13th Triennial World Congress, San Francisco, USA

CONTROL DESIGN FOR A HELICOPTER LAB PROCESS

Mats Åkesson, Erik Gustafson and Karl Henrik Johansson

Department of Automatic Control
Lund Institute of Technology
P.O. Box 118, S-221 00 Lund, Sweden
`akesson@control.lth.se`

Abstract: A two-week control design project in a graduate course is described. The issue is to design a controller for a multivariable helicopter lab process. The described project illustrates the whole procedure from modeling and identification to implementation and validation of a control system. The suggested control structure consists of a gain scheduler together with two SISO-controllers and a feedforward. The closed-loop system is shown to respond well to step reference signals.

Keywords: Control education; Helicopter; Control applications; Identification; Multivariable control

1. INTRODUCTION

It is important to attract students to courses in control engineering. One way of doing this is to exemplify the theory with interesting applications. For the future professionals it is also urgent that engineering skills are practiced during the education. Therefore students in automatic control should face projects and laboratories that concern not only theoretical design issues but also, for instance, implementation aspects. The Department of Automatic Control teaches eight annual courses in the engineering curricula at Lund Institute of Technology. A number of laboratory sessions are included in all courses and in three of them a two-week project is part of the requirements.

In this paper we describe a control design project done in the System Identification Course. Some information about the course plan is given together with the project outline. The main part of the paper treats the modeling and control issues for the helicopter model shown in Figure 1. The laboratory process is developed and built at the Automatic Control Laboratory at ETH in Zürich, see (Mansour and Schaufelberger, 1989) and (Schaufelberger, 1990). The process has two inputs and two outputs and it is highly nonlinear. In the

Fig. 1. The ETH helicopter lab process.

course project described here, a model is derived for the process and a controller based on decoupling and gain scheduling is designed. For each operating point, a linear multivariable dynamic model is identified. The experiments, system identification, and controller design were all done using standard computer tools available at the department, see (Åström and Lundh, 1992).

The outline of the paper is as follows. In Section 2 some information about the control courses at our department is given together with a time schedule for a course project. Section 3 describes the modeling, system identification, control design, as well as the evaluation of the design. The design procedure is summarized and some course project aspects are mentioned in Section 4.

2. A CONTROL COURSE IN LUND

At Lund Institute of Technology control education is centralized to one department. The Department of Automatic Control is responsible for all undergraduate and graduate control courses given to students in engineering physics, electrical engineering, computer engineering, mechanical engineering as well as chemical engineering (see `http://www.control.lth.se/education.html`). A major goal for the education is to provide the students with a strong background in control theory and an engineering ability to make control systems that work. Practical work is an integral part of all courses, ranging from four-hour laboratory experiments in the introductory courses to two-week projects in the advanced level courses.

The project described in this paper was performed in the System Identification Course. This graduate course aims to give theoretical and practical knowledge of methods for developing mathematical models from experimental data. The course, based on the book (Johansson, 1993), also emphasizes the importance of physical modeling. The number of students following the course is usually around thirty, including a number of foreign students participating in exchange programs such as ERASMUS.

The identification course is given annually and consists of lectures, tutorials, laboratories, a project and a written exam. During the project period, groups of 2–4 students are working full-time for about two weeks on different tasks. The work is presented by the group both as a written report and an oral presentation. The projects serve to promote project management but also to act as valuable practice before a Master's project. A typical project would involve identification of a laboratory process followed by design of a controller. Among the processes are inverted pendulums, tank processes, servo motors, ball and beam processes and robots. In Figure 2, a time schedule of a sample two-week project is shown. Initially the project group together with their supervisor outline the project. The modeling and identification together with the controller design is often an iterative procedure where also simulation play a key role. Then the design is implemented in a real-time environment and evaluated on the true plant. During the oral presentation, other groups provide criticism and ask questions about the chosen methods.

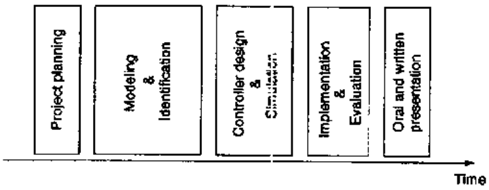

Fig. 2. Time schedule for a two-week course project.

