FREQUENCY-DOMAIN IDENTIFICATION OF BO 105 DERIVATIVE MODELS WITH ROTOR DEGREES OF FREEDOM

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Abstract

In general, helicopter linear state space models are formulated for the 6 degrees of freedom for the rigid body motion. Such models can adequately represent the low and mid frequency helicopter dynamics. However, when high-frequency validity is needed they show larger deficiencies because the main rotor dynamics are neglected. It is investigated if higher order models with rotor degrees of freedom can be determined from BO 105 flight test data by a system identification approach. A frequency-domain method was used to extract two different models of 10th and 14th order. The obtained results show that the extraction of extended helicopter models from measured rotor and rigid body data is feasible and provides a realistic description of the aircraft dynamics. The prediction capability of an identified model is demonstrated in verification results.

Introduction

System identification is broadly defined as the deduction of system characteristics from measured data. It provides the only possibility to extract parametric aircraft models (e.g. state space matrices) from flight test data and therefore gives a reliable characterization of the dynamics of the actually existing aircraft. Main applications of system identification are seen in areas where higher accuracies of the mathematical models are required: Simulation validation, control system design (in particular model-following control system design for in-flight simulation), and handling qualities.

A review of the present state of the art in rotorcraft system identification is given in [1]. In general, rigid body derivative models with six degrees of freedom are used. Here, the rotor dynamics are usually approximated by equivalent time delays. Such models can accurately describe helicopter dynamics in the low and mid frequency range (e.g. up to about 10 rad/sec for the BO 105). They are broadly applicable to many areas such as piloted-simulation, simulation validation, handling qualities, etc.. For a reliable description of the higher frequency range, however, extended models with explicit rotor degrees of freedom are required for a more realistic representation of the rotor dynamics. Such models are needed for high bandwidth flight control, and in particular for in-flight simulation.

To support the design of the model following control system (MFCS) for the DLR In-flight simulator BO 105 ATTHeS (**A**dvanced **T**echnology **T**esting **He**licopter **S**ystem) a first approach to identify an extended model from flight test data was made [2]. The obtained result proved to be very useful and clearly indicated the need for higher order models. However, an increasing model complexity with more degrees of freedom and a larger number of unknown parameters can drastically complicate the identification due to e.g. insufficient information content in the data. To investigate the feasibility of higher order model identification, a frequency-domain identification technique was used to determine different models from flight tests ranging from the conventional 6 degrees of freedom (DOF) rigid body model up to a 9 DOF, 14th order model including a second order flapping and coning representation of the rotor dynamics.

The paper first characterises the flight test data base and the frequency-domain identification method. Deficiencies of 6 DOF models are addressed. Then it is concentrated on the rotor blade measurements needed for the rotor identification. Results obtained from an 8 DOF, 10th order model and a 9 DOF, 14th order model are compared and discussed in detail. Finally, verification results are presented.

Flight Test Data Base

A flight test program was conducted on a DLR BO 105 helicopter to obtain data especially designed for system identification purposes. Trim configuration was steady state horizontal flight at 80 knots in a density altitude of about 3000 feet. The tests were flown in conditions of calm air. Having established trim the pilot gave a prescribed input signal to one of the controls. To help him generating the input, a CRT was installed in the cockpit that showed both, the desired signal and the actual control movement. Two basically different types of inputs were flown:

1. a modified multi-step 3211 signal with a total time length of 7 seconds. This signal, developed at DLR, excites a wide frequency band within a short time period. Therefore, it is also suited for slightly unstable systems when long duration tests cannot be flown without additional stabilization. Stabilization should be avoided as it can cause significant identification difficulties due to output/input correlations. At the end of the input signal the controls were kept constant until the pilot had to retrim the aircraft. Figure 1 first presents the 3211 input for the longitudinal stick and the helicopter response. During the excitation part (first 7 seconds) the roll rate follows the control, then the response is dominated by the aircraft modes. A comparison of the rate responses demonstrates the high coupling between the degrees of freedom.

2. frequency sweeps from about 0.8 Hz up to the highest frequency the pilot could generate (2 to 4 Hz, depending on the control). On the CRT the lowest frequency was shown as 'starting help'. Then the pilot progressively increased the frequency on his own. Total time length of the sweeps was about 50 seconds, followed by the retrim of the aircraft to the initial steady state condition. Using the same vertical scale as for the 3211 input data Figure 2 shows a typical frequency sweep for the longitudinal stick. Again, the strong coupling into the other rates is evident.

Within one test run only one control was used to excite the on-axis response and to avoid correlation with other controls. Because of the long time duration of the frequency sweeps, these tests required some stabilization by the pilot to keep the aircraft response within the limits of small perturbation assumptions for linear mathematical models.

This paper presents identification results obtained from 3211 inputs. The frequency sweep data were used for the model verification.

Measurements used for system identification included body angular rates, linear accelerations, attitude angles, speed components, blade flapping, rotor azimuth, and control inputs at the pilot's stick and rotor blade. They were mainly obtained from conventional sensors: rate and vertical gyros, accelerometers located close to the CG, and potentiometers at the pilot controls. Speed was measured by a HADS air data system, using a swiveling pitot static probe located below the main rotor. Each rotor blade was instrumented with a pair of strain gauges at the equivalent hinge offset to measure blade flapping. Potentiometers provided the blade control angles from two blades and a saw-tooth potentiometer gave the rotor azimuth signal. All data were sampled and recorded on board of the helicopter. As identification results are extremely sensitive to phase shift errors, emphasis was placed on the removal of analogue (anti-aliasing) filters. To avoid aliasing errors, flight tests were conducted to define appropriate high sampling rates.

The BO 105 instrumentation and signal conditioning are described in more detail in [3].

Data Processing and Reliability analysis

Main data processing steps were

1. data conversion to a unique sampling rate of 100 Hz,
2. measurement corrections for to the aircraft CG position,
3. rotor tip path plane calculation, and
4. digital filtering to remove high frequency noise.

An absolute prerequisite for reliable system identification results is a high accuracy in the flight data measurements. Therefore, the data compatibility was first analysed during the flight tests using a fast Least Squares technique to immediately detect data errors. A more detailed data accuracy check was conducted after the tests.

Selected test data (except for the rotor data) were also provided as a data base for the AGARD Working Group WG 18 on *Rotorcraft System Identification*. The Group first concentrated on a data quality analysis before applying the measurements for the identification of 6 DOF models. As a contribution to the WG and in conjunction with the US/German Memorandum of Understanding (MOU) on "Helicopter Flight Control" the US Army conducted a comprehensive study on the BO 105 data compatibility and reconstruction [6]. In general, the data were found to be excellently applicable for system identification. Typical for helicopters, the airdata measurement problem became again obvious: linear velocity measurements either needed scale factor corrections or the use of reconstructed data was recommended.

Frequency-Domain Identification Technique

DLR has gained extensive experience with a time-domain Maximum-Likelihood technique applied to both, fixed wing and rotary wing aircraft for the identification of linear and non-linear models. Rotorcraft identification mainly concentrated on the BO 105 helicopter to support DLR research work [2], [4]. Further applications were associated with the XV-15 tilt rotor [5] and, within the AGARD WG, with PUMA and AH-64. The time-domain method has often proved to be a powerful technique and excellently applicable for the extraction of state space models from flight test data. This experience is based on the determination of models with up to 6 DOF. With increasing model order, however, time-domain techniques encounter some difficulties that can limit their applicability. For helicopter models with rigid body and rotor DOF, identification problems can be caused by:

1. large frequency range of the eigenvalues,

   - unless specific explicit weighting is applied, time-domain methods provide higher weighting of the lower frequencies which can degrade the identification of the high frequency eigenvalues (rotor).

   - the time duration of a data record is determined by the lowest eigenvalue whereas the required sampling rate is given by a multiple of the highest frequency of interest. A large number of data samples drastically increases computing time and storage, and, in consequence, costs.

2. large number of unknowns,

   in addition to the increasing number of unknown derivatives, a higher number of 'useless' bias terms has to be determined to compensate for data initial condition offsets and drift effects.

Because of these difficulties in time-domain identification of extended rotorcraft models, DLR started to define an alternative technique that allowed a reduction in both the number of unknowns and the number of required data points. Based on the work from V. Klein [7], a frequency-domain method was developed [8], [9].

The principle of the DLR frequency-domain identification method is shown in Figure 2. In flight tests the control inputs and the corresponding aircraft response are measured and recorded. After data processing and compatibility analysis the measurements are transferred to the frequency-domain format by calculating the Fourier transforms that are used for the identification.

In the time domain the aircraft dynamics are modeled by linear differential equations describing the external forces and moments in terms of accelerations, state (x), and control variables (u), where the coefficients in the state matrix A and the control matrix B are the stability and control derivatives.

$$\dot{x}(t) = A \cdot x(t) + B \cdot u(t)$$

The observer or measurement equation is

$$y(t) = C \cdot x(t) + D \cdot u(t)$$

Assuming periodic signals, i.e. $x(0) = x(T)$, the equations are transferred to the frequency-domain format:

$$j\omega \cdot x(\omega) = A \cdot x(\omega) + B \cdot u(\omega)$$

The observer or measurement equation is

$$y(\omega) = C \cdot x(\omega) + D \cdot u(\omega)$$

where $x(\omega)$, $u(\omega)$, and $y(\omega)$ are the Fourier transformed variables.

The differences between the measured data and the model response are minimized by the identification algorithm that iteratively adjusts the model coefficients. In this sense, aircraft system identification implies the extraction of physically defined aerodynamic and flight mechanics parameters from flight test data. Usually, it is an off-line procedure as some skill and iteration are needed to select appropriate data, develop a suitable model formulation, identify the coefficients, and, finally, verify the results. Here, model formulation involves consideration of model structure and elimination of non-significant parameters. As the identified model usually is obtained from a small number of flight tests, a model verification step is mandatory to prove its validity and its suitability for different applications.

