

DESIGN AND SIMULATION OF AIRCRAFT CONTROLS WITH 3D ENVIRONMENT OPTIONS

Katalin GÓSI¹ and András SZÉLL²

¹Department of Control Engineering and Information Technology

gosi@seeger.iit.bme.hu

²Department of Measurement and Information Systems

szell@mit.bme.hu

Budapest University of Technology and Economics
Budapest, Hungary

Abstract: The aim of the present work was to develop a system running on two computers, one of which carrying out the calculations necessary for the control and the simulation, the other one setting the parameters and performing graphic and 3D visualization. Realization of the project was done in a MATLAB environment, using Simulink.

Some of the state-space planning method was realized by using the physical model of an F16 aircraft [2]. Only the control designed by the LQG/LTR method will be shown, further solutions can be found in [5].

Keywords: aircraft control, LQG/LTR, virtual reality

1. Relevant concepts

Aircraft control is an important area of control engineering where the new trends in non-linear and linear control theory are used. Under simple flight-conditions the non-linear dynamic model of aircrafts can be linearized, and appropriate controls can be designed by modern linear methods.

1.1. State variable description of aircrafts

The quantities composing the state variable vectors, the coordinate system necessary for their determination, and the control surfaces can be seen in Fig 1. The vector can be composed of four components: position, orientation, and speed and angular speed vectors:

$$X^T = [p_{North} \quad p_{East} \quad h \quad (\varphi \quad \theta \quad \psi) \quad (v_T \quad \alpha \quad \beta) \quad (P \quad Q \quad R)]$$

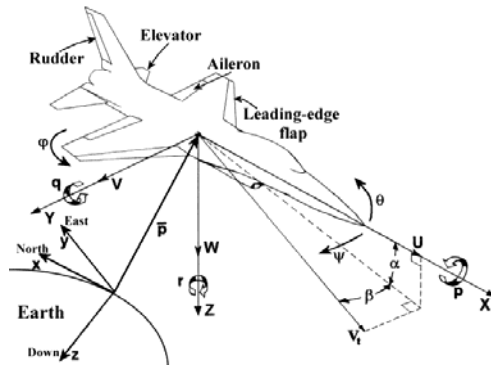


Figure 1. State variables and control surfaces of the aircraft

1.2. Multivariable frequency-range analysis

The noise-effects affecting a system controlled by feedback are of two types: primarily low frequency noises arising in the system and generally high frequency noises arising in the sensors. The reference signal is also of low frequency, like the step function. Defining tracking error and noise effects, the concepts of sensitivity and complement sensitivity can be introduced, which are in close connection with the singular values of the system, and by using these new concepts, limitations to the singular values of the system can be introduced.

Upon examination of the constant error, a lower limit to the minimal singular value can be given, this way zero error can be approached to any degree. By increasing this lower limit, the minimal singular value can be approached to the maximal singular value, as a result of which response-speed will be the same in every branch of the system. This is called the low frequency equalization of the singular values. At this point, the system can be supplemented by a constant pre-compensator, which influences the intervening signal.

The inaccuracies arising from the neglected high frequency dynamics of the aircraft model, like flexibility and high frequency vibrations, belong to the high frequency noises. By applying the multivariate Nyquist criterion for the maximum of the singular values of the closed loop, the real system will also be stable.

In order to design a linear control, the model has to be linearized around an operating point. However, this operating point will change in the course of simulation of a real system, but applying the upper limit above, the system will become robust for similar parameter-changes.

2. Full state-feedback by the LQG/LTR method

As opposed to output feedback, it is impossible to construct a compensator of any dynamic construction with full state-feedback. However, its application will show the best result that can be expected of a system designed by output-feedback. Its further advantage is that the calculations that required complicated optimization can now be simplified, and conforming to a few sensible assumptions the system guarantees the stability of the closed loop.

In reality, it is generally impossible to measure all state variables. Therefore, a state-estimator is designed which – knowing the measurable outputs – gives the estimated values of the state variables, which are fed back. In this work full state-feedback is performed by LQ control and state estimation is done by Kalman-filter. This method is called LQG (*Linear Quadratic Gaussian*) procedure. One of its advantage is that the structure of the compensator is predetermined. It would be further advantage that in case of LQ controls designed by state-feedback the stability of the closed system is guaranteed even in cases of complex MIMO systems. However, a state-vector estimated by a Kalman-filter is fed back instead of the real conditions, losing this way the guaranteed robustness. Thus, the LTR (*Loop Transfer Recovery*) part of the LQG/LTR method is about how we can restore the lost favorable characteristics. The method provides a form in which it is worth searching for the Q and R design parameters when doing the full state feedback calculation.

