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FLIGHT PATH RECONSTRUCTION
A POWERFUL TOOL FOR DATA COMPATIBILITY CHECK

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Abstract

The estimation of process parameters requires a sophisticated data aquisition system and well prepared tests. Small remaining errors in the recorded data result in large parameter errors. A compatibility check of the measured data is therefore an important step in parameter estimation procedure. This paper first describes the used test-aircraft and its measuring equipment. The nonlinear equations used for the data compatibility check are given after a short introduction of the theoretical background. Results of the compatibility check are shown in time histories and in tabular form. The paramter estimation using compatible data and a model which includes corrections estimated in the compatibility check give very good results as shown. The paper is closed with some physical aspects for further improvement of parameter estimation.

Preface

The institute of flight guidance of the university of Braunschweig has started parameter estimation of a test aircraft four years ago. The project is part of the research program of the Sonderforschungsbereich SFB 212 "Sicherheit im Luftverkehr", sponsored by the Deutsche Forschungsgemeinschaft (DFG). Research projects like observer design or aircraft control design need sophisticated aircraft models. Today, pilot training requires sophisticated aircraft simulation too (Lit. 1). Detailed information on this process of which the equations are known can be obtained by parameter identification. No efforts may be spared in preparing the flight test and checking the data aquisition system, if reliable estimates of parameters are called for. Compatibility check of measured data is a further step, to correct data errors prior to parameter estimation. The possibility of using nonlinear models improves the accuracy of both steps.

1. Flight test possibilities

The university of Braunschweig owns a DO 28 aircraft, which is equipped with all necessary sensors to measure the inertial and aerodynamic states with high quality. The DO 28 has been used for on-line wind measuring as well as for the verification of new concepts of aircraft control systems and for observer design. During the last year the aircraft has also been used for parameter estimation flight tests.

1.1 Flight test vehicle

The flight test vehicle is a twin engine aircraft of the type Dornier DO 28. Its maximum start weight is 3700 kg. The two piston engines achive 380 hp maximum power each and they allow a crusing speed of 272 km/h. The fuselage of the DO 28 has rectangular section, which gives much room for the implementation of scientific equipment.

1.2 Measuring and data aquisition system

The inertial data are measured by an INS platform and additionally by accelerometers for all three body fixed axes and by gyros for the turn-rates around these axes. All the inertial sensors are located near the center of gravity. The air data are measured by a pitot tube placed on top of the rudder, which gives static and dynamic pressure and by a "flight log" at the tip of the airplane's noseboom concerning angle of attack and angle of sideslip. The total temperature is also available for airspeed correction. All control surfaces are driven by electrical servomotors, their position and that of the throttle are measured by potentiometers. The rotation speed of the propellers and the manifold pressure of the engines are measured additionally.
The measured signals can be used on-line in the onboard computer or they can be recorded on a PCM tape (figure 1). The on-board computing facilities consist of a Norden 11/34M main-computer and a Mudas communication computer. They handle on-line calculations with 23 cps on-bord. A PCM tape records the data with 92 cps sampling frequency. The data is recorded on four tracks with eight channels each, which have a resolution of 12 bit. The actual time information is contained additionally in the PCM code.

1.3 Problems in PCM data analysis

The recorded PCM data is read into the pre-analysis computer one track after the other for each flight test. Every flight test is defined by a start and a stop time.
We did found time shifts between the tracks up to 0,5 seconds after the read-in procedure. The reason is, that the read-in procedure does not begin exactly at the start time, its start delay is random. This failure can be corrected in a next step.
Another problem arises, when a data sample is not readable (synclos) in one track. Then this data set is substituted by the next readable one. Therefore the read-in flight data contains time shifts which vary from track to track. This failure can not be corrected until today. Fortunately there exist only a few syncloses within a flight test data set.

2. Method of analysis

We consider the general problem: a set of measured flight test time histories is given and the values of the set of unknown parameters in the model equations have to be determined to provide the best representation of the actual aircraft response. Maximum Likelihood method has proven to be one of the most appropriate technique for the solution of this problem.