Some of the key characteristics of the DLR frequency-domain technique with specific respect to rotorcraft identification are:

1. The basic approach assumed periodic signals with practically the same value for the first and the last data points of a test. Flight test data often do not meet this requirement. Therefore, the model formulation can optionally be extended by a correction term that allows the use of nonperiodic signals

[8], [9]. For data with different initial and final values the example given in Figure 3 clearly shows that the correction term for nonperiodic signals is absolutely necessary to avoid large identification errors.

2. Different data runs can be concatenated to extract one common model. This 'multiple run' approach is also routinely used in the time-domain identification and has proved its effectiveness particularly for rotorcraft.

3. The identification can be started with a least squares technique to obtain parameter estimates without any a priori knowledge. In a second step these values are then improved by a more powerful iterative Maximum Likelihood method.

4. All frequencies are equally weighted. Depending on the model and the users physical insight, the appropriate frequency range to be matched can be selected. This option gives a high flexibility e.g. when frequencies should be excluded or when a defined frequency range is to be investigated separately (e.g. only rotor dynamics).

5. In contrast to time-domain techniques, time delays or equivalent time delays can be estimated directly. Using the roll acceleration response due to a lateral stick input, Figure 4 first shows an identification result without including any time delays. It is clearly seen that the model response leads the measured data as the effect of the rotor response dynamics are not included in the rigid body model. When this effect is approximated by an equivalent time delay the model response is significantly improved in both phase and amplitude. It demonstrates the importance of a reliable time delay estimation. It has be shown that the time delay also highly influence important derivatives, e.g. roll control and roll damping [4].

6. With increasing instabilities of the system under test time domain-identification becomes more and more complicated because the calculation of the identified model response diverges and it is difficult to estimate correcting bias terms. To overcome this problem a specific procedure to stabilize the identification procedure was implemented in the DLR Maximum Likelihood time-domain method. When the frequency-domain method was applied to flight test data from unstable system (e.g. XV-15) no difficulties were encountered and no sensitivity of the technique with respect to instabilities was seen.

7. In comparison to time history data only a small number of frequency data has to be considered (the standard approach uses about 50 frequencies to be matched whereas often some thousand data points are used for the time-domain methods). It is evident that particularly for larger models significantly less computing time is required.

8. In time-domain methods constant terms must be added to the state and observer equations to compensate for control zero offsets and state initial condition errors. The estimation of these bias terms significantly increases the number of unknowns. It is particularly true when multiple runs are evaluated where each individual run needs its own set of bias parameters (a standard case in rotorcraft identification). The biases are only needed for error compensation without any really useful information. As they are related to the frequency at zero rad/sec, the bias estimation can be avoided in frequency-domain techniques by not considering the 'zero frequency' in the estimation. It is a major advantage of frequency-domain methods and clearly helps to improve the overall identification.

Identification Results

In the following sections identification results are presented that were obtained from a multiple run evaluation of four different runs with modified 3211 inputs for the longitudinal and lateral stick, collective, and pedals. First, conventionally used 6 DOF models and their constraints are addressed. Then, it is concentrated on extended models with rotor degrees of freedom. Rotor data measurements are shown and the identification results for two models with different complexity are discussed.

Limitations of 6 DOF models

Because of its rigid rotor system with a high hinge offset the BO 105 helicopter response due to a control input is highly coupled in all degrees of freedom. Consequently, at least a coupled 6 DOF model, representing the rigid body motion, is required. The rotor, however, who has a dominant effect on the helicopter motion, is not explicitly modeled. Based on the assumption that the rotor dynamics are at much higher frequencies than the body modes, the steady state rotor influence is absorbed into the rigid body derivatives and the higher frequency dynamics are neglected. As response to a control input, such models assume an instantaneous tilt of the rotor tip path plane and consequently predict an immediate helicopter angular acceleration. Consequently, the model response leads the real helicopter response as already shown in Figure 4. Only when rotor dynamics are additionally approximated by equivalent time delays in the controls a more realistic model can be obtained Figure 4. It is useful for applications in the lower and mid frequency range (up to about 10 rad/sec for the B0105), like handling qualities and piloted simulation. However, models intended for application to high-bandwidth control system design must be accurate up to frequencies of about 18-20 rad/sec [10], which is certainly beyond the range of applicability of 6 DOF models.

The design of the feedforward controller used in the model following control system (MFCS) for the DLR in-flight simulator ATTHeS is based on the inverted BO 105 model. Inversion of the equivalent time delays however physically means time 'lead': future values of the state variables are needed which is impossible for an on-line real time process like in-flight simulation. The identified equivalent time delays for the 6 DOF BO 105 model ranged from 40 milliseconds for the pedal up to about 100 milliseconds for the longitudinal stick and collective. Neglecting these delays leads to drastical errors in the MFCS [2]. Clearly, the rigid body models must be extended by an explicit representation of the rotor dynamics effects. Therefore, a first extended model was defined using pitch and roll acceleration as state variables [2]. This approach gives a good and valid approximation of the rotor influence, in particular in the roll motion. The identified 8 DOF model was used successfully for the controller design and has helped to improve the in-flight simulation performance significantly [11], [12]. This experience also demonstrated that there is a strong need for models with a more reliable description of the initial response characteristic than the conventional 6 DOF models can provide. A logical consequence is the identification of models with rotor degrees of freedom. It implies, however, that measurements of the blade motions are required.

Rotor data measurements

For blade flapping measurements the DLR BO 105 rotor was instrumented with a pair of strain gauges at the location of the equivalent hinge offset. When static calibrations (non-rotating blade) turned out to be not satisfactory, the signal calibration was done at the rotation blade under conditions of airloads and centrifugal forces [13]. Flapping data obtained from a collective input are given in Figure 5. It can be seen that the data have practically the same response characteristic in mean value, amplitude change, and higher order effects. The obtained data accuracy also allowed the calculation of a reliable tip path plane motion by a multiblade coordinate transformation to obtain longitudinal and lateral flapping and coning, variables that are defined in a body fixed non-rotating axis system. They are shown, as a representative example, in Figure 6 for longitudinal, lateral, and collective control inputs. Higher frequency noise is small proving that the calibrations and measurements of the individual blades are consistent to each other. The primary axis responses can clearly be recognized. The time histories of longitudinal flapping due to longitudinal stick and coning due to collective indicate that the rotor response has at least a 2nd order system characteristic. The lateral flapping response due to a lateral stick input shows a significantly different characteristic as both, the roll moment of inertia and the fuselage aerodynamic moments in the roll axis are small.

Before the data were used in the identification, another data quality check was conducted by comparing the tip path plane data with results obtained from a nonlinear simulation program. The generally good agreement gave additional confidence in the reliability of the measurements and their suitability for system identification [14]. Figure 7 compares measured and simulated data from a frequency sweep segment.

Identification of extended models

The basic approach for extending the conventional 6 DOF rigid body model formulation by rotor degrees of freedom is illustrated in Figure 8. The state vector of the rigid body motion

$$x^T = (u,\ v,\ w,\ p,\ q,\ r,\ \Phi,\ \Theta)$$

is extended by the tip path plane variables

$$x^T = (A_{1s},\ B_{1s},\ A_0)$$

or, depending on the model order

$$x^T = (A_{1s},\ B_{1s},\ A_0,\ \dot{A}_{1s},\ \dot{B}_{1s},\ \dot{A}_0)$$

The model structure includes two sets of equations representing the fuselage and the rotor characteristics. There are also clearly defined submatrices giving rigid body and rotor behavior and the corresponding couplings. In comparison to the conventional model this structure is closer to reality and can provide a more detailed insight into the helicopter dynamics. However, an increase in model size also implies an increase of unknown parameters and makes the identification more difficult. Problems related to convergence of the method, correlation of the parameters, insufficient information content, etc. become more evident and can degrade the results or can even make the identification impossible. A detailed model structure analysis is necessary to reduce the number of unknowns so far as physically meaningful. Derivatives in the 6 DOF model that mainly included rotor effects can be eliminated from the fuselage equations as the rotor is now explicitly modeled. The development of an adequate model structure, however, is still a major research task. A first approach to extend the rigid body models by rotor states was presented in [15]. Here, in a so called 'hybrid formulation', highly reduced rotor equations for the regressive flapping mode and an approximation for the lead/lag effects were used. As intended, this formulation predicted an accurate high frequency response of the tip path plane. However, significant errors in the lower frequency range of the rotor response must be accepted.

The DLR approach tried to identified all parameters needed in the rotor equations to represent the total flapping (and coning) rotor response. The lead/lag motion was also approximated by a second order transfer function for the lateral control input. Two of the obtained results with different rotor model order are discussed in the following section: 1) a 10th order model with 8 DOF and 2.) a 14th order model with 9 DOF.

Identification of a 10th order model

In addition to the rigid body motion, the rotor was modeled by two differential equations representing

- longitudinal flapping as 1st order system,
- lateral flapping as 1st order system.

The model has 8 DOF and is of 10th order (without counting the 2nd order lead/lag approximation). The observer equations used the rigid body variables

- linear accelerations,
- speed components,
- rates,
- attitude angles,

and the rotor variables,

- longitudinal and lateral flapping,
- differentiated longitudinal and lateral flapping.

As control variables the four helicopter controls longitudinal and lateral stick, collective, and pedal were used. No use was made of pseudo control inputs, where measured states are treated as controls.

With the extension the model structure can be separated into two groups: two new equations describing the rotor dynamics and, in principal, the original 6 DOF equations characterizing the fuselage. In comparison to the 6 DOF model structure some major changes were made, in particular:

1. the roll and pitch damping derivatives L_p and M_q were neglected in the fuselage equations,
2. longitudinal and lateral stick control derivatives were eliminated from the fuselage equations and only used in the rotor equations,
3. the fuselage equations were extended by rotor state derivatives to represent the fuselage/rotor coupling.

