ATTHeS was equipped with an innovative measurement system for the hover position above a target. A video camera in combination with a computer for processing the optical information was used as an integrated sensor system for the measurement of the relative position of the aircraft to a target. Deviations from the target were evaluated and converted to command signals for the model following control system (MFCS). For the flight tests, a black square mounted on a car roof was used as target. The helicopter approached the car in a prescribed altitude with the MFCS engaged in Position Hold Off mode. When the camera was focused on the target, the Position Hold mode was engaged and the control system had to keep the helicopter above the target (left part of Figure 14) with constant altitude and heading. In this mode, the pilot flew hands off. Actually, he even could not see the car below the helicopter. In flight tests it was demonstrated that the helicopter stayed above the target and even followed the moving car successfully. Evaluations of flight tests with 8 minutes duration showed a maximum relative position error of about 3 m for the moving car and of about 1.5 m for the stopped car [10]. As a representative example, the Figure 14 gives the position error from a test run, when the car was driven in a full circle.

Conclusions

Based on the common effort from CERT/ONERA and DLR in evaluating BO 105 hover flight test data and applying system identification methods to extract derivative models, the following main conclusion are summarized:

Flight Tests and Data Reliability

- For system identification flight tests prescribed control inputs are used separately for the individual control axes to excite the aircraft modes. No further control inputs are applied. For the hover flight test, however, the dynamically unstable aircraft behaviour required additional stabilizing control inputs in all axes to keep the aircraft response within small perturbation assumptions. To avoid output/input correlations, it was tried to use pulse or step-type inputs. The data evaluation did not reveal correlations and confirmed the validity of this approach.

- Data compatibility showed excellent agreement between rates and angular measurements. Blade flapping measurements were accurate. They were transferred to body axes and provided an appropriate description of the main rotor tip path plane motion.

- A major problem area are air data measurements. For hover, the installed air data system provides lateral and horizontal velocities and static pressure. For operational use the data may be appropriate, for system identification they were considered as not suitable. Therefore the velocities were reconstructed using the kinematic relationship between accelerations and velocities. For the reconstruction of the non-measured vertical velocity, an additional equation for the height rate was very helpful. The data reconstruction proved to be highly sensitive to the velocity initial conditions, which also could not be taken accurately enough from the measurements. They were estimated by system identification techniques and a plausible and consistent set of velocity data was obtained. But there is still a remaining uncertainty on the reliability. In consequence, significantly more accurate air data measurements are required for future flight tests.

Identification Results

A conventional 6 DOF rigid body model and a 9 DOF model with main rotor flapping and coning DOF were identified. Results obtained from CERT and DLR were compared. Common conclusions are:

- Conventional 6 DOF models require equivalent time delays of about 40 and 80 milliseconds for the control variables to approximate the influence of the main rotor dynamics. As they cannot be neglected, an application of 6 DOF models is only advisable, when time delays can be accepted. For models with rotor DOF, like the 9 DOF model, time delays are small, eg. to compensate the influence of the hydraulics, and can usually be neglected. They represent the helicopter dynamics more accurately, in particular at higher frequencies.
- In comparison to the 6 DOF rigid body model, the response of the extended model shows slightly better agreement with the measured data. However, the improvement is less significant than expected. Comparisons of the eigenvalues of the identified models demonstrate that the higher order models have similar low frequency modes as the rigid body model and give realistic additional rotor modes. It indicates that the identification provides reliable results for the given model structure.
- CERT/ONERA and DLR generated identification results from a common flight test data base by applying their individual techniques. A comparison of the results showed good agreement and confirmed the reliability of the models.
- Identified models with rotor DOF were applied for the control law design of the DLR In-Flight Simulator BO 105 ATTHeS for hover and low speed flight conditions. In flight tests the quality of the model following control system was successfully demonstrates. It also confirms that the presently available models meet the requirements for high bandwidth control system design.

Outlook

It is planned to continue the German/French cooperation on the *Smart Helicopter* program for a three years time period starting in 1996. For the identification subtask, CERT and DLR will jointly evaluate flight test data from the CEV Dauphin 6075. The helicopter was instrumented and the first fight test were recently conducted. Like for the BO 105, the work is concentrated on the hover and low speed regime.

Acknowledgement

The CERT part of this work was supported by DRET (Direction des Recherches Etudes et Techniques)

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Derivatives	DLR 6 DOF	CERT 6 DOF	DLR 9 DOF	CERT 9 DOF
X_u	-.345	-0.338	-0.255	-0.307
Y_v	-0.131	-0.148	-0.164	-0.162
Z_w	-0.295	-0.251	-0.102	-0.179
L_p	-8.54	-10.89	-	-
L_q	2.42	2.38	0.33	0.52
M_u	0.0431	0.0583	0.028	0.014
M_w	0.051	0.059	0.01	-
M_p	-1.105	-1.9	-	-
M_q	-2.32	-1.79	-0.039	-
N_v	0.096	.066	0.055	0.049
N_r	-0.974	-1.10	-0.939	-0.938
$Z_{\delta col}$	-0.238	-0.23	-	-
$M_{\delta x}$	0.0719	0.0724	-	-
$L_{\delta y}$	0.171	0.196	-	-
$N_{\delta ped}$	0.0477	0.0474	0.043	0.045

