ON-LINE SIMULATION AS A MEASURE TO INCREASE SAFETY IN FLIGHT-TESTING OF HIGH PERFORMANCE AIRCRAFT

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Abstract

Testing of modern high performance aircraft is performed in an environment that includes a considerable amount of modelling and simulation. An initial flight clearance is given based on the outcome of comprehensive pre-flight investigations. During flight test then the initial envelope is explored cautiously towards the given limitations. The model is validated with flight test analysis results. Depending on the outcome of these validations a refinement of the clearance will be required.

At DaimlerChrysler Aerospace AG (DASA) this envelope expansion process is being supported by "Parallel Simulation". It is made up in such a manner that a non-linear simulation model is operated simultaneously while the test aircraft is up in the air flying. Immediately before execution of a particular manoeuvre the simulation model is set up in a way that it is driven solely by pilot's inputs via telemetry. Flight mechanical equations for estimation of an aircraft's new state are being integrated independently. Thus this process provides a comparison of traces of aircraft state variables (calculated versus measured) in real-time. Results illustrate how this tool is being used. The tool mainly proves that the model qualitatively represents the real aircraft. For certain investigations also quantitative agreement can be achieved.

1. Introduction

Modern technologies in aeronautics provide development engineers with a variety of highly sophisticated development tools. One of these tools is simulation. It is based on mathematical models as well as on more or less detailed data bases, which describe the properties of the test article. These models are derived from e.g. windtunnel measurements or theoretical calculations. Simulation methods have inherent uncertainties and tolerances, which are known, though. Nevertheless, prior to flying, information on the e.g. dynamic behaviour of the test article is based only on these models. Since flight test takes place at the end of the development process of an aircraft, it must, prior to flying, rely only on system information, which is based on these models. For the purposes of this paper aerodynamic modelling will be of the most interest, but there are also other disciplines which are just as important.

There have been wide discussions on the role of modelling and simulation in the entire development process, especially in conjunction with flight test. These were often based on the fact, that running a simulator is less expensive than conducting a test flight. W. J. Norton, amongst many others, discusses the balance between both in [1]. The purpose of this paper now is to show how flight test as well as modelling and simulation can be used simultane-

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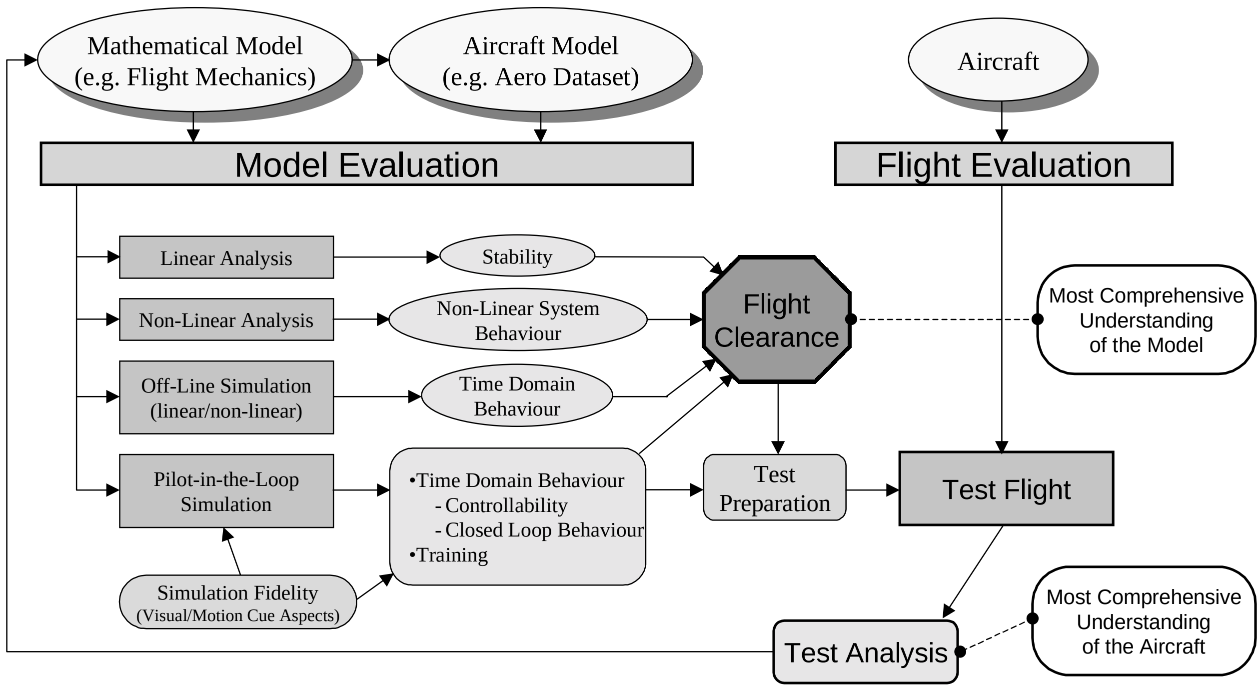

