Feedforward control concepts through Interactive Tools

J.L. Guzmán * **T. Hägglund** ** **K.J. Åström** ** **S. Dormido** ***
M. Berenguel * **Y. Piguet** ****

* *Dep. de Lenguajes y Computación, Universidad de Almería, 04120
Almería, Spain. (Tel: +34 950 015849; e-mail:joguzman@ual.es)*
** *Department of Automatic Control, Lund University, Box 118
SE-22100 Lund, Sweden (e-mail: {kja,tore}@control.lth.se)*
*** *Dep. Informática y Automática, ETSI Informática, UNED, 28040
Madrid, Spain (e-mail: sdormido@dia.uned.es)*
**** *Calerga Sàrl, 35, av. de la Chablière, 1004 Lausanne, Switzerland
(e-mail: yves.piguet@calerga.com)*

Abstract: This paper presents an interactive software tool for basic and advanced concepts of feedforward control. The ideal compensator is analyzed to show how the effects of the load disturbances are eliminated from the process output. Furthermore, it is also shown that the ideal compensator is seldom realizable, since the compensator may be non-causal, it may be unstable, it may have infinite high-frequency gain because of derivative action, and it may require a more complicated structure than what is available. The drawback of not taking the feedback controller into account during the typical open-loop feedforward design is also studied. The proposed software tool helps to evaluate all these situations in an interactive way, enabling users to find possible design solutions to these problems. © *Copyright IFAC 2011.*

Keywords: Feedforward control, load disturbances, control education, interactivity.

1. INTRODUCTION

Disturbances is one of the most important aspect of control problems. In fact, without disturbances, process uncertainty, or unstable dynamics there would not be any need for feedback. Load disturbances are disturbances that enter the control loop somewhere in the process and drive the system away from its desired operating point. Load disturbances typically have low frequency and efficient reduction of load disturbances is a key issue in process control systems (Åström and Hägglund, 2005).

Traditionally, disturbances have mostly been considered indirectly, e.g., by introducing integral action in the feedback controller. Feedforward control from measurable disturbances provides a possibility to make control actions before any disturbance response has occurred in the process output. This fact makes it a very powerful complement to the feedback controller. Feedforward control was used as early as 1925 for drum level control in the three-element control configurations (Seborg et al., 1989). Many of the other early applications dealt with control of distillation columns (Nisenfeld and Miyasak, 1973). In the early applications, use of feedforward was almost a prerequisite to solve the control problems in these difficult applications. Nowadays, feedforward is implemented in most distributed control systems and the technique is used also for rather simple control problems to improve the control performance.

The basic idea for design of the feedforward compensator is very simple. The ideal compensator is formed as the dynamics between the load disturbance and the process output divided by the dynamics between the control signal and the process output, with reversed sign. If this feedforward compensator is used, the effects of the load disturbance are eliminated from the process output.

However, the ideal compensator is seldom realizable. The compensator may be non-causal, it may be unstable, it may have infinite high-frequency gain because of derivative action, and it may require a more complicated structure than what is required. These facts make the design problem non-trivial, and there is a need for dealing with these issues from an educational point of view.

In process control, the structure of the feedforward compensator is normally either just a gain or a lead-lag filter. Sometimes a delay is also needed to ensure that the compensation is not made too early. More complicated compensator structures are uncommon. Most basic control textbooks mention the feedforward technique, and present the design philosophy of the ideal compensator. They normally also mention the realizabililty problems, but they seldom go any further and present design rules.

Almost all design procedures for feedforward control are based on an open-loop design, i.e. the feedback controller is not taken into account when the feedforward compensator is designed. This drawback is pointed out in (Guzmán and

Hägglund, 2011), and it will be illustrated also in this paper.

Feedforward control is a key element to be included in automatic control courses, where all the issues discussed above are fundamental parts in the education of future control engineers and practitioners. Therefore, this paper presents an interactive tool as support to the feedforward design problem with the goal to help in the understanding of these concepts. The purpose is to enhance learning by exploiting the advantages of immediately seeing the effects of changes that can never be shown in static pictures.

