A METHOD TO DERIVE THE USAGE OF HYDRAULIC ACTUATORS FROM FLIGHT DATA

H. Kannemans, H.W. Jentink
National Aerospace Laboratory, NLR
Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

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Abstract

The quantification and prediction of the health status of aircraft are challenging aspects of Prognostics and Health Management (PHM). The Dutch PHM Consortium (DPC[1]) develops concepts for prognostics and health management of aircraft. Within this framework there is a need to know the operation of the hydraulic system in flight. Usage data can be derived from data measured with dedicated sensors, but to keep aircraft weight, sensor failures and costs as low as possible there is a requirement to minimise the number of such sensors. Therefore a technique is developed to derive information about the operation of the hydraulic system from parameters measured during the flight for general purposes, the recorded flight data. Condition Parameters and Remaining Life Time of components can be derived with the technique. The force produced by the hydraulics and the displacements of the piston, being representative parameters for wear, can be calculated from flight data and an aerodynamic model of the aircraft. In terms of flight mechanics the actuator displacement and force on the actuator are directly related to control surface deflection and hinge moment. These two parameters are calculated applying flight simulation models and flight data. The technique and some results for the RNLAF (Royal Netherlands Air Force) F-16 are presented.

Notation

B	wing span
$\bar{c}$	mean aerodynamic chord
C_D	nondimensional aerodynamic drag coefficient
C_h	nondimensional aerodynamic hinge moment coefficient
C_l	nondimensional aerodynamic roll moment coefficient
C_m	nondimensional aerodynamic pitch moment coefficient
C_n	nondimensional aerodynamic yaw moment coefficient
D	drag
h	altitude
M	Mach number
p	roll rate
q	pitch rate
q_c	dynamic pressure
r	yaw rate
S	reference surface
V	velocity
α	angle of attack
β	angle of side slip
δ_a	flaperon deflection
δ_e	elevator deflection
δ_r	rudder deflection

[1] The work presented in the paper is based on activities performed by the Dutch PHM Consortium (DPC). Partners are: Perot Systems Nederland B.V. - active in the area of software in Prognostic and Health Management systems for IT environments, Agent Technology, Machine Learning, Data Mining, Data Warehousing and IT integration. National Aerospace Laboratory NLR - the central institute in the Netherlands for aerospace research and development, active in monitoring aircraft subsystems and data analysis using the FACE technology, PHM demonstrator and domain knowledge, TNO TPD Netherlands Organization for Applied Scientific Research - active in sensors, acoustics, materials, instrumentation, optics, measurement techniques and PHM for subsystems. SUN Electric Systems - active in the area of hardware like sensors, measurement techniques, maintenance and testing of aircraft subsystems and ground support equipment.

Subscripts

SB	speed brake
UC	under carriage
0	basic coefficient

Abbreviations

CP	Condition Parameter
DPC	Dutch PHM Consortium
FACE	Flight fatigue Analysis and Combat Evaluation system
NLR	National Aerospace Laboratory
PHM	Prognostics and Health Management
PROMIS	PROGnostics by Model based Interpretation of Signals
RNLAF	Royal Netherlands Air Force
rms	root-mean-square

1 Introduction

Prognostics and Health Management is a technique with potentially considerable logistic and maintenance profits. The knowledge of the current and the prediction of the future health state of components in aircraft may guide the maintenance activities and spare parts logistics. One of the subsystems to be monitored is the hydraulic system of the aircraft. A concept has been adopted in the DPC for the information exchange in the PHM system. For the hydraulic system, and for other subsystems, the health states are quantified applying the PROMIS concept [1] which is based on the trending and prognostics of condition parameters (CPs). CPs of the components in the hydraulic system depend on how the system is used. The use can be derived from data measured with sensors, but to keep aircraft weight, sensor failures and costs as low as possible there is a requirement to minimise the number of sensors. Therefore a technique is developed to calculate the use from parameters measured during the flight for general purposes, the recorded flight data.
From literature it is clear that the condition of a hydraulic actuator is dependent on piston displacements and its operating pressures during its life cycle [1], [2], [3], [4] and [5]. Displacements are expressed both in the total travel distance and the number of reversals of travel direction. The actuator use is sometimes defined in a number of cycles for the actuator [2]. The force produced by the hydraulics and the displacements of the piston, being the representative parameters for wear, can be calculated, as will be demonstrated in the present study using RNLAF F-16 flight data and aerodynamic data. A generic concept is developed that can be applied to existing or future aircraft.
The hydraulic actuators for the control surfaces are for the F-16, as for most aircraft, the largest actuators causing most of the fluid flow in the hydraulic system. There is a focus on these actuators for health management in hydraulic systems. In terms of flight mechanics the actuator displacement and force on the actuator are directly related to control surface deflection and hinge moment respectively. These two parameters are calculated in flight simulation models. The relationships are applied in the present study to obtain time series of these parameters, where flight data time series are the input. The approach described in this report is based on following two starting points:

