ICAD BASED CONTROL OF A PRESSURE-LEVEL PILOT PLANT

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Abstract

A practical example of multivariable control analysis and design for a pilot plant within Individual Channel Analysis and Design (ICAD) framework is presented. The pressure-level plant is used for studying the dynamics of variables like gas pressure and liquid level that often occur in the process industries. The device is very problematic since it is highly nonlinear and it is not diagonal dominant. High level noise is also present on both outputs while additional problem is non-repeatability of the dynamics. On the basis of the ICAD analysis, a simple low-order linear diagonal controller was designed that met the prescribed specifications.

1 Introduction

Despite the existence of many methods for the analysis and design of SISO (single-input single-output) control systems, it is well known that there exist systems for which satisfactory quality of control may not be assured by using these methods. In such cases we have to use approaches that do not treat a MIMO (multiple-input multiple-output) system as a set of SISO systems but as a uniform system with all cross-interactions preserved. The drawback here is that algorithms for design are usually very complex and result in complicated solutions. Experiences in industry have shown that simple and effective solutions are needed. A proof of this fact is that the majority of continuous plants are controlled by PID controllers.

The purpose of this paper is to present a practical example of controller analysis and design for a pilot plant by using the multivariable control framework known as Individual Channel Analysis and Design (ICAD). The pressure-level pilot plant UML was developed by Hochschule für Technik, Wirtschaft und Kultur in Leipzig (Germany). It was built for control studying purposes as variables like pressure and level are frequently dealt with in process industry. In the paper production process a similar problem is encountered [3] as the one studied in the present paper, i.e. the control of a pressurised paperstock flow. The other reason for choosing this plant for experimentation is because it poses numerous challenges to the designer.

Many practical applications have been treated by ICAD and it turns out that ICAD is an excellent tool when control for a system demanding a high level of robustness to plant uncertainty has to be designed. Among them there are various problems like combustion control [4], helicopter flight control [2, 9], submarine depth control [8] and control of an automotive gas turbine [11].

This paper is organised as follows. The basic characteristics of the pilot plant are presented in Section 2. Section 3 gives a brief review of ICAD. The design process is depicted in Section 4 and the conclusions of the paper stated in Section 5.

2 The description of the pilot plant

A schematic representation of the pilot plant is shown in Figure 1.

The central part of the device is a closed tank where air-pressure and water-level can be controlled through two pumps. The device also has some valves through which one can vary air- and water-outflow. The operating conditions of the plant change by changing the position of those valves (the linearised model has different parameters). Unfortunately these valves can be set only manually.

The pilot plant UML poses numerous problems to achieving good quality of control. It is highly nonlinear due to the fact that the flow through valves is proportional to square root of the pressure, the flow through the air pump is proportional to square of the voltage, the flow through the water pump is proportional to the fifth power of the voltage and there is also an additional nonlinear connection due to the product between two plant states. Also, output signals are excessively noise corrupted limiting attainable closed-loop bandwidths and the plant is not diagonal dominant. The repeatability of the device is not good especially in open-loop operation while closed-loop operation was not affected to the same extent.

