Technische Universität Berlin
Institut für Luft- und Raumfahrt
Fachgebiet Flugmechanik Flugregelung und Aeroelastizität
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1. Homework - Flight Control
Analysis of dynamic aircraft behaviour and design of a stability augmentation system

In this homework, you will analyse the flight dynamics of the VFW 614 and design controllers to modify the process dynamics in longitudinal and lateral-directional motion. You will use classical control design methods.
As a passenger aircraft, the VFW 614 is a low-wing aircraft equipped with two jet engines. It should replace the Douglas DC-3 and have features of a robust propeller aircraft.

VFW-614, ©Airbus

The reference state by which the non-linear equations of motion have been linearised is the stationary horizontal flight at an altitude of 4000 ft at a speed of 180 KTAS[1]. The equations in the state space are given in the longitudinal motion with

$$\begin{bmatrix} \delta\dot{q} \\ \delta\dot{\alpha} \\ \delta\dot{V} \\ \delta\dot{\Theta} \end{bmatrix} = \begin{bmatrix} -0,9981 & -2,5072 & -3,518\cdot 10^{-4} & 0 \\ 0,9709 & -0,9632 & -0,0025 & 0,0099 \\ -0,1274 & 4,6526 & -0,0219 & -9,7234 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta q \\ \delta\alpha \\ \delta V \\ \delta\Theta \end{bmatrix} + \begin{bmatrix} 0,1335 & -5,6897 \\ -0,0048 & -0,1038 \\ 2,9885 & -0,6188 \\ 0 & 0,0518 \end{bmatrix} \begin{bmatrix} \delta_t \\ \delta_e \end{bmatrix}$$

and in the lateral movement with

$$\begin{bmatrix} \delta\dot{r} \\ \delta\dot{\beta} \\ \delta\dot{p} \\ \delta\dot{\Phi} \end{bmatrix} = \begin{bmatrix} -0,4956 & 1,9243 & -0,1206 & 0 \\ -0,9795 & -0,193 & 0,0963 & 0,1055 \\ 2,107 & -5,5049 & -3,3388 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \delta r \\ \delta\beta \\ \delta p \\ \delta\Phi \end{bmatrix} + \begin{bmatrix} -0,4515 & -1,318 \\ 0 & 0,0362 \\ -9,498 & 1,9929 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix}.$$

The following tasks are designed to correspond to the procedure used in the design of flight controllers. First you should analyse the eigenbehaviour, derive requirements for the controller and then design the controller. In the last step you will evaluate the controller in a non-linear simulation (SEPHIR).

[1]KTAS stands for the true airspeed in knots

1 Task: Analysis of the eigenbehaviour

The reference point corresponds to the state of the aircraft shortly before entering the glide path (landing). Analyse the eigenbehaviour of the aircraft for the upcoming landing approach by performing the following tasks:

1. **Analysis I:** Examine the flight qualities using the MIL-F-8785C specification and fig. 2 in longitudinal and lateral-directional motion. In addition to the complete system of equations, use the approximations for short-period and dutch-roll modes. The calculation can be done by programming, but your solution approach has to be documented in a transparent way! The starting point is the state space! Compare the results between the considered approximation and the complete system of equations! Assume a maximum deflection of 20 deg for the control surfaces.

2. **Analysis II:**Examine the non minimum phase behavior of the aircraft for elevator and thrust!

3. **Requirements:** Based on the results of the last task, derive requirements for the controller design with regard to its eigendynamics!

2 Task: Design of a flight controller with damper support in the longitudinal motion (SAS)

The aircraft is designed to be flown manually, with the pilot commanding elevator deflections and thrust. To improve the flight characteristics of the pitch motion, a damper is integrated as controller. Edit the following tasks:

1. **Architecture:** Draw the general block diagram for manual flight control with damper support (SAS).

2. **Controller Design I:** Use the approximation of the short-period mode and modify analytically (without the instruction `rlocus()`, but by means of written calculation) the eigenresponse by means of a suitable feedback in such a way that the degree of damping of the short-period mode is 0.7. Draw the block diagram of the pitch motion and integrate the controller into the block diagram!

3. **Controller Design II:** For the approximation of the pitch motion (short-period mode), you can modify both the damping and the undamped natural frequency by means of the full state feedback method. Perform the procedure completely analytically to obtain a damping ratio of 0.7 and an undamped natural frequency of $f_0 = 0.4775$ Hz! Check the prerequisites for the application of the method and specify which sensors can be used to measure the two state variables! Document all calculation steps. Prove in the approximation and by means of the complete state space equation that your design goals have been achieved! Draw the block diagram of the pitch movement (blocks should only contain derivatives, no matrices) and integrate the controller into the block diagram!

4. **Verification I:** Show the effects of the controller on short-term and long-term dynamics by performing simulations with the complete system of equations in the state space without and with controllers (both designed controllers) for steps in the elevator and compare the results with each other! Display all the control variables in addition to the state variables!

