Improved Design of the Weighting Matrices for the *S/KS/T* Mixed Sensitivity Problem—Application to a Multivariable Thermodynamic System

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***Abstract*—This paper describes an improved design procedure for the weighting matrices of the $S/KS/T$ mixed sensitivity problem. Using low-order models, as usual in industrial processes, and based on recent works, the new design will allow to significantly reduce the time response overshoots, without degrading the speed of these responses. Weighting matrices are designed in such a way that they depend only on a few parameters, which can be easily adjusted by means of the proposed methodology. Experimental results in the simultaneous control of two temperatures of a pilot plant (which constitutes a typical example of industrial process) are included in order to validate the proposed methodology.**

***Index Terms*—Control application, mixed sensitivity problem, multivariable H_∞ control, process control, weighting matrix.**

I. Introduction

THIS paper deals with the design of appropriate weighting functions for the mixed sensitivity problem, which appears in the context of synthesis of H_∞ controllers. Many articles have been published during the last few years in which a particular control application has been solved by means of this approach, see for instance [1]–[4] as some representative examples. However, despite the importance of the design of the weighting functions, no description appears in these works regarding the methodology for the choice of those particular functions.

A widely employed approach for the synthesis of H_∞ controllers has been the S/T mixed sensitivity problem [5], [2], [6], [7]. A systematic method for the design of the weighting matrices has been published in [8], which provides a methodology for this approach. The main advantage of this methodology is the simplicity of the tuning procedure, as just one parameter per output must be adjusted following a very simple and intuitive rule. Besides this, the synthesis of the controller is based on the selection of the nominal and nonnominal system models. In industrial processes, it is very common to employ low-order models, which are typically accurate at low frequencies, but not necessarily around bandwidth frequencies. As a consequence, using this approach the closed-loop system may show excessive oscillation even with a not relatively small rise time.

In order to overcome this problem, the use of the $S/KS/T$ is suggested in this paper, which implies the addition of a weighting matrix for the control sensitivity function $K(s)S(s)$. A design method for this weight is proposed, but with a different goal with respect to the one widely employed in the specialized literature. The conventional design of this weight tries to make the system robust against additive uncertainty [9]–[11]. In that sense, this weighting matrix uses to be designed as a high pass filter, which limits the control bandwidth [12]–[15]. This purpose is also attained by the weight of the complementary sensitivity function $T(s)$ in [8], but with respect to multiplicative output uncertainty. In other cases, a constant weighting matrix $W_{KS}(s)$ is introduced in order to avoid saturations and numerical problems [6], [16].

In the proposed approach, the design of the control sensitivity weight has the aim of reducing the overshoots of the time responses, but without significantly affecting the speed of these responses. The design is based on an estimate of the system around the bandwidth frequencies, making use of the time response of the real plant. In order to keep up the ease and intuition principles of design, the weight W_{KS} is chosen depending on a few parameters, which may be adjusted by means of the proposed methodology. Therefore, no advanced knowledge on control theory is needed to synthesize the controller.

The paper includes real experiments to illustrate the application of the proposed method to solve a practical control problem. It consists in the control of two temperatures in a pilot plant, which constitutes a typical example of multivariable control in industrial processes.

The remainder of the paper is organized as follows: the mixed sensitivity problem in the context of the H_∞ control is presented first. Next, the guidelines for the computation of the weighting matrices are described in Section III, followed by a summary of the design procedure in Section IV. After that, in Section V a case study is described, in order to check the validity of the proposed method. The paper ends with some conclusions in Section VI.

II. The H_∞ Mixed Sensitivity Problem

The H_∞ optimization problem can be posed in the standard formulation [17], shown in Fig. 1. In this figure, $P(s)$ is the generalized plant, $K(s)$ is the controller, u are the control signals,

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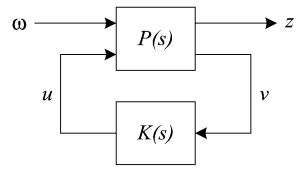


Fig. 1. General formulation of the control problem.

