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Disturbance compensation on uncertain systems: Feedforward control design for stable systems

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Abstract: This paper considers the design of feedforward controllers when model uncertainty is present. The main contribution is an alternative approach to the generation of the feedorward control action on the basis of the Internal Model Control formulation. This new structure allows for completely independent tuning of the feedback and feedforward controllers and provides an explicit expression for the achieved nominal performance degradation when the uncertain case is considered. The formulation of the feedforward controller as an Internal Model Controller allows existing design approaches to be applied and uncertainty effect taken into account by means of the corresponding analysis equation.

Keywords: Feeforward control, Internal Model Control.

1. INTRODUCTION

The use of a feedforward control action is well recognized as a complement to the feedback controller in order to compensate the effect of a measurable disturbance. Under this assumption, when a disturbance occurs, corrective action starts immediately in order to cancel the disturbance before it affects the controlled variable. This fact makes possible a faster disturbance attenuation than by using only feedback control (the disturbance can only be corrected after his effect on the controller variable) Stephanopoulos [1984] Shinskey [1967]. The introduction of a feedforward controller obviously increases the complexity of the control system but may provide a faster and more efficient way of compensating the disturbance than with the exclusive use of a feedback controller.

The idea of the corrective feedforward control action is to start compensating for the disturbance effect before it really affects the output variable. Therefore the scenario where the use of feedforward control action can easily provide advantages are, mainly, those where the effect of the control variable on the process output is slower than the disturbance variable, either due to long process time constants or a transport delay. Early examples provided by Luyben [1969] show their application to distillation columns albeit other situations can be found in the literature Morari and Zafirou [1989], Weng and Ray [1997] Zhang and Agustriyanto [2001] Gooden et al. [1999] McNab and Tsao [1997].

The extensive practical use of this control structure motivated some theoretical research to be initiated. From the works of Sternad and Soderstrom [1988] that consider a design problem based on a stochastic disturbance characterization and the formulation of the design problem as a Linear Quadratic problem. That work was further extended in Soderstrom [1999] to the case where measurable disturbances are correlated with some unmeasurable ones. On another side, some works more related to the proposal of feedforward schemes have also appeared. It is remarkable the structure proposed by Morari and Zafirou [1989] that presents a feedforward controller within the Internal Model Control framework. An alternative can be found in the work of Grimble [1999a] and Grimble [1999b] where the solution to a combined feedforward/feedback design problem is done within a polynomial approach. One of the important features of Grimble [1999a] is that the problem formulations can explicitly incorporate uncertainty considerations into the design of the feedforward component.

It is noticed that a combined feedforward-feedback scheme provides two degrees of freedom which allows for two different design objectives to be tackled (one can design for both set-point tracking and disturbance rejection). Whereas the feedforward controller is used for disturbance rejection, it demands a model description, at least approximate, of the effect of the disturbance on the process output. Therefore, feedback action will also provide the benefit of compensating for possible model inaccuracies. From a design point of view is therefore important the way both controllers interact.

Within the Internal Model Control formulation Morari and Zafirou [1989] of the combined feedforward-feedback control scheme, an independent design of both controllers can be performed. However, as uncertainty is considered,

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the design relations do not maintain this property and the analysis equations become somewhat *messy* (where both uncertainty on plant and disturbance transfer function appear). To overcome this aspect and to provide a more suitable framework for design is the main contribution of this paper. Instead of adding feedforward action to an Internal Model Controller an Internal Model Feedforward Controller is formulated.

The rest of the paper is organized as follows. A presentation of existing schemes and approaches to feedforward control is faced first in section 2. In order to present the considerations that arise when uncertainty is considered and possible design advantages for the resulting combined feedback-feedforward control scheme. Section 3 presents the proposed scheme based on an Internal Model Control conception of the feedforward controller and an analysis of the control properties for both the nominal and uncertain cases is presented. A characterization of the degradation effect of uncertainty is also provided in section 4. Section 5 outlines the design procedure for the feedforward controller and an example is presented in section 6. Section 7 conducts the conclusions of the work.