The proposed tool allows interactive comparisons among the responses to load disturbances for the open-loop process, the open-loop feedforward controller, the feedback controller (without feedforward), and the combination of feedback and feedforward controllers, respectively. The interactive capabilities of the tool help to understand the contribution of the feedforward action in the load disturbance rejection.

Typical feedforward open-loop design rules based on gains or lead-lag filters can easily be tuned and designed using the methods presented in (Seborg et al., 1989; Coughanowr, 1991). The drawback of not taking the feedback controller into account during the typical open-loop design can be observed (Brosilow and Joseph, 2002; Isaksson et al., 2008), and the feedforward compensator can be interactively designed in order to take this phenomenon into account. Furthermore, new tuning rules which take the feedback controller into account during the feedforward design process are included in the tool (Guzmán and Hägglund, 2011).

2. THEORETICAL BASIS

The feedforward control problem is illustrated by the block diagram in Figure 1. The diagram consists of the basic feedback loop with feedback controller C, process $P_1 P_2$, and the signals setpoint y_{sp}, control signal u and process output y. A measurable load disturbance d influences the feedback loop according to the figure, with transfer function $P_2 P_3$ between load d and process output y. The load disturbance is fed through a feedforward compensator $-G_{ff}$, and the output from the compensator is added to the feedback control signal. The goal is to design the feedforward compensator G_{ff} so that the effect of the disturbance d on the process output y is minimized.
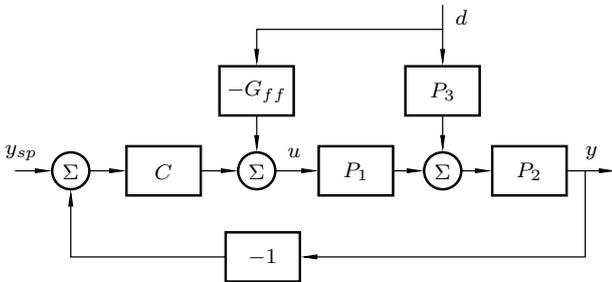

Fig. 1. Block diagram illustrating the feedforward control problem.

In this work, the three process transfer functions are modeled as first-order systems with time delay, i.e.

$$P_1 = \frac{K_1}{1+sT_1}e^{-sL_1}, \; P_2 = \frac{K_2}{1+sT_2}e^{-sL_2}, \; P_3 = \frac{K_3}{1+sT_3}e^{-sL_3} \tag{1}$$

It is assumed that the feedback controller is a PI or PID controller with transfer function

$$C = K\left(1 + \frac{1}{sT_i} + sT_d\right), \tag{2}$$

where $T_d = 0$ in case of PI control. In this paper, the PID controller tuning is not analyzed and it is always tuned using the AMIGO method, which optimizes the load disturbance attenuation for a reasonable robustness (Åström and Hägglund, 2005). Notice that this work is focused on analyzing the feedforward design for a given feedback loop.

Four structures of the feedforward compensator G_{ff} are treated in this paper:

Static: $\qquad\qquad G_{ff} = K_{ff}$

Static with delay: $\qquad G_{ff} = K_{ff}e^{-sL_{ff}}$

Lead-lag: $\qquad\qquad G_{ff} = K_{ff}\dfrac{1+sT_z}{1+sT_p}$

Lead-lag with delay: $\quad G_{ff} = K_{ff}\dfrac{1+sT_z}{1+sT_p}e^{-sL_{ff}}$

Most design methods for feedforward are based on the open-loop transfer function between d and y, which is given by (with $y_{sp} = 0$)

$$Y = P_2(P_3 - P_1 G_{ff})D \tag{3}$$

Perfect feedforward, which means that the effect of d is eliminated in y, is obtained when

$$G_{ff} = \frac{P_3}{P_1} = \frac{K_3}{K_1} \cdot \frac{1+sT_1}{1+sT_3}e^{-s(L_3 - L_1)} \tag{4}$$

which is a lead-lag with delay where

$$K_{ff} = \frac{K_3}{K_1} \qquad T_z = T_1 \qquad T_p = T_3 \qquad L_{ff} = L_3 - L_1 \tag{5}$$