Derivatives	DLR 9 DOF	CERT 9 DOF
$Z_{\beta 0}$	-155.5	-163.6
$L_{\beta s}$	-116.1	-100.5
$M_{\beta c}$	-28.4	-24.2
$L_{\beta c}$	-5.43	-10.09
$M_{\beta s}$	-3.02	-
βc_q	1.176	1.125
$\beta c_{\beta s} = -\beta s_{\beta c}$	2.35	1.87
$\beta s_{\beta s} = \beta c_{\beta c}$	-10.6	-10.2
βo_q	24.7	22.3
$\beta o_{\delta col}$	4.38	4.36
$\beta c_{\delta x}$	-0.032	-0.032
$\beta s_{\delta x}$	-0.0088	-0.0093
$\beta s_{\delta y}$	-0.015	-0.012

Table 1. Comparison of identified major derivatives for BO 105 in hover

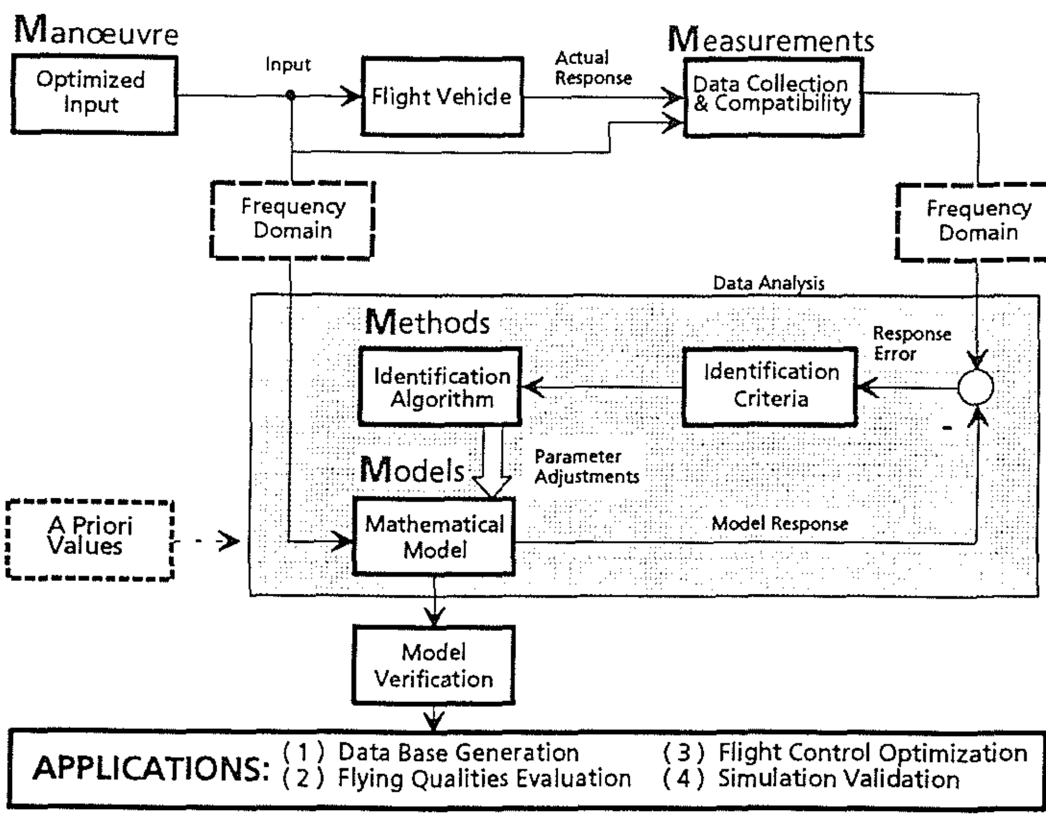

Figure 1. Principal approach for system identification

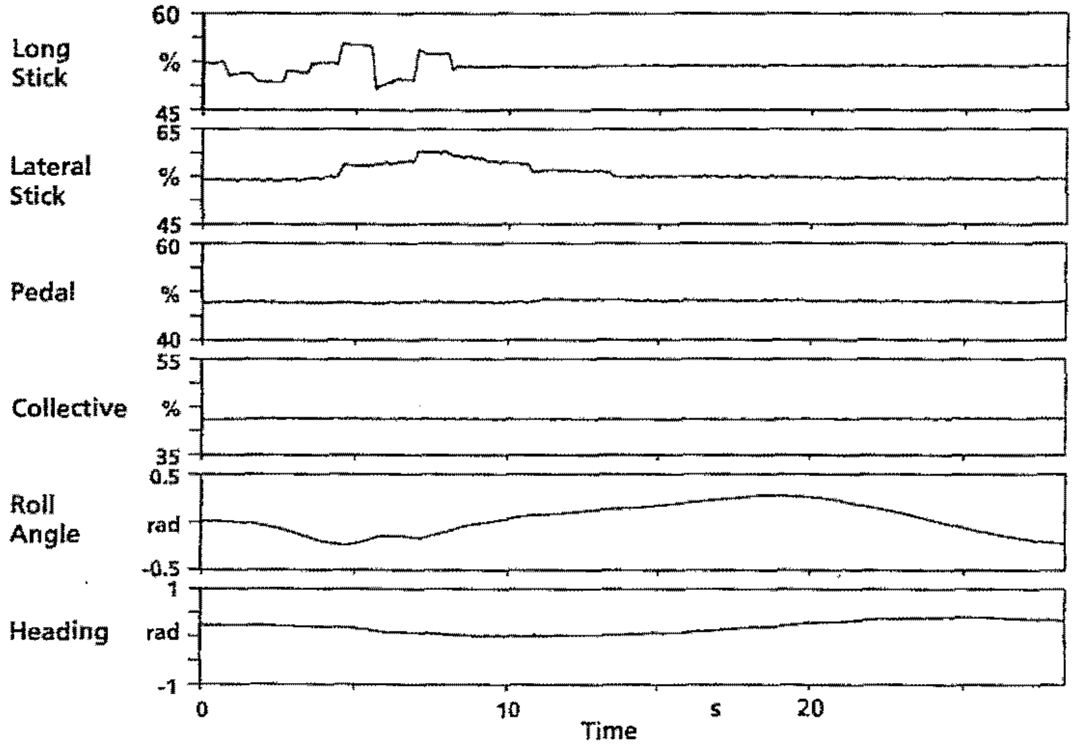

Figure 2. System identification control inputs for 80 knots flight condition and roll and heading response

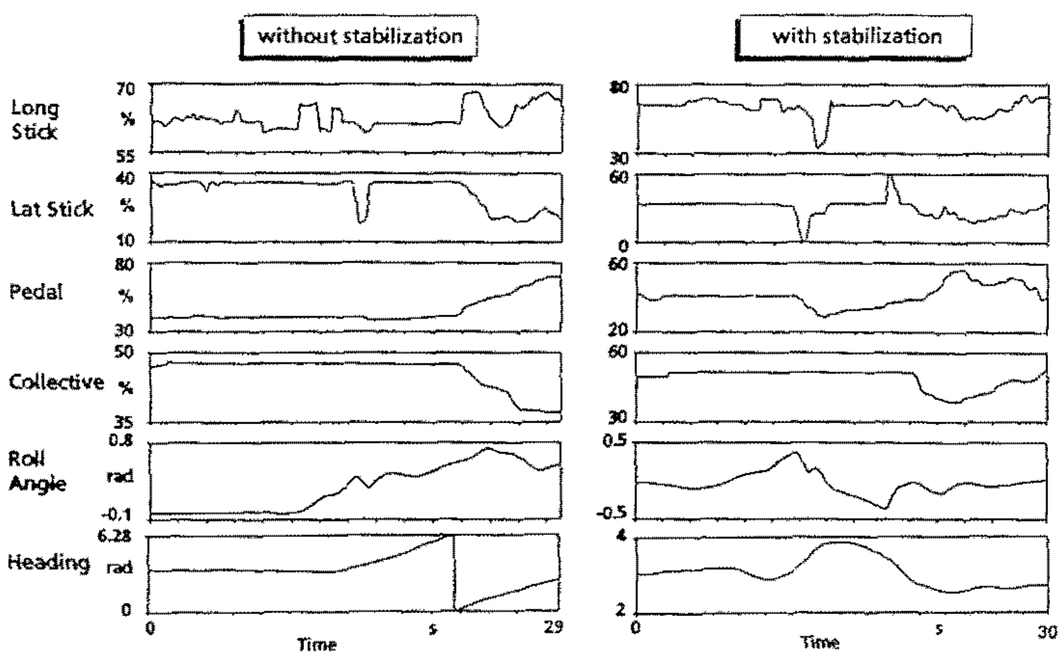

Figure 3. System identification control inputs for hover flight condition and roll and heading response. Flight tests without and with stabilization by the pilot