1. **The flight mission is known.** The flight path flown by the aircraft is available, e.g. in the general flight data format (flight data recorder).
2. **The aerodynamic model is known** from wind tunnel measurements as usually applied in simulator models and may be derived from an existing simulator model.

Not only the usage of actuators of the control surfaces can be retrieved without failure prone sensors using the approach, but also other actuators acting against aerodynamic forces. Examples given in this report are the actuators for the undercarriage and the speed brakes.
The technique described in this report has considerable potential for estimating CPs of hydraulic actuators. The information of the operation of the hydraulic system also gives insight in additional parameters of the hydraulic system such as the total hydraulic fluid flow in the system. These insights are applied in other

tasks of the PHM project. The total flow in the system and the fluctuations in the flow are determining the loads on the hydraulic pumps and pressures over filters [1]. The output of the model is therefore input for tests in the on-ground hydraulics system test bench, for simulation activities and for the development of PHM algorithms for the hydraulic system.
In this study two different starting points for the proposed method are analysed: (1) flight data from a FACE measurement system and (2) flight test data from the NLR measurement system. The NLR measurement system [6] allows the registration of control surface deflections enabling validation of predicted control surface deflections.

2 Theory

The theory on the technique developed during this study is based on the assumptions that the mission is known and the aerodynamic model is known, allowing the determination of the required two control surface parameters (deflection and hinge moment) accurately applying advanced software modules.
As depicted in figure 1 the following modelling steps can be distinguished:

1. define flight mission resulting in a 4 dimensional (3 position co-ordinates and time) track,
2. compute control surface deflections as a function of time, by applying an aerodynamic simulator model inversely,
3. determine hinge moments applying the (same) simulator model.

The first step, defining the flight mission, can be skipped in case the analysis starts from in-flight recorded data preferably including speed, altitude and attitude rates (e.g. FACE-data of at least 25Hz). The first two steps can be skipped in case the in-flight recorded data includes control surface deflection parameters (e.g. as delivered by the NLR measurement system installed in the F-16).
As high accuracy is not needed for the purpose of health monitoring, simplifications can be applied in the flight model and as a result the simulations will run quickly. A simplification will be the replacement of a full free-flight six degrees of freedom aerodynamic model by a simple three degrees of freedom model containing the aerodynamic moment models only.
The simplified aerodynamic model reads as follows:
pitch moment equation

$$
\begin{aligned}
C_m = {} & C_{m_0}(M,\alpha,h) + C_{m_\alpha}(M,\alpha,h)\alpha \\
& + C_{m_q}(M,\alpha,h)\frac{q\bar{c}}{V} + C_{m_{\dot{\alpha}}}(M,\alpha,h)\frac{\dot{\alpha}\bar{c}}{V} \\
& + C_{m_{\delta_e}}(M,\alpha,h)\delta_e
\end{aligned}
$$

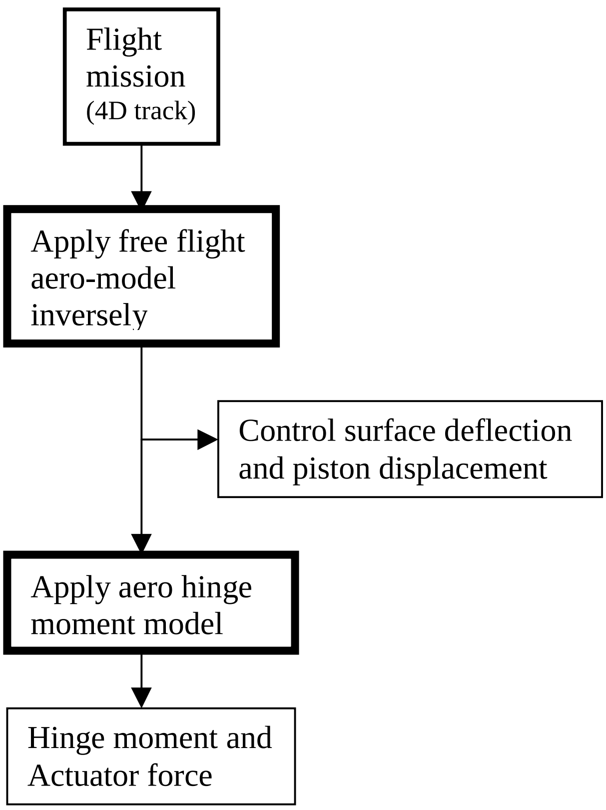

Figure 1 Simulation of control surface actuator parameters.