2.1. Turning control

One of the necessary conditions for linear flight is that the values of certain state variables of lateral direction should be zero. In [5], this was realized by LQ method and output feedback. Now our aim is that φ follow a given reference signal, r_φ , while β remains zero, thus, $r_\beta=0$. This way, the state variables to be controlled are as follows: β , sideslip angle, φ , the banking angle, angular velocity components indicating the changes of β and φ , i.e., p and r , the speed of rotation and turning, respectively. The deviation of the *aileron* and that of the *rudder* are also present in the vector of state variable x in the system to be designed.

The maximal and minimal singular values of the system are shown in Fig. 2a with solid line. The constant error of the closed loop would be too big, because the integrating feature is missing, DC-amplification is also small, and the differences between the singular values are also big, thus, the system is not balanced. Therefore, as a first step, the model was extended by an integrator and a pre-compensator on both branches. The new singular values can be seen as broken lines in Fig 2a. It can be seen that the maximal value decreased in high frequency and the minimal value increased in low frequency, conforming to the remarks in section 1.2. The state variables of the thus extended system will be as follows: $x = [\beta \ \varphi \ p \ r \ \delta_a \ \delta_r \ \varepsilon_\varphi \ \varepsilon_\beta]^T$, the output will be: $y = [\varphi \ \beta]^T$.

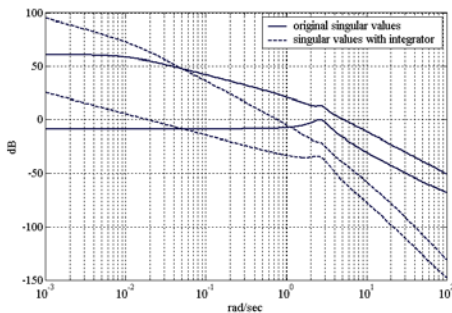


Figure 2a. Singular values

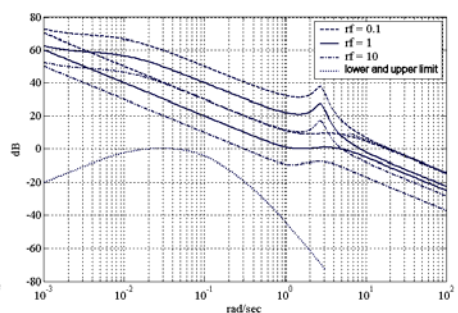


Figure 2b. r_f values

It was assumed for the calculation of frequency-range robustness limits that the accuracy of the aircraft model under 2 rad/sec is within 10%, and above that everything increases above the limit with a slope of 20 dB/decade. From this, the high frequency limit can be calculated. Any inaccuracy is caused by the errors in the aircraft model, e.g. flexibility missing from the model. Low frequency disturbances may be caused by gusts of wind, therefore, the lower limit was determined by a wind model described in [1]. The singular values must remain within the lower and upper limits indicated by the dotted lines in Fig. 2b. for robustness.

Designing the state estimator

The design of the Kalman-filter can be traced back to the calculations of the full state feedback, thus, the design parameters are indicated similarly. After some preliminary examinations, the calculations were performed using values $Q = \text{diag}\{0.01 \ 0.01 \ 0.01 \ 0.01 \ 0 \ 0 \ 1 \ 1\}$. The other design parameter is $R = r_f I$. Figure 2b shows, that there is no problem with the limits caused by the wind blasts for any values of r_f , but the high frequency limit is damaged at $r_f = 0.1$, thus with this alternative the system would lose its robustness for high frequency noises.

After the selection of the design parameters and the calculation of the so called Kalman amplification the next step was the realization of the state feedback.

The design of the state feedback

The state estimator had excellent frequency and temporal range characteristics when at $r_f = 1$. In accordance with the method described in section 5.3 of [5] it is possible to find a K value the use of which makes it possible to approach the loop amplification of a system equipped with a state estimator only. The first parameter should be chosen as $Q = \rho Q_0 + C^T C$ and the second parameter should be $R = \rho^2 I = r_c I$, where $\rho \rightarrow 0$ must be met. The best choice proved to be $r_c = 10^{-11}$; in this case limitations were not disturbed, the deviation from the ideal curve was also acceptable, thus, the step response was appropriate.