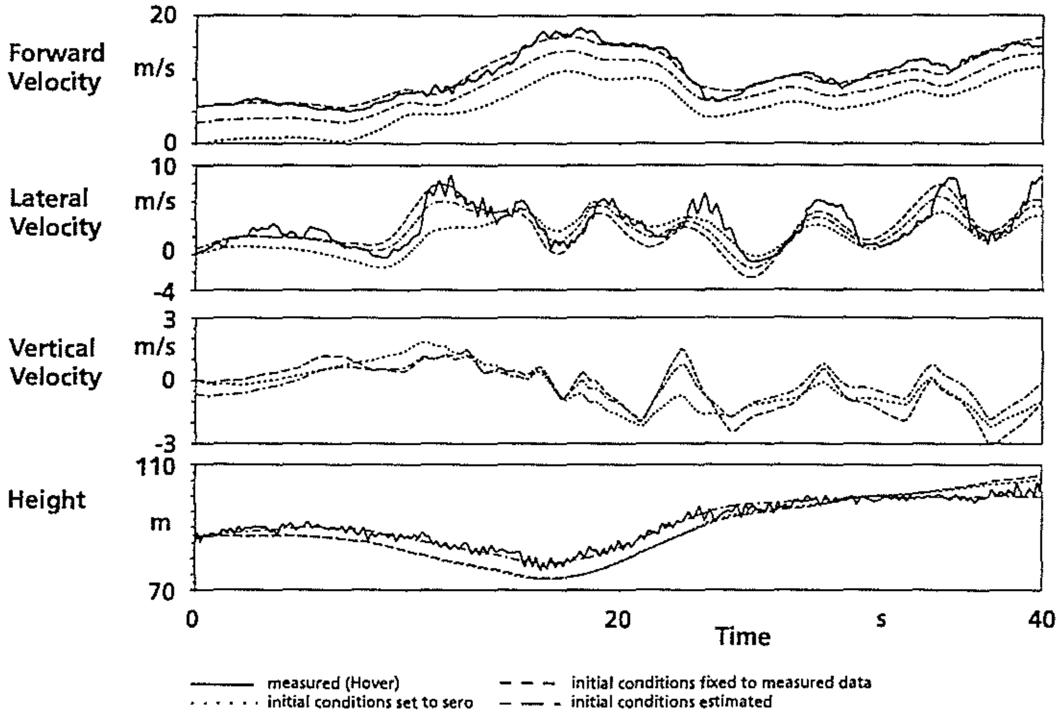

Figure 4. Velocity reconstruction and its sensitivity to initial conditions

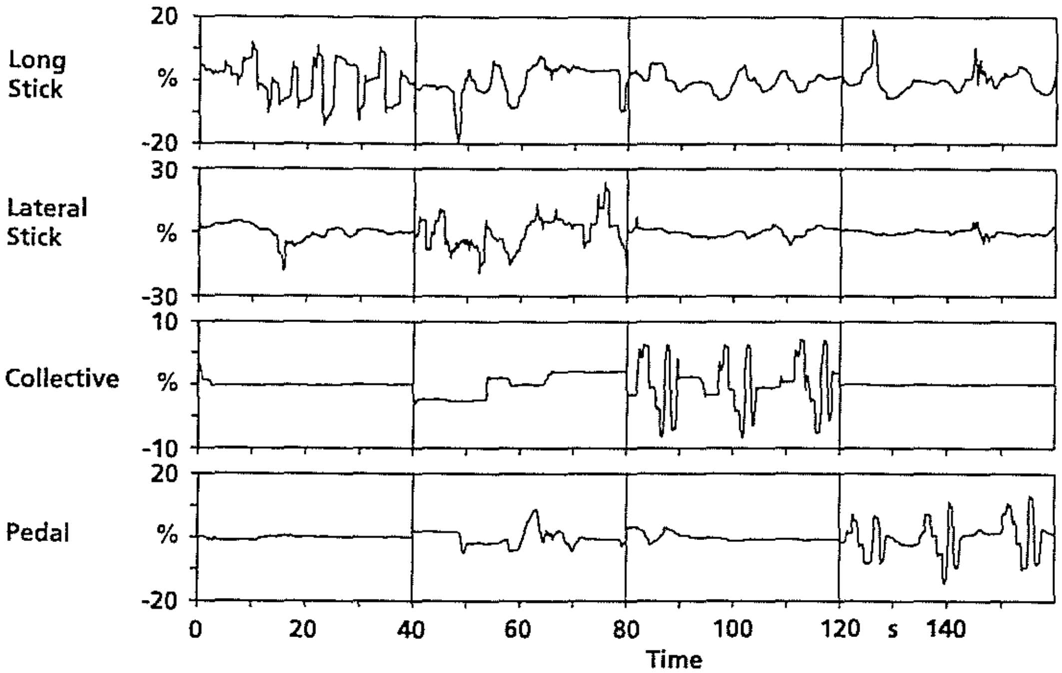

Figure 5. Control inputs of the common data set selected for the identification

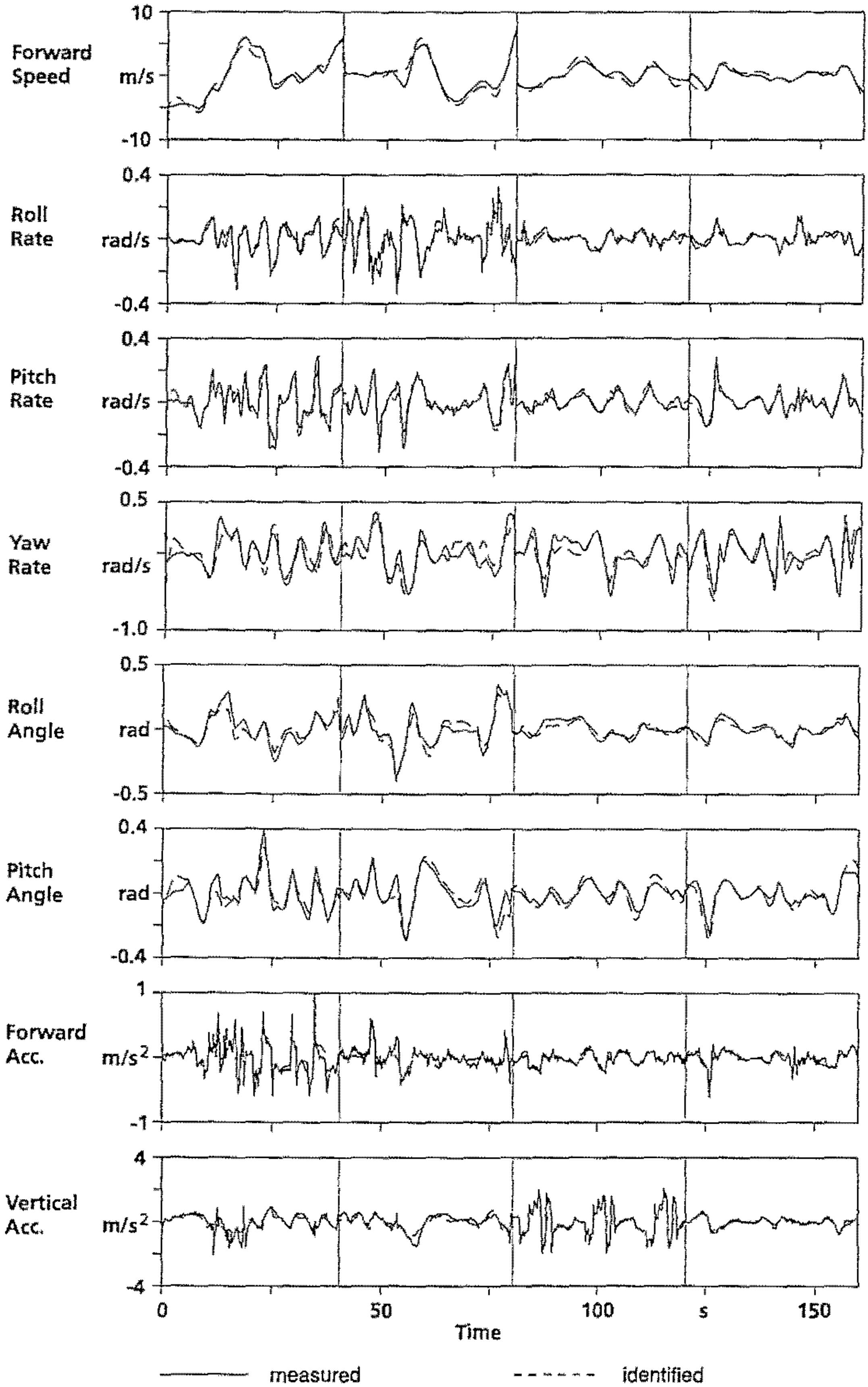