2. FEEDFORWARD-FEEDBACK CONTROL APPROACHES

This section presents the use of feedforward control action on the classical feedback and Internal Model Control structures. The corresponding advantages with respect to the feedback control system in compensating measurable disturbances are presented as well as the main design advantage that the Internal Model Control based one (although their equivalence) provides. This presentation will enable, in the next section, to introduce an alternative approach that shares their advantages but allows a suitable way of addressing the design under model uncertainty considerations.

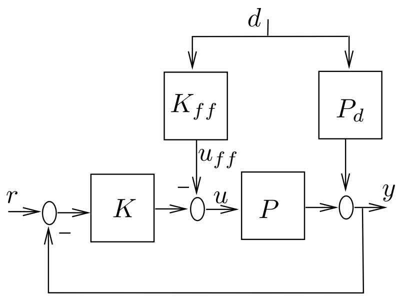

Fig. 1. Classical Feedback + Feedforward control

The classical feedback-feedforward control system structure is shown in figure (1), where the process output, y, can be described in terms of the plant transfer function, P, the transfer function describing the way the measurable disturbance enters the process output, P_d, and the controllers K and K_{ff} as:

$$y = \frac{KP}{1+KP} r + \frac{P_d - K_{ff}P}{1+KP} d \quad (1)$$

whereas in the Internal Model Control, the structure depicted in figure (2) is suggested in Morari and Zafirou [1989]. In this case the output is given by:

$$y = \frac{QP}{1+Q(P-\overline{P})} r + \frac{(P_d - Q_{ff}P) + (\overline{P_d}P - P_d\overline{P})Q}{1+Q(P-\overline{P})} d \quad (2)$$

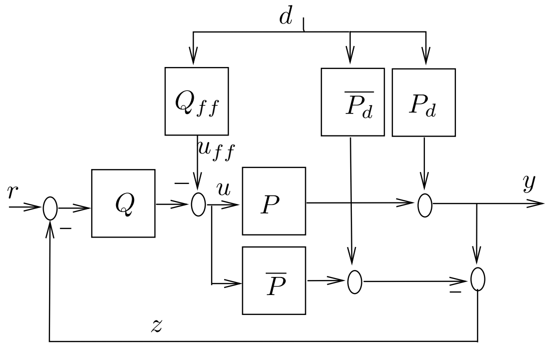

Fig. 2. Internal Model Control Feedback + Feedforward control

where an additive uncertainty description has been assumed for both system models:

$$P(jw) = \overline{P}(jw) + \Delta(jw) \quad |\Delta(jw)| \le l(w) \forall w \quad (3)$$

$$P_d(jw) = \overline{P_d}(jw) + \Delta_d(jw) \quad |\Delta_d(jw)| \le l_d(w) \forall w \quad (4)$$

where $l(w)$ and $l_d(w)$ are the upper bounds for the additive uncertainty description; $\overline{P}$ and $\overline{P_d}$ are the assumed nominal models; and Q and Q_{ff} are referred as the Internal Model Controllers. A nice feature of this structure is that becomes completely equivalent to the classical one if both sets of controllers are related by means of:

$$K = \frac{Q}{1-\overline{P}Q} \qquad K_{ff} = \frac{Q_{ff} - \overline{P_d}Q}{1-\overline{P}Q} \quad (5)$$

From this equivalence, both structures become equivalent and they can be used indistinctly. However if we compute the corresponding expressions for the process output variable under a nominal situation ($\Delta = \Delta_d = 0$) we obtain:

$$y = \frac{K\overline{P}}{1+K\overline{P}} r + \frac{\overline{P_d} - K_{ff}\overline{P}}{1+K\overline{P}} d \quad (6)$$

$$y = Q\overline{P}r + (\overline{P_d} - Q_{ff}\overline{P})d \quad (7)$$

The Internal Model Controller approach generates a 2-DOF controller that allows the independent design of the two controllers in which Q can be tuned for good tracking and Q_{ff} for disturbance rejection. This is not the case of the classical structure.