2.1 General Maximum Likelihood formulation

The model containing the unknown parameters can be splitted into state equations, observation equation and measurement equation:

$$\dot{\underline{x}} = \underline{f}[\underline{x}(t), \underline{u}(t), \underline{\theta}, t, \dots] \qquad \underline{x}(t_0) = \underline{x}_0$$

$$\underline{y}_D = \underline{h}[\underline{x}(t), \underline{u}(t), \underline{\theta}, t, \dots]$$

$$\underline{y}_M(t_k) = \underline{y}_D(t_k) + \underline{n}(t_k)$$

where:

$\underline{x}$ - vector of states
$\underline{y}$ - vector of observations
$\underline{u}$ - vector of control inputs
$\underline{\theta}$ - vector of parameters
$\underline{n}$ - vector of measurement noise
$\underline{t}$ - time
index M - measured
index D - estimated

All equations are allowed to be nonlinear in states and in parameters.
The maximum likelihood estimate of $\underline{\theta}$ is obtained by minimizing the negative log likelihood function:

$$L(\underline{X}|\underline{\Theta}) = \ln p(\underline{X}|\underline{\Theta}) \rightarrow \mathrm{Max}$$

$$L(\underline{X}|\underline{\Theta}) = C_0 - \frac{1}{2} \cdot \sum_{k=1}^{N} \{\underline{y}_M(t_k) - \underline{y}_D(t_k)\}^T \cdot \underline{\underline{R}}^{-1} \cdot \{\underline{y}_M(t_k) - \underline{y}_D(t_k)\} - \frac{N}{2} \cdot \ln|\underline{\underline{R}}|$$

where $\underline{R}$ denotes the measurement noise covariance matrix.
The maximum likelihood estimate of the unknown parameters $\underline{\theta}$ is obtained iteratively using quasi-linearisation method through the equation:

$$\hat{\underline{\Theta}}_{j+1} = \hat{\underline{\Theta}}_j + \Delta\hat{\underline{\Theta}}_j$$

$$\hat{\underline{\Theta}}_{j+1} = \hat{\underline{\Theta}}_j + \left\{\sum_k^N \left(\frac{\partial \underline{y}_D}{\partial \underline{\Theta}}\right)^T \cdot \underline{\underline{R}}^{-1} \cdot \left(\frac{\partial \underline{y}_D}{\partial \underline{\Theta}}\right)\right\}^{-1} \cdot \left\{\sum_k^N \left(\frac{\partial \underline{y}_D}{\partial \underline{\Theta}}\right)^T \cdot \underline{\underline{R}}^{-1} \cdot (\underline{y}_M - \underline{y}_D)\right\}$$

The sensitivity matrix $\partial \underline{y}/\partial \underline{\theta}$ is calculated by numerical differences for small perturbation of the parameter vector Θ. Details of the nonlinear maximum likelihood formulation are described in (Lit.2), (Lit.3).

3. Data compatibility check

Parameter estimation shows erroneous results of the stability and control characteristics (Lit.5), if some of the various data channels are not compatible with the others. Improved accuracy of the identification results can be obtained only with corrected and compatible data. The concept of a data compatibility check using standard kinematic equations of aircraft motion (Lit.6) has been successfully performed in the past by applying Kalman filter or maximum likelihood algorithmus.
The given mathematical model for data compatibility check has been improved step by step using flight test data of the DO 28. This extended model allows to identify offsets, scaling factors and initial values as well as time shifts and wind speeds.

3.1 Aspects to the nonlinear model for compatibiliy check

Assuming a flat nonrotating earth, all inertial states can be easily reconstructed using the standard kinematic equations of aircraft. The vector of airspeed $\underline{V}$ has to be calculated from vector of flight path speed $\underline{V}_K$ and the vector of wind speed $\underline{V}_W$ (fig.2):