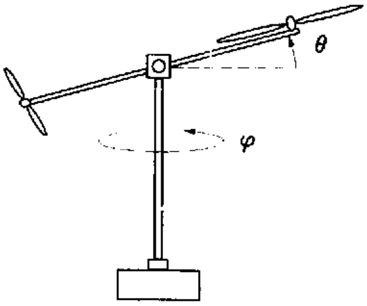

Fig. 3. Definition of the pitch angle θ and the yaw angle φ.

3. THE HELICOPTER LAB PROCESS

The helicopter process has two inputs and two outputs and its nonlinear behavior must be considered to obtain good control performance. The process is splendid for introducing control design in a realistic way. A similar construction but with a more sophisticated actuator is discussed in (Choi *et al.*, 1994). The helicopter lab process offers a number of issues common in control design for a wide range of processes. Among these are

- Control structure selection. True multivariable controllers as well as simple SISO controllers with or without feedforward can be tested on it.
- Nonlinearities. The process dynamics is nonlinear, and there are constraints on the control signals as well as on the states. Compensation has to be considered to obtain good performance.
- Open-loop instability. Since the open-loop process is unstable, identification experiments have to be performed in closed loop.

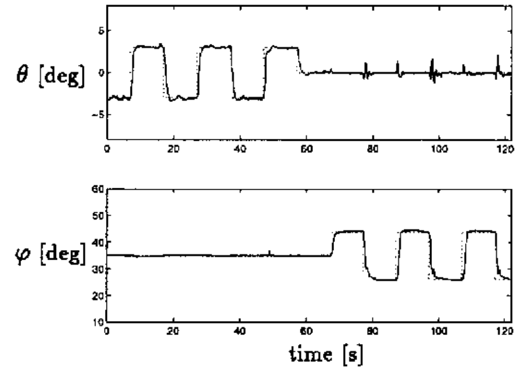

Fig. 4. The helicopter lab process controlled by two SISO controllers at $\theta_0 = 0$. Note the coupling from φ to θ.

3.1 *Modeling*

In Figure 3 a sketch of the helicopter lab process is shown. The process consists of a rod onto which two rotors are attached, the main rotor and the tail rotor. As illustrated in the figure, the mechanical construction has two degrees of freedom. The inputs to the process are the voltages u_1 and u_2 affecting the main and the tail rotor, respectively. The outputs are the pitch angle θ and the yaw angle φ. When no control signals are applied, the helicopter will tend to an end position at $\theta = -45$ degrees. A linearization of the process dynamics at an operating point gives the input–output relation as

$$\begin{pmatrix} \theta \\ \varphi \end{pmatrix} = \mathbf{G} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \qquad (1)$$

where G_{ij} are continuous-time transfer functions. The cross couplings are described by G_{12} and G_{21}. These are nonzero due to gyroscopic couples and centrifugal forces.

A first approach is to neglect the cross couplings and design two SISO controllers connected as θ–u_1 and φ–u_2. The results for two well-tuned controllers are shown in Figure 4. The SISO controllers succeed to reduce the effect of the cross coupling G_{21} but not G_{12}. This experiment motivates our choice of control structure: two SISO controllers together with a feedforward compensator from u_2 to u_1. However if the bandwidth for the yaw dynamics is reduced, then the effect of the cross coupling would be less accentuated. Thus if a diagonal controller structure is chosen, there will be a trade off between the pitch and yaw performance.

3.2 *Identification*

The identification experiments were done using standard methods, see for instance (Johansson, 1993), and discrete-time linear models were estimated in Matlab (Ljung, 1991). In this section we briefly describe the identification procedure together with some interpretations of the results.