roll moment equation

$$C_l = C_{l_0}(M,\alpha,h) + C_{l_\beta}(M,\alpha,h)\beta + C_{l_p}(M,\alpha,h)\frac{pb}{2V}$$
$$+ C_{l_r}(M,\alpha,h)\frac{rb}{2V} + C_{l_{\dot\beta}}(M,\alpha,h)\frac{\dot\beta b}{2V} +$$
$$+ C_{l_{\delta_a}}(M,\alpha,h)\delta_a + C_{l_{\delta_r}}(M,\alpha,h)\delta_r$$

yaw moment equation

$$C_n = C_{n_0}(M,\alpha,h) + C_{n_\beta}(M,\alpha,h)\beta + C_{n_p}(M,\alpha,h)\frac{pb}{2V}$$
$$+ C_{n_r}(M,\alpha,h)\frac{rb}{2V} + C_{n_{\dot\beta}}(M,\alpha,h)\frac{\dot\beta b}{2V} +$$
$$+ C_{n_{\delta_a}}(M,\alpha,h)\delta_a + C_{n_{\delta_r}}(M,\alpha,h)\delta_r$$

These three equations do have three unknowns. These unknowns are:

elevator deflection $\delta_e = (\delta_{e_1} + \delta_{e_2})/2$
aileron deflection $\delta_a = (\delta_{a_1} + \delta_{a_2})/2$
rudder deflection δ_r

Following approximations may very well be made:

1. the coefficients $C_\bullet$(M,α,h) ($C_\bullet$ stands for derivatives of C_m, C_l and C_n) are usually available as look-up tables as is the case for the method presented in this study; eventually they may be simplified by replacing them by low order polynomial functions or may even be simplified to constants,
2. neglecting the side force equation which is already out of the three degrees of freedom model suggests to neglect the side slip angle β as well, since in-flight data usually does not include the angle of sideslip, therefore this simplification has been adopted in the actual study,
3. from the three body attitude accelerations the aerodynamic moments C_m, C_l and C_n can be computed, assuming the moments of inertia are known,
4. the three moment equations can be resolved now for the unknowns δ_e, δ_a and δ_r, in this study it is assumed that the flaperon does not affect the yaw moment and the rudder does not affect the roll moment.

At this point the control surface deflections are known and the computation of the hinge moments can be started and turns out to be straightforward.
The aerodynamic hinge moment model for the aileron control surfaces usually reads:

$$C_{h_a} = C_{h_{0_a}}(M,h) + C_{h_{\alpha_a}}(M,h)\alpha + C_{h_{\delta a_\bullet}}(M,h)\delta_a$$

for the elevator control surfaces:

$$C_{h_e} = C_{h_{0_e}}(M,h) + C_{h_{\alpha_e}}(M,h)\alpha + C_{h_{\delta\alpha_e}}(M,h)\delta_e$$

and for the rudder control surface:

$$C_{h_r} = C_{h_{r\beta}}(M,h)\beta + C_{h_{\delta_r}}(M,h)\delta_r$$

To assess the use of actuators to move the under carriage and speed-brake, the analysis starts from the drag equation:

$$C_D = C_{D_0}(M,\alpha,h) + C_{D_{\alpha^2}}(M,\alpha,h)\alpha^2$$
$$+ \Delta C_{D_{UC}}(M,\alpha,h) + \Delta C_{D_{SB}}(M,\alpha,h)$$

The separate drag terms for under carriage and speed brake indicate the force acting on these structures and will be used as basis to compute the forces on the driving actuators. In addition for the under carriage also the gravitational force has to be taken into account.

3 Results

3.1 Results for FACE data processing

As an example processed FACE data of 25 Hz are shown in figure 2 for pitch motion related parameters. The FACE data were recorded on board the F-16. From the known aircraft state parameters the right elevator deflection has been computed. As a following step the right elevator hinge moment has been computed.