$$\underline{V} = \underline{V}_K - \underline{V}_W$$

The wind speed $\underline{V}_W$ is calculated from a quasi stationary geodetic wind-field, whose parameters will be estimated. This approximation fits well, because flight tests for parameter estimation are mostly done in smooth air.
Time shift corrections are also necessary, because the used sensors have different time constants and some of them are not located near the center of gravity. The PCM data recorded may contain some additional random time shifts too. Large parameter estimation failures will occur, if these effects are neglected (Lit.5). These corrections are done iteratively. The time shifts are appoximated with band-limited dynamics of first order (PT1s), whose time constants have to be larger than the data sample interval for proper numerical integration. According to the identified time constants the data are shifted within the next computation run to the compatibility check.
The recorded pitch rate q is limited in its absolute amplitude to 10 degree per second in all flight tests. However, during the exitation sequences the aircraft turnes with pitch rates faster than the recorded limited pitch speed during short periods. Therefore a constant pitch rate Δq_i is additionally estimated for each of the small time intervalls.
The accelerometers are not located in the center of gravity and therefore the measured accelerations a_x and a_z have to be corrected with the pitch rate q and the pitch acceleration.
The angle of attack α is affected by the pitch rate too, because it is measured at the tip of the airplane's noseboom.

3.2 Nonlinear model for compatibility check

All these effects mentioned above, which affect the measured data, have been modelled and have been estimated with the data compatibility check. In the nonlinear kinematic equations the following effects have been included in detail:
The measurement of the control variables a_x, a_z and q are assumed to be biased. The pitch rate q is additionally multiplied with a scaling factor. The measurement of the observation variables pitch angle Θ_f and angle of attack α are assumed to be biased too. The wind field is modelled as quasi stationary function in the two components u_{Wg} and w_{Wg} with linear dependence on time t and flight altitude H. Further all input and observation variables are assumed to be affected by time shifts in reference to the pitch rate q.
These considerations lead to the following nonlinear model for compatibility check:

State equations:

$$\ddot{x} = a_x + b_{ax}$$

$$\ddot{z} = a_z + b_{az}$$

$$q = k_q \cdot q_m + b_{qm} + \Delta q_i$$

$$\Delta q_i = \begin{cases} 0 & \text{for } t < t_{iu},\ t > t_{io} \\ \Delta q_i & \text{for } t_{iu} \leq t \leq t_{io} \end{cases}$$

$$\dot{q} = (q - q_{old}) / \Delta t$$

$$\ddot{x}_\tau = \ddot{x}_\tau + x_{axf} \cdot q^2 - z_{axf} \cdot \dot{q}$$

$$\ddot{z}_\tau = \ddot{z}_\tau + z_{azf} \cdot q^2 + z_{azf} \cdot \dot{q}$$

$$u_{Wg} = u_{Wgo} + u_{Wgt} \cdot (t - t_o) + u_{Wgh} \cdot (H - H_o)$$

$$w_{Wg} = w_{Wgo} + w_{Wgt} \cdot (t - t_o) + w_{Wgh} \cdot (H - H_o)$$

$$u_f = u_{Kf} - (u_{Wg} \cdot \cos\theta - w_{Wg} \cdot \sin\theta)$$

$$w_f = w_{Kf} - (w_{Wg} \cdot \cos\theta + u_{Wg} \cdot \sin\theta)$$

$$\alpha = \text{atg} \quad (w_f - x_{\alpha cg} \cdot q_\tau)/u_f)$$

$$V = \sqrt{u_f^2 + w_f^2}$$

$$GS = u_{Kf} \cdot \cos\theta + w_{Kf} \cdot \sin\theta$$

$$\dot{H} = u_{Kf} \cdot \sin\theta - w_{Kf} \cdot \cos\theta \qquad H(t_o) = H_o$$

$$\dot{u}_{Kf} = \ddot{x}_\tau - g \cdot \sin\theta - q \cdot w_{Kf} \qquad u_{Kf}(t_o) = u_{Kf_o}$$

$$\dot{w}_{Kf} = \ddot{z}_\tau - g\,(1 - \cos\theta) + q \cdot u_{Kf} \qquad w_{Kf}(t_o) = w_{Kf_o}$$

$$\dot{\theta} = q \qquad \theta\,(t_o) = \theta_o$$

band limited PT_1 $(T_i \geq \Delta t)$

$$\dot{\theta}_{f\tau} = -(\theta_{f\tau} - \theta) / T_{\theta f} \qquad \theta_{f\tau}\,(t_o) = \theta_o$$

$$\dot{\theta}_{I\tau} = -(\theta_{I\tau} - \theta) / T_{\theta I} \qquad \theta_{I\tau}\,(t_o) = \theta_o$$