Making use of the rotor symmetry some parameters in the rotor equations were constraint to the same identified value (e.g. rotor flapping damping).

Figure 9 compares the measured rotor response due to a longitudinal stick input to the identified model response. Although there is a basically good agreement, the deficiencies are obvious when the stick is moved. The amplitudes of the longitudinal flapping response cannot be matched and the coupling into the lateral flapping is not satisfactory. The result clearly indicates that the model with first order rotor flapping equations is not suitable.

Identification of a 14th order model

In the 10th order model, the rotor model order was not appropriate. Therefore it was extended to

- longitudinal flapping as 2nd order system,
- lateral flapping as 2nd order system,
- coning as 2nd order system.

This model has 9 DOF (6 rigid body, 2 flapping, 1 coning) and is of 14th order. (Again, the lead/lag approximation is not counted). Again, based on rotor symmetry, some of the identified rotor derivatives were constraint to the same value. Following the rotor equations derived in [16] and [17] the terms related to the rotor inertia were treated as known and fixed to the theoretical value of twice the rotor RPM. As coning was also included as rotor DOF, the collective control derivatives could be reduced to only one in the coning equation.

The observer vector used in the 10th order model was extended by the coning measurement and its differentiation. Again, there were no pseudo control inputs. About 75 unknown derivatives were estimated. Here, a more detailed analysis still has to be conducted to investigate the consistency and 'robustness' of the individual parameters in order to probably reduce this high number of unknowns.

Using the same data segment as in Figure 9, Figure 10 presents the flapping and additionally the coning response of the 14th order model. A comparison with Figure 9 clearly shows that the new rotor model gives a good agreement in all rotor motion time histories. It illustrates that the rotor DOF have at least to be modeled as second order systems.

The complete set of rotor response time histories due to the three main rotor controls are given in Figure 11, for three runs with longitudinal and lateral stick and collective inputs. The fit with the measured data is excellent for the total data length. Some smaller deviations in the coupled responses (mainly in coning) are acceptable. For completeness, the comparison for the rigid body states are given in Figure 12, where a run with a pedal input is additionally included. The good agreement confirms that an adequate model order was defined and the obtained model accurately matches both, the rotor and the rigid body measurements. There are a few larger discrepancies in the speed components. Here, it should be noted that the original speed measurements are plotted and the differences also reflect problems related to the air data measurement itself.

Comparison of identified models

In comparison to the identification of conventional 6 DOF models, the determination of extended models with explicit rotor DOF requires a higher effort in both, helicopter instrumentation and data evaluation. To investigate the obtainable benefits the identification results were compared in the format of eigenvalues, frequency spectra, and transfer functions. Some of the results are given in the following sections.

Comparison of eigenvalues

Table 1 summarizes the eigenvalues of the three identified BO 105 models:

1. 8th order, 6 DOF rigid body,
2. 10th order, 8 DOF with 1st order rotor flapping, and
3. 14th order, 9 DOF with 2nd order rotor flapping and 2nd order coning

The first four modes in the table (phugoid, dutch roll, spiral,pitch) are associated with the rigid body motion. A comparison with the higher order models shows that they stay practically the same. The higher frequency modes then change with the inclusion of rotor states. When the 1st order flapping is added (10th order model), the aperiodic roll mode becomes oscillatory, representing the roll/flap coupling. The remaining real pole at about 15.5 rad/sec can be considered as an approximation of the regressive flapping. For a physically more realistic representation of this mode the rotor flapping must be modeled as a 2nd order model, as it was done in the 14th order model. Now, the regressive flapping becomes a complex pole and the previous aperiodic pole (pitch-2) characterizes the advancing flapping. As the 14th order model also included a second order coning equation the additional complex poles for the coning motion could also be identified. Finally, the eigenvalues for the complex dipol of the lead/lag approximated are presented. This approximation can only be used with extended models.

Considering the changes in the eigenvalue characteristics with model extension it certainly can be stated that the obtained modes physically make sense and do provide a realistic description of the helicopter dynamics. Their values are characteristic for the BO 105 and indicate that it was possible to extract suitable higher order models from flight test data. Of course, the high frequency eigenvalue for the advancing flapping certainly can be questioned as the data cannot provide reliable information in a frequency range of about 100 rad/sec. Nevertheless, the results prove the high potential of the identification technique and give confidence in the obtained models.

Comparisons of frequency spectra and transfer functions

From the model comparisons in the frequency domain format some representative results, given in Figure 13 and Figure 14, concentrate on the conventionally used 6 DOF model and the 14th order extended model.

Figure 13 shows the amplitudes of the pitch and roll rate frequency spectra for

- the measured data,
- the 6 DOF rigid body model,

- the 9 DOF, 14th order model.

As it can be expected there are only some smaller differences in the lower and mid frequency range up to about 1 Hz. With increasing frequencies, however, the rigid body model amplitudes are smaller than the measurements, whereas the extended model almost perfectly agrees with the measured data. In the roll rate spectrum a peak is seen at about 2.3 Hz. It corresponds to the lead/lag motion. The fact that it is also accurately represented by the extended model demonstrates the quality of the applied lead/lag approximation.

The differences between the rigid body and the extended model become even more obvious when transfer functions are compared. Figure 14 presents the Bode plots for the transfer functions roll rate due to lateral stick and pitch rate due to collective. Again, there is a good agreement between measurement and the responses from both models for lower frequencies. But for the higher frequency range the 6 DOF model shows large discrepancies in both, magnitude and phase. Here, the improvements obtained from the extended model are obvious.

Verification of the identified model

Verification is a key final step in the system identification process for assessing the predictive capability of the extracted model. As the criteria used by identification methods are based on curve fitting between measured data and model responses, a good agreement for the considered data does not necessarily prove a general model validity. Therefore, the verification should always be conducted with

- data not used in the identification and
- inputs other than those applied for the identification runs.

For the verification of the extended models, flight test data from frequency sweeps were used as these inputs are significantly different from the 3211 signals.

For the 14th order extended model Figure 15 and Figure 16 compare the measured data and the model response for a collective and a lateral stick frequency sweep. The good agreement in both, rotor and rigid body variables confirms an adequately selected model structure and demonstrates a high predictive capability of the identified model. It should be noted that the model was extracted from data with only about 25 seconds time duration per run whereas the sweep is about 50 seconds long, covering a broad frequency range. Some differences are seen in the off-axis response from the lateral stick sweep. But they are quite small as it should be noted that the scales for the pitch rate and roll rate are different by a factor of three.

Conclusions

Conventional 6 DOF rigid body helicopter models are only appropriate for applications in the lower frequency domain. As they neglect the rotor dynamics, deficiencies in the higher frequency range cannot be avoided. Some improvements can be obtained by approximating the rotor dynamics by equivalent time delays. However, this approach is not generally applicable and finally cannot satisfactorily represent the neglected rotor influences. Therefore, extended linear models with explicit rotor degrees of freedom were formulated. The model parameters were extracted from flight test data using a frequency-domain identification technique.

The paper concentrated on two extended models. The first one, a 10th order model with 8 DOF included first order flapping. The second one, a 14th order model with 9 DOF, allowed second order flapping and 2nd order coning. The main conclusions from this work are:

1. Rotor data, required for the identification of the rotor equations, could be calibrated and measured with good accuracy.
2. The tip path plane motion was derived from blade flapping measurements and could be verified by simulation comparisons.
3. Identification results obtained from the 10th order model formulation indicated that the rotor flapping is not adequately described by a first order system.
4. The identified 14th order model with a second order flapping representation showed good agreement between measurements and model response and proved an appropriate model structure.
5. The eigenvalues for the 6 DOF model and the two extended models were compared. It was shown that the eigenvalues representing the rigid body modes were practically the same for all models. The additional poles, obtained with increasing model size, were physically meaningful and realistic for the BO 105 helicopter.
6. The verification results generated from dissimilar data (frequency sweeps) showed good agreement for the 14th order model and confirmed the model accuracy. They also provide additional confidence in the identification technique.

Summarizing it can be stated that the DLR frequency-domain identification approach has shown that the extraction of higher order helicopter models including rotor degrees of freedom is feasible when appropriate flight test data are available. The obtained results are certainly promising and motivate to continue the identification of extended rotorcraft models for applications that require more accurate models (e.g. the control-system design for the DLR in-flight simulator ATTHeS). Future work should concentrate on a more refined model structure and on flight test inputs that can still increase the data information content for the high frequency rotor data.