Figure 6. Identification result obtained from the 6 DOF model

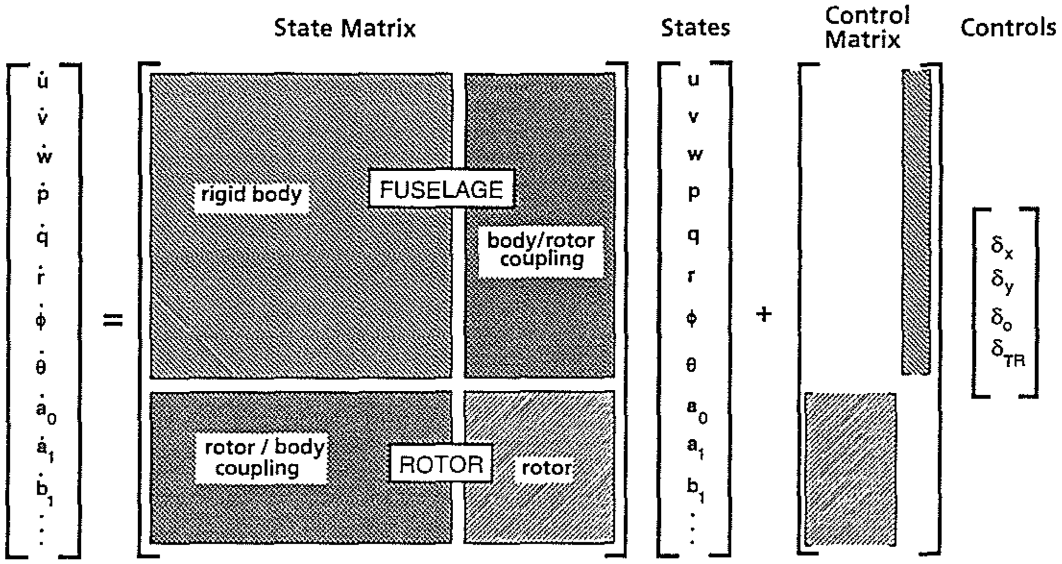

Figure 7. Principle of extended model structure

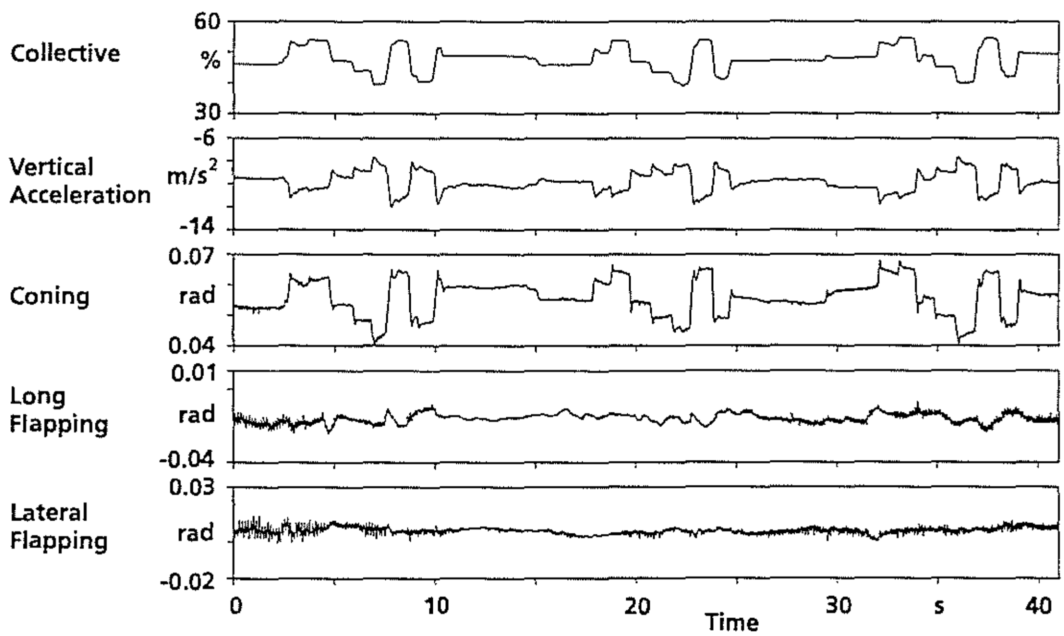

Figure 8. Rotor data quality check: measured rotor response due to collective inputs and correlation of the coning and vertical acceleration data