3.2 Results for NLR measurement system data processing

3.2.1 Measured and simulated data

Processed NLR measurement system data are shown in the figures 3a through 3c. The data used to produce the results shown in the figures 3 were recorded on a flight with the F-16.

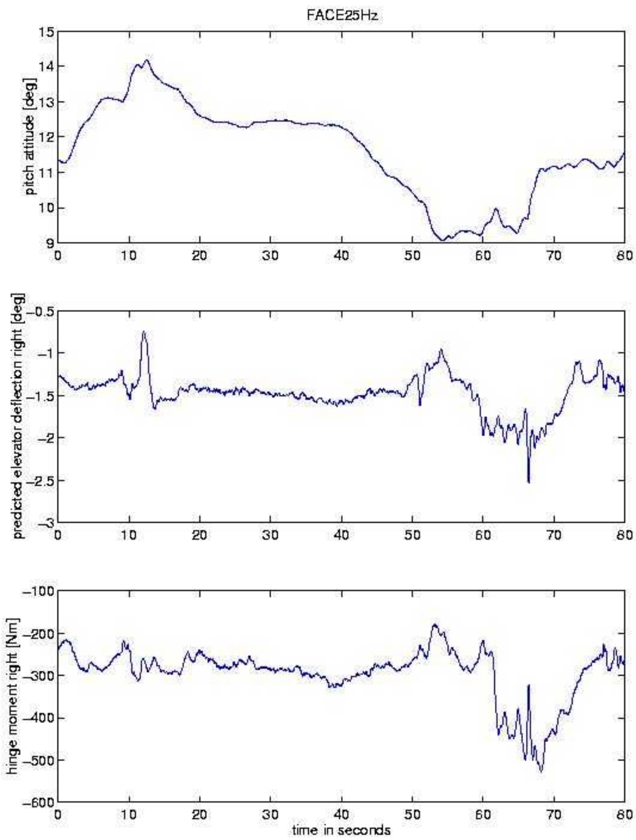

Figure 2 Results from FACE data (25 Hz); pitch motion related parameters (top: pitch attitude, middle: predicted elevator deflection, bottom: hinge moment).

3.2.2 Analysis

It turns out that good agreement exists for the flaperon deflection (see the second window of the figures 3a and 3b). The predicted elevator deflection seems to be underestimated at least for a part of the time (see the second window of the figure 3b). Some further analysis did show that the error in the predicted elevator deflection correlates with the angle of attack. This fact indicates that the influence of the angle of attack on the elevator effectiveness was insufficiently incorporated in the aerodynamic model. There is a significant discrepancy between the measured and predicted rudder deflection (see the second window of figure 3c).

This discrepancy may partly be caused by a slip angle (not measured). Therefore it is recommended to determine the side slip angle during follow-on research. The side slip angle can be estimated assuming a constant zero wind field.

In general a very accurate match between measured and predicted control deflection cannot be expected since the wind tunnel data on which the aerodynamic model is based are slightly different with respect to the real flight case and in addition minor differences may result from the applied simplifications in the aerodynamic models.

Nevertheless the results obtained are useful to predict the displacements and forces of the piston of the control surface actuators during the development phase of a PHM system. It is concluded that the approach developed to derive essential information about the operation of the hydraulic system works satisfactorily.

3.2.3 Characteristic usage figures

Each particular manoeuvre of the aircraft reduces the remaining lifetime in a characteristic way. Therefore characteristic usage figures have been computed for each manoeuvre based on the recorded flight data. Two characteristic usage figures will be discussed here: the accumulated piston displacement and the rms of the actuator force. These figures can be used to compute life time consumption once the characteristic wear figures become available from the manufacturer. The usage figures are computed in two different ways: (1) based on measured control surface deflections and (2)