5. **Controller Design III:** The phugoid can be damped by a feedback of the speed to the thrust[2]. Use the controller designed with the full state feedback of the short-period mode and set up the modified equation system (state space)! Use the root locus method (you can use the `rlocus` statement) to design the controller in the backward path so that the phugoid has a damping of 0.707.

[2]This method is not used due to the demand for thrust calmness! Instead, the feedback $\theta \rightarrow \delta_e$ is used, for example.

6. **Verification II:** Show the effect of the controller designed in the last sub-task on the long-term dynamics due to steps in the elevator. Compare the results of the simulations with simulations without phugoid damping. Why can the pilot better maintain a given speed with a feedback from speed to thrust?

3 Task: Design of a base controller for decoupling lateral aircraft movement (SAS)

In the lateral motion there is a strong coupling between yaw and roll motion. To reduce this coupling, parts of a basic augmentation system for lateral motion are to be designed. In the first step a yaw damper is dimensioned to dampen the dutch-roll mode. In the second step a sideslip free turn should be made possible. For this purpose edit the following tasks:

1. **Controller Design:** In order to reduce the influence of the Dutch-Roll mode, it should be damped. Design a yaw damper using the root locus method and suitable feedback. The damping ratio should be $\zeta_{DR} = 0.7$.

2. What problems does this type of controller cause when you are turning? Explain your answer. Search for a possible solution in chapter 14.3.1 of the 3rd edition of the book "Flugregelung" or chapter 4.4 of the book "Aircraft Control and Simulation". Apply the method and check, in simulation studies, if the chosen method is effective! Also plot the control variables!

3. **Verification:** Explain why it is necessary to deflect not only the ailerons but also the rudder in a coordinated way when turning. Name the possibilities of implementing this in a controller and decide for one. Show in a simulation study that your approach leads to improvements.

4 Task: Testing the controllers in the nonlinear simulation

After you have designed your controllers, they are now to be tested in the nonlinear simulation. The following simulation campaigns must be performed **with** and **without** controllers: **Climb** and **standard rate turn**.

- **Climb** from the trimmed reference state at a rate of $1000\ \frac{\text{ft}}{\text{s}}$ to a height of 6000 ft. Keep the speed constant by using thrust.

- Fly a 2-min **standard rate turn** at the trimmed reference state. The turn direction is up to you. Maintain the altitude and keep the bank angle constant.

- The maximum allowed deviations in sink and climb rate are $200\ \frac{\text{ft}}{\text{s}}$. The height may be exceeded or undershot by a maximum of 50 ft. The maximum deviations in speed are -5 kt and 20 kt. The maximum deviation in standard rate turn is ± 10 s.

Complete the following tasks:

1. In contrast to the simulations you performed with the linear state space equations, the nonlinear simulation (as with the real aircraft) results in differences with regard to the measured variables. Explain them and present a solution how to avoid problems with the measured variables!

2. Go to the ISIS page and download the **test card** template. Your group consists of several members. Think about an operational procedure plan for the flight simulations and document it. Remember that other group members can support the pilot flying. Use the testcard for comments during the test and attach it to the report! Document differences from the flight test plan and derive any improvements in flight test planning for the next campaign! Note: It is intended that all members of the group will be able to perform the flight tests.

3. Perform the simulator tests with the open-loop aircraft! Evaluate the results with regard to specified tolerances. Use the data recordings for this purpose. Use the impressions you gained during the tests (verbal comments should be noted on the test card) to assess the flight characteristics.

4. Carry out the simulator tests with the closed-loop aircraft (your controllers)! Evaluate the results with regard to the specified tolerances. Use the data recordings for this purpose. Use the impressions you gained during the experiments (verbal comments, test card) to assess the flight characteristics and compare the dynamics of the open-loop aircraft with the closed-loop aircraft! Note: For the evaluation only the results of one pilot have to be used. Please note, however, that it makes sense to compare the open- and closed-loop flight of the same pilot!

Hints

Please note the following information:

- Last acceptable submission of the homework is on **13.12.2023 at 23:59** o'clock at ISIS.
- Later submissions will not be considered!
- The homework must be done by at least three students.
- Only one solution is valid per group.
- The report must contain a cover page (title, group no, names, student ID), a table of contents and a declaration of originality (Eigenständigkeitserklärung) to be signed by all students!
- Matlab/Simulink or SciLab/Xcos is recommended as an aid. A comprehensible and sufficient approach should be presented for tasks that are carried out with these tools. The corresponding source code has to be attached to the appendix and the text has to refer to the place in the source code! The result is to be mentioned in the text. The codes must be provided as well (all functions used), and they should be operative.
- If you use Matlab/SciLab for calculations, always show the basic approaches.
- For simulations with Simulink/XCos, it is necessary to specify the simulation step size, simulation time and integration method used in addition to the model.
- Tasks that have to be performed analytically or require a detailed calculation are to be derived comprehensibly in the text. Numerical values should only be used at the end of the calculation! In case of doubt, the state space representation is always the starting point of every derivation!
- **SI units should always be used.** For plots and figures, angles must be displayed in 1°.
- Graphics must be legible. If necessary, the font size of the graphic must be adapted to the font size of the text! Each axis of a diagram must be completely labelled (formula symbol and unit)! Screenshots of figures (e.g. Simulink) are not allowed.
- Foreign intellectual property must be labelled! This is especially the case for derivations or images taken from a book or script. Wikipedia is not an accepted source for derivations!