Fig. 1: Simulation and Flight Test

ously in order to increase safety and effectiveness of flight test.

The strong coupling between modelling and simulation on one side and flight test on the other is illustrated in Fig. 1. Model evaluation is based on mathematical models (e.g. the 6 DOF flight mechanical equations) and data bases (e.g. aerodynamic datasets). System dynamic behaviour can now be evaluated via simulations with different degrees of complexity, as can be seen from the figure. The final, most complex stage is manned simulation, its complexity can be varied with respect to hardware as well as visual and motion cues fed back to the pilot. The available model will be tested against different criteria as given in a specification, e.g. MIL Standard [2]. The results all contribute to the flight clearance, which describes the currently available capabilities of an aircraft within an initial flying envelope. It is a summary in the sense, that it gives the most comprehensive understanding of available models.

On the basis of a flight clearance preparations for flight test are being made. One part of these preparations is "flying" a test card in a manned simulator prior to becoming airborne. During flight test then the initial envelope is being explored cautiously towards the given limitations. Continuos analysis, mainly in-between flights, will give information on the appropriateness or the accuracy of the models involved. Due to this analysis flight test results therefore give the most comprehensive understanding of the aircraft since e.g. model simplifications are not present anymore. This information then is fed back to the model generation process. Thus based on an updated model a revised flight clearance can be achieved, supporting in turn the envelope expansion process in flight test.

Already in [1] a discussion is conducted on whether flight test is to be substituted partially by simulation due to its relatively high cost and time effort. In order to cope with this discussion at DaimlerChrysler Aerospace (DASA) Flight Test strong efforts are being under way to provide the development process with qualified analysis information as early as possible, thus performing on-line analysis in real-time as much as possible. In the sector of aerodynamics and flight mechanics DASA's on-line simulation tool is being used. This tool gives in real-