When $L_3 < L_1$, the effect of the input comes too late to compensate for the disturbance. In this case, the optimal parameters given by (5) give a non-causal feedforward compensator, since L_{ff} becomes negative. This means that perfect feedforward is not possible in this situation, and $L_{ff} = 0$ has to be used.

It is common to just have a static feedforward compensator. In this case

$$G_{ff} = K_{ff} = \frac{K_3}{K_1} \tag{6}$$

eliminates the effect of the disturbance in steady state. It is also common that disturbance d enters at the same position of the process as the control signal, which means that $T_1 = T_3$ and $L_1 = L_3$, see (Shinskey, 1996). In this case, the static feedforward is the optimal feedforward.

A summary of the typical open-loop design rules for the different compensator structures is:
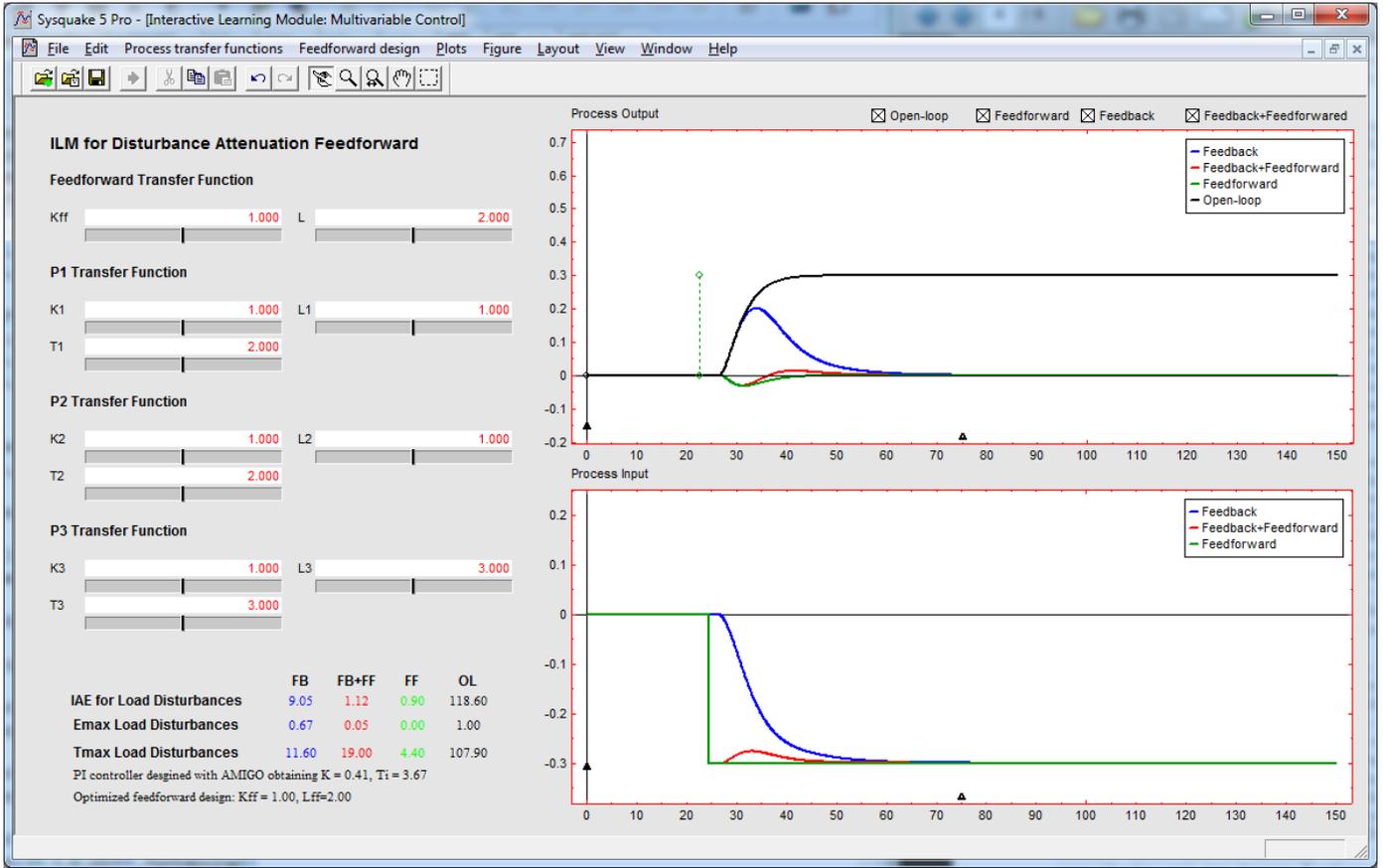
Fig. 2. Interactive tool user interface with the example from section 4.1