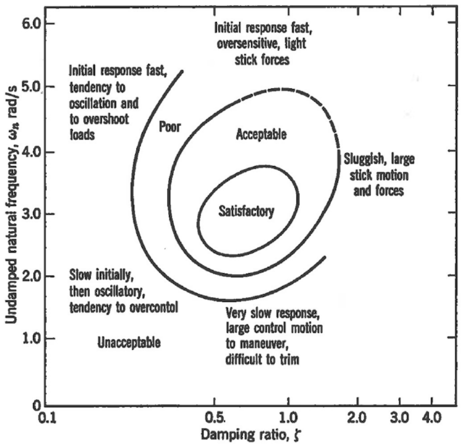

Figure 1.5 Longitudinal short-period oscillation—pilot opinion contours (O'Hara, 1967).

Figure 1: Requirements for the short-period mode

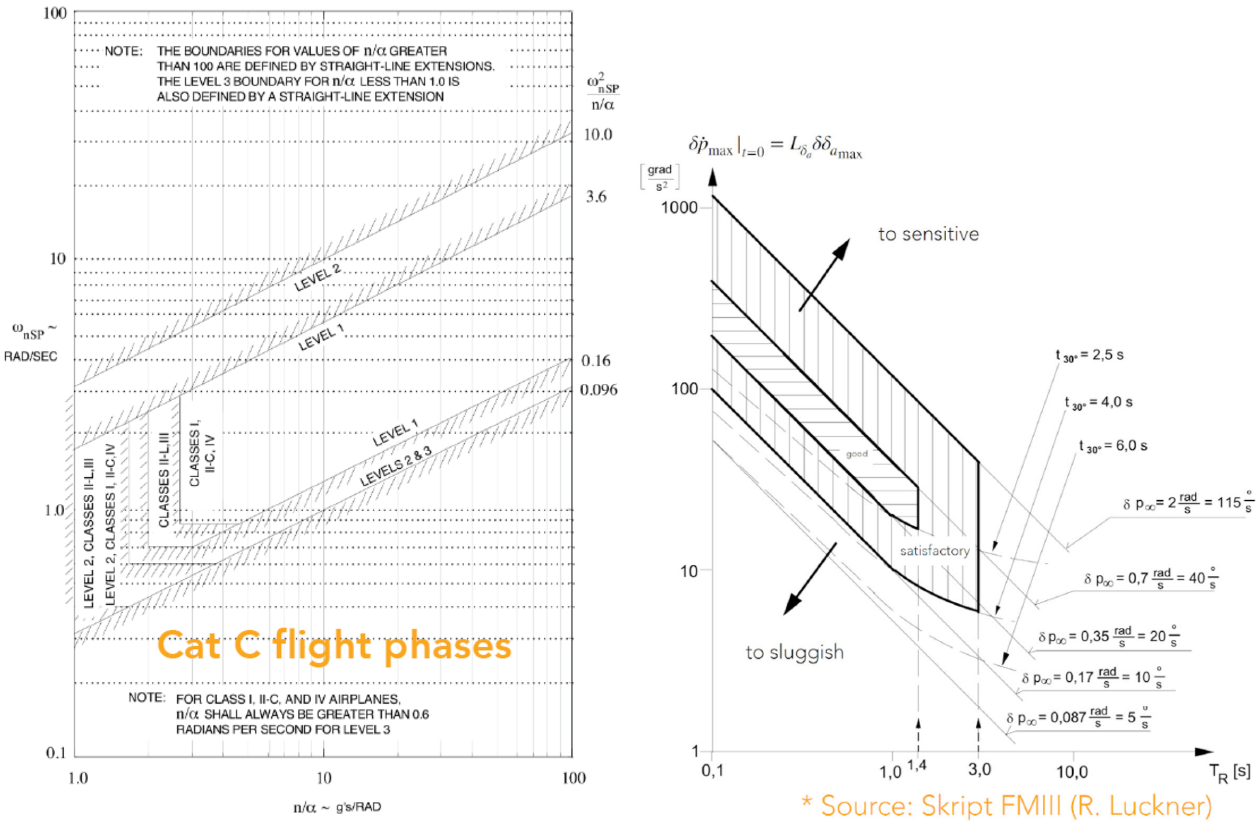

Figure 2: Requirements for the CAP-factor (from MIL-F-8785C) and roll motion