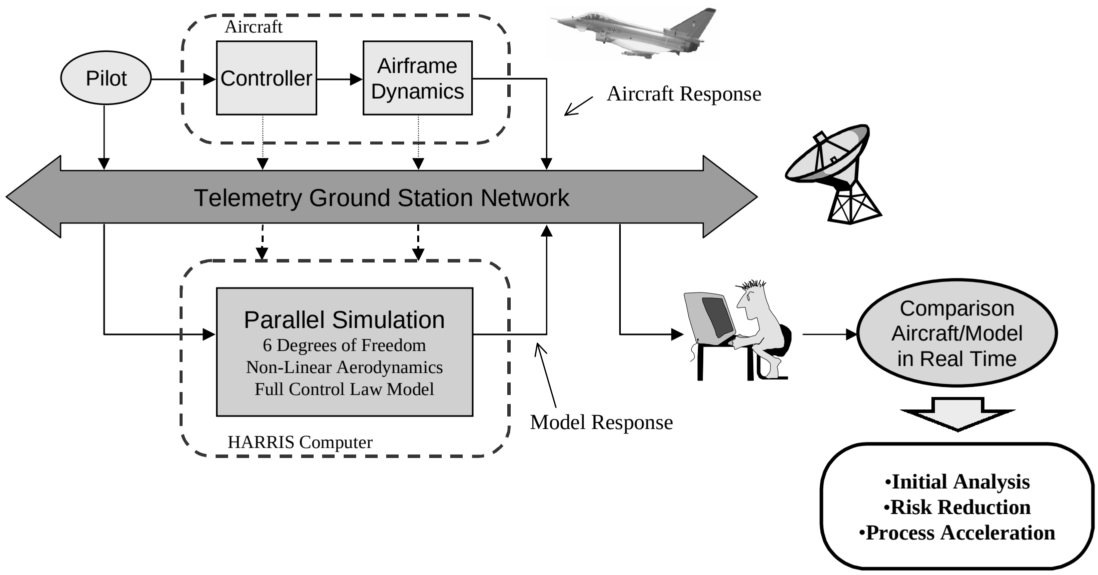

Fig. 2: Integration of On-line Simulation into Telemetry Network

time sufficient information on the validity of the available model. Since the given flight clearance is based on this model, see Fig. 1, basically a valid model supports confidence in the available flight clearance. Confidence in this clearance in turn supports flight safety and an efficient envelope expansion process.

2. On-line Simulation Tool

DASA's on-line simulation tool is based on the available pilot-in-the-loop simulation facility, which already takes a vital part in the development process, see Fig. 1. For flight test purposes the core of this simulator has been "hooked up" to telemetry. The goal was to drive the simulator via telemetry with the pilot's inputs to the aircraft simultaneously in real-time. Since the pilot sits in the real cockpit and experiences real visual cues, simulation cockpit and artificial vision are not needed for the parallel simulation. "Only" the real-time computer (HARRIS Nighthawk) is required.

The real-time computer is "hooked up" to the telemetry network in such a way, that relevant data can be monitored in real-time by this machine and used as input for the simulation programme. This programme calculates the model response on the basis of the telemetry data and the real-time computer feeds back these results into the telemetry network, as soon as they are available. Thus, the calculated result is behind "reality" actually the amount of duration of one calculation cycle. Since these calculation cycles are very short the time lag is hardly visible. The advantage of this set-up is, that calculated simulation data can be monitored via the usual telemetry network. Already available monitoring tools of the ground station's workstation network can be readily used, thus simulated results can be plotted against measured and telemetered results immediately. The entire set-up is explained schematically in Fig. 2.

The flight mechanical model is "hooked up" as follows: All relevant information of the state of the aircraft is monitored. This includes flight mechanical variables (free stream conditions and control surface deflections) as well as control law parameters (internal signals to set the controller at the desired condition). These data are used to internally steer the model in order to continuously follow the changing state of the moving aircraft. Thus the model is always at the same condition as the aircraft, which is the necessary requirement for later independent integration of the aircraft's state. This situation applies to a setting of the trim switch to the "trim" position, as given schematically in Fig. 3.

For analysis purposes of certain manoeuvres the model is "released" from telemetry prescribed conditions of the aircraft. After a stabilisation period of some seconds to achieve steady state flight conditions and the best available agreement between model state and aircraft state the model is disconnected via the trim switch as follows: State variables (free stream conditions and control surface deflections as well as internal signals to set the controller at the desired condition) are being disconnected and not anymore taken from telemetry. Instead, transmitted signals of pilot's inputs to the aircraft are taken now to stimulate the model. This is equivalent of a movement of the trim switch, indicated schematically in Fig.3, to the left into the "free" position. Flight mechanical equations are now being integrated independently from the aircraft, the controller works on its own and takes the calculated aircraft state as input for calculation of the necessary control surface deflections. The only connection between model and aircraft are the signals of the pilot's inputs. The model is "free" now.