Note

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Motion	6 DOF, 8th order	8 DOF, 10th order	9 DOF, 14th order
	rigid body	rigid body 1st lon/lat flap	rigid body 2nd lon/lat flap, 2nd coning
Phugoid	[−0.22, 0.34]	[−0.23, 0.34]	[−0.22, 0.34]
Dutch Roll	[+0.20, 2.51]	[+0.15, 2.56]	[+0.14, 2.53]
Spiral	(0.03)	(0.03)	(0.03)
Pitch-1	(0.45)	(0.42)	(0.43)
Roll	(8.54)	-	-
Roll/flap	-	[0.82, 14.7]	[0.77, 13.5]
Regressing flap	-	(15.5)	[0.91, 7.38]
Pitch-2	(3.91)	(3.51)	-
Advancing flap	-	-	[0.16, 106]
Coning	-	-	[0.52, 32.67]
Lead/lag approximation	-	[0.015, 14.7]	[0.015, 14.7]

Shorthand notation:

$[\zeta, \omega_0]$ implies $s^2 + 2\zeta\omega_0 s + \omega_0^2$, ζ = damping, ω_0 = undamped natural frequency (rad/sec)
(1/T) implies (s + 1/T), (rad/sec)

Table 1. Comparison of BO 105 eigenvalues for different model structures

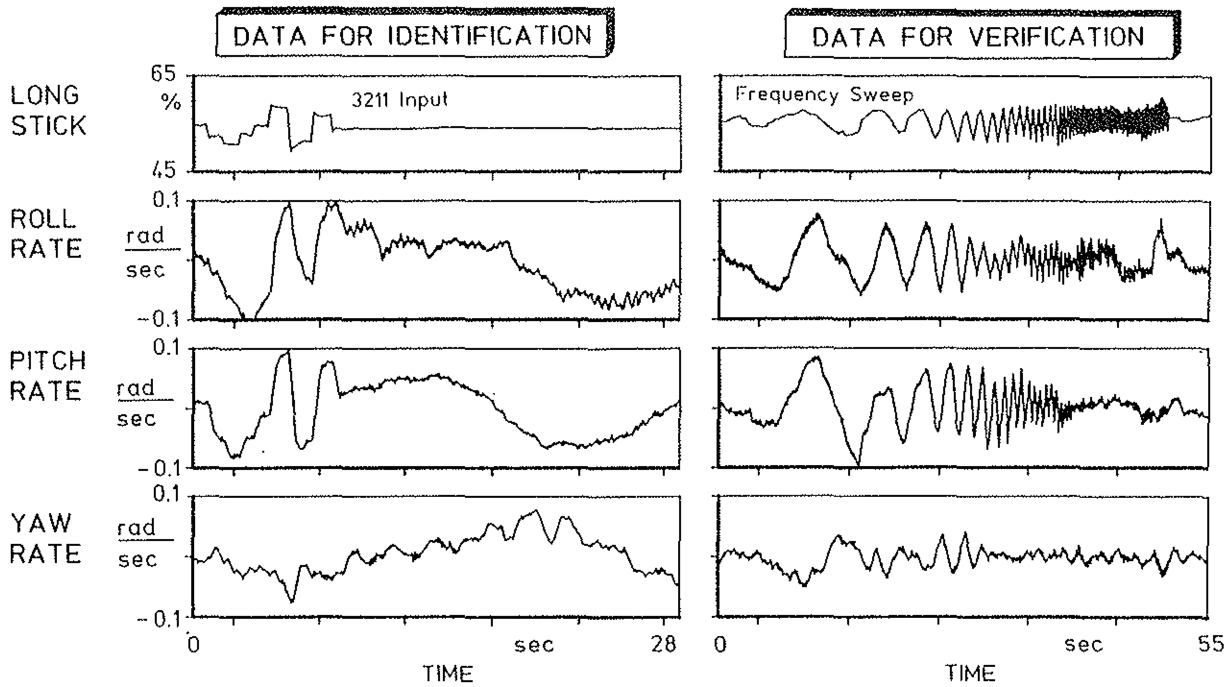

Figure 1. Representative BO 105 flight tests data for system identification

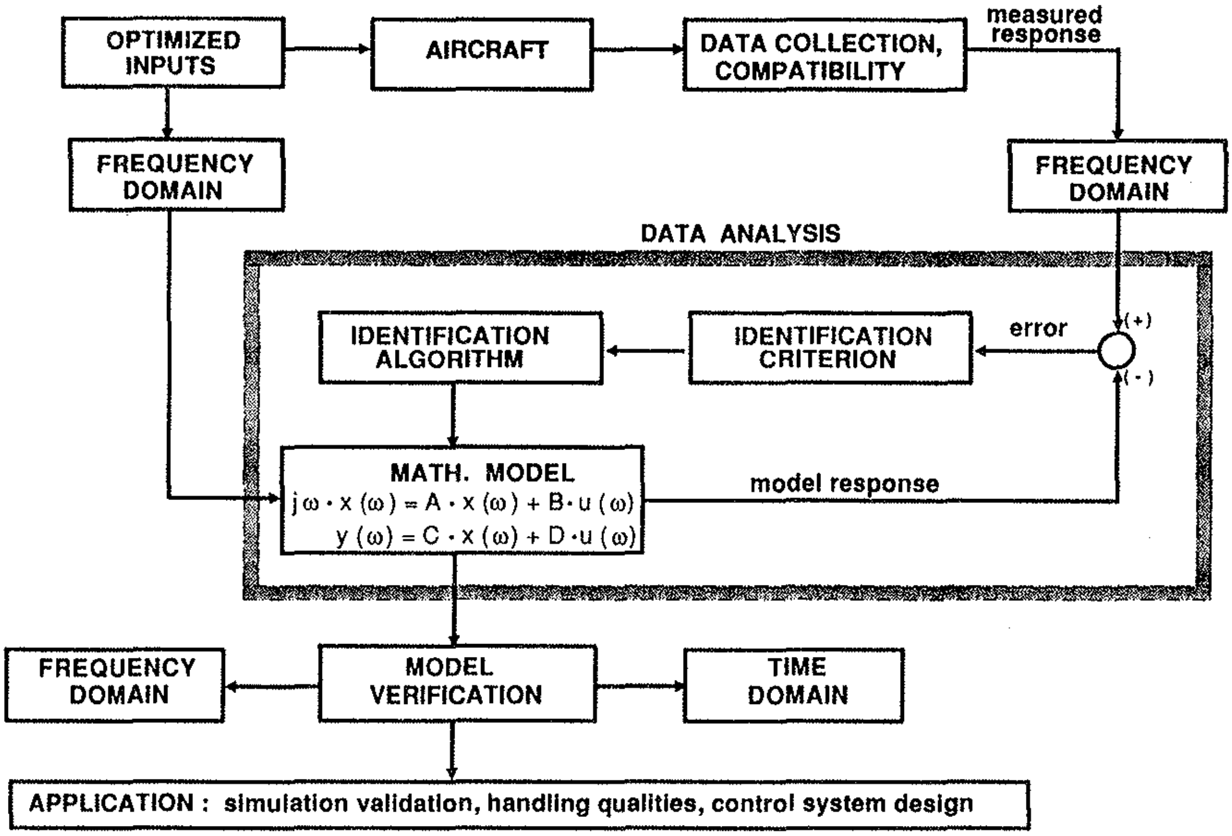

Figure 2. Frequency-domain identification procedure

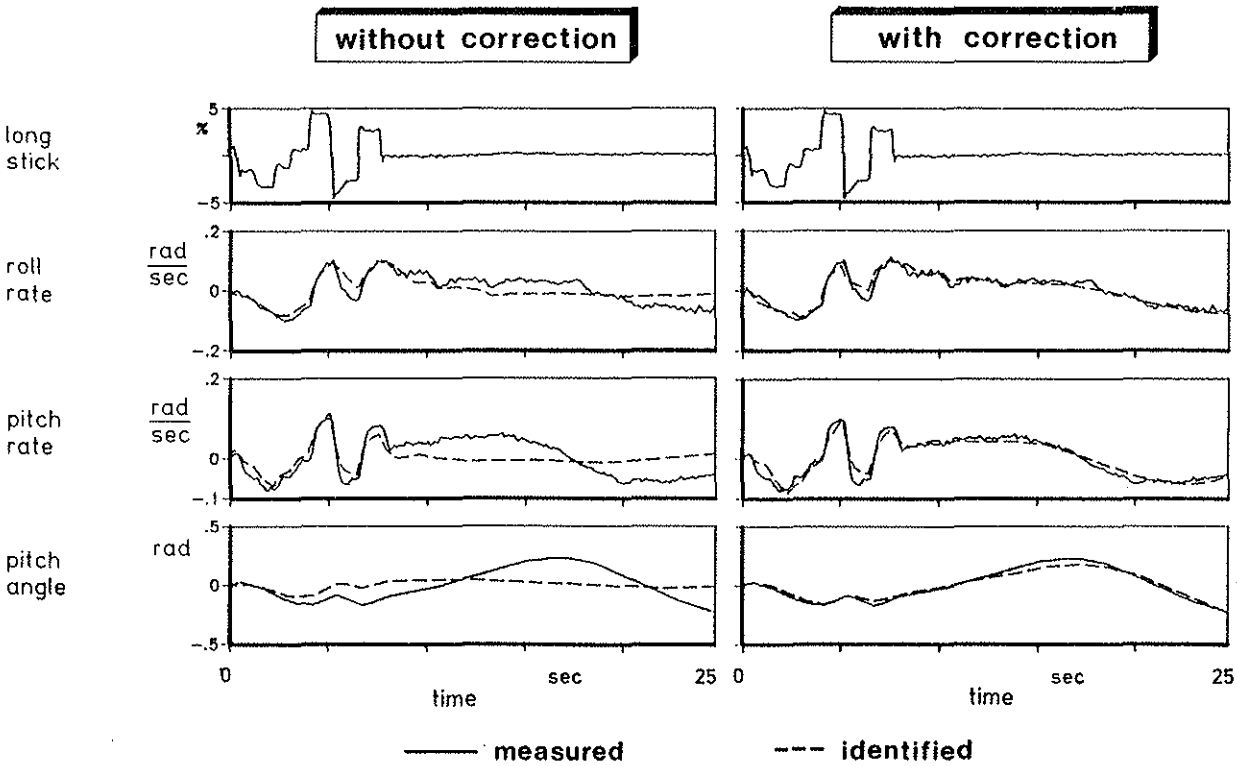

Figure 3. Influence of the correction for nonperiodic state variables

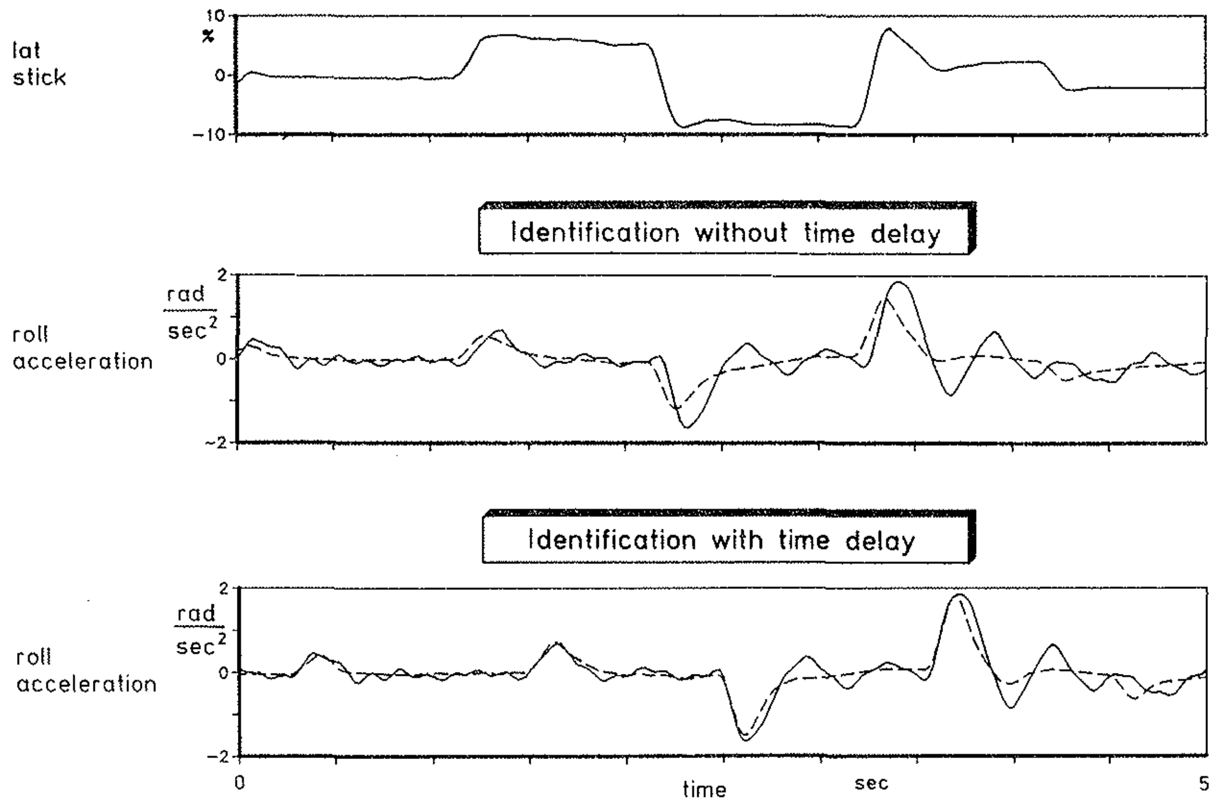

Figure 4. **Comparison of identification results for a 6 DOF model with and without time delay estimation**
(—— measured ---- identified)