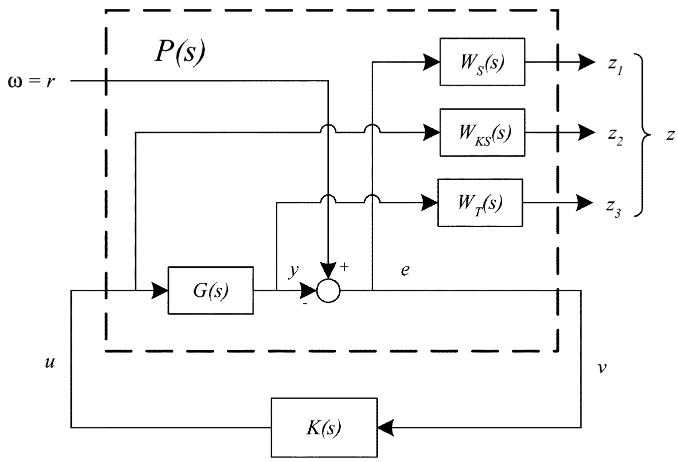


Fig. 2. $S/KS/T$ mixed sensitivity configuration.

v are the measured variables, ω is the exogenous signals, and z are the so-called error variables.

The optimal H_∞ control problem with this configuration consists in computing a controller such that the ratio between the energy of the error vector z and the energy of the exogenous signals ω is minimized. This ratio can be computed as the H_∞ norm of the closed-loop transfer function matrix from w to $z, T_{zw}(s)$ [15], [18], [19].

There are many alternatives for building up the generalized plant, $P(s)$, depending on the control objectives. In the case of the $S/KS/T$ *mixed sensitivity problem*, the configuration of the generalized plant is as shown in Fig. 2 (see [14]). It can be seen that $P(s)$ is composed of a nominal plant $G(s)$ and a set of weights. In this case, the expression of the resulting closed loop transfer function $T_{z\omega}(s)$ is as follows:

$$T_{z\omega}(s) = \begin{bmatrix} W_S(s)S_o(s) \\ W_{KS}(s)KS_o(s) \\ W_T(s)T_o(s) \end{bmatrix}$$

where $S_o(s)$ is the output sensitivity transfer matrix, $KS_o(s)$ is the output control sensitivity transfer matrix, and $T_o(s)$ is the output complementary sensitivity transfer matrix [14].

The terms $W_\mathrm{S}(s), W_{KS}(s)$, and $W_T(s)$ constitute their respective weighting matrices, which allow to specify the range of relevant frequencies for the corresponding closed-loop transfer matrix.

Since the controller is obtained from the generalized plant, the synthesis problem with this configuration is reduced to the choice of a nominal model $G(s)$ and the design of some appropriate weighting matrices which will impose the control specifications.

This configuration is intended to deal with the tracking problem, although it could be adapted with slight modifications for disturbance rejection [14]. On the other hand, it is expected that this approach does not perform properly in strongly ill-conditioned systems [20].

III. Design Methodology of the Weighting Matrices

As aforementioned, the synthesis of a controller using the $S/KS/T$ mixed sensitivity configuration requires the choice of three weighting matrices. In [8], a systematic design procedure for the weighting matrices involved in the S/T mixed sensitivity problem, $W_S(s)$ and $W_T(s)$, was described. In the work presented here, these matrices are supposed to be chosen following the same procedure.

According to that, the design of the weighting matrix W_T is intended to provide system robustness with respect to multiplicative output uncertainties, while W_S allows some performance conditions to be imposed for the system.

It should be emphasized that the main advantage of the method in [8] was the simplicity of the tuning procedure. In fact, only one parameter per output, denoted by κ_i ($i = 1, \dots q$, being q the number of outputs), is needed to be adjusted following a very intuitive rule: *as the value of κ_i increases, a faster (although more oscillatory) response is attained for the corresponding output*.