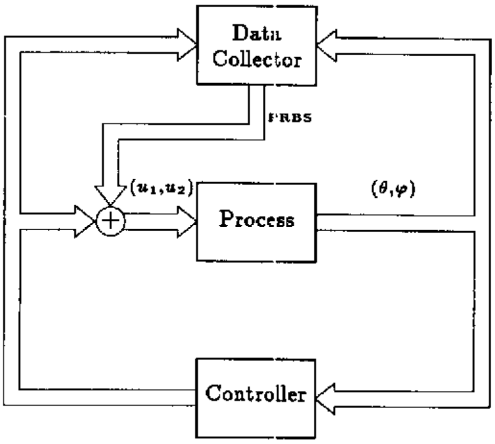

Fig. 5. The experiment setup. The identification experiments were performed in closed loop using two 486 PCs.

The laboratory equipment consisted of the lab process and two 486 PCs, see Figure 5. Since the process is unstable, the identification experiments were performed in closed loop and two PI-controllers were used to stabilize the process. The controllers were implemented in one of the computers using the real-time capability in Simnon (Elmqvist *et al.*, 1986) while the other computer was used for data acquisition. Identification experiments were carried out adding a PRBS (pseudo-random binary sequence) to u_1 and u_2, respectively. The sampling time was chosen to 50 ms and series of 2000 data points were collected. An experiment result is shown in Figure 6 where the PRBS has been added to u_2. Notice in particular how the yaw angle φ is affected. Each data series was split into two parts, one for identification and one for validation.

The process is nonlinear in the pitch angle θ. Therefore, the operating region was divided into three intervals. Identification experiments were done for the operating points θ_0 equal to zero and ± 24 degrees.

First we consider the estimation of G_{11}. Standard criteria for model selection such as residual plots, simulation, pole-zero plots, Akaike's prediction error, etc, suggested a third order ARMAX model

$$\hat{A}_{11}(q)\theta(t) = \hat{B}_{11}(q)u_1(t) + \hat{C}_{11}(q)e(t)$$

where q is the forward-shift operator. In Figure 7 the (continuous-time) pole locations for the three operating points are shown. Notice in particular how the two poles closest to the origin are moving. This is in accordance

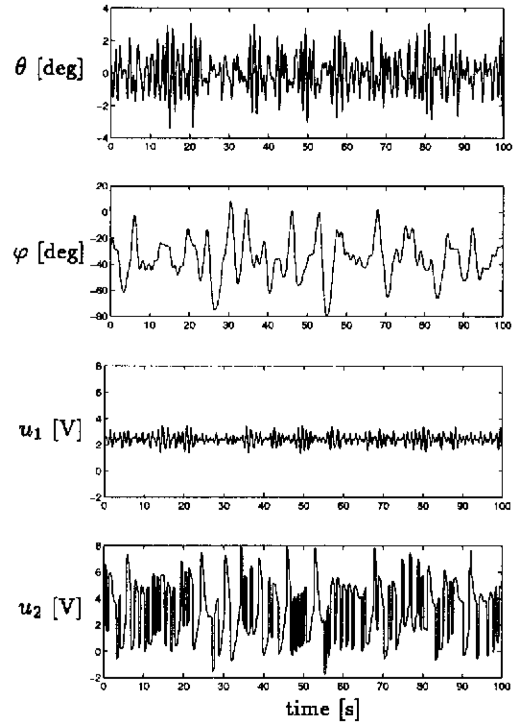

Fig. 6. Data from a typical identification experiment. A PRBS is present in u_2.

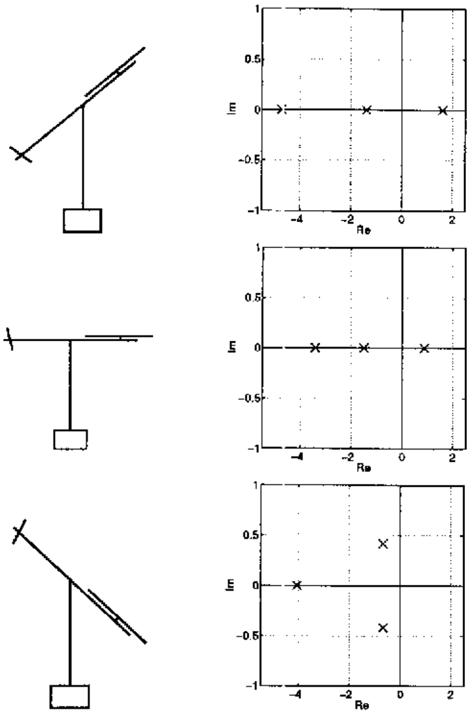

Fig. 7. Continuous-time poles of $\hat{G}_{11}$ for three operating points. $\theta_0 = 24,\ 0,\ -24$ degrees.