Static: $$G_{ff} = \frac{K_3}{K_1}$$

Static with delay: $$G_{ff} = \frac{K_3}{K_1} e^{-s(L_3 - L_1)}$$

Lead-lag: $$G_{ff} = \frac{K_3}{K_1} \frac{1 + sT_1}{1 + sT_3}$$

Lead-lag with delay: $$G_{ff} = \frac{K_3}{K_1} \frac{1 + sT_1}{1 + sT_3} e^{-s(L_3 - L_1)}$$

(7)

where it is assumed that $L_3 \geq L_1$. If $L_3 < L_1$, the delay should be omitted in the compensator.

3. INTERACTIVE TOOL

One of the most important features for developing interactive tools is the *abstraction*. In the context of this work, abstraction refers to associate theoretical concepts with graphical elements. That is, visualizing the concepts with graphical and dynamic pictures, knowing this as visualization. In order to design technical systems or simply to understand the physical laws that describe their behavior, scientists and engineers often use computers to calculate and graphically represent different quantities.

In control engineering, these quantities include among others: time and frequency responses, poles and zeros in the complex plane, Bode, Nyquist, and Nichols diagrams, phase planes, etc. Frequently, these quantities are closely related and constitute different visions of a single reality. The understanding of these relationships is one of the keys to achieve a good learning of the basic concepts and it enables students to accurately design control systems (Dormido, 2004). The tool presented in this paper has been developed following this previous idea, as shown below.

3.1 Description

This section briefly describes the main features of the developed tool. The tool has been implemented in Sysquake, a Matlab-like language with fast execution and excellent facilities for interactive graphics (Piguet, 2004). Windows, Mac, and Linux operating systems are supported. One consideration that must be kept in mind is that the tool's main feature -interactivity- cannot be easily illustrated in a written text. Nevertheless, some of the advantages of the application are shown below. The reader is cordially invited to experience the interactive features of the tool.

This interactive learning module has been developed to make it possible to quickly obtain a good intuition and a good working knowledge of basic and advanced feedforward control concepts. As the previous modules developed (Guzmán et al., 2008b,c,a, 2009), the module is composed of several parts. There are two icons that can be accessed, namely, *Instructions* and *Theory*. *Instructions* gives access to a document that contains suggestions for exercises, while *Theory* provides access to relevant theory by means of the Internet. Different menus are available to load examples and choose between different configurations

of the tool. The graphics can be manipulated directly by dragging points, lines, and curves or by using text-edits and sliders. Notice also that for all the graphics available in the tool, the vertical and horizontal scales can be modified using three black triangles available on the graphics (▲, ▼).