In both cases, perfect disturbance rejection can be accomplished by choosing:

$$K_{ff} = Q_{ff} = \frac{\overline{P_d}}{\overline{P}} \quad (8)$$

If such an assignment can be done both designs are equally trivial. However this assignment usually provides a non causal, or even unstable, controller. Therefore some alternative approach has to be taken to design the feedforward controller. In this situation the possibility of design Q_{ff} independently of the feedback controller can be really advantageous.

If the presence of uncertainty is considered, simple relations (6) and (7) are no longer valid and the complete and interacting expressions (1) and (2) have to be used.

3. PROPOPOSED INTERNAL MODEL FEEDFORWARD CONTROLLER COMPENSATOR

This section presents an alternative approach to face the problem of disturbance compensation when a measure of the disturbance is available as well as a model of the effect of the measurable disturbance on the process output.

The rationale behind this proposal is slightly different from the ones presented in the preceding section. Both approaches, classical and IMC, are based on the incorporation of a computed feedforward control action as a complement to the control action determined by an already existing feedback controller. Specially for the case of the IMC based, the approach based on figure (2) is seen to incorporate feedforward control action to an Internal Model Controller. What is proposed here is to base the computation of the feedforward control action on the Internal Model Control principles. According to this, the feedforward control action, u_{ff}, is computed on the basis of a feedforward controller, Q_{ff}, and by comparison of the effect this feedforward control action has on both the plant model and the real plant. Therefore Q_{ff} becomes a real Internal Model Controller, in fact an Internal Model Feedforward Controller. Figure (3) shows this arrangement.

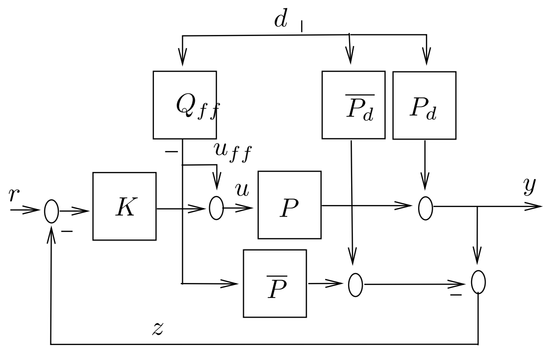

Fig. 3. Proposed Internal Model Feedforward Control

Note this is different from the situation depicted in figure (2) where the model is feed with the *total* control action. This way, the difference returning signal, z, provides a measure of how good performs *the feedforward controller*, whereas in (2) this signal is generated by the combination of both controllers Q and Q_{ff}.

Assuming, without any loss of generality, the reference signal is set to zero the output variable can be written as:

$$y = (\overline{P_d} - Q_{ff}\overline{P})d + (1 + PK)^{-1}(\Delta_d - Q_{ff}\Delta)d \quad (9)$$

from where we can observe the following properties:

Property 1 (Nominal Stability): As long as the plant; $\overline{P}$; and the way the disturbance enters the process output; $\overline{P_d}$; are stable, the stability of the closed loop combined control system is determined by the stability of the feedback control system (therefore determined by K) and the stability of the feedforward controller Q_{ff} (as it acts on open loop).

Property 2 (Nominal Performance): In the absence of uncertainty, ($\Delta_d = \Delta = 0$), the design of the feedforward controller becomes completely independent of the feedback controller. The effect of the disturbance on the output variable is obtained from (9) as:

$$y = (\overline{P_d} - Q_{ff}\overline{P})d \quad (10)$$

Therefore the ideal feedforward controller that yields $y = 0$ is given by an identical expression as in (8): $Q_{ff} = \frac{\overline{P_d}}{\overline{P}}$. As it has been commented this expression may lead to an improper or even unstable transfer function and alternative approximation approaches are needed.

Property 3 (Perfect Input Load Disturbance rejection): In case the disturbance enters at the plant input we will have $P = P_d$. Therefore $\Delta_d = \Delta$. Under this assumption, (9) leads to:

$$y = (\overline{P} - Q_{ff}\overline{P})d + (1 + PK)^{-1}(\Delta - Q_{ff}\Delta)d \quad (11)$$

and it is seen that by setting $Q_{ff} = 1$ we get $y = 0$ even for the uncertain case.