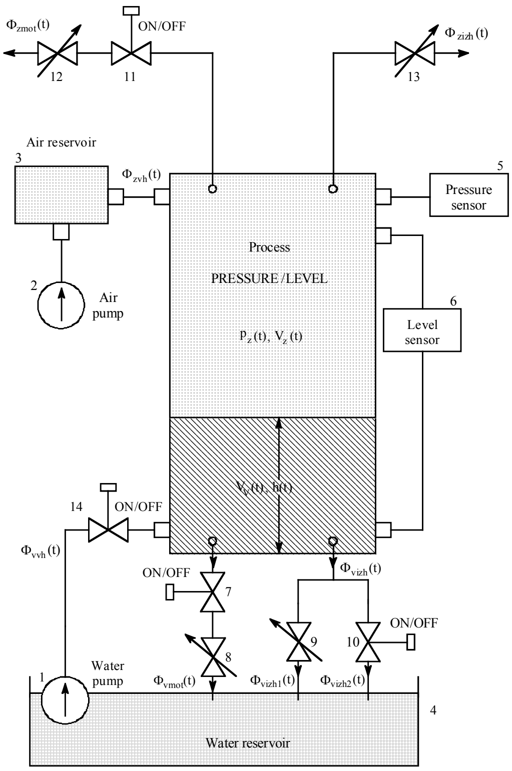

Fig. 1. Schematic representation of the pilot plant

Problematic behaviour of the plant limits selection of a suitable operating point, therefore the same operating conditions as proposed in [1] were chosen. A sufficiently large linear area where no problems with non-repeatability were encountered was hard to find.

The modelling of the plant is dealt with in some other papers. The plant was modelled by nonlinear differential equations in [1] while in [10] neural networks are used for modelling. Both papers prove that nonlinear behaviour of the plant cannot be neglected if one wants accurate description of its operation.

A decision has to be made as to which control algorithm to apply. Because of nonlinearity of the plant whose parameters also change we could use adaptive control or at least apply some type of nonlinear controller. Since our wish was to use simple controller we tried to design frequency-domain compensator robust enough so that closed-loop system cannot be destabilised because of differences between the plant and its linear model.

The model obtained in [1] was the basis for control analysis and design. We used the linearised model of the plant that included dynamics of the actuators and the sensors. The plant can be represented with a transfer function matrix of the form

$$\mathbf{G}(s)=\begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix}=\frac{1}{(0.8s+1)(s+1)(1.5s+1)(5.54s+1)(82.15s+1)} \quad (1)$$
$$\times\begin{bmatrix} 0.834(69.3s+1)(1.5s+1) & 61.0s(0.8s+1)(s+1) \\ -13.49(1.5s+1) & 13.49(6.57s+1)(0.8s+1)(s+1) \end{bmatrix}.$$

The plant model is of fifth order and is stable and minimum phase.

Our goal was to design such a control that the water-level and the air-pressure follow the reference signals despite all the problems described above. Let us now depict the starting control specification:

- gain cross-over frequencies of the channels should be 1 rad/s,
- channel phase margins should be at least 45 degrees,
- channel gain margins should be at least 10 dB, and
- steady-state errors should be zero.

3 ICAD as an approach to analysis of the systems

Individual channel analysis and design (ICAD) is an application-oriented framework, mainly for the analysis of multivariable control systems. It was developed and presented in [11]. The characteristics of the approach are its transparency and flexibility. It enables us to meet the user's control requirements directly in a way that is well suited for the engineering context. We have to point out that ICAD is not a design method *per se*. Rather, it is a structural framework for analysis and design of the multivariable control systems. ICAD allows us to design control for a multivariable system using some other SISO method. Then we can assess the performance of the closed-loop system using ICAD from the open-loop channel characteristics. One fact that makes this approach so special is that highly successful and well-known classical methods principally of Nyquist-Bode type are made possible.

The configuration of the diagonal control system is depicted in Figure 2.

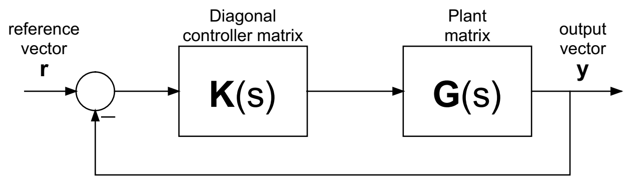

Fig. 2. The configuration of the diagonal control system

By using ICAD, an m-input m-output multivariable system in Figure 2 can be represented by m SISO channels. Each of the SISO channels has the same form: to each output y_i a reference signal r_i is assigned and the individual channel C_i is closed by a negative unity loop. The influence of cross-reference signals is not neglected. The cross-reference signals are filtered by a transfer function and added to a certain output. If a diagonal controller $K(s)$ (or m SISO controllers $k_i(s)$) stabilises the system and the reference signals are finite then the closed-loop contributions of the reference signals on any output are finite. Hence, filtered cross-reference signals can be treated as normal disturbances on the output of the SISO system.