Thrust and intake momentum are being calculated continuously with an appropriate engine model. Actuation dynamics are being calculated from an appropriate model as well. Non-linear aerodynamic characteristics are being taken from the tables of the dataset. The controller is implemented with its FORTRAN coded version. Finally for integration of the aircraft's dynamics the fully non-linear flight mechanics equations are being used.

For reasons of a simple connection of the model to the real world some assumptions are being made: Mass, centre of gravity and moments of inertia are being calculated on the basis of total fuel content knowledge from tables continuously. Once the model is let "free" their values are being kept constant at that value, which was present at the moment of release. This procedure ensures that fuel sloshing during the manoeuvre will not lead to erroneous readings from the tables. Experience has shown, that this simplification is valid for short time periods as investigated here.

The integration of flight mechanical equations is dependent on the available initial values of the state variables. For this reason a good agreement between model and aircraft is achieved during a stabilisation period of several seconds prior to a manoeuvre, respectively model release. Once the model is free and integration is performed independently from the aircraft small initial deviations between model state and aircraft state will accumulate to larger deviations due to the integration. This behaviour limits the on-line simulation tool to analysis periods of about 20 to 30 seconds duration.

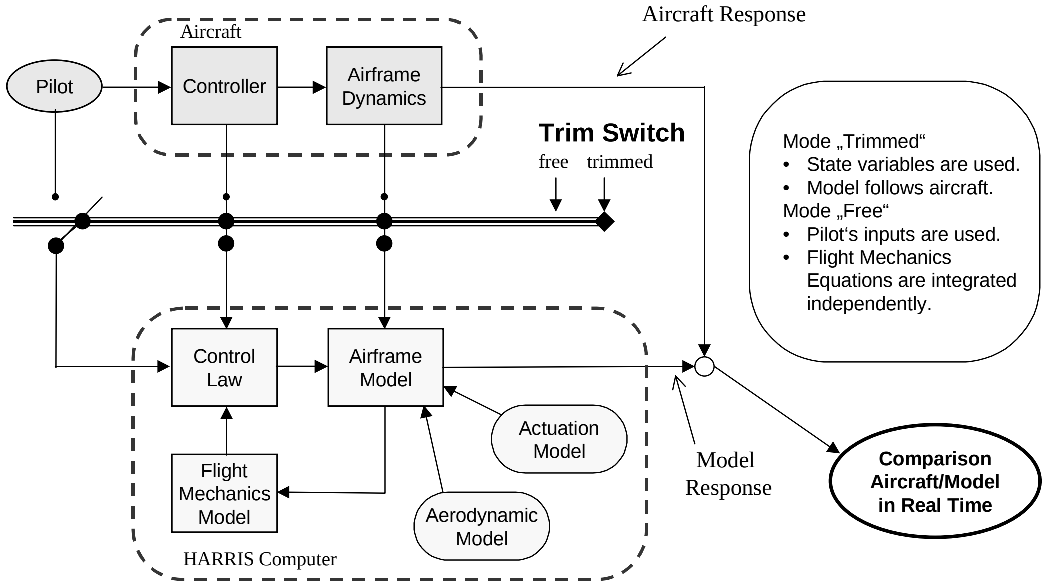

Fig. 3: Flight Mechanic Coupling of On-line Simulation with Telemetry Data

The tool as described above has been integrated into DASA's Military Flight Test Ground Station. It is being used successfully during envelope expansion flying of Eurofighter Typhoon development aircraft.

3. Results

In the following some results of application of on-line simulation will be given. Data have been measured during a typical envelope expansion flight test period conducted on one of DASA's Eurofighter Typhoon development aircraft. For this reason only relative magnitudes of results will be given.