When developing a tool of this kind, one of the most important things that the developer has to have in mind is the organization of the main windows and menus of the tool to facilitate the understanding of the control technique for the user (Dormido, 2004). The main window of the tool is divided into several sections represented in Figure 2 (basic screen of the developed interactive tool) which are described as follows:

- *Time-domain graphics.* There exist two graphical elements on the right side of the screen, which represent the system output (Process Output) and the controller output (Process Input). The graphics show the simulation results of the control algorithm selected for a step change in set-points and load disturbance (in the inputs). Over these graphics the user can interactively modify the amplitudes of the set-points and the disturbances dragging the black and green dots, and also to change the scales dragging the small black triangles. There are four different checkboxes located at the top of the figure that allow to choose the desired option to be simulated. These options are Open-loop (open-loop response from the load disturbance), Feedforward (response for feedforward control without feedback), Feedback (only feedback response), and Feedback+Feedforward (combined response for feedback plus feedforward).
- *Process and control parameters.* The different parameters available in the tool are shown on the left-hand side of the screen (see Figure 2). These elements allow to modify process and feedforward controller parameters, respectively. So, it is possible to modify the process parameter for each transfer functions shown in Figure 1. For the feedforward controller, the compensator parameters described in the structures (7) can be modified interactively. The feedforward structure can also be modified from a menu option such as described below.
- *Performance and interaction parameters.* Some parameters to characterize performance are available in the tool. Performance information with respect to disturbance responses is provided just below the process and control parameters for each control option selected (those options in the checkboxes located at the top of figure Process Output). The load disturbance response is characterized by the integral absolute error (IAE), the maximal error (emax), and the time to reach the maximum (tmax). The integral absolute errors and the maximal error values are normalized to unit step changes. Furthermore, in this part of the tool, the PI control parameters obtained with the AMIGO method and the current feedforward parameters are permanently shown.
- *Menu options.* Several menu options can be chosen from menu bar. There are four menu entries with specific parameters of the tool: Process transfer functions, Simulation parameters, Feedforward design, and Load/Save. The Process transfer functions menu al-

lows to change the structure of the process transfer functions. It is possible to choose among a pure gain, a pure gain plus time delay, and first-order system plus time delay. Furthermore, several fixed examples are included in the tool, where some of them are described in the following section. The Simulation parameters menu allows to modify the sampling time and also disable the use of graphics autoscale. From the Feedforward design menu, it is possible to configure different options and parameters for the feedforward compensator. In fact, all the structure options shown in (7) can be selected. Finally, the Load/Save options menu is used to store and recall the results using the Save design and Load design dialogs.

Finally, notice that the simulations in the interactive tool consist of solving linear differential equations with constant coefficients and the complete system is sampled at constant sampling rate and the sampled equations are iterated. Hence, the choice of the sampling time from the Simulation parameters menu must be in accordance with the closed-loop system dynamics.

4. ILLUSTRATIVE EXAMPLES

This section summarizes the main ideas and drawbacks for the typical open-loop design of feedforward compensators. It is shown that the open-loop design works well in cases when perfect feedforward is obtained. In other cases, the feedback controller may deteriorate the response and also the feedforward action may give control signals that are considered too aggressive.

4.1 Perfect cancelation and feedback effect

We start with an example where $L_3 \geq L_1$, which means that this is a case where perfect feedforward is possible.

The process transfer functions are

$$P_1 = \frac{1}{2+s}e^{-s} \qquad P_2 = \frac{1}{2+s}e^{-s} \qquad P_3 = \frac{1}{1+3s}e^{-3s}$$

(8)

The feedback controller C is a PI controller tuned using the AMIGO rule (Åström and Hägglund, 2005), which gives the parameters $K = 0.41$ and $T_i = 3.67$.

The four different compensators in (7) can be used interactively in the software tool. It can, e.g., be seen that perfect feedforward is obtained when the lead-lag compensator with delay is used. However, when other compensator structures are used, no perfect cancelation is possible, such as shown in Figure 2, where the feedforward compensator with a gain plus time delay is used $G_{ff} = e^{-2s}$.