Property 4 (Robust Stability): When uncertainty in both the plant model, $P = \overline{P} + \Delta$, and the disturbance transfer function, $P_d = \overline{P_d} + \Delta_d$, are considered, the robust stability of the closed loop combined control system is determined by the robust stability of the feedback control system ($\|(1 + \overline{P}K)^{-1}K\Delta\|_\infty < 1$) and the stability of the feedforward controller Q_{ff} (as it acts on open loop).

Property 5 (Robust Performance) When uncertainty in both the plant model, $P = \overline{P} + \Delta$, and the disturbance transfer function, $P_d = \overline{P_d} + \Delta_d$, are considered, the effect of the disturbance on the output process variable is determined by the combined action of both the feedforward and feedback controllers. Therefore a complete design for Robust Performance will imply a joint tuning of both controllers in order to minimize:

$$\|(\overline{P_d} - Q_{ff}\overline{P}) + (1 + PK)^{-1}(\Delta_d - Q_{ff}\Delta)\|_\infty \quad (12)$$

This expression is similar to that frequently encountered in Feedback Control system design Doyle et al. [1992], where Robust Performance is accomplished by simultaneously guaranteeing Robust Stability and Nominal Performance. However this framework does not fit with the combined feedback-feedforward control system as the analysis to be presented in the next section will show. However, as it is seen from (9) and (10) an explicit expression for the degradation of the nominal performance is got. This is a distinctive feature of the proposed scheme over the existing feedforward approaches and allows the Robust Performance design to be alternatively posed as to minimize the effect of model uncertainty on the achieved nominal performance:

$$\|(1 + PK)^{-1}(\Delta_d - Q_{ff}\Delta)\|_\infty \quad (13)$$

4. ROBUST PERFORMANCE ANALYSIS

As it has been mentioned in Property 5, eq. (9) clearly shows the effect of the uncertainty with respect to the achieved nominal performance. As a consequence expression (12) could be taken as the design expression for disturbance attenuation on the uncertain case. This expression suggest a direct design of both feedforward and feedback controllers in order to achieve a better Robust Performance. However, an alternative analysis is possible where the effect of the uncertainty on the achieved nominal performance is to be minimized. This view could be understood as extending the nominal performance to the whole set of plants. At each frequency there will be a contribution of the combined effect of plant and disturbance model uncertainty given by $|(1 + PK)^{-1}(\Delta_d - Q_{ff}\Delta)d|$. It is therefore natural to express a condition for Robust Performance as:

$$\|W(1 + PK)^{-1}(\Delta_d - Q_{ff}\Delta)\|_\infty = \|WS(\Delta_d - Q_{ff}\Delta)\|_\infty < 1 \quad (14)$$

for any admissible perturbations, Δ and Δ_d, and where W is a suitable weight that determines the desired frequency range where it is desired to maintain the performance degradation as small as possible. It is worth to remark that the $S = (1 + PK)^{-1}$ term corresponds to the *real* closed loop Sensitivity function. Therefore an expression in terms of the nominal closed loop transfer functions is to be obtained. From the plant description as $P = \overline{P} + \Delta$ the Sensitivity function can be written as:

$$S = \overline{S}(1 + \overline{S}K\Delta)^{-1} \quad (15)$$

Therefore, at each frequency, we have [1]:

$$\begin{aligned} &|WS(\Delta_d - Q_{ff}\Delta)| \le 1 \\ \Leftarrow\ &|W\overline{S}(1 + \overline{S}K\Delta)^{-1}(\Delta_d - Q_{ff}\Delta)| \le 1 \\ \Leftarrow\ &|W\overline{S}(\Delta_d - Q_{ff}\Delta)||(1 + \overline{S}K\Delta)^{-1}| \le 1 \\ \Leftarrow\ &|W\overline{S}(\Delta_d - Q_{ff}\Delta)| + |\overline{S}K\Delta| \le 1 \end{aligned} \quad (16)$$

and the following expression is got for Robust Performance:

$$\big||W\overline{S}(\Delta_d - Q_{ff}\Delta)| + |\overline{S}K\Delta|\big| \le 1 \quad \forall w \quad (17)$$