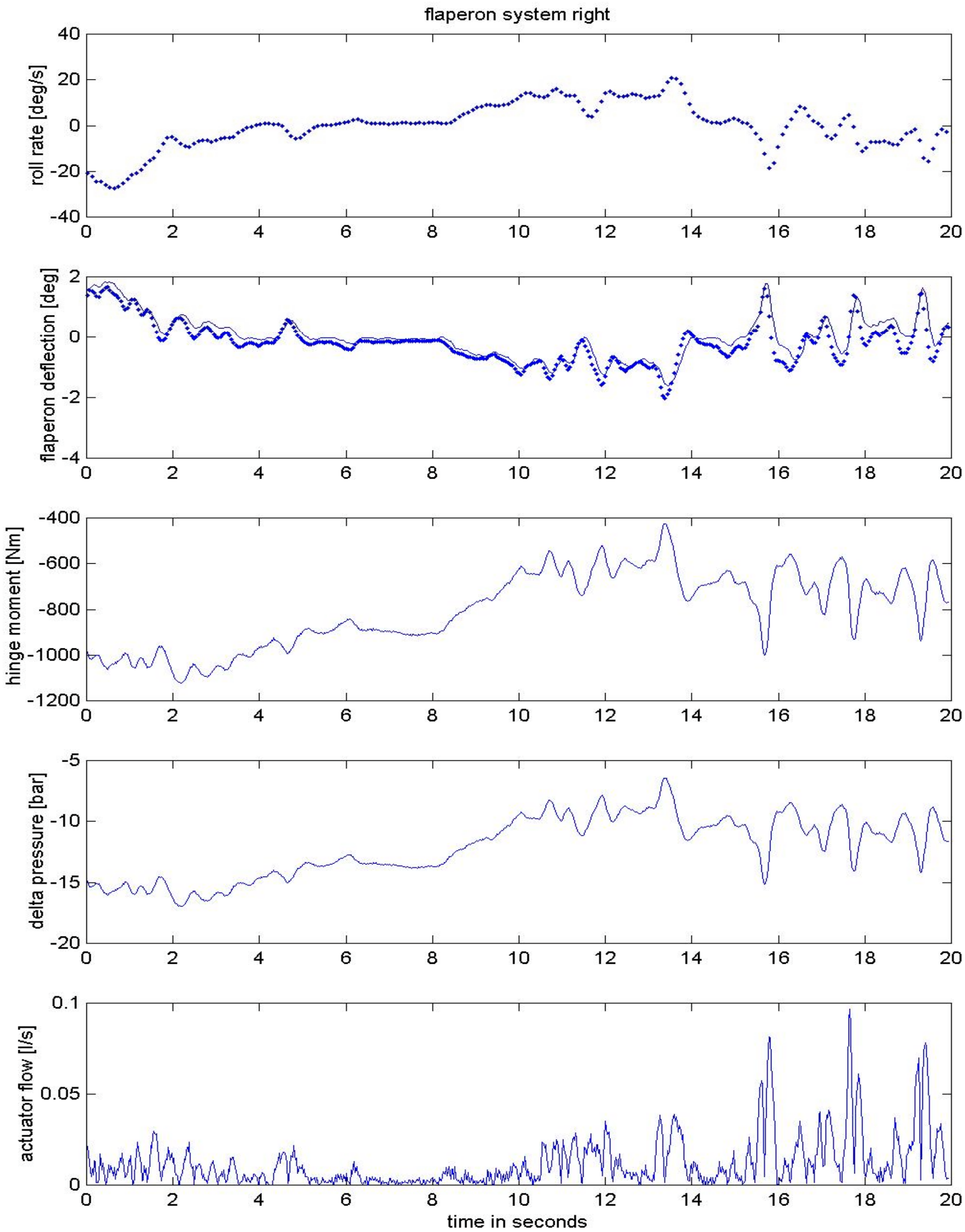

Figure 3a Results from NLR measurement system data; parameters related to the right flaperon system; the thick dotted lines show directly measured data, the thin drawn lines show predicted data.