Figure 2 shows the disturbance responses for the open-loop process (in black), the open-loop feedforward (in green), the feedback without feedforward (in blue), and the feedback plus feedforward (in red) cases, respectively. Notice how the contribution of the feedforward compensator is observed from the Process Input graphic in the figure. The feedback controller without feedforward (in blue) reacts after the disturbance effect, but the feedforward action (in green for open-loop feedforward and in red for feedback+feedforward) helps to anticipate to the disturbance influence.
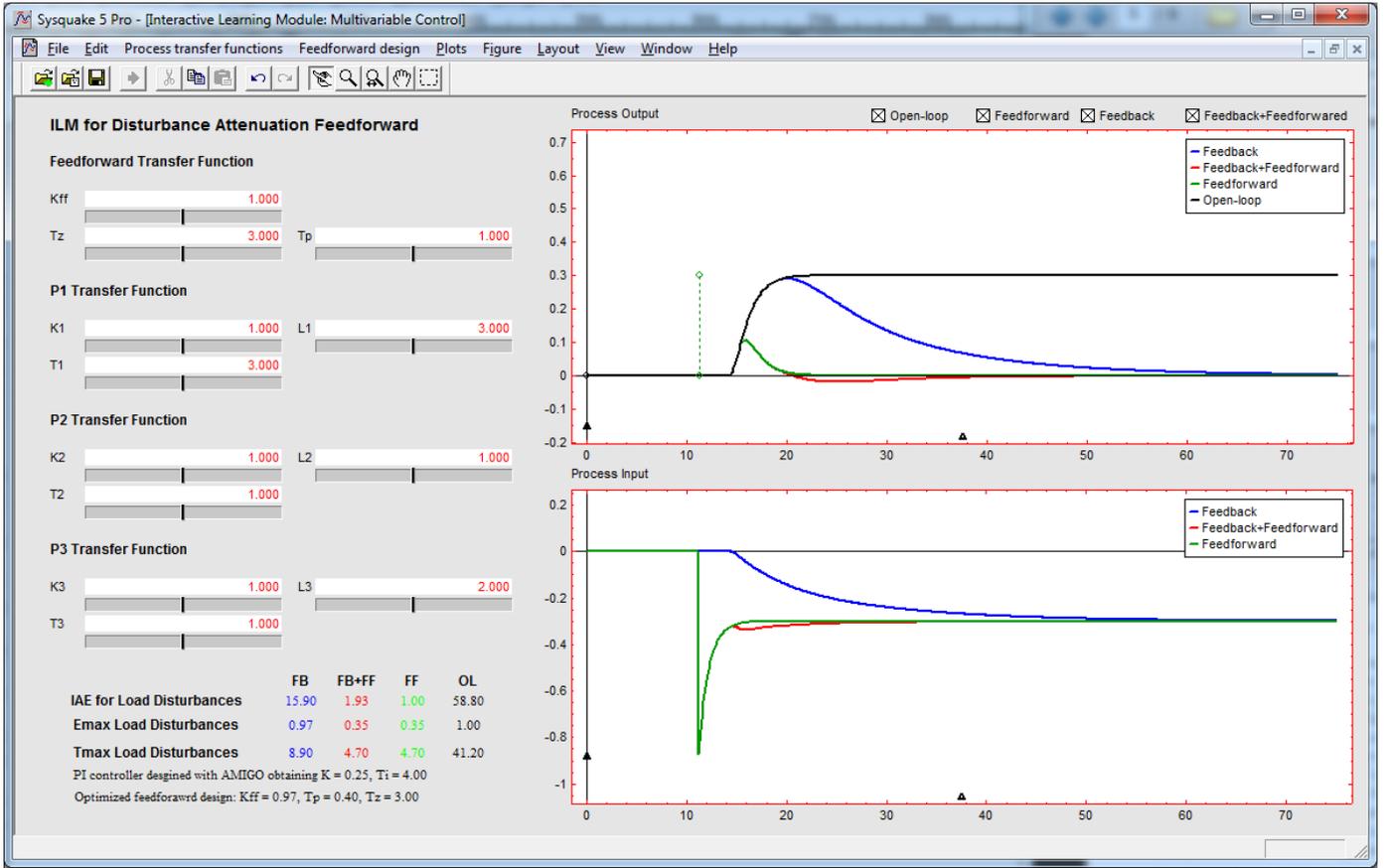
Fig. 3. Example from section 4.2 for the non perfect cancelation case.