This expression clearly shows the interplay contributed by each part of the control scheme due to the presence of uncertainty. If there is no plant uncertainty, $\Delta = 0$, expression (17) can be stated as:

$$|W\overline{S}\Delta_d| \le 1 \quad \forall w \quad \Rightarrow \quad \|W\overline{S}l_d\|_\infty \le 1 \quad (18)$$

and minimization of the performance degradation due to the uncertainty in P_d becomes a typical sensitivity minimization problem:

$$\|\overline{S}\|_\infty < 1/\|Wl_d\|_\infty \quad (19)$$

Therefore the design problem can be completely decoupled: the feedforward controller Q_{ff} can be designed first in order to get nominal performance and, on a second step, the feedback controller, K, is got in order to determine the performance degradation due to plant modelling errors.

On the other hand, if the disturbance effect in process output is perfectly characterized, $\Delta_d = 0$, expression (17) becomes:

$$\big||W\overline{S}Q_{ff}\Delta| + |\overline{S}K\Delta|\big| \le 1 \quad \forall w \quad (20)$$

Therefore, if we use the upper bound $l(w)$ on the plant uncertainty, the previous expression can be given the form of a constraint for the feedforward controller Q_{ff} as:

$$|Q_{ff}| < \frac{1 - |\overline{S}K|l}{|W\overline{S}|l} \quad \forall w \quad (21)$$

[1] $\Leftarrow$ should be understood as: is implied by assuring that

Provided the constraint for Robust Stability is satisfied ($\|\overline{S}Kl\|_\infty \le 1$). Along the same lines as in the Internal Model Controller tuning Morari and Zafirou [1989], in order to satisfy constraint (21) the feedforward controller can be augmented by a low-pass filter, providing a detuning of the nominal performance in order to satisfy the robustness constraint. According to this, assume we have a feedforward controller, $\overline{Q_{ff}}$ designed on the basis of the corresponding nominal models, $\overline{P}$ and $\overline{P_d}$, the final feedforward controller expression will be given by

$$Q_{ff} = \overline{Q_{ff}}F_{ff} \quad (22)$$

where F_{ff} is a filter that can be taken with usual from in Internal Model Control design as

$$F_{ff} = \frac{1}{(\lambda_{ff}s + 1)^n} \quad (23)$$

where the order n can also be used to deal with realizability considerations about the nominally got feedforward controller, $\overline{Q_{ff}}$.

In case uncertainty in both P and P_d are present, (17) shows the term that will affect the nominal performance achieved by the combined control scheme, given by (10), is not completely determined by the terms that characterize Robust Stability, $\|SK\Delta\|_\infty \le 1$, but a second term that accounts for the interaction among both controllers, $W\overline{S}(\Delta_d - Q_{ff}\Delta)$. This point prevents from the possibility of establishing a complete parallelism, as it has been mentioned above, with the typical Robust Performance condition on feedback control systems Doyle et al. [1992].

In the developments above, (17) has been used as a measure of performance degradation. If we put (17) into (12) in order to deal with the original Robust Performance expression, we will have to deal with the interaction of three terms:

- Nominal Performance term: $(\overline{P_d} - Q_{ff}\overline{P})$.
- Robust Stability term: $\overline{S}K\Delta$.
- Interaction term: $W\overline{S}(\Delta_d - Q_{ff}\Delta)$.

whereas in feedback Robust Control Theory Doyle et al. [1992] just the Nominal Performance and Robust Stability terms appear.

5. PROCEDURE FOR FEEDFORWARD CONTROLLER DESIGN

This section discusses a simple procedure for the design of the feedforward controller Q_{ff}. A direct alternative could be to set up a general optimization approach by identifying a suitable generalized control problem and performing, for example, $\mathcal{H}_\infty$ optimization along the lines of Zhou and Doyle [1998]. However, from the preceding discussion, a simple procedure is proposed here based on the explicit separation of the nominal and perturbing terms due to uncertainty in the disturbance effect on process output (9).