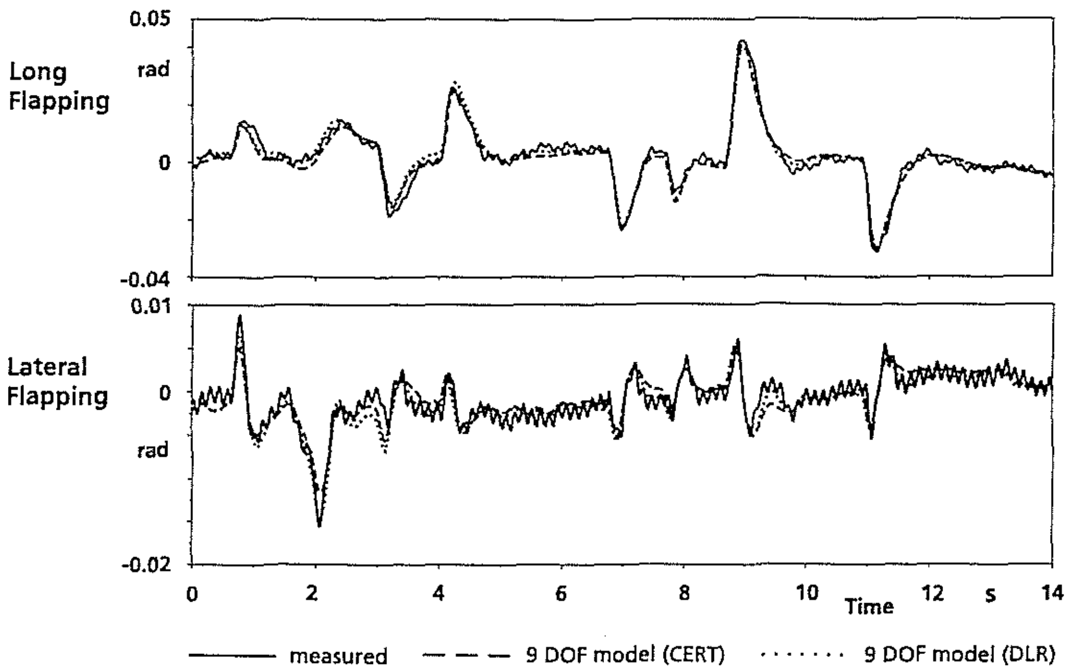

Figure 9. Comparison of the measured rotor response and the responses of the 9 DOF models identified by CERT and DLR for a representative data segment from the first data run shown in Figures 5 and 6 (from 14 to 28 seconds)

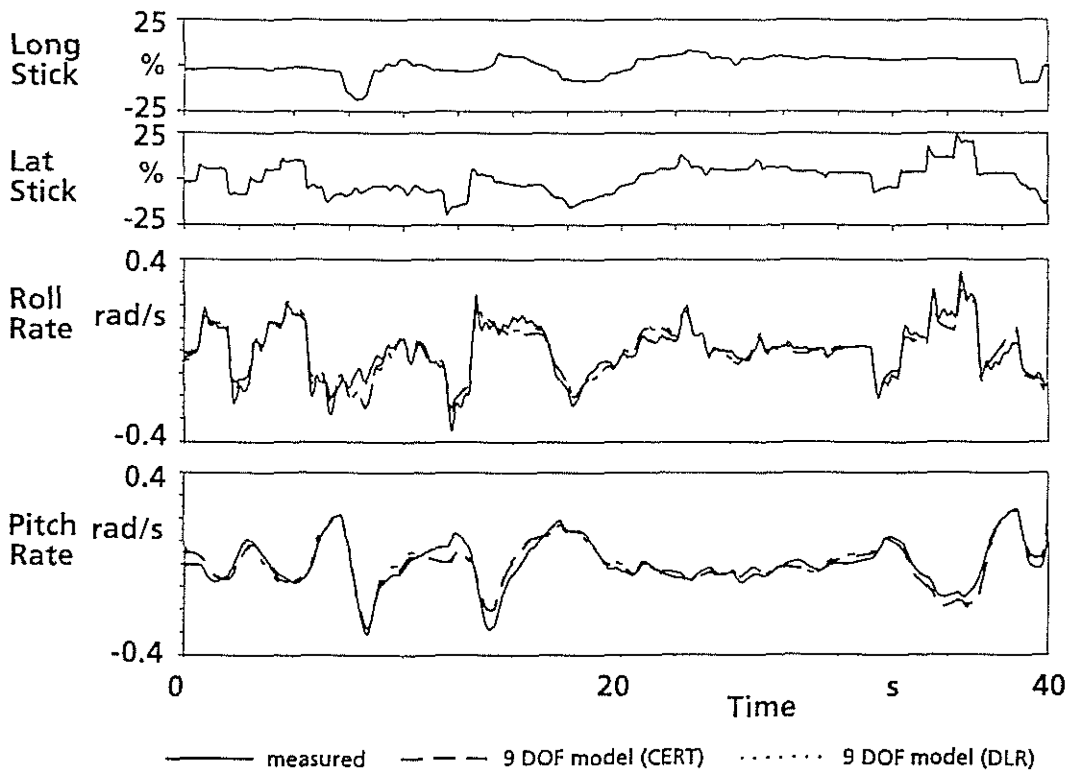

Figure 10. Comparison of the measured roll and pitch rates and the responses of the 9 DOF models identified by CERT and DLR for the first data run shown in Figures 5 and 6 (mainly lateral stick control inputs)