3.1 Yaw-Roll Doublet

At first traces for a typical data gathering manoeuvre are given in Fig. 4. It is a yaw-roll doublet performed in quick succession. The entry condition for this manoeuvre was above 1g flight condition, thus the given traces combine a longitudinal portion of the manoeuvre (turning and pulling to the desired flight condition) and a lateral portion (yaw-roll doublets for data gath-

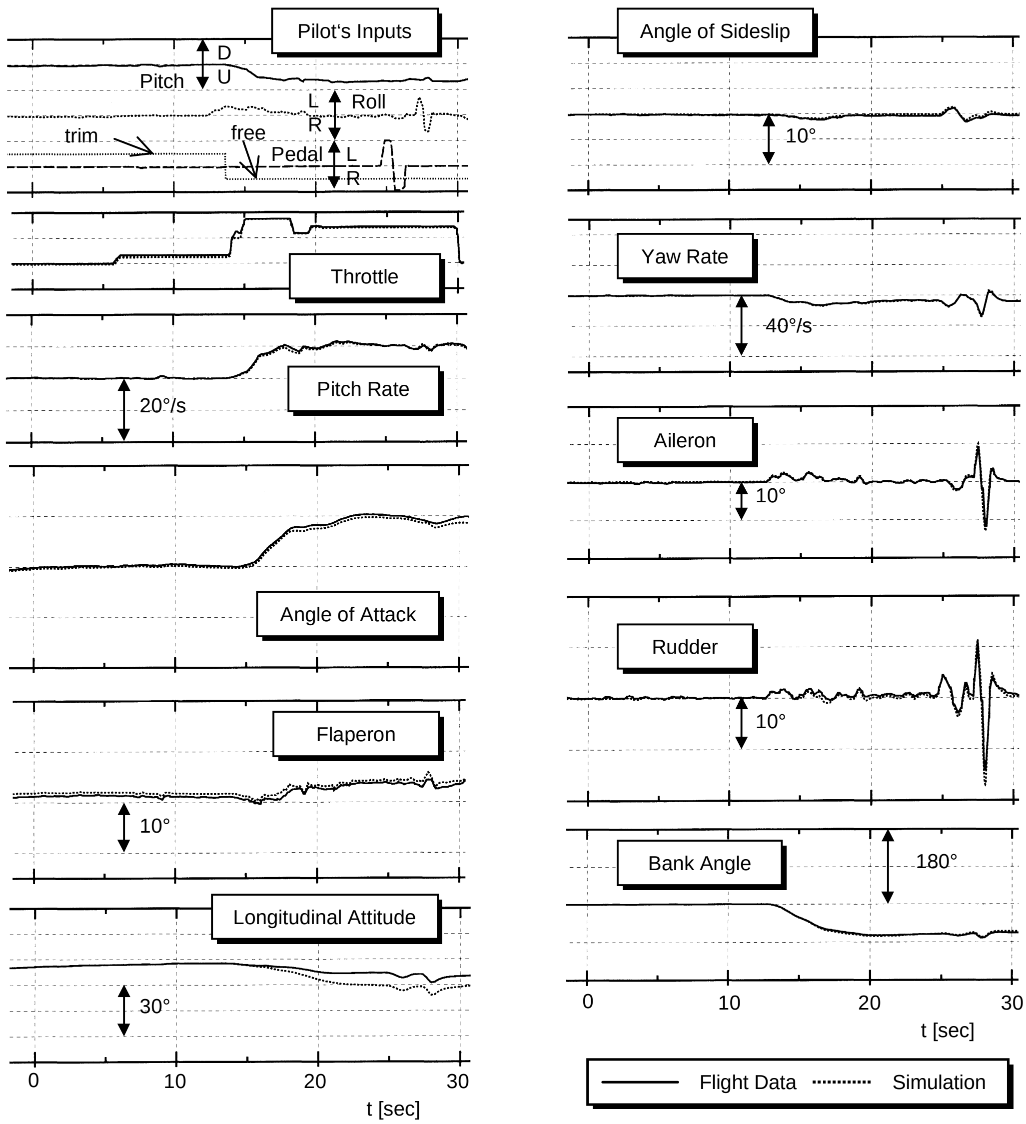

Fig. 4: On-line Simulation Results for a Yaw-Roll Doublet

ering). This type of manoeuvre is used for aerodynamic parameter identification purposes. Since this type of analysis generally is not available in real-time results of the on-line simulation can give a first impression on the fidelity of the dataset. – It should be noted at this point that all plots presented here have been taken from original “telemetry room hard copies”. This demonstrates in another way the capabilities of available tools in order to provide results as fast as possible.