The basic procedure is, according to the Internal Model Control philosophy, to design first a feedforward controller based on nominal model information only and, on a second step, augment this controller by a low pass filter. Discussion of the previous section on the uncertainty effect on the final performance will be used to guide the tuning of this filter. Effectively, when a detuning filter is introduced, it will have two opposite effects: (i) it will deteriorate the achieved nominal performance and, (ii) will reduce the performance degradation due to uncertainty. A *tradeoff* among them is needed. For this purposes, two measures are defined first:

- *Nominal Performance detuning (NPD)*: Measures the effect of introducing the filter, $Q_{ff} = \overline{Q_{ff}} F_{ff}$, in terms of performance loss with respect to the achieved nominal performance, $Q_{ff} = \overline{Q_{ff}}$.

$$NPD = \frac{\|\overline{P_d} - \overline{Q_{ff}P}\|_\infty - \|\overline{P_d} - \overline{Q_{ff}}F_{ff}\overline{P}\|_\infty}{\|\overline{P_d} - \overline{Q_{ff}P}\|_\infty} \quad (24)$$

  Instead of measuring the error, $\|\overline{P_d} - \overline{Q_{ff}P}\|_\infty$, also a weighted version;$\|W(\overline{P_d} - \overline{Q_{ff}P})\|_\infty$; of the approximation problem could be taken. With this respect the weight W can be taken, for example, as the same as in (14) - determining the region where performance is stressed is, also, the frequency region where uncertainty effect is desired to be reduced.
- *Performance Degradation (PD)*: Provides a measure of the effect the introduction of the filter has into the performance degradation terms that appear in the disturbance effect on process output (9). If, according to (17) the following upper bound for (14), is used

$$\|WS(\Delta_d - Q_{ff}\Delta)\|_\infty \leq$$
$$\|W\overline{S}l_d\|_\infty + \|W\overline{S}Q_{ff}l\|_\infty + |\overline{S}Kl\|_\infty \quad (25)$$

  where l and l_d are corresponding bounds on plant and disturbance transfer function uncertainties. From (25) the term determined by Q_{ff} is identified and the Performance Degradation index (PD) index defined as:

$$PD = \frac{\|W\overline{S}l_d\|_\infty + \|W\overline{S}Q_{ff}l\|_\infty + |\overline{S}Kl\|_\infty}{\|W\overline{S}\Delta_d\|_\infty + |\overline{S}K\overline{\Delta}|\|_\infty}$$
$$= 1 + \frac{\|W\overline{S}Q_{ff}l\|_\infty}{\|W\overline{S}l_d\|_\infty + \|\overline{S}Kl\|_\infty} \quad (26)$$

According to (24) and (26) the time constant of the filter F_{ff} is to be chosen such that a tradeoff among both factors is achieved. The feedforward controller design procedure can now be outlined as follows:

(1) Design a feedback controller according to the specified feedback properties. This step does not need to take necessarily disturbances into account.
(2) Design a feedforward controller, $\overline{Q_{ff}}$ on the basis of the nominal models, $\overline{P}$ and $\overline{P_d}$. This design can be done by trying to approximate the ideal feedforward controller $\overline{Q_{ff}} = \overline{P}/\overline{P_d}$ or by existing model matching procedures such as the $\mathcal{H}_2$ optimal design of Morari and Zafirou [1989] or a min-max approach along the lines of Vilanova [2006].
(3) Augment the obtained feedforward controller by a low pass filter F in order to obtain the final feedforward controller as $Q_{ff} = \overline{Q_{ff}}F$. The filter (23) degree is chosen in order to make the controller transfer function strictly proper. On the other hand, the filter time constant λ_{ff} is chosen to simultaneously minimize (24) and (26).