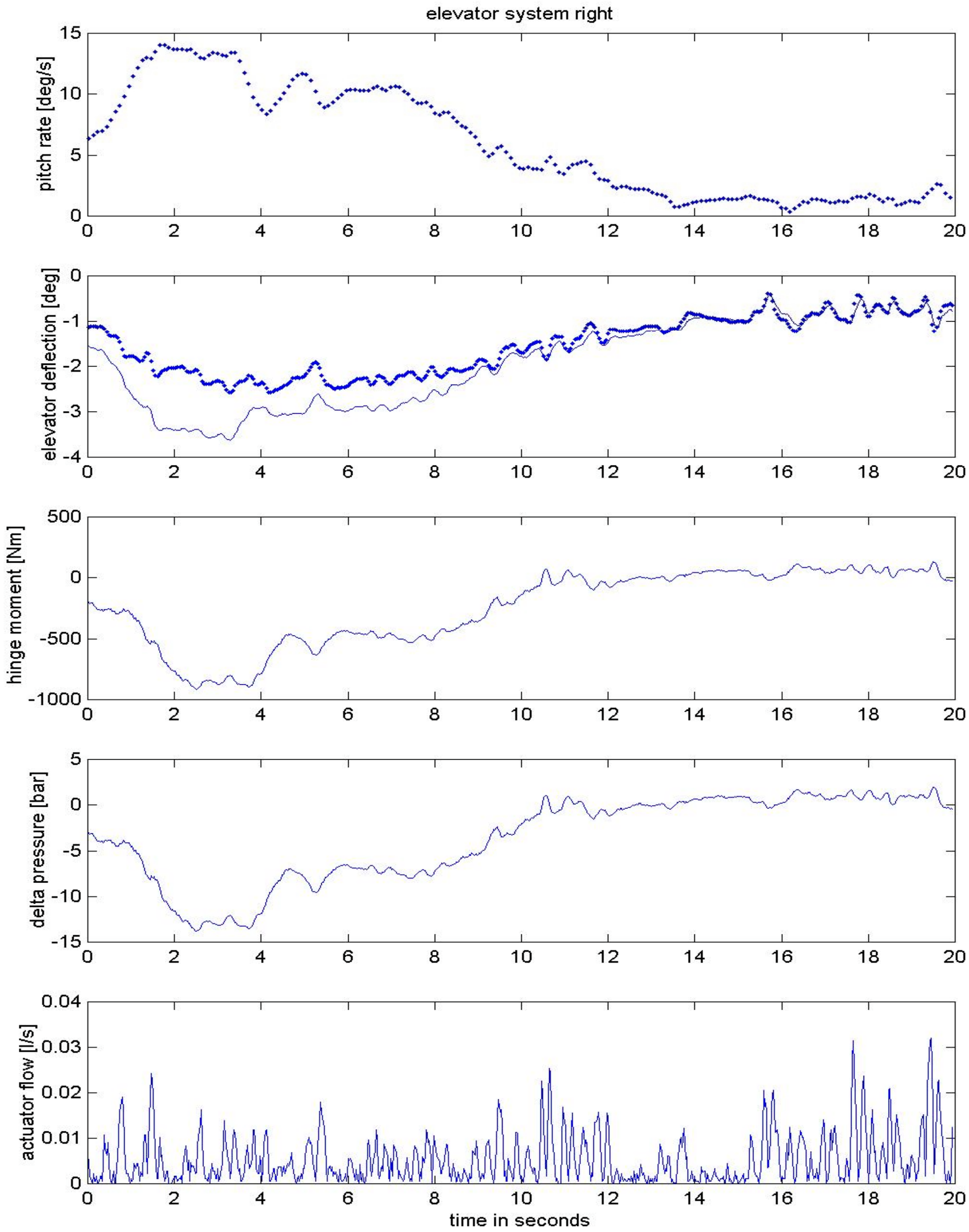

Figure 3b Results from NLR measurement system data; parameters related to the right elevator system; the thick dotted lines show directly measured data, the thin drawn lines show predicted data.