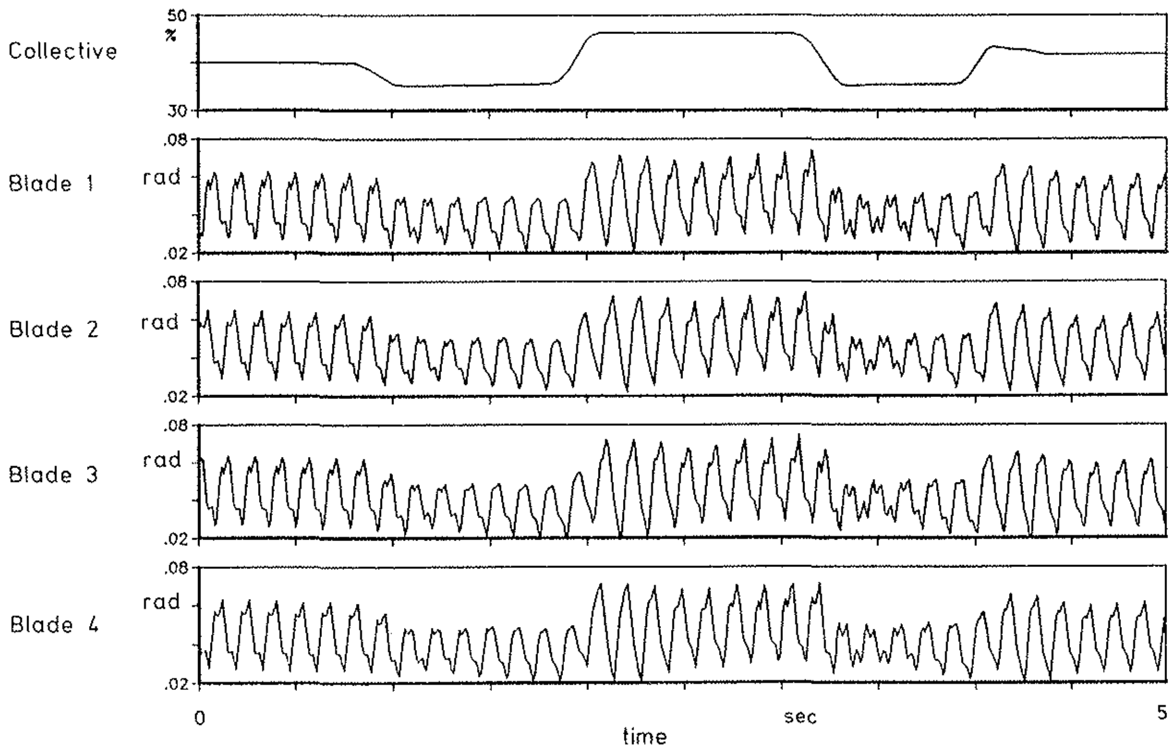

Figure 5. **Blade flapping measurements for a collective control input**

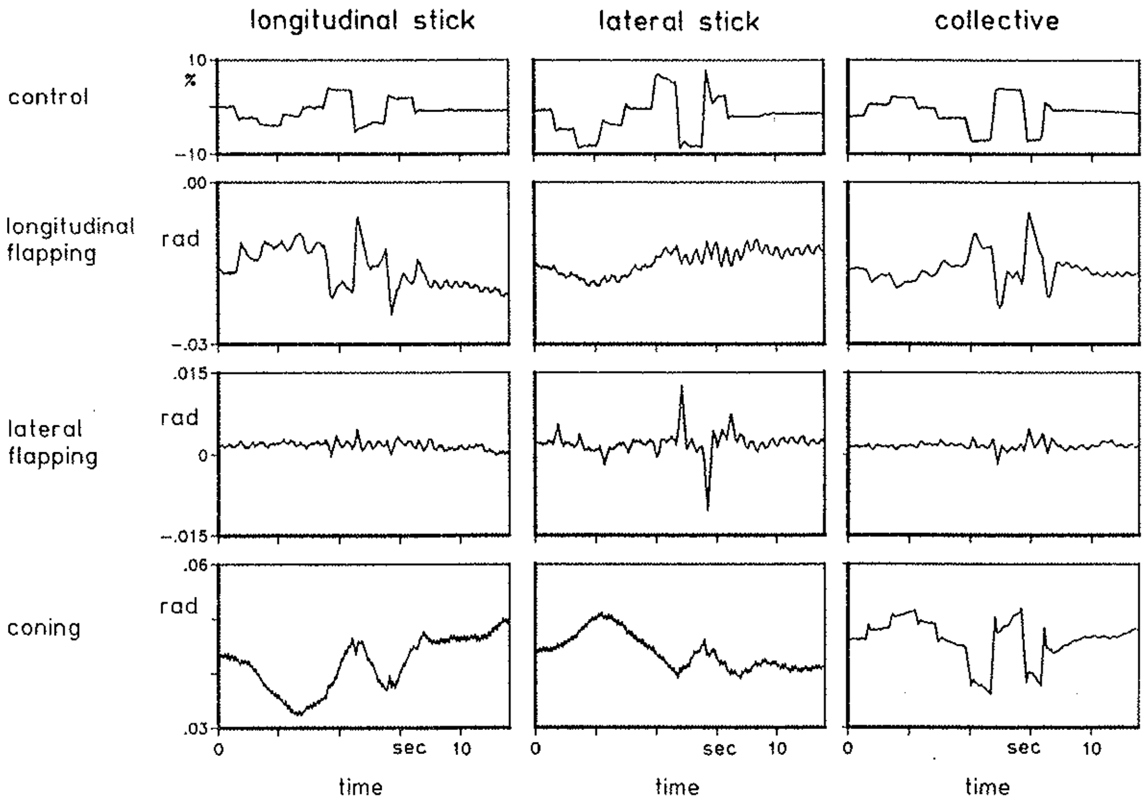

Figure 6. Tip path plane response, derived from blade flapping measurements

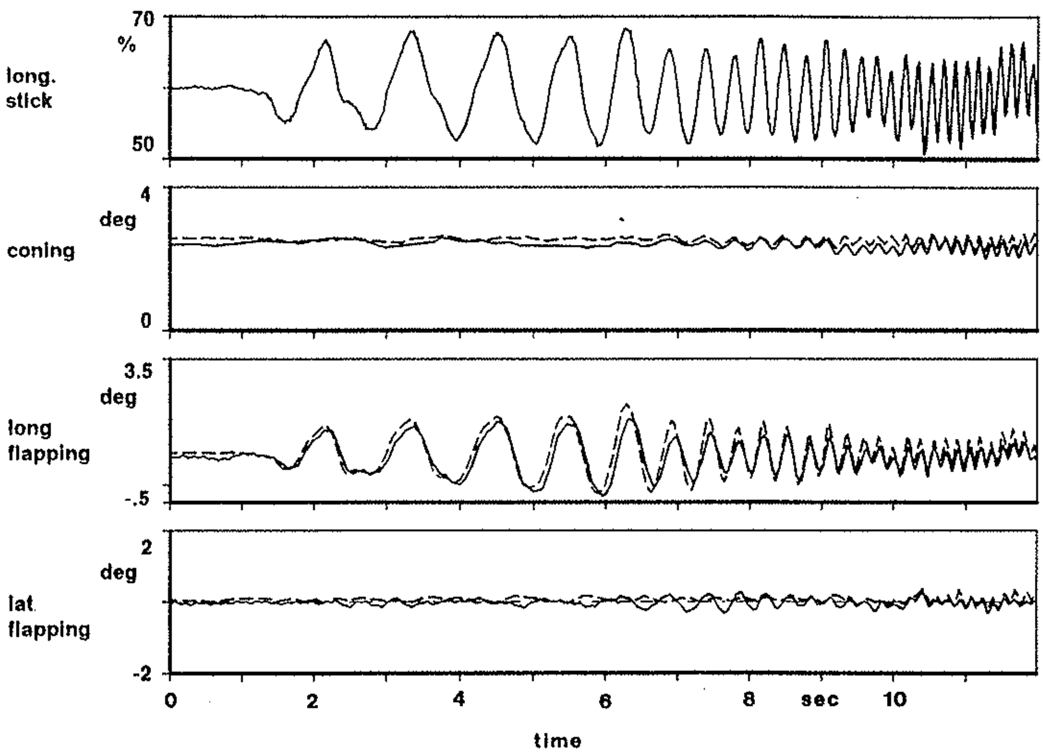

Figure 7. Comparison of measured and simulated tip path plane responses
(—— measured ---- nonlinear simulation)

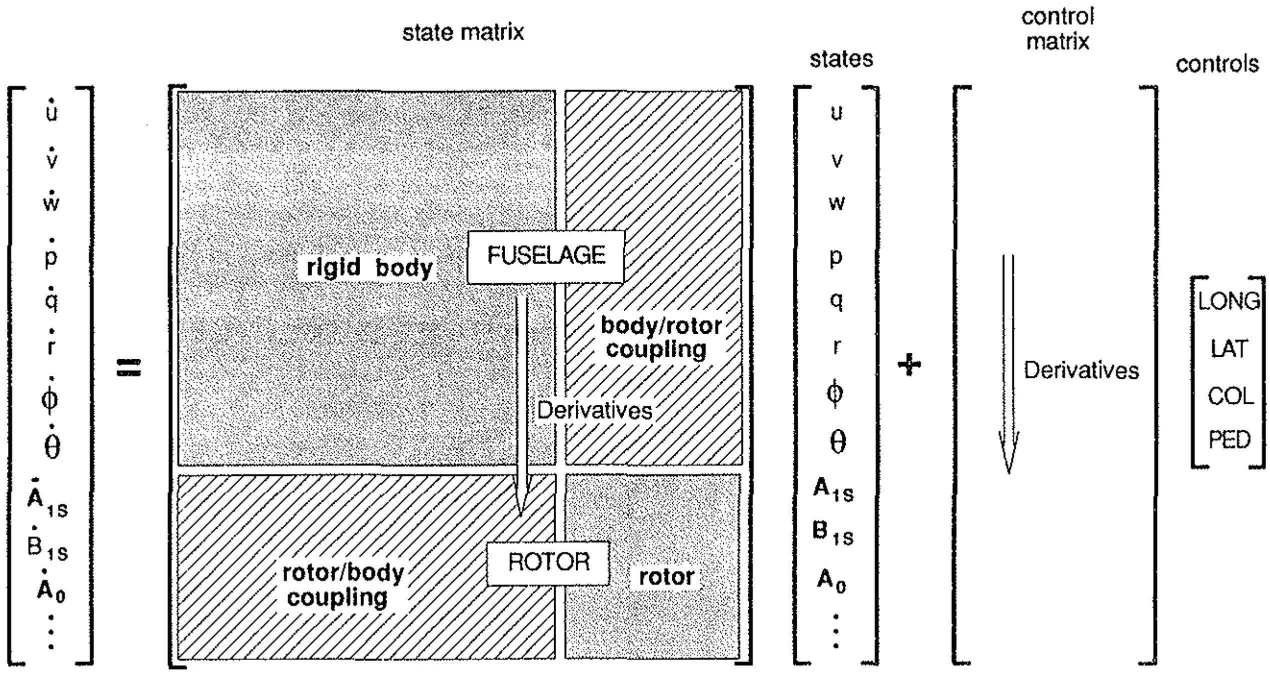