with the poles of a linearized mathematical pendulum. For example at the operating point $\theta_0 = -24$ degrees the helicopter has complex conjugate poles close to the imaginary axis just like a downward hanging pendulum. However, because of the construction of the helicopter lab process, $\theta_0 = 0$ does not correspond to a horizontal pendulum.

A second order model was judged to be the best choice for the transfer function estimate $\hat{G}_{22}$. If the third pole in $\hat{G}_{11}$ is interpreted as a time constant for the main rotor, the lack of this pole in $\hat{G}_{22}$ is reasonable due to that the tail rotor is much faster than the main rotor. The estimated model $\hat{G}_{22}$ turned out to be a complex pair of poles close to the origin, that is, approximately a double integrator. The pole locations depend less on the operating point while the steady-state gain varies between 0.88 and 1.84.

It is hard to determine a physical model for the cross coupling G_{12}. Furthermore, it showed up to be difficult to perform an identification experiment which excited the system such that an accurate model could be estimated. Therefore a first order model structure was chosen. Using data from an experiment as in Figure 6 the resulting estimate was a low pass filter. As shown in next section, this model fulfilled its purpose.

3.3 *Controller Design*

In the following the controller design is described and evaluated. In order to improve the performance shown in Figure 4, a feedforward together with two pole-placement SISO controllers are designed. Gain scheduling of the SISO controllers and the feedforward are shown to give good performance for various operating points. At ETH, PD and observer-based state-space controllers are used in laboratory sessions, see (Mansour and Schaufelberger, 1989) and (Glattfelder *et al.*, 1995).

Consider the process **G** in equation (1). By applying a decoupling matrix **T**, SISO control design methods can be used for the decoupled process **GT**, for instance, see (Seborg *et al.*, 1989). By neglecting G_{21}, as was motivated above, a decoupling matrix giving the desired feedforward is

$$\mathbf{T} = \begin{pmatrix} 1 & -\hat{G}_{12}/\hat{G}_{11} \\ 0 & 1 \end{pmatrix}$$

In our case, the derived feedforward was a high pass filter designed for the operating point $\theta_0 = 0$. Due to spikes in the control signals (compare Figure 10), a limiter was introduced in the feedforward path. The structure of the final controller is shown in Figure 8.

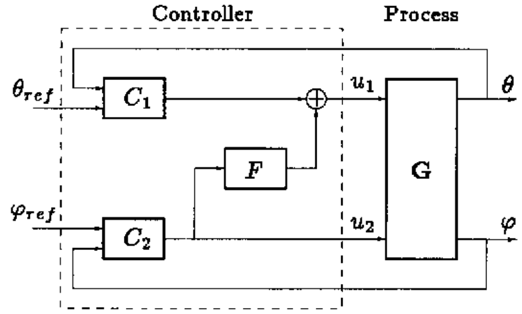

Fig. 8. Structure of the final controller. Gain scheduling is used for adaptation to various operating points.

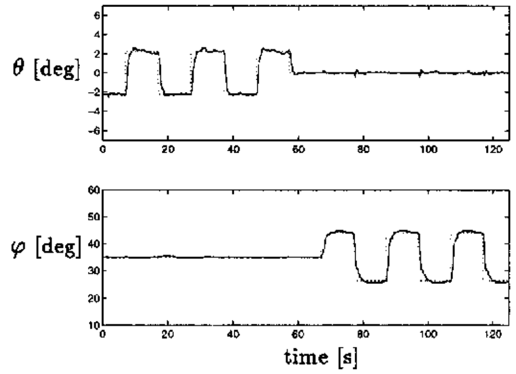

Fig. 9. The helicopter controlled by two SISO controllers and a feedforward compensator for $\theta_0 = 0$. Compare Figure 4.