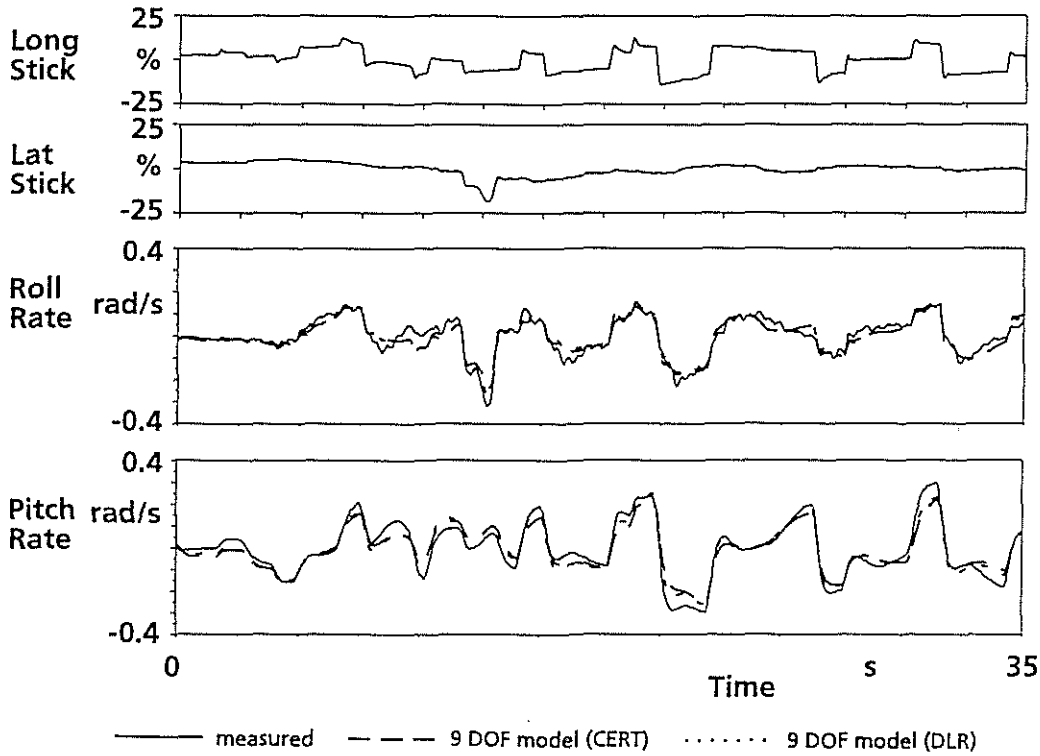

Figure 11. Comparison of the measured roll and pitch rates and the responses of the 9 DOF models identified by CERT and DLR for the second data run shown in Figures 5 and 6 (mainly longitudinal stick control inputs)

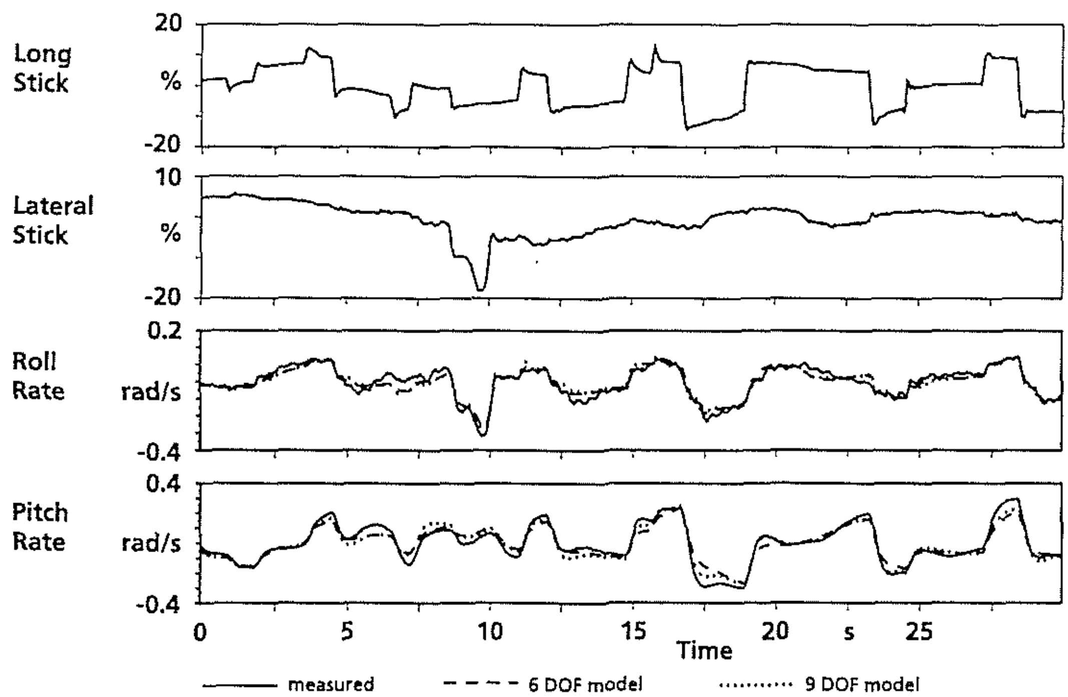

Figure 12. Comparison of the measured roll and pitch rates and the responses of the identified models with 6 and 9 DOF for the second data run with mainly longitudinal stick control inputs (flight data as in Figure 11)