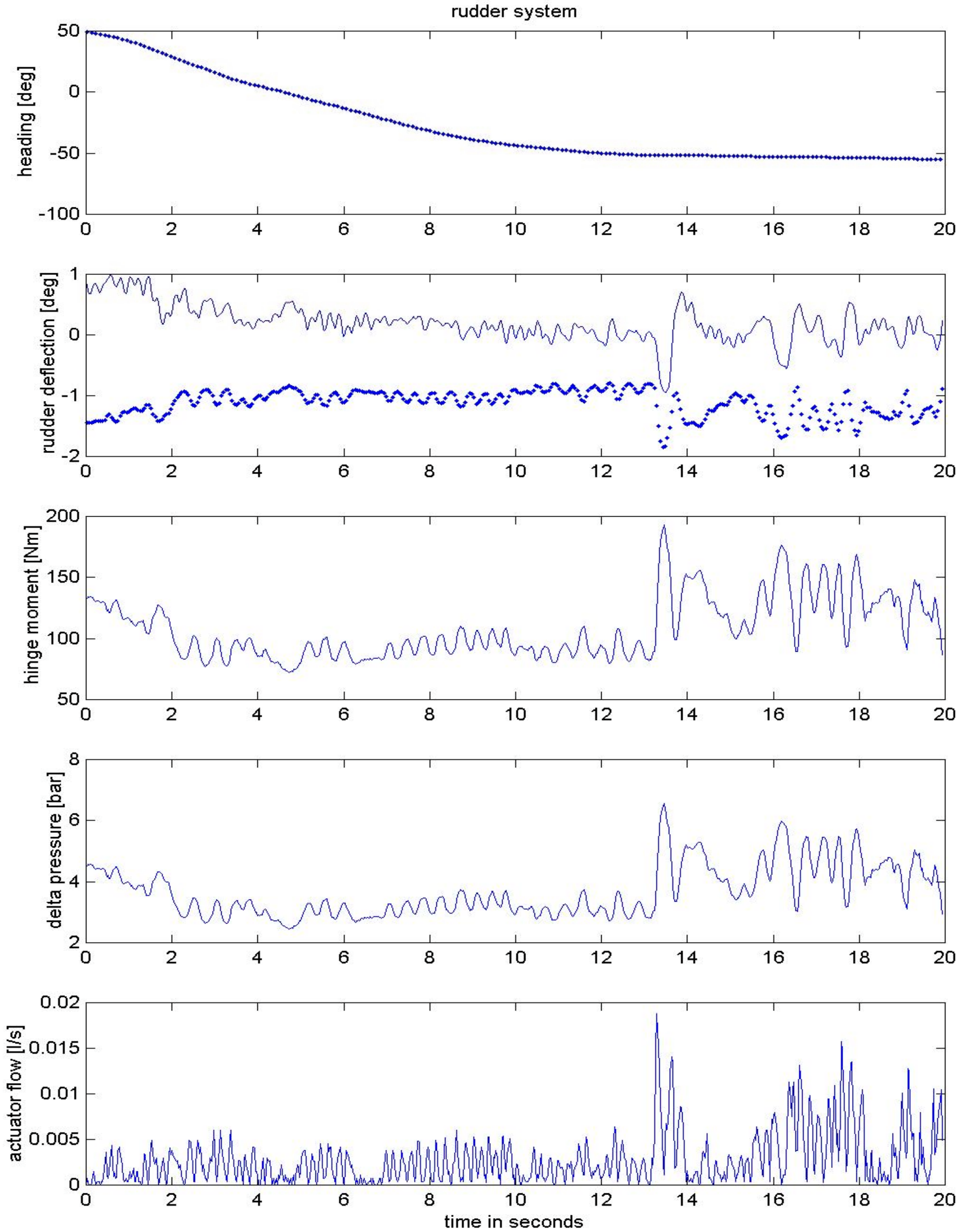

Figure 3c Results from NLR measurement system data; parameters related to the rudder system; the thick dotted lines show directly measured data, the thin drawn lines show predicted data.

based on predicted control surface deflections. The difference between predicted and measured result is the error in the predicted usage figures.

In order to gain more insight these errors are plotted in figure 4a for five successive manoeuvres. The plots of figure 4a show strong correlation between the errors and the magnitude of the usage figures. Therefore these errors can be reduced. A possible explanation for the errors is that the surface deflection derivatives being linear or linearised in the aerodynamic model are in reality non-linear. Since the observed errors are strongly correlated, these errors can be significantly reduced by calibrating the usage figures with the results of the flight test data.
Applying the calibrations, depicted in figure 4a as straight lines, the errors reduce significantly (see figure 4b).
Note that the calibration of the usage figures, can, as an alternative, be replaced by the calibration of more fundamental data, applied in an earlier stage of the prediction method, such as calibration of the aerodynamic model or the calibration of the predicted control surface deflection.

3.3 Results for under carriage

Actually no flight test time series data are available for the under carriage and speed-brake of the F-16. As a consequence the forces acting on these structures can only be computed for one or more well-defined conditions. As an example table 1 shows a simulation result for the under carriage at the condition Mach = 0.3, altitude = 0 m and angle of attack = 10^{o}. Note that the hydraulic flow can be computed since the retraction time of the under carriage is known.

4 Conclusions

A technique is developed to derive information about the operation of the hydraulic system of a aircraft from flight data. Aerodynamic and flight mechanics models are utilised for the technique. Usage information of hydraulic components and insight in the operation of the hydraulic system in an aircraft can be retrieved with the technique.