Two-degree-of-freedom SISO controllers, C_1 and C_2, on the form

$$R(q)u_1(t) = -S(q)\theta(t) + T(q)\theta_{ref}(t)$$

were designed for the decoupled process **GT**. A pole-placement strategy was used where both controllers were chosen to have integral action, see (Åström and Wittenmark, 1990). The closed-loop poles were placed in a Butterworth configuration giving bandwidths of approximately 4 and 2.5 rad/s, respectively.

By comparing Figure 9 with Figure 4 the result with the feedforward F is illustrated. Notice that the effect of G_{12} is almost eliminated for positive step responses, while the reduction is smaller for negative ones. An explanation for this asymmetry could be that the tail rotor changes direction of rotation when tracking the positive step, so the linearity assumption on the model need not hold in practice. One possibility to solve this is to make the feedforward dependent on the step direction.

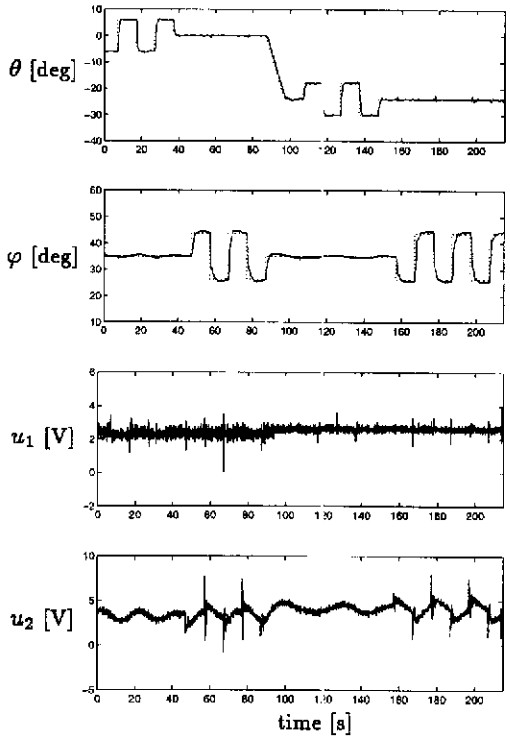

Fig. 10. Results with the final gain scheduling controller shown when changing operating point from $\theta_0 = 0$ to -24 degrees.

Gain scheduling was used to adapt the system to various operating points. The gains in both SISO controllers were varied together with the gain in the feedforward. This gave a closed-loop behavior approximately independent of the operating point. The controllers have been implemented on velocity form to give smooth transfers when switching from one gain to another, see (Åström and Wittenmark, 1990). This also facilitates the antireset windup handling. Furthermore, hysteresis has been included to avoid chattering between different gains.

Finally, the control design was evaluated. In Figure 10 responses to reference steps using the final controller are shown. After 85 seconds the operating point is moved from $\theta_0 = 0$ to $\theta_0 = -24$ degrees. The process outputs behave well. The noise in u_1 is due to the high pass characteristic of the feedforward. Note also the action in u_2 during the reference changes in θ. This indicates that there is in fact a coupling between u_1 and φ, i.e., G_{21} is nonzero. However the yaw controller succeeds in eliminating this phenomenon.

4. SUMMARY

A two-week control design project in a graduate course has been described. The issue was to design a controller for a multivariable helicopter lab process. Heuristic modeling, system identification, control design as well as implementation on a real-time system were included. The main parts in the final controller were a gain scheduler together with two SISO-controllers and a feedforward path. The closed-loop system was shown to respond well to step reference signals.

The described project illustrates the whole procedure from modeling and identification to implementation and validation of a control system. Care was taken to practical issues such as antireset windup and smooth parameter changes. These are examples of important points when confronted with real control systems in industrial applications. It is our belief that projects of this type clearly improves the engineering skills of the students. More information about the undergraduate and graduate education at our department is given in (Åström and Lundh, 1992).

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