6. EXAMPLE

This section will show, by means of a simple example, the application of the proposed procedure for feedforward controller design. The following transfer functions are assumed for the plant and load disturbance:

$$P(s) = K_p \frac{e^{-L_p s}}{T_p s + 1} = \frac{e^{-1.5s}}{3s+1} \quad (27)$$

$$P_d(s) = K_d \frac{e^{-L_d s}}{T_d s + 1} = \frac{e^{-s}}{2s+1} \quad (28)$$

The parameters of both transfer functions are assumed to be known with a 15% uncertainty. According to this variation, the following frequency dependent bounds are established with respect to the nominal models:

$$l(w) = \frac{1}{|1 + 1.2jw|} \qquad l_d(w) = \frac{1}{|1 + 0.8jw|} \quad (29)$$

With respect to the feedback controller, as it has been described above, the ISA-PID tuned according to the Internal Model Control Vilanova [2006] is used. The usual choice $\lambda_{fb} = 0.8L_p$ is used. As the main concern of the example is that of the feedforward controller we will not go further into the discussion of this choice for λ_{fb}. The nominal feedforward controller is designed according to

$$\overline{Q_{ff}} = \arg\min_{Q} \|W(\overline{P_d} - Q\overline{P})\|_\infty \quad (30)$$

by using a frequency weight determined by $W(s) = (0.3s + 1)/s$, therefore specifying performance for low frequencies (specially steady state : $s = 0$). With the supplied data the nominal feedforward controller results to be:

$$\overline{Q_{ff}} = \frac{1.92s^2 + 3.64s + 1}{0.6s^2 + 2.3s + 1} \quad (31)$$

Figure (4) shows the performance exhibited by the feedforward controller $Q_{ff} = \overline{Q_{ff}}F_{ff}$ for various selections of (λ_{ff}) with respect to the optimal case.

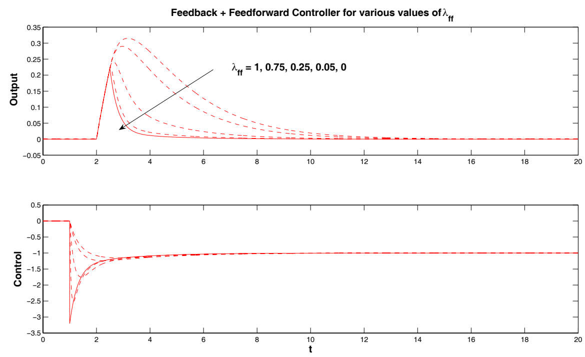

Fig. 4. Disturbance attenuation by means of Q_{ff} by using different selections for λ_{ff}

In order to help selecting the appropriate value for λ_{ff} the (24) and (26) measures are plotted against λ_{ff}. Figure (5) shows the value $\lambda_{ff} = 0.27$ is the one that provides the intersection among both measures. Of course, if we weight both factors giving more importance to the nominal detuning or to the attenuation of the uncertainty effect, this point will change.

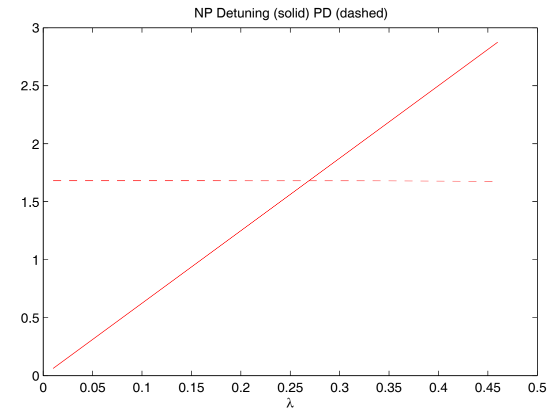

Fig. 5. NPD (24) and PD (26) as functions of the filter time constant λ_{ff}

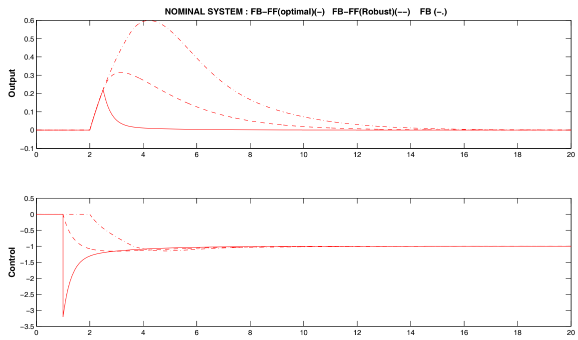

Fig. 6. Output and control signals for the selection $\lambda_{ff} = 0.27$ when operating on the nominal system.