The analysis of the system is simplified for the pilot plant where m=2. That means that our domain is restricted to two-input two-output control systems that represent the largest subset of multivariable control problems. The analysis of such systems was presented in [5, 6] while the design issues are dealt with in [7]. In such cases the multivariable structure function $\gamma(s)$ is defined by

$$\gamma(s) = \frac{g_{12}(s)g_{21}(s)}{g_{11}(s)g_{22}(s)} \tag{2}$$

and individual channel transfer functions $C_i(s)$, i = 1, 2, are defined as

$$C_i(s) = k_i(s)g_{ii}(s)\left[1-\gamma(s)h_j(s)\right] \ , \quad j = 1{,}2, \ j \neq i \tag{3}$$

where

$$h_j(s) = \frac{k_j(s)g_{jj}(s)}{1+k_j(s)g_{jj}(s)}, \quad j = 1{,}2. \tag{4}$$

A main advantage of the ICAD approach is the possibility of assessing the robustness of a MIMO system. An important result obtained in [5] is that phase and gain margins associated with the open-loop channel transmittances for a 2-input 2-output system are measures of robustness of the closed-loop system stability to plant uncertainty provided that the Nyquist plots of the multivariable structure functions $\gamma h_j(s)$ do not go near the (1,0) point (this stands for 1+j0) except at frequencies significantly greater than the gain cross-over frequencies ω_{ci} of each channel.

Another advantage of ICAD is that it often enables the controller to be of simple form but still assures the robustness of the closed-loop system.

Many practical applications have been treated by ICAD and it turns out that ICAD is an excellent tool when control for a system demanding a high level of robustness to plant uncertainty has to be designed. Among them there are various problems like combustion control [4], helicopter flight control [2, 9], submarine depth control [8] and control of an automotive gas turbine [11].

4 The controller design process

Despite the fact that the central part of the device is of multivariable nature (the cross-interactions cannot be neglected) the structure of the plant itself imposes its division into a pneumatic subplant and a hydraulic one. Adopting such a view of the plant again recommends ICAD for its analysis.

The first step when using ICAD is to analyse the multivariable structure function $\gamma(s)$ of the plant. The Nyquist plot of the multivariable structure function $\gamma(s)$ is shown in Figure 3.

The plant is neither row diagonal dominant nor column diagonal dominant in the sense of Rosenbrock [12] but $\gamma(s)$ is still small in magnitude what does not indicate any troubles in controller design because of strong cross-interactions in the plant even though we might expect some if we consider the fact the plant is neither row diagonal dominant nor column diagonal dominant.

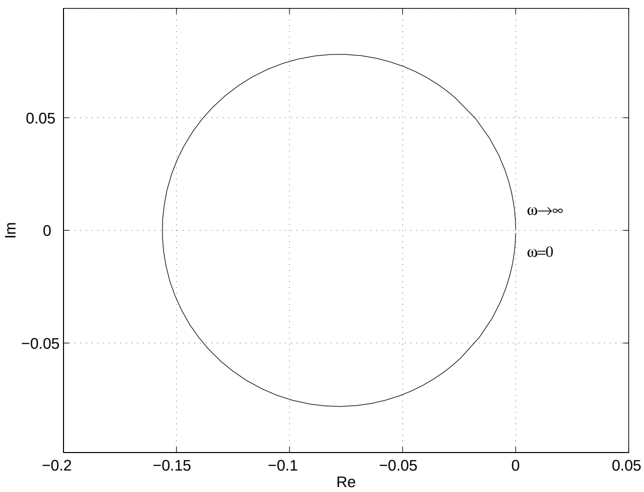

Fig. 3. Nyquist plot of multivariable structure function $\gamma(s)$

Since the Nyquist plot of $\gamma(s)$ in Figure 3 never goes near the point (1,0), the controller will be robust provided both channels have satisfactory phase and gain margins.