In Figure 2, it can be observed that the feedforward compensator gives responses without any overshoot for the open-loop case (in green). However, when the loop is closed (in red), the feedback controller deteriorates the control, and responses with overshoots are obtained. The settling times of the responses are also increased to almost twice the open-loop times. Comparing the control signals in Figure 2, it is obvious that the feedback controller adds a component to the process input that is not negligible, and therefore should be taken into account in the feedforward design (Guzmán and Hägglund, 2011).

In (Guzmán and Hägglund, 2011), a feedforward design procedure is presented that takes the feedback controller into account. The procedure is divided into two steps.

In a first step, the time constant T_p is reduced from the nominal value $T_p = T_3$, with the goal to minimize the IAE value. Since the IAE value is calculated and presented in the tool, this optimization can easily be done by hand. The optimal value presented in (Guzmán and Hägglund, 2011) is given by

$$T_p = \begin{cases} T_3 & L_1 - L_3 \leq 0 \\ T_3 - \dfrac{L_1 - L_3}{1.7} & 0 < L_1 - L_3 < 1.7T_3 \\ 0 & L_1 - L_3 > 1.7T_3 \end{cases}$$

In the second step, the gain K_{ff} is reduced from the nominal value $K_{ff} = K_3/K_1$ to avoid the overshoot. The search for a suitable value of K_{ff} can also be done by hand using the tool. The optimal value presented in (Guzmán

and Hägglund, 2011) is given by

$$K_{ff} = \frac{K_3}{K_1} - \frac{K}{T_i} IE$$

where

$$IE = \begin{cases} K_2 K_3 (T_1 - T_3 + T_p - T_z) & L_3 \geq L_1 \\ K_2 K_3 (L_1 - L_3 + T_1 - T_3 + T_p - T_z) & L_3 < L_1 \end{cases}$$

4.2 Non perfect cancelation

Let us now consider an example where $L_3 < L_1$, which means that perfect compensation is not possible. The process transfer functions are:

$$P_1 = \frac{1}{1+3s} e^{-3s} \qquad P_2 = \frac{1}{1+s} \qquad P_3 = \frac{1}{1+s} e^{-2s} \quad (9)$$

The controller is tuned using the AMIGO rule (Åström and Hägglund, 2005), which gives the parameters $K = 0.29$ and $T_i = 3.85$.

Since $L_3 < L_1$, no delay should be included in the feedforward compensator, i.e. $L_{ff} = 0$. It means that only two of the four compensators given in (7) are considered in this case.

The lead-lag compensator is designed following the rules (7), where $K_{ff} = K_3/K_1$, $T_z = T_1$ and $T_p = T_3$.

Figure 3 shows the disturbance responses obtained using the lead-lag feedforward compensator, for the open-loop

and closed-loop cases. Furthermore, the open-loop process and the feedback without feedforward responses are shown. Even though perfect feedforward is not possible in this case, the feedforward action gives a significant improvement of the disturbance response compared with pure feedback. As in the previous example, it is also obvious that the closed-loop responses suffer from overshoots and longer settling times because of the action from the feedback controller.

Using the interactive tool, it is possible to analyze how the lead-lag compensator gives better performance than the static compensator, but this is to the prize of a significant peak in the control signal. The magnitude of this peak can be calculated as

$$u_{\text{init}} = K_{ff} \frac{T_z}{T_p} d \tag{10}$$

In this example, the load magnitude $d = 0.3$ gives the peak $u_{\text{init}} = -0.9$, while for a static compensator the control signal remains at -0.3. Peaks like this are common when lead-lag compensators are used for feedforward compensation.