Figure 8. Principal approach to extend the conventional 6 DOF model by rotor DOF

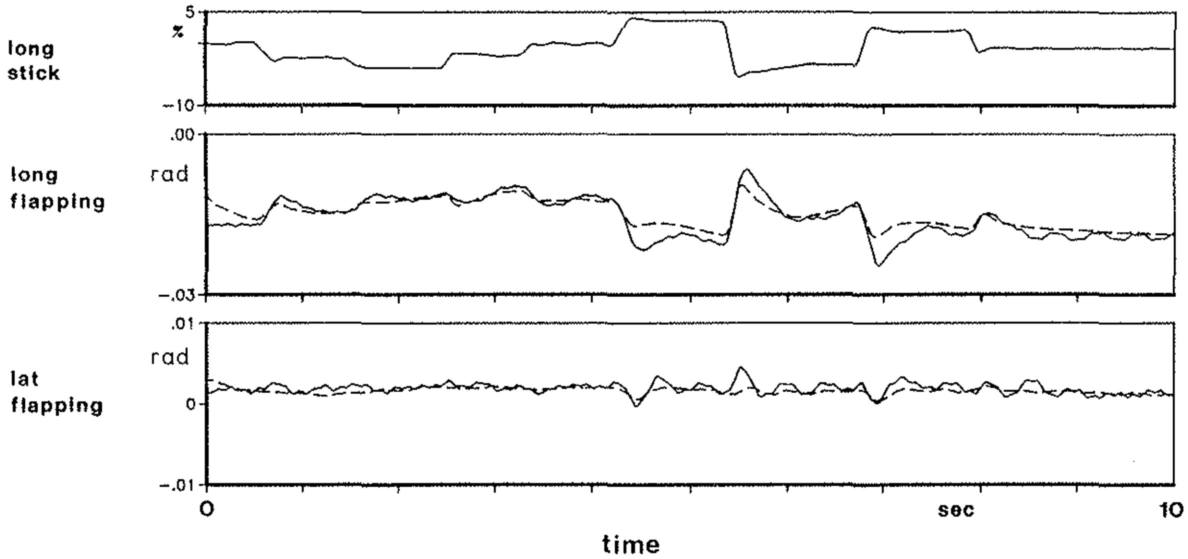

Figure 9. Comparison of measured rotor data to the response of an identified 10th order model with 8 degrees of freedom
(—— measured ---- identified)

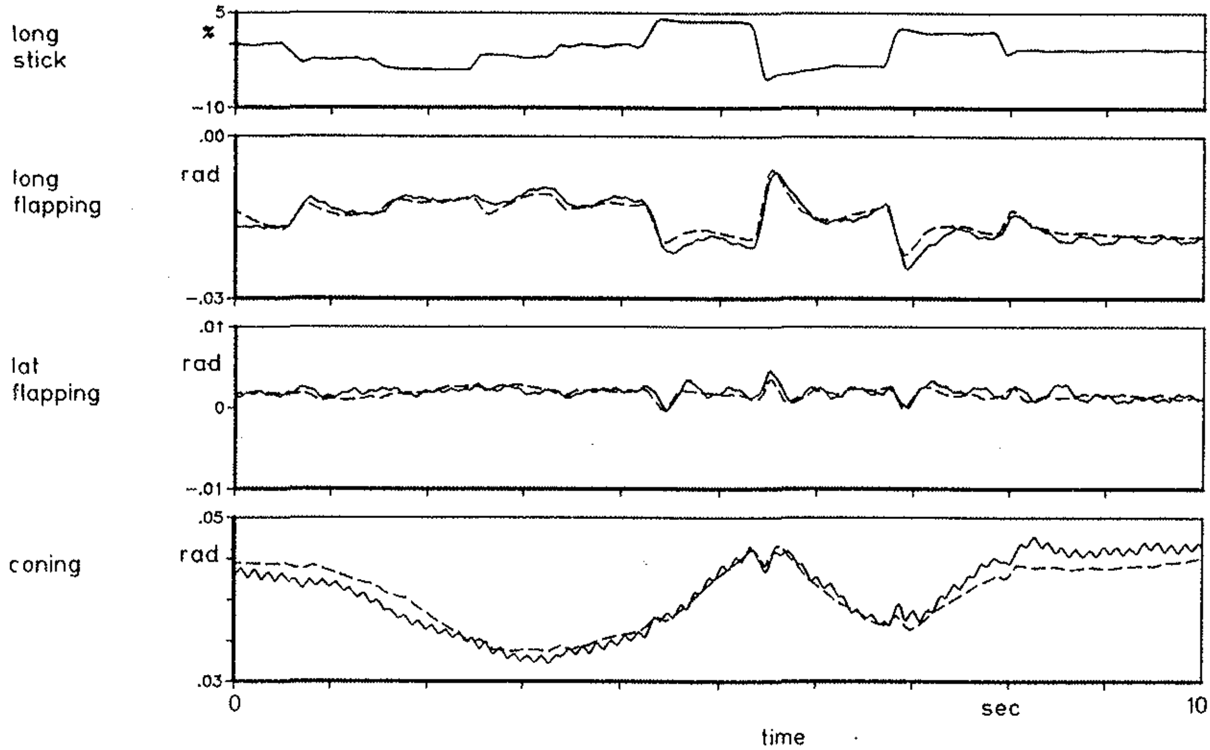

Figure 10. **Comparison of measured rotor data to the response of an identified 14th order model with 9 degrees of freedom**
(—— measured ---- identified)