In Figure 4 Bode plots of individual transfer functions $g_{11}(s)$ and $g_{22}(s)$, respectively, are shown. Since $\gamma(j\omega)$ (and consequently $\gamma h_1(j\omega)$ and $\gamma h_2(j\omega)$) is small in magnitude, the two Bode plots in Figure 4 are practically equal to Bode plots of transfer functions $g_{11}(1\text{-}\gamma h_2)$ and $g_{22}(1\text{-}\gamma h_1)$. The gain cross-over frequencies of the two channels are ω_{c1}=0.114 rad/s and ω_{c2}=0.0122 rad/s, respectively, and therefore there is a significant difference between channel bandwidths. The consequence of the mentioned is that the controllers can be designed individually in the ICAD framework.

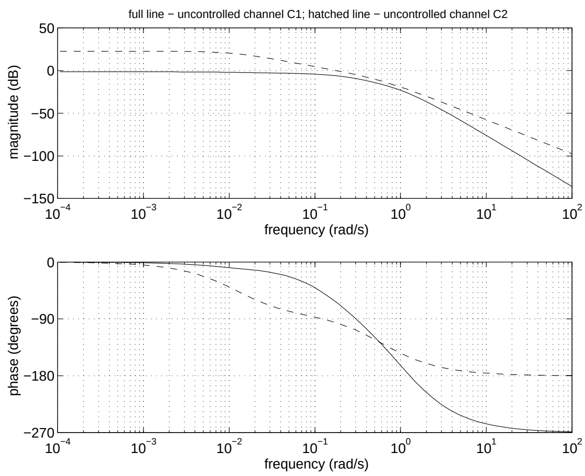

Fig. 4. Bode plots of both uncontrolled channels, i.e. individual transfer functions $g_{11}(s)$ and $g_{22}(s)$, respectively

A controller was designed to meet the specifications in Section 2 with $k_1(s)$ and $k_2(s)$ given by

$$k_1(s) = \frac{26.7s^2 + 17.1s + 1.44}{s^2 + 1.85s}$$
$$k_2(s) = \frac{12.3s^2 + 9.6s + 0.095}{s^2 + 1.3s}. \qquad (5)$$

The controller was designed following the procedure in the previous section where individual controller transfer function was designed using the well-known frequency-domain design techniques (the shaping of the frequency response in Bode diagram).

The Nyquist plots of the multivariable structure functions $\gamma h_1(s)$ and $\gamma h_2(s)$ shown in Figure 5 never approach the (1,0) point confirming robustness of the controllers (5). The Bode plots of both channels are shown in Figure 6 (channel C_1 with full line and channel C_2 with the hatched one). It can be observed from Figure 6 that all the demands are met. Naturally we decided to use controllers (5) for closed-loop operation with the device. A/D and D/A conversions were carried out by the interface PCI-20428W. A sampling time of 0.1 second was used. The output and input signals are shown in Figures 7 and 8, respectively. The output y_1 is proportional to the air pressure while y_2 is proportional to the water level.

It is observed in Figure 7 that the outputs of the plant are corrupted with noise of high magnitude. Otherwise the responses of the system are satisfactory. Mean values of individual outputs follow corresponding reference signals very quickly, the overshots are small and the system reaches the prescribed operating point in a short time. The fact that makes the use of the controllers (5) questionable is the oscillation of input signals shown in Figure 8. These oscillations overload the actuators and could lead to destruction of the pumps.