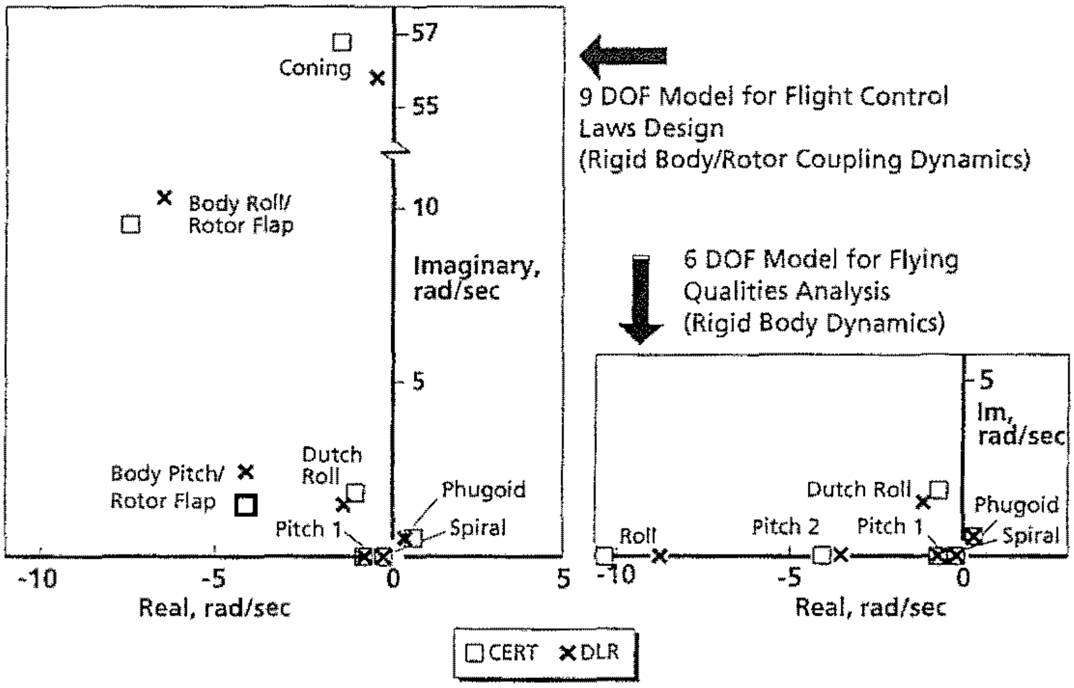

Figure 13. Comparison of poles from the 6 DOF and 9 DOF models identified by CERT and DLR

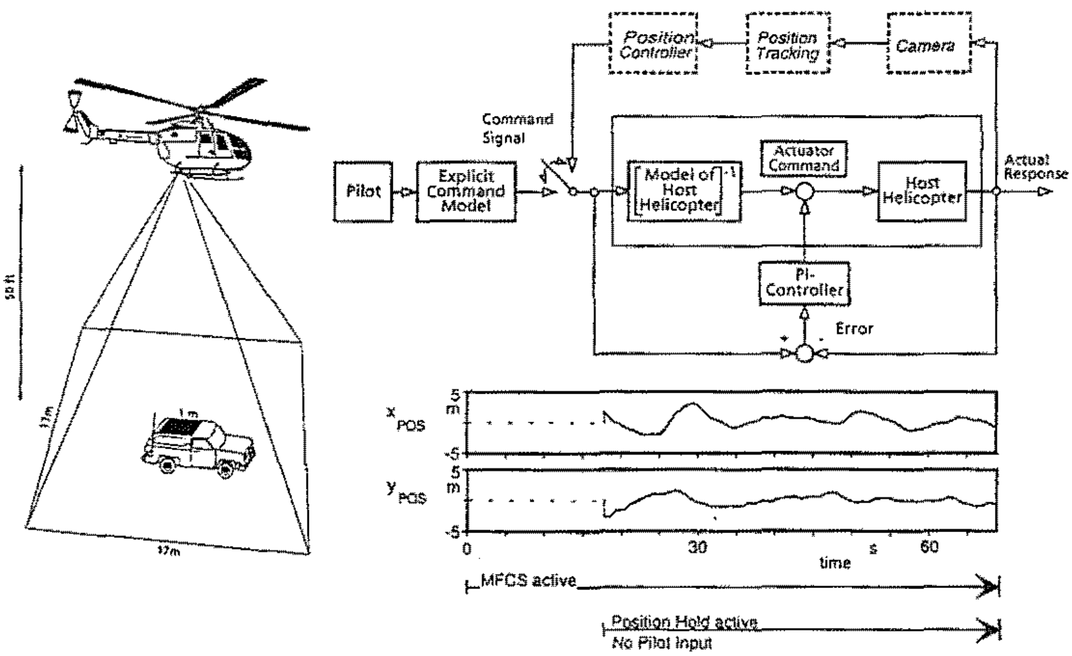

Figure 14. Application of the identified extended model for the control system design for In-Flight Simulation: Principle of In-Flight Simulation with additional feedback for an automatic position hold tracking task, Flight test set up, and results for a position hold over a car, moving in a full circle.