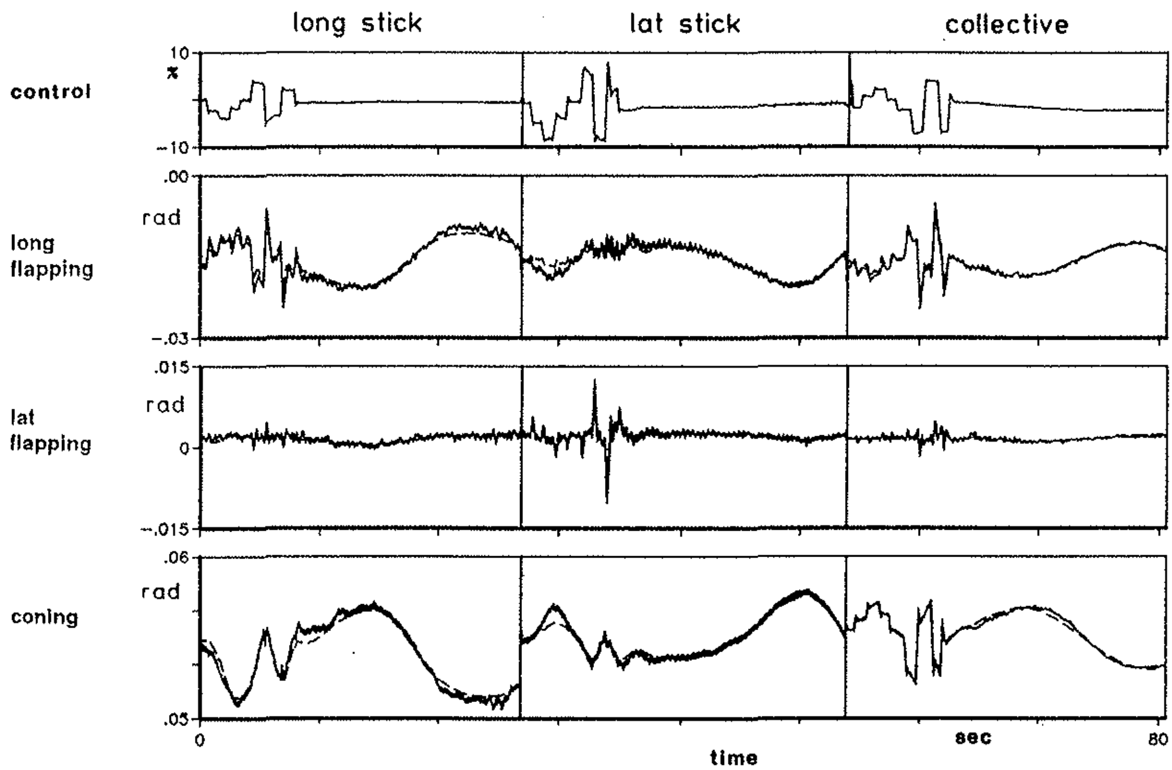

Figure 11. **Comparison of measured rotor data to the response of an identified 14th order model with 9 degrees of freedom**
(—— measured ---- identified)

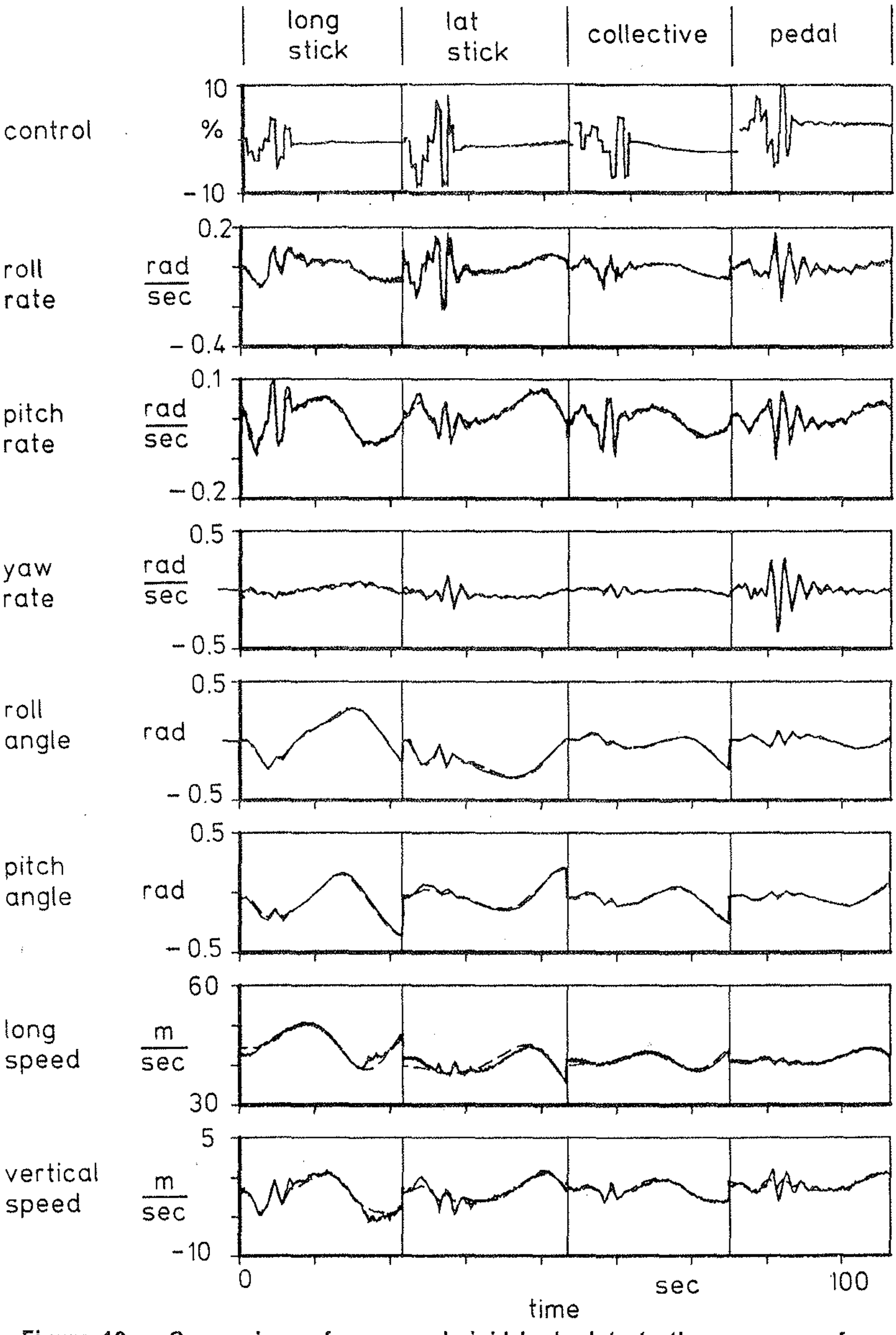

Figure 12. **Comparison of measured rigid body data to the response of an identified 14th order model with 9 degrees of freedom**
(—— measured ---- identified)

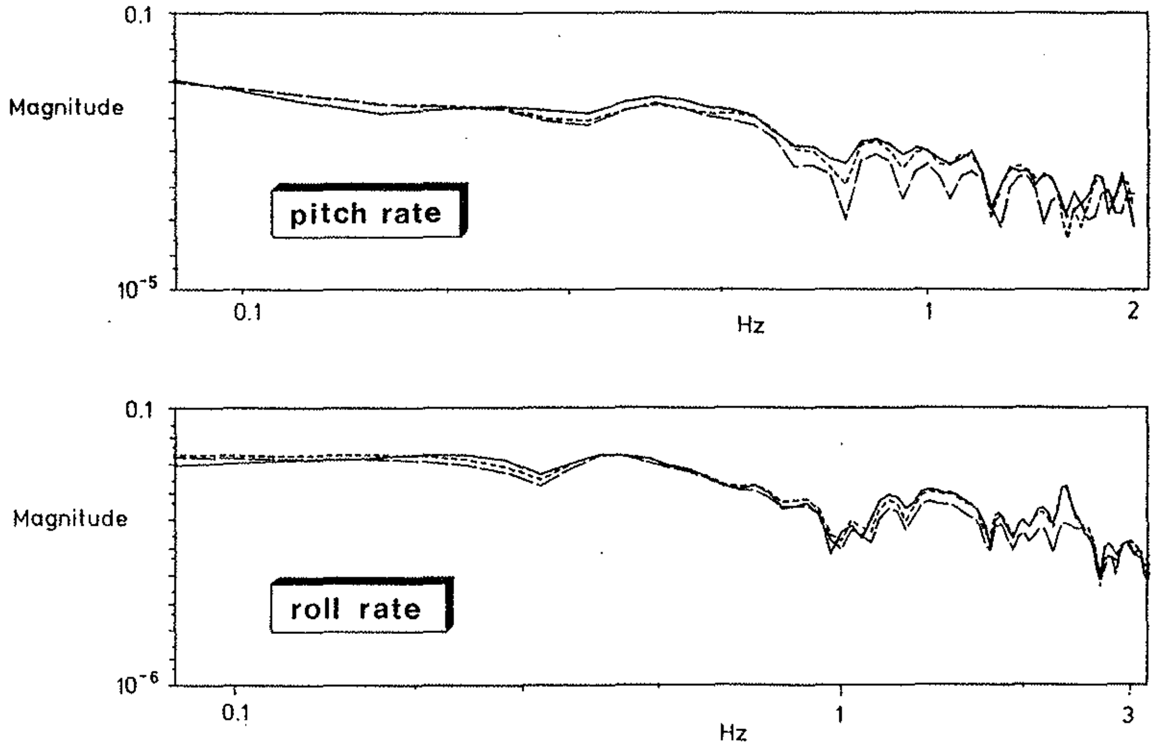

Figure 13. **Comparison of the frequency spectra from the measurements and two identified models**
(—— meas. – – – id., 6 DOF ---- id., 9 DOF, 14th order)