At first Fig. 4 gives on the left side the traces of the pilot’s inputs stick pitch, stick roll and pedal. The application of the yaw-roll doublet in quick succession can easily be observed once the pilot has pulled to the desired entry condition. The fourth trace in this diagram gives the state of the trim switch as explained in the previous section. The second diagram of this figure gives the throttle position.

The third diagram gives a comparison between measured and calculated pitch rate, hardly any difference can be observed. The fourth diagram shows the comparison for angle of attack. Here the simulated value is slightly less than the measured one, the shape of both curves is equal though.

The fifth diagram gives the comparison for the flaperon deflection. Eurofighter Typhoon has four flaps at the trailing edge of the wing, which are used for pitch and roll control simultaneously. The given flaperon deflection represents the average symmetric portion of the deflection of all four flaps. It can be observed from these traces that there is a slight shift between measurement and simulation over the entire time slice, also for those times when the trim switch is set to “trim”. This can be attributed to several causes, e.g. differences in pitching moment between aircraft and aerodynamic model for this particular flight condition or differences in engine intake momentum due to deficiencies in the engine model. Nevertheless though the dynamics of both curves are equal. This is an indication that the model behaves basically like the aircraft.

Finally for the longitudinal motion analysis of this manoeuvre the traces for longitudinal attitude are given in the sixth diagram on the left side of Fig. 4. Shortly after the trim switch was set to “free” a divergence between measured and simulated results can be observed. Experience has shown that this parameter reacts most sensitive to differences between model and real world, e.g. differences in pitching moment. This behaviour is mainly due to the integration process generally used for this type of system. With this process small disturbances at the beginning are normally amplified during calculations, thus causing the divergence of these traces.

Results for the lateral motion analysis of this manoeuvre are given in the right half of Fig. 4. Traces for angle of sideslip, yaw rate, control surface deflection for aileron and rudder, and finally bank angle are being given. In all cases on-line simulation result almost perfectly match the measured curves, which is an indication of the high fidelity of the available aerodynamic model.

These results prove that the given model does represent the behaviour of the aircraft properly. Independently from this investigation post-flight analysis results of aerodynamic parameter identification (not reported here, but see e.g. [3]), which go into detail of the aerodynamic model come to an equivalent conclusion. The achieved results of on-line simulation cannot go into such detail as aerodynamic parameter identification can, but they support confidence in the given clearance already during the flight.

3.2 Wind-up Turn

The second manoeuvre presented here is a wind-up turn (WUT). In this particular case the WUT was performed to check whether the flight control system (FCS) of the aircraft limits the angle of attack according to the design. Traces for the longitudinal motion of this manoeuvre are given in Fig. 5 in the same manor as they were given for the previous manoeuvre.

Shortly after switching the on-line simulation from “trim” to “free” (first diagram) the pilot initiates a left turn and starts to pull gradually to the aft position. In order to reach the desired performance he also pushed the throttles to