However, this synthesis method is based on the initial selection of the nominal and nonnominal models of the system. As said in the introduction section, it is very common in industrial processes to employ low-order models (first or second-order transfer functions), which are typically accurate at low frequencies, but not necessarily around bandwidth frequencies. As a consequence, using this approach *the closed-loop system may show excessive overshoot even with a not relatively small rise time*.

The addition of the weighting matrix $W_{KS}(s)$ is proposed in order to decrease the overshoot in the time responses of the system, without significantly degrading the speed of the response.

Notice that the inclusion of this weighting matrix will allow the avoidance of some numerical problems. In particular, the inclusion of this weight implies that the direct transmission matrix from the control signals, u, to the error variables, z, has full column rank (see [16], for instance), which is a necessary condition for the synthesis of an H_∞ controller [18].

The proposed design methodology for $W_{KS}(s)$ is as follows.

An initial selection of $W_{KS}(s) = I_{m\times m}$ is adopted, where m is the number of system inputs. With this initial choice of $W_{KS}(s)$, the weighting matrices $W_S(s)$ and $W_T(s)$ are designed as described in [8], adjusting the values of κ_i until achieving very fast but highly oscillatory step responses. This kind of responses is employed to estimate the corresponding oscillation frequency, $\omega_{di}(i = 1, \dots q)$, of each system output.

Once the oscillatory frequencies have been estimated, a new $W_{KS}(s)$ is proposed as a full $(q \times m)$-matrix. Taking into account that the *i*th element of the error vector z_2 (see Fig. 2) is obtained as

$$z_{2i}(s) = \sum_{j=1}^{m} W_{KSij}(s)u_j(s)$$

the *ij*th element of $W_{KS}(s)$ may weight the way in which the *j*th control signal affects to the *i*th output signal. Therefore, since the purpose of the weighting matrix $W_{KS}(s)$ is to reduce the oscillation in the system outputs, a bandpass filter centered at the above estimated frequency ω_{di} is proposed for the *ij*th element of $W_{KS}(s)$. Notice that with this approach, we are avoiding strong attenuation of high frequencies, hence avoiding a significant increase in the rise time.

The following expression for the *ij*th element of the weighting matrix is proposed

$$W_{KSij}(s) = \frac{\left(s + \frac{\omega_{di}}{10\rho_{ij}}\right)(s + 10\rho_{ij}\omega_{di})}{\left(s + \dfrac{\omega_{di}}{\rho_{ij}}\right)(s + \rho_{ij}\omega_{di})} \quad (1)$$

which only introduces one additional parameter ρ_{ij} to be adjusted. The selection of the value for this parameter depends on the influence of the variation of the *j*th control signal on the *i*th output (system gain) of the real system at the bandwidth frequency ω_{di}. To evaluate this gain, it may be useful to go back to the experiments providing frequencies w_{di}, and compare the required variation in the control signal with respect to the variation in the output signal. As the value of parameter ρ_{ij} increases, less oscillatory (although slower) response is obtained for the corresponding output. In case of no evident influence, the related element of $W_{KS}(s)$ may be omitted. In a similar way, it may be useful to carry out a controllability analysis of the system, but taking into account the frequency range in which the model fits to the real plant.

Finally, it should be noticed that the gains of these filters are equal to one at both low and high frequencies. This agrees with the fact that, as indicated in [18], the system needs to be scaled as a previous step.

IV. Summary of the Improved Design Procedure

In the previous section, the principles for the design of the new weighting matrix W_{KS} has been described. According to that, the steps to be followed in order to synthesize the controller are summarized here.

1) Choose a nominal model. It is not necessary to be a high-order model.
2) Estimate the multiplicative output uncertainty of the system with respect to the chosen nominal model.
3) Choose a start-up weighing matrix $W_{KS}(s)$ equal to the identity matrix, and design the weighting matrices $W_T(s)$ and $W_S(s)$ as described in [8], using initial values of $\kappa_i = 0$. Then, tune the parameters κ_i (by increasing their values) until a fast and quite oscillatory time response is achieved.
4) Estimate the frequencies ω_{di} for each output, as described in Section III.
5) Refine $W_{KS}(s)$, as pointed out in Section III. Values of ρ_{ij} must be adjusted by comparing the amplitudes in the oscillations of the *i*th output versus the *j*th input.