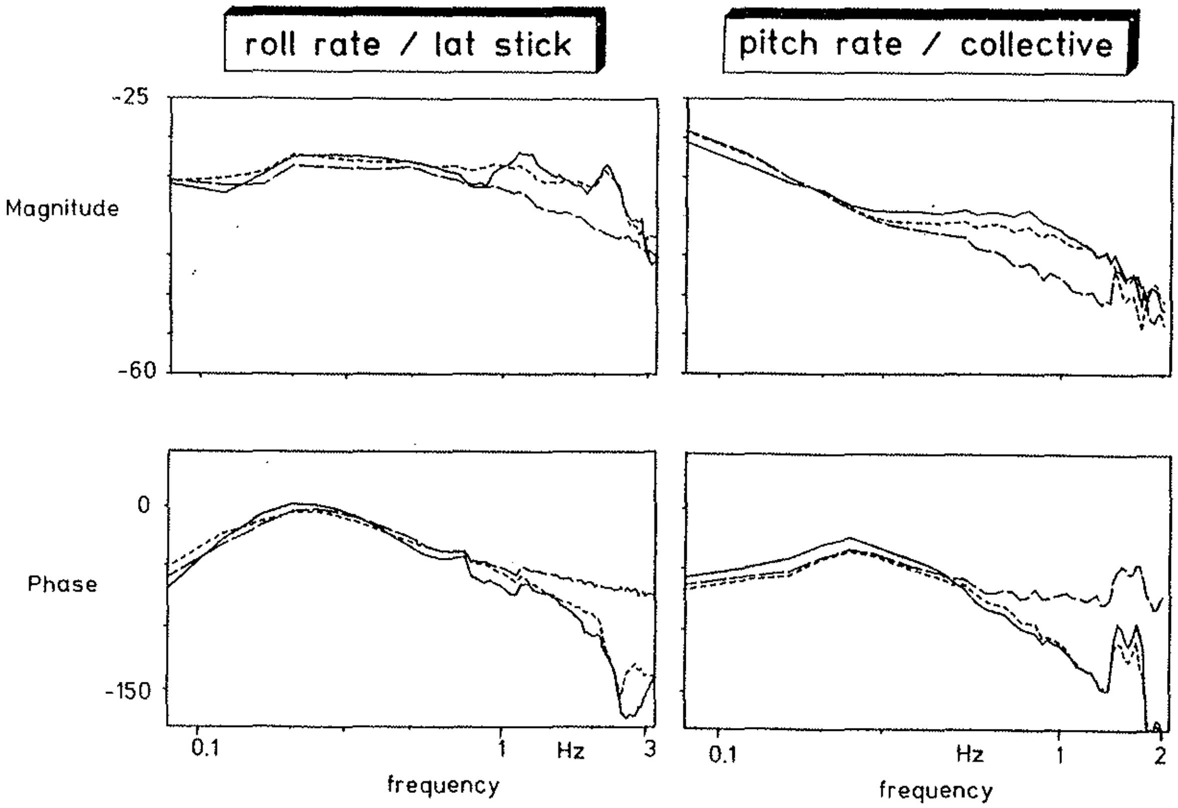

Figure 14. **Comparison of transfer functions from the measurements and two identified models**
(—— meas. – – – id., 6 DOF ---- id., 9 DOF, 14th order)

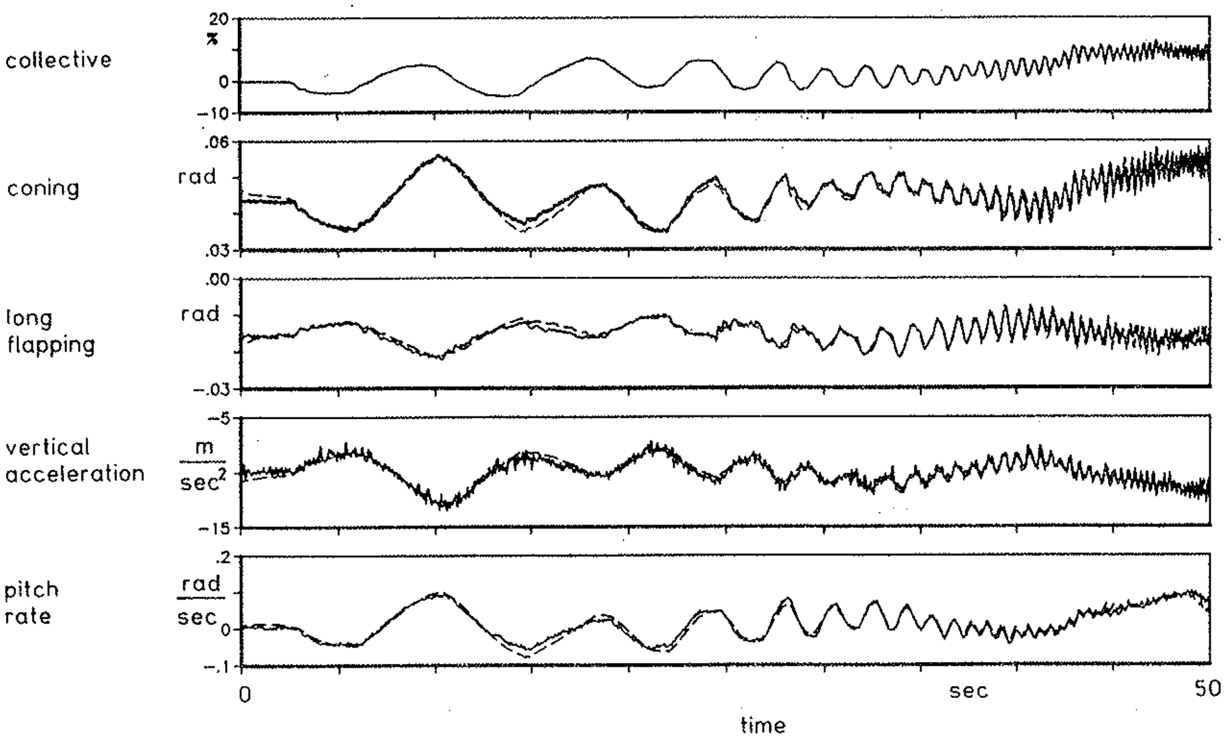

Figure 15. Verification of the identified 14th order model with data from a collective frequency sweep
(—— measured ----- model response, 9DOF, 14th order)

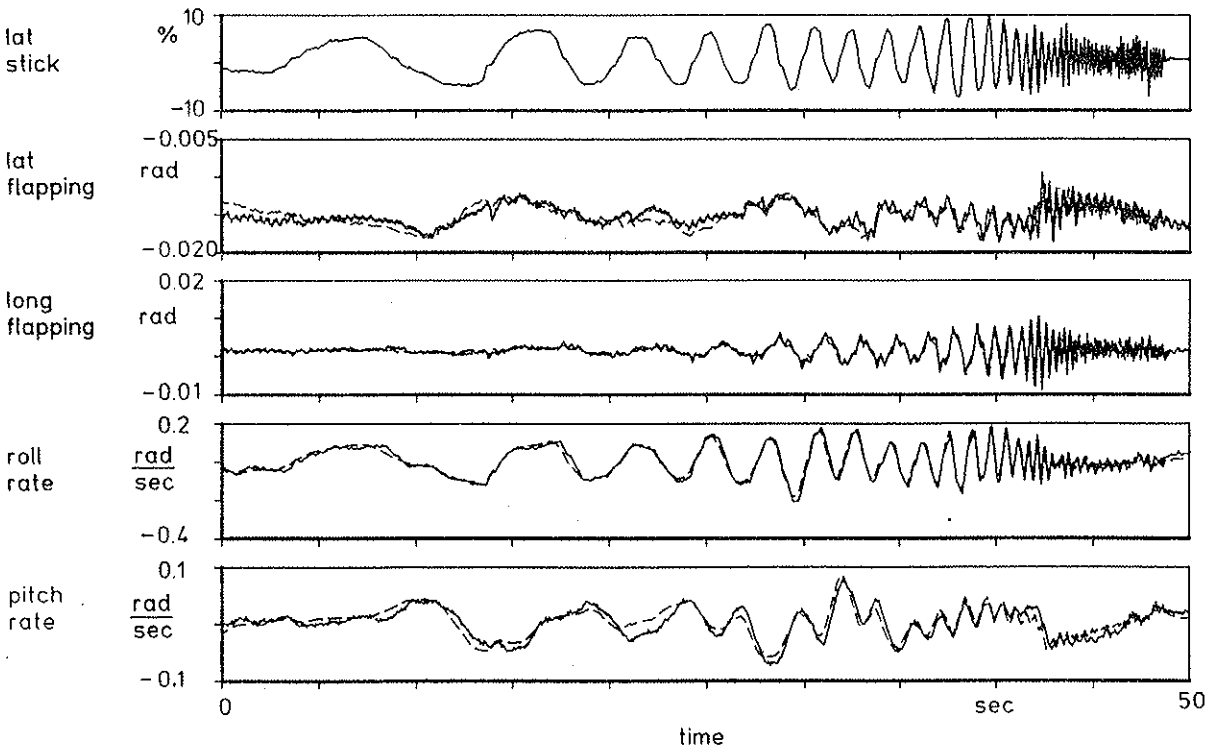

Figure 16. Verification of the identified 14th order model with data from a lateral frequency sweep
(—— measured ----- model response, 9DOF, 14th order)