$$\dot{GS}_\tau = -(GS_\tau - GS) / T_{GS} \qquad GS_\tau\,(t_o) = GS_o$$

$$\dot{H}_\tau = -(H_\tau - H) / T_H \qquad H_\tau\,(t_o) = H_o$$

$$\dot{V}_\tau = -(V_\tau - V) / T_V \qquad V_\tau\,(t_o) = V_o$$

$$\dot{\alpha}_\tau = -(\alpha_\tau - \alpha) / T_\alpha \qquad \alpha_\tau\,(t_o) = \alpha_o$$

$$\dot{q}_\tau = -(q_\tau - q) / (x_{\alpha cg} / V) \qquad q_\tau\,(t_o) = q_o$$

$$(\ddot{x}_\tau)^{\cdot} = -(\ddot{x}_\tau - \ddot{x}) / T_{ax,\,az} \qquad \ddot{x}_\tau\,(t_0) = \ddot{x}_0$$

$$(\ddot{z}_\tau)^{\cdot} = -(\ddot{z}_\tau - \ddot{z}) / T_{ax,\,az} \qquad \ddot{z}_\tau\,(t_0) = \ddot{z}_0$$

Observation equations:

$$Y_1 = \theta_{I\tau}$$

$$Y_2 = \theta_{f\tau} + b_{\theta f}$$

$$Y_3 = H_\tau$$

$$Y_4 = GS_\tau$$

$$Y_5 = V_\tau$$

$$Y_6 = \alpha_\tau + b_\alpha$$

The following problems arouse because of improper modelling:
A bias estimated for the pitch angle from the INS platform Θ_I has to be removed of the model because it were strong correlated with the time shift of flight altitude τ_H. A scaling factor for the angle of attack $f\alpha$ did not give satisfactory results too. The scatter of its estimated value was too big. The stationary wind speed w_{Wg0} is assumed to be zero for most of the runs of the compatibility checks. The value of this wind component is relatively small and does not change the other results exept of the time shift of the flight altitude τ_H and the bias of the angle of attack $b\alpha$, on the other hand estimation of w_{Wg0} reduces much the convergence speed of the compatibility check.

4. Compatibility check of measured aircraft data

The DO 28 aircraft, flying in clean configuration at about 2000 ft altitude, was trimmed at 85 kt and 100 kt indicated airspeed. Flight tests with other speed will follow in the near future. At each trim flight condition, several flight tests have been carried out with different multistep elevator inputs (Lit.7) commanded by the on-board computer.
The compatibility check is done with a sample frequency of about 46 cps and a set of data which comprises the whole phugoid sequence.

4.1 Results of the data compatibility check

All resulting time histories of the data compatibility check give good matches with the measured data as is shown in figure 3. The assumed linearised wind model does not account for stochastic wind disturbance. Therefore in some flight test data some poor match of the angle of attack is seen (figure 4), but the match of the other time histories is still good. The estimated data corrections are listed in table 1 for all runs. These results can be summarized as follows:

1. Bias errors in the measurement of the control variables pitch rate q and accelerations a_x and a_z are small and practically negligible. The bias of a_x increases slightly with the pitch angle.
2. The scaling of the pitch rate q is approximately 0,875, therefore the measured pitch rate is about 12,5% bigger than the real (estimated)one.
3. The bias of the measured pitch angle $b_{\Theta f}$ is about 2° for all flight tests.
4. The bias of the measured angle of attack $b\alpha$ varies from the flight test to flight test because the wind component w_{Wg0} is not modelled.
5. The estimated time shifts of the data differ widely. The differences mostly can be traced to failures in the PCM data records and to stationary values of w_{Wg0}.
6. The used quasi-stationary wind model is a good approximation of the reality in most cases, but sometimes some gust effects can still be seen in the recorded data.