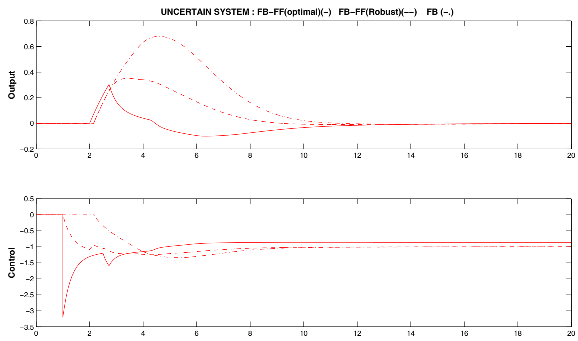

Fig. 7. Output and control signals for the selection $\lambda_{ff} = 0.27$ when operating on the uncertain system (simultaneous 15% parameter error.

The performance of the selected filter, therefore final feedforward controller is shown in figure (6) showing the proformance when acting on the nominal system and in figure (7) where a parametric uncertainty of 15% in each system and perturbation model is considered. As it can be seen, the Robust Feedforward controller is able to maintain the performance for the uncertain case closer to the nominal one.

7. CONCLUSIONS

This paper has addressed the design of feedforward control action, as a complement to a feedback controller, when model uncertainty is considered. It has been shown that the Internal Model Control approach to controller design provides a suitable framework and a feedworward compensation scheme is proposed under this considerations. The proposed approach is based on the application of the Internal Model Control approach to the feedforward controller, irrespective of the implementation or design approach used to tune the feedback controller.

Analysis equations provided a clear insight and measures for the interplay among the feedback and feedforward controllers and show how the nominal and uncertain cases can be considered separately.

REFERENCES

J.C. Doyle, B. Francis, and A. Tannenbaum. *Feedback Control Theory*. Maxwell-McMillan Publishing, 1992.

K. Gooden, P. Morgan, D. White, and R. Rink. Minimum variance feedforward control of a once-through steam generator. *IEEE Canadian Conference on Electrical and Computer Engineering, Edmonton, Alberta, Canada*, pages 951–959, 1999.

M. Grimble. Polynomial solution of the 31/2.dof h2/h-inf feedforward control problem. *IEE Proceedings.Part D.*, 144(6):549–560, 1999a.

M. Grimble. Restricted structure feedforward and feedback stochastic optimal control. *38th IEEE Conference on Decision and Control, Phoenix, Arizona, USA*, 1999b.

W. L. Luyben. Feedback and feedforward control of distillation columns with inverse response. *Inst. Chem. Eng. Symp. Ser*, 32:39–48, 1969.

R. McNab and T.C. Tsao. Frequency response based feedforward control design wth uncertainy considerations. *American Control Conference, Alburquerque, New Mexico, June*, 1997.

M. Morari and E. Zafirou. *Robust Process Control*. Prentice-Hall International, 1989.

F.G. Shinskey. *Process Control Systems. Application Design Adjustement*. McGraw-Hill, 1967.

T. Soderstrom. Feedforward, correlated disturbances and identification. *Automatica*, 35:1656–1571, 1999.

G. Stephanopoulos. *Chemical Process Control. An introduction to Theory and practice*. Prentice-Hall International, 1984.

M. Sternad and T. Soderstrom. LQG-optimal feedforward regulators. *Automatica*, 14(4):557–561, 1988.

R. Vilanova. Revisiting imc based design of PI/PID controllers for foptd models. *11th IEEE International Conference on Emergin Technologies and Factory Automation, Prague, 20-22, September*, 2006.

C. K. Weng and A. Ray. Robust wide-range control of steam-electric power plants. *IEEE Trans. on Control Systems Technology*, 5(1):74–88, 1997.

J. Zhang and R. Agustriyanto. Inferential feedforward control of a distillation column. *American Control Conference, Arlington, VA. 25-27 June*, 2001.

K. Zhou and J.C. Doyle. *Essentials of Robust Control*. Englewood Cliffs; Prentice Hall, 1998.