Figure 3a shows the changes in φ (broken line) and β (solid line) as a function of time, where $r_\varphi = 0.5 \text{ rad} \approx 30^\circ$ was chosen.

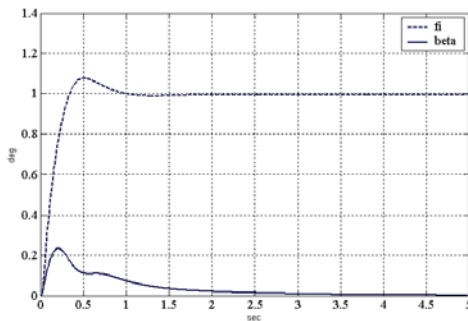


Figure 3a. Controlled outputs φ and β



Figure 3b. 3D model of the aircraft

3. 3D visualization and result evaluation

After the planned controllers are simulated, their simulation results have to be evaluated, and according to the results, the controller parameters or even the algorithm itself, might be modified. This multistage process can be very long and time-consuming, but a much shorter evaluation time could boost up the process. Although the individual operation of the controllers can be followed in the graphs, the simultaneous observation of their interaction is difficult in the traditional way: the multitude of state variable graphs can be interpreted only with close attention. Instead of graphs, a less strict view so naturally arising in aviation engineering simplifies this process: The 3D visualization demonstrates the 3 state variables of both orientation and position simultaneously, and through real time visualization the 3 angular velocity parameters can also be observed. In sum, such a visualization gives an easily interpretable overview of the aircraft state variables.

For the 3D rendering we selected a versatile tool which is well integrated into MATLAB, the Virtual Reality Toolbox. The VR Toolbox makes it possible to simply generate or load virtual reality models (in VRML environment), and to visualize the received parameters by issuing MATLAB commands, or by creating appropriate connections in Simulink.

The VRML is an open standard, therefore our model can be modified by most 3D editing programs, and a simple browser plugin can render the resulting VR worlds. The created virtual environment consists of a true to life F-16 aircraft model, without unnecessary ornamentation. The developed VR module can handle different aircraft or helicopter models by simply loading different VRML files, though it was not necessary in our case. It is prepared for visualization of *orientation* and *position*, and also *control surfaces* follow the state changes of the physical model. The *velocity* and *height* data are shown in a window at the bottom of the screen. In addition to the dynamics of the aircraft, the *trajectory* arising after simulation is also generated [6].

In the course of parameter transfer we had to take into consideration that the coordinate system and the rotations used in VRML are different from those in aviation engineering, so the necessary coordinate transformations based on [3] had to be performed previously. Due to the well-placed camera positions, the visualized path and the sum of the state changes can be interpreted easily, therefore it is suited for fast evaluation or as a general overview before considering the 2D curves.

Simulation can run simultaneously with visualization, or can be disconnected from it, in order to test controllers of any complexity. In the second case, simulation is rendered in real time only later, from the simulation results.

4. Parallel visualization

As current control algorithms require ample hardware resources, our application supports distributed visualization and computation. The controller simulation can run on either a powerful computer or on an embedded system with special hardware accelerators, while the visualization and the controller configuration GUI runs on a desktop PC with accelerated 3D graphics.

The two parts of the system communicate via TCP/IP; a dedicated link between these modules is preferred for the great amount of data transferred between the GUI client and the server. For real-time simulation timing and network synchronization had to be solved, as described in [6].

A sophisticated graphical user interface was made to support configuration of the control algorithms as well as to manage the server and the network setup. Control settings and simulation results can be stored and loaded later for fast reviews. This framework connects the separated control design and result evaluation features of the system.

5. Summary

One of the controllers planned for F-16 aircraft has been shown above. More details can be found under [5]. The LQG/LTR method was used for planning, while the simulation data were visualized in 3D environment as well. As well known in aviation, an F-16 aircraft is unstable in itself; if it deviated from straight line motion, it would crash without control. This can be avoided by linear controllers, but due to nonlinear dynamics, it can be done only within certain limits. There exist dynamic parameters, and even parameter changes that are not included in the model we used. These can strongly influence the stability of the planned controllers. Thus, it is worth dealing with more robust controllers.

3D visualization has proven to be useful. We made steps in order to create interactive interventions, for spontaneous disturbances, like gusts, that appear in reality – the reaction of the controllers to them would be quite spectacular in 3D. One step toward interactivity was to develop real time visualization. For load balancing purposes, the visualization is parallel with simulation, the two parts of the system communicate with each other via network. This architecture also makes it possible to create embedded control solutions with good simulation and result evaluation tools.

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