Table 1: Simulation result for the under carriage

Condition	Mach number	0.3
	Altitude	0 m
	Angle of attack	10^{o}
Prediction	Maximum hinge moment main gear left	44.8 Nm
	Maximum hinge moment main gear right	44.8 Nm
	Maximum hinge moment nose gear	22.4 Nm
	Maximum pressure difference piston left	7470 Pa
	Maximum pressure difference piston right	7470 Pa
	Maximum flow left	0.82 l/s
	Maximum flow right	0.82 l/s

The technique was applied for the RNLAF F-16. Recordings of speed, altitude and attitude rates were gathered for several manoeuvres. Aerodynamic parameters of the F-16 were retrieved from simulation models. By processing these data it was demonstrated for the flight control surface actuators and for the undercarriage actuator that the parameters necessary for calculating CPs of actuators can be deduced.
Several simplifications were introduced in models to keep calculation times short. A test of the technique was the comparison of the measured deflections of flight control surfaces with calculated deflections. It turns out that acceptable agreement exist for the flaperon and elevator deflections. However, the rudder deflection shows poor agreement. The poor agreement in rudder deflection is still not well understood, but omitting the side slip and herewith side wind effects might be the reason. This study shows that the technique will be useful to predict the displacements and forces of the piston of the control surface actuators

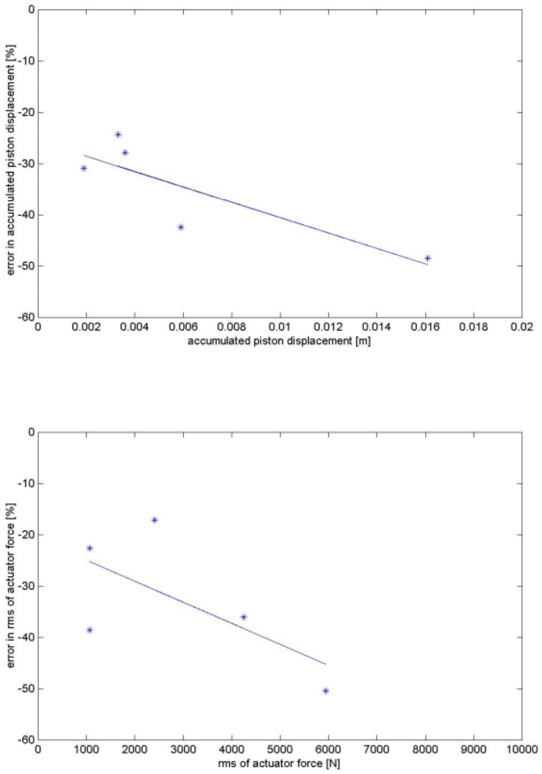

Figure 4a Correlation of errors in the prediction as function of the magnitude of usage figures for the elevator system (the straight lines indicate the best fit; top: accumulated piston displacement, bottom: rms of actuator force).

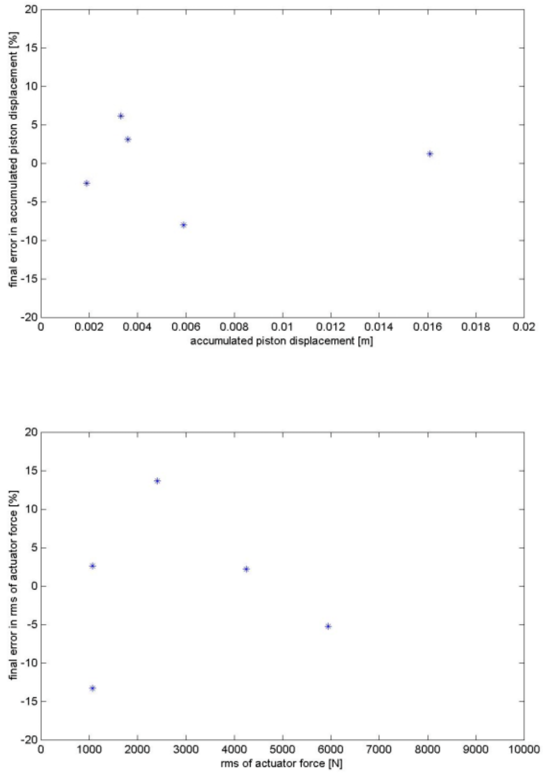

Figure 4b Errors in the prediction as function of the magnitude of usage figures for the elevator system after calibration (top: accumulated piston displacement, bottom: rms of actuator force).

system. Also information about hydraulic fluid flow and pressures in the system as a function of time is obtained. The predicted fluid flow and pressures may control a hydraulic test rig.

The method developed gives insight in the operation of a hydraulic system such that it can be used for:

- PHM development
- usage determination
- test rig simulations.

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