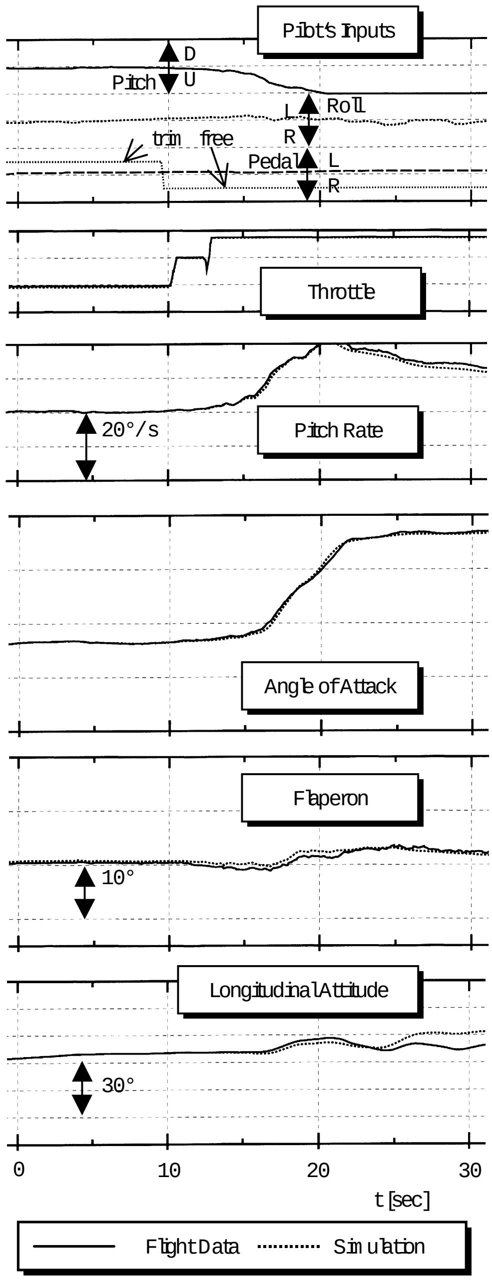

Fig. 5: **On-line Simulation Results for a Wind-up Turn**

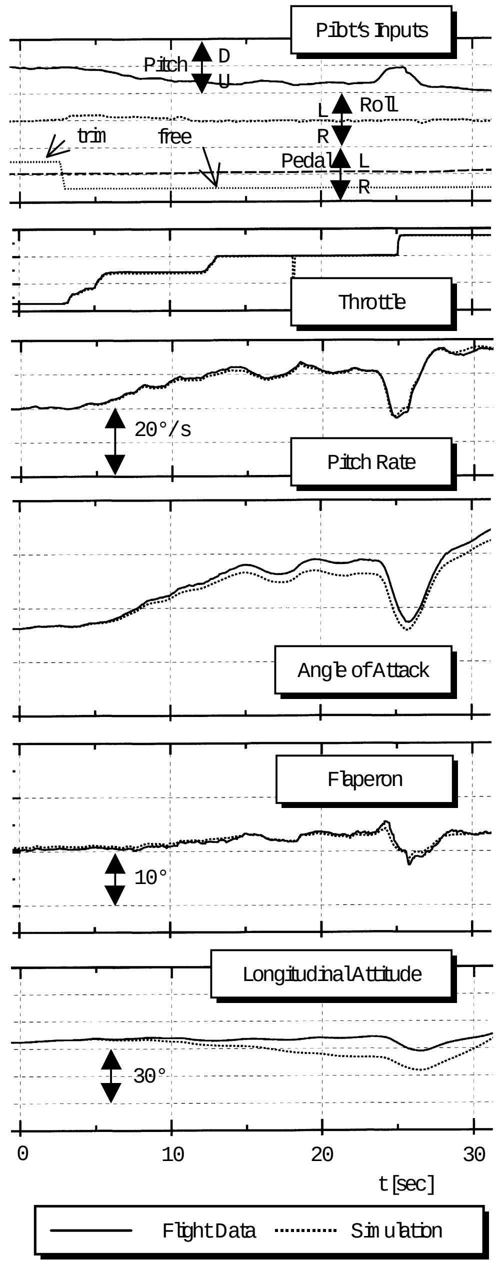

Fig. 6: **On-line Simulation Results for a Turn Manoeuvre**

max position after release of the model. A comparison of given results for pitch rate (third diagram) shows the start of a slight divergence only after more than 10 sec of "free" model flight. Angle of attack traces (fourth diagram) lie very well on top of each other and one can easily see how angle of attack is limited to a maximum value, although the pilot is still pulling aft. The response of the aircraft proves the design to be valid. The FCS limits the model to almost the same value for the aircraft as for the model.