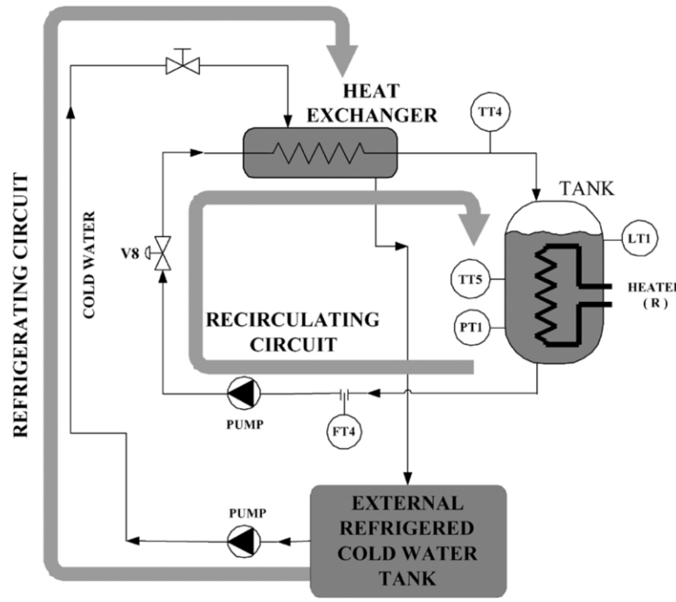


Fig. 3. Diagram of the experimental thermodynamic system.

V. Application to an Experimental Thermodynamic System

In this section, the validity of the proposed design procedure is tested in a multivariable thermodynamic system, which constitutes a typical example of industrial process. The improvement achieved is made clear by direct comparison of experimental results attained with the original methodology and with the upgraded one.

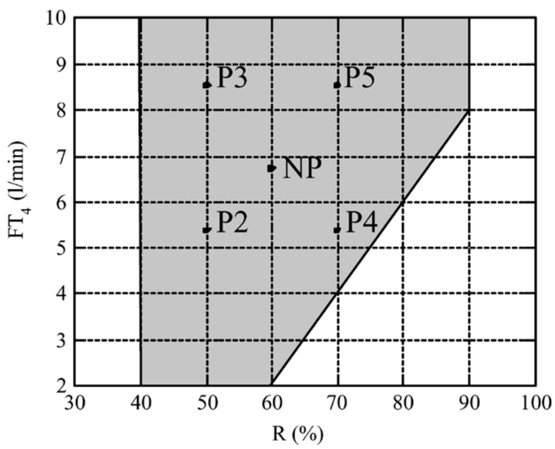
A. System Description

The plant at hand is basically a system that uses water as the working fluid, where several thermodynamic processes of mass and energy interchange can take place. This *pilot plant* is made of industrial components, such as a water tank, a water heating resistor, a heat exchanger, pumps, and different pneumatic valves. A diagram, showing the main components of the plant as well as the placement of various devices, is presented in Fig. 3.

The purpose of the experiments is the simultaneous control of some temperatures. In this particular case, these temperatures are the tank temperature (TT_5) and the output exchange temperature (TT_4) (see Fig. 3). The control signals are the heat supplied to the water in the tank by a resistor (R), and the water flow in the recirculating circuit (FT_4), which is regulated by the size of the valve aperture V_8. The heat exchanger lowers the temperature of the recirculated water driven by a pump, using a constant flow of cold water (refrigerating circuit). This constitutes a MIMO system with two inputs and two outputs.

B. Linear Models

In this experimental plant, the working space is bounded due to physical conditions. This working space is shown in Fig. 4, where the minimum and maximum allowed values of the control variables for a proper behavior of the plant can be observed. Also, the nominal operating point considered and four other