5. Parameter estimation after compatibility check

The parameter estimation is calculated with unmodified data records. All identified bias, scaling factors, wind speeds and time shifts estimated in the model for compatibility check are included into the parameter estimation model as constants. This procedure works quite well, as shown in figure 5 all measurement is good matched. The match of the measurement time histories is somewhat worse compared with those of the compatibility check. That is because the parameter estimation model contains no information about process noise contrary to the model of the compatibility check which uses the measured accellerations as input signals. Gust effects change the forces acting on the aircraft (Lit. 4) and the forced accellerations are measured by accelerometers with high bandwith.
Estimated parameter sets of different flight tests of the same trim speed show comparable values. However parameter sets estimated for different trim speed show small variations of the polar curve, especially the point of minimum drag differs. This effect can be explained physically. The different flight tests done with different trim speed are using different regions of the polar curve. The coefficient of lift C_A for stationary trim flight

$$C_A = \frac{2 \cdot m \cdot g}{\rho \cdot V^2 \cdot S}$$

illustrates this interrelation. A parameter estimation using two or more flight tests with different trim speed is expected to calculate a more sophisticated parameter set.

6. Concluding Remarks

A process for the compatibility check of measured aircraft responses has been presented. For the longitudinal motion this process includes the estimation of bias errors, scaling factors, time shifts and a quasi-stationary wind field. This procedure works quite well and will be extended to six-degree-of freedom in future.

7. Literatur

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6. Application of the Kalman Filter to Flight Path Reconstruction From Flight Test Data Including Estimation of Instrumental Bias Error Corrections, H.L. Jonkers, Ph.D. Thesis, Technol. Univ. Delft (Netherlands).
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8. Table of compatibility check results

	test 1 85 kt	test 2 85 kt	test 3 85 kt	test 4 100 kt	test 5 100 kt	test 6 100 kt
uv0/10^{1}	5.245	4.894	4.831	5.859	4.492	4.542
wv0	7.722	6.785	7.234	5.275	4.013	4.056
th0/10^{-1}	1.478	1.319	1.171	0.774	0.869	0.652
bax/10^{-2}	-5.249	-1.553	-1.948	-2.151	-1.707	-1.296
baz/10^{-2}	7.650	8.816	8.203	7.149	8.439	8.758
bq/10^{-2}	-2.892	-2.955	-3.077	-3.175	-2.885	-3.086
bthf/10^{-2}	2.235	3.648	3.791	3.275	5.217	3.705
bal/10^{-2}	-7.123	-4.942	-5.867	-4.679	-6.546	-5.811
kq/10^{-1}	8.738	8.702	8.743	8.801	8.801	8.741
time shifts:						
t-ax	- 3	2	52	33	19	4
t-az	- 3	2	52	33	19	4
t-thi	- 2	- 3	- 2	- 2	- 2	- 2
t-thf	4	6	4	30	4	5
t-hb	- 16	- 18	- 19	- 40	- 16	- 5
t-gs	- 13	- 15	- 15	11	- 14	- 17
t-tas	5	12	- 7	- 24	- 8	- 4
t-al	3	4	10	4	1	3
t-hp		- 18				