Flaperon traces (fifth diagram) show the already observed and discussed offset between measurement and simulation. Finally in the sixth diagram the results for longitudinal attitude indicate a divergence as observed earlier.

3.3 Turn

The last example of this presentation gives comparisons for an arbitrary turn during a test flight. The data is given in Fig. 6 in the same manor as for the previous example. For this particular case a special stabilisation period was not applied. The given time slice shows more than 25 sec of “free” flight of the model during manoeuvring. Due to the missing stabilisation period a distinct divergence between measurement and simulation results can be observed for angle of attack and longitudinal attitude. Nevertheless the characteristics of both curves are nearly identical. The given traces for flaperon deflection show again a very good agreement. This is an indication for the validity of these results although divergence is already present and it also documents a certain robustness of the method.

Qualitative agreement between measurement and simulation as given here does already prove the validity of the model. If there is also a requirement for quantitative agreement, as for the limiting angle of attack given before, the method requires a good stabilisation phase before releasing the model and the event of interest should occur within 15 sec of model release.

3.4 Discussion

Results of application of DASA’s new on-line simulation tool have been demonstrated with three typical examples. Their quality generally documents a very good agreement between model and aircraft behaviour. It could be shown that a proper stabilisation period prior to releasing the model is helpful for the achievements of results to be compared quantitatively. System dynamics e.g. in control surface deflection are generally very well matched. It is valuable to have this information immediately in flight. Thus providing confidence into the predicted properties of the aircraft dynamics and into the available clearance. Thus enabling test engineers to make decisions on the further progress of the flight on the basis of early analysis results. It is expected that this method will support improvements in process fidelity and enhance effectiveness of test flights.

4. Conclusions

Testing of modern high performance aircraft today is performed in a very high sophisticated environment. This means, that flight-testing of these aircraft is preceded by a considerable amount of modelling and simulation. Simulation in this context can be based on different degrees of complexity. These pre-flight investigations also comprise stability analyses for the augmented aircraft as well as for the closed loop aircraft-pilot system. Generally, based on the outcome of these comprehensive investigations, an initial flight clearance is given. During flight test then the initial envelope is explored cautiously towards the given limitations. The model is validated with flight test analysis results. Depending on the outcome of these validations a refinement of the clearance will be required.

At DaimlerChrysler Aerospace AG (DASA) this envelope expansion process is being supported by a tool, which is called “On-line Simulation”. It is made up in such a manner that the non-linear simulation model, which is used basically for manned simulation, is operated simultaneously while the test aircraft is up in the air doing e.g. envelope expansion flying. The used simulation model comprises the best model standard available. This means the model includes e.g. non-linear aerodynamics, full control laws as well as hardware assumptions for the actuation system of the aircraft. During flight the model is steered to follow generally the given aircraft state, as best as possible via the available telemetry information. Prior to a certain validation manoeuvre the aircraft is stabilised to a stationary flight condition. Immediately before execution of the particular manoeuvre the simulation model is “let free”. This means, that from this time on the model is not steered anymore. It is now driven solely by pilot’s inputs via telemetry. Flight mechanical equations for estimation of an aircraft’s new state are now being integrated independently from telemetry inputs. Thus this process provides a comparison of traces of aircraft state variables (calculated versus measured) in real-time, simultaneously while the aircraft is performing the actual manoeuvre.

Three representative results illustrate how this tool is being used. They show the capabilities of this tool. The tool proves that the model qualitatively represents the real aircraft. For certain investigations also quantitative agreement can be achieved. In this case though the aircraft needs to be stabilised prior to release and the event of interest should occur within 15 sec of release. Otherwise divergences between measured and simulated traces would not allow a quantitative comparison anymore.

The main advantage of this tool is the instantaneous availability of analysis results during a test flight. This provides increased confidence into the given clearance. It enables the test engineers to make decisions during flight on the basis of these analysis results.

5. Acknowledgement

The on-line simulation tool could only be realised through the support of many people working within DASA, notably Dr. G. Schulz of the simulator department and Mr. J. Keidel of the Flight Test Ground Station team

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