The logical decision at this point was a choice of lower bandwidths for the individual channels. We decided to lower the bandwidth of the second channel (water level) more. So new specifications for the closed-loop system were chosen:

- gain cross-over frequency of C_1 should be 0.8 rad/s,

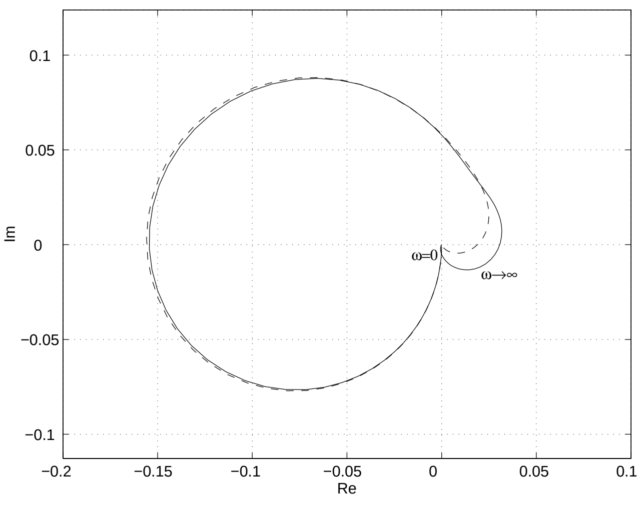

Fig. 5. Nyquist plots of multivariable structure functions $\gamma h_1(s)$ (full line) and $\gamma h_2(s)$ (hatched line)

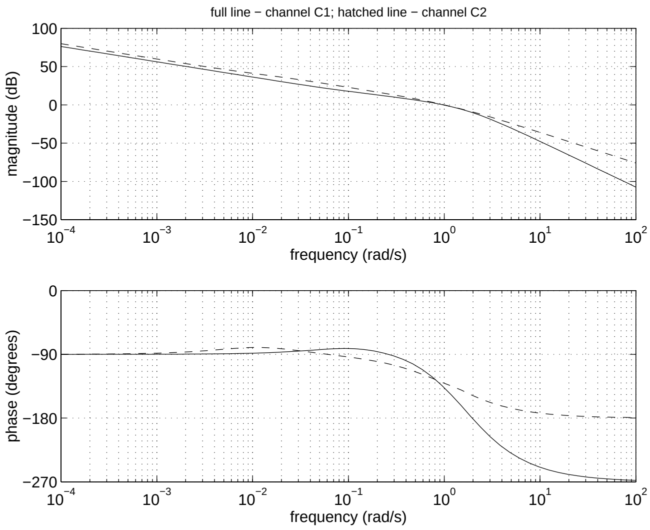

Fig. 6. Bode plots of open-loop transfer functions for both channels

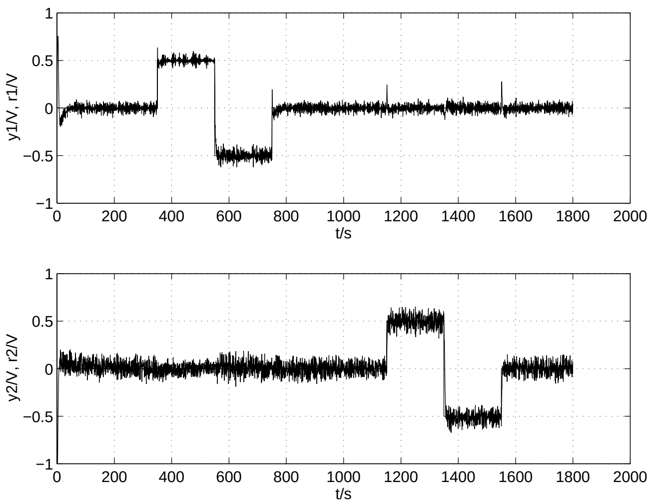

Fig. 7. Responses of the air pressure (up) and the water level (down) when using controllers (5)

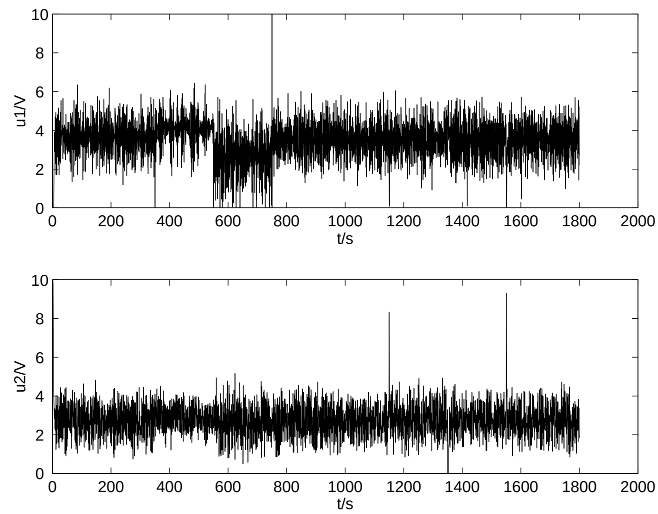

Fig. 8. Input signals u_1 (up) and u_2 (down) when using controllers (5)

- gain cross-over frequency of C_2 should be 0.4 rad/s,
- channel phase margins should be at least 45 degrees,
- channel gain margins should be at least 10 dB, and
- steady-state errors should be zero.

The specification stated above were met by the controllers:

$$k_1(s) = \frac{13.6s^2 + 8.91s + 0.626}{s^2 + 1.11s}$$
$$k_2(s) = \frac{2.02s^2 + 1.06s + 0.0392}{s^2 + 0.33s}. \tag{6}$$

The Nyquist plots of the multivariable structure functions $\gamma h_1(s)$ and $\gamma h_2(s)$ are shown in Figure 9 with full line and hatched line, respectively. They never approach the (1,0) point confirming that the gain margin and the phase margin obtained by loop shaping are indeed robustness measures of the closed-loop system.

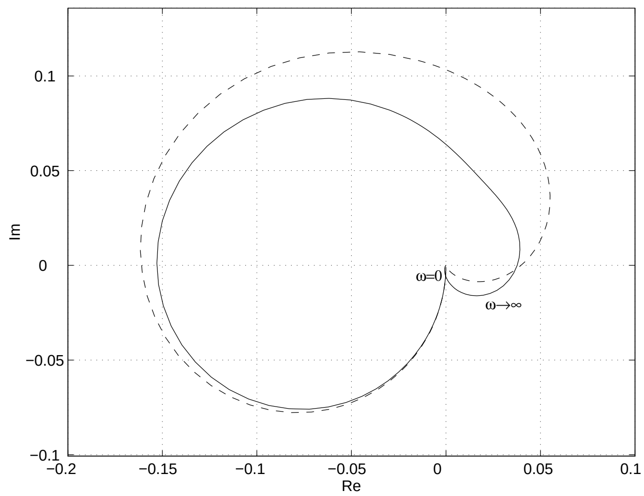

Fig. 9. Nyquist plots of multivariable structure functions $\gamma h_1(s)$ (full line) and $\gamma h_2(s)$ (hatched line)