9. Pictures

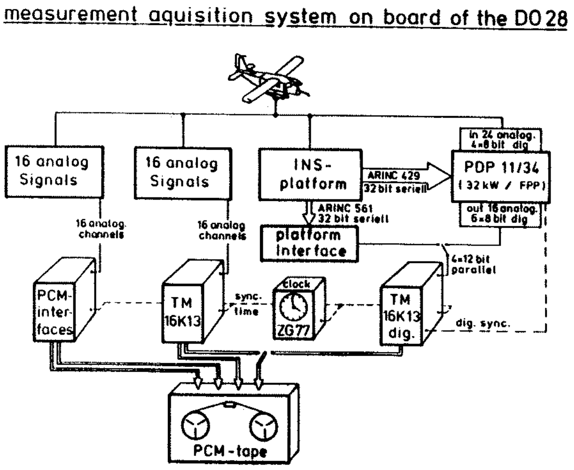

figure 1: Sensors and data aquisition on-bord

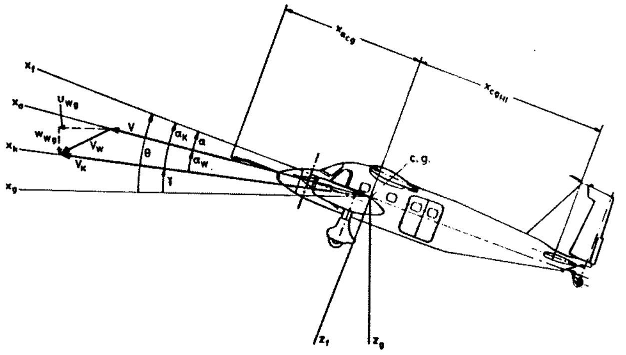

figure 2: Vectors of speed in longitudional motion

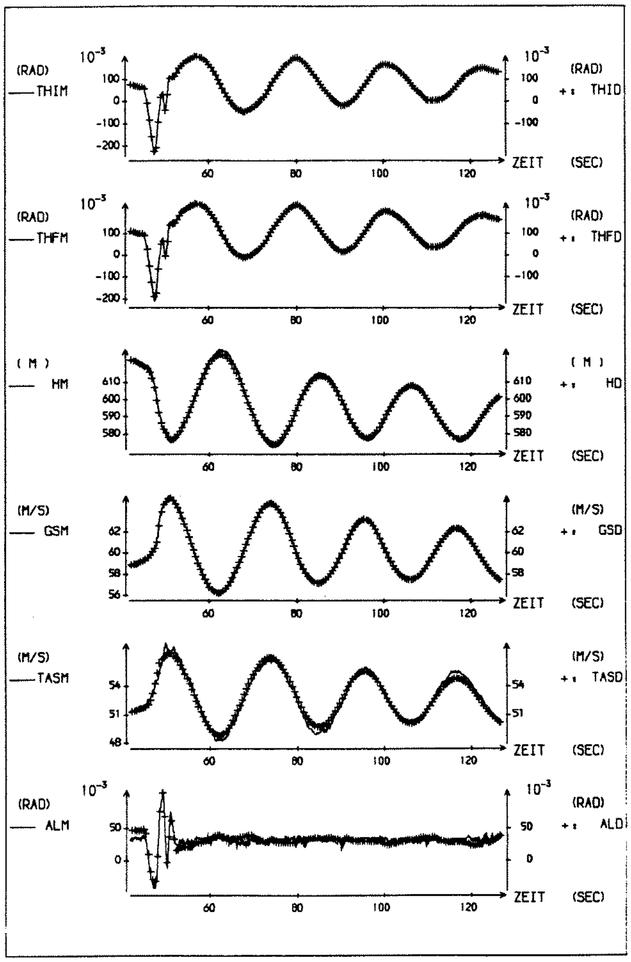

figure 3: Data combatibility check estimated versus measured data

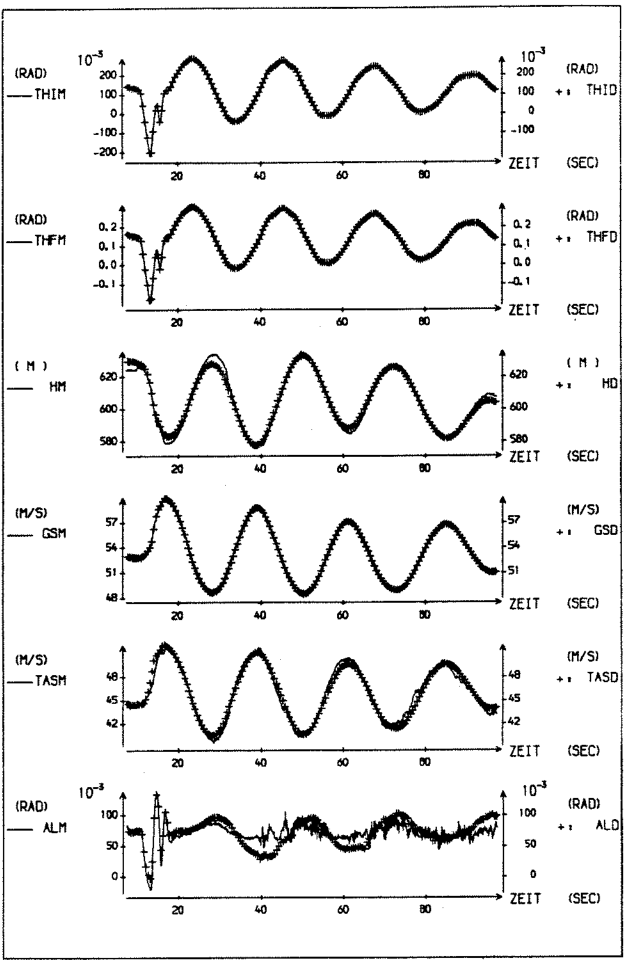

figure 4: Data combatibility check estimated versus measured data with gust effects