There are situations when the magnitude of the initial peak u_{init} is considered too high. This peak can be reduces by changing any of the parameters in G_{ff}. In (Guzmán and Hägglund, 2011), it is suggested to keep the values of K_{ff} and T_z, and to reduce u_{init} by increasing T_p. The effect of this variation of T_p can be studied interactively using the tool.

The interactive tool also includes new tuning rules allowing to face all the issues discussed in these examples, such as the consideration of feedback effect on the feedforward design, IAE minimization with restrictions on the process output overshoot, and the reduction of the initial control peak (Guzmán and Hägglund, 2011).

5. CONCLUSION

A new interactive learning module for basic and advanced feedforward control concepts has been described. The module belongs to the collection of interactive learning modules that are an attempt to make figures in the book (Åström and Hägglund, 2005) interactive. The interactive tool allows to understand the basic idea of feedforward, starting from an open-loop design and also showing how it contributes to the feedback control for disturbance attenuation. Furthermore, the main drawbacks of the typical open-loop design rules are easily analyzed, such as the effect of the feedback controller on the feedforward compensation or the large initial control signals for lead-lag compensators when perfect feedforward is not available. The software tool also includes advanced design rules to improve these problems.

The module is implemented in Sysquake and is available for free on the web at `http://www.calerga.com` and `http://aer.ual.es/ilm/`.

REFERENCES

Åström, K.J. and Hägglund, T. (2005). *Advanced PID Control*. ISA - The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC 27709.

Brosilow, C. and Joseph, B. (2002). *Techniques of Model-Based Control*. Prentice-Hall. New Jersey.

Coughanowr, D.R. (1991). *Process Systems, Analysis and control*. McGraw-Hill. New York.

Dormido, S. (2004). Control learning: Present and future. *Annual Reviews in Control*, 28, 115–136.

Guzmán, J.L., Åström, K.J., Dormido, S., Hägglund, T., Berenguel, M., and Piguet, Y. (2008a). Interactive Learning Module: Basic Modelling and Identification Concepts. *Proceedings of the 17th IFAC World Congress*. Seoul (Korea).

Guzmán, J.L., Åström, K.J., Dormido, S., Hägglund, T., Berenguel, M., and Piguet, Y. (2008b). Interactive learning modules for PID control. *IEEE Control System Magazine*, 28(5), 118–134.

Guzmán, J.L., Åström, K.J., Dormido, S., Hägglund, T., Berenguel, M., and Piguet, Y. (2009). Interactive Learning Module for Control Interaction Understanding. *Proceedings of the European Control Conference*. Budapest (Hungry).

Guzmán, J.L., García, P., Hägglund, T., Dormido, S., Albertos, P., and Berenguel, M. (2008c). Interactive tool for analysis of time-delay systems with dead-time compensators. *Control Engineering Practice*, 16(7), 824–835.

Guzmán, J.L. and Hägglund, T. (2011). Simple tuning rules for feedforward compensators. *Journal of Process Control*, 21(1), 92–102.

Isaksson, A., Molander, M., Modén, P., Matsko, T., and Starr, K. (2008). Low-order feedforward design optimizing the closed-loop response. *Preprints, Control Systems*. Vancouver, Canada.

Nisenfeld, A. and Miyasak, R. (1973). Applications of feedforward control to distillation columns. *Automatica*, 9, 319–327.

Piguet, Y. (2004). *Sysquake 3 User Manual*. Calerga Sàrl, Lausanne, Switzerland.

Seborg, D., Edgar, T., and Mellichamp, D. (1989). *Process dynamics and control*. Wiley. New York.

Shinskey, F. (1996). *Process control systems. Application design adjustment*. McGraw-Hill. New York.