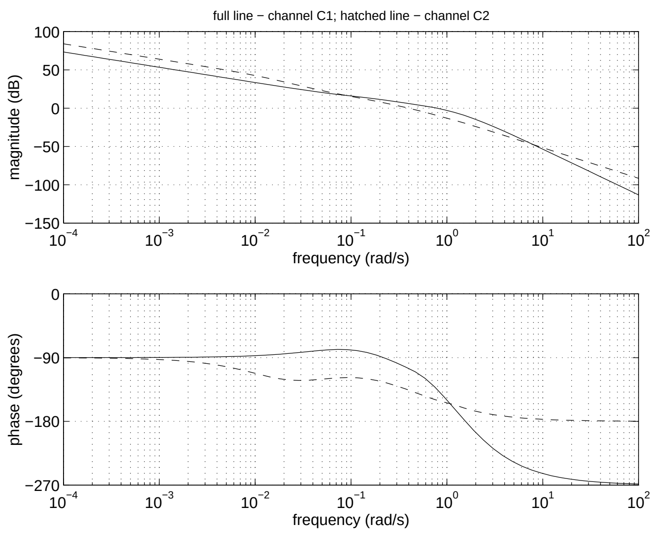

Fig. 10. Bode plots of open-loop transfer functions for both channels

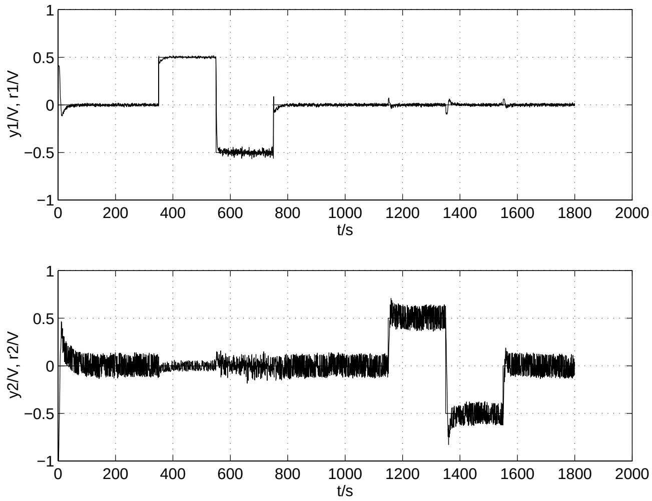

Fig. 11. Responses of the air pressure (up) and the water level (down) when using controllers (6)

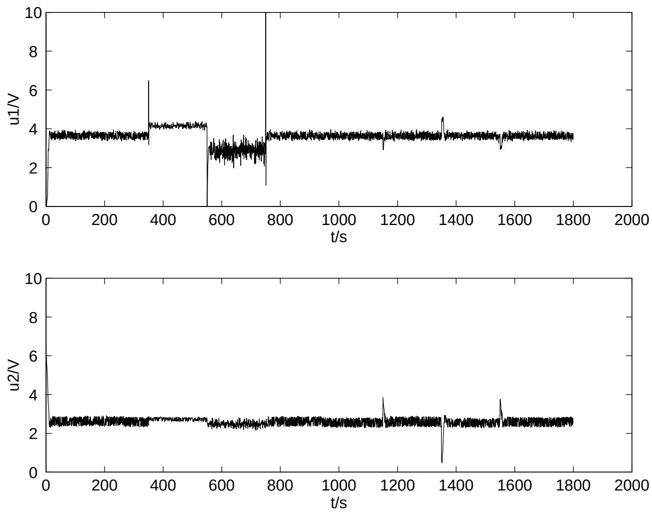

Fig. 12. Input signals u_1 (up) and u_2 (down) when using controllers (6)

Open-loop channel Bode plots are shown in Figure 10 (channel C_1 with full line and channel C_2 with hatched one). It can be observed from Figure 10 that the shape of Bode plots did not change drastically. Cross-over frequencies are lower as required but a slight overshot in the phase plot of channel C_1 can be observed. This in turn causes that an almost flat range is present in the gain plot and the response of the system could be slower than expected.

After analysing the properties of the closed-loop system on its model the effect of control was tested on the pilot plant. Responses of both channels and input signals are shown in Figures 11 and 12, respectively. It is obvious that the decrease of channel bandwidths was justified. Output signals still follow corresponding references quickly enough. However, oscillations of input and output signals are much smaller and the wearing out of pumps is not critical anymore.

5 Conclusions

The purpose of this paper was to show a practical example of control design assisted by ICAD. Despite the problematic nature of the plant it turned out that the specification for the closed-loop system was easily met by a diagonal controller. Phase and gain margins associated with open-loop channel transfer functions C_1 and C_2 were large enough to ensure that inaccuracies in the model could not lead to an unstable closed-loop system. The only thing that makes achievement of the prescribed specification difficult is the high level of noise on the outputs of the system. Consequently, a decision to lower bandwidths of both channels was taken. Operation of the modified system was satisfactory. It is worthwhile pointing that the controller that met the specifications was of a very simple form. In fact, two SISO controllers of the second order were used.

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