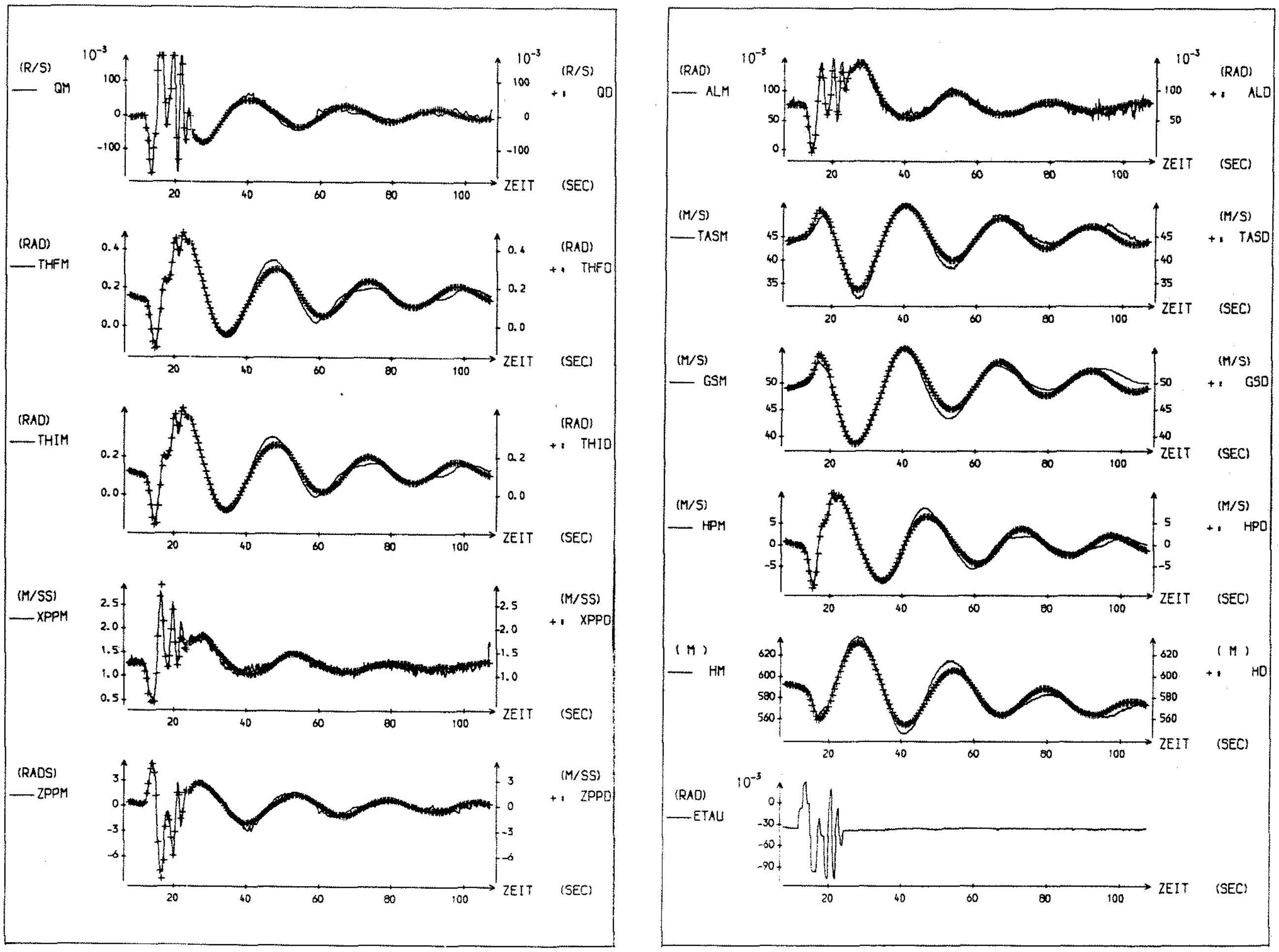

figure 5: Parameter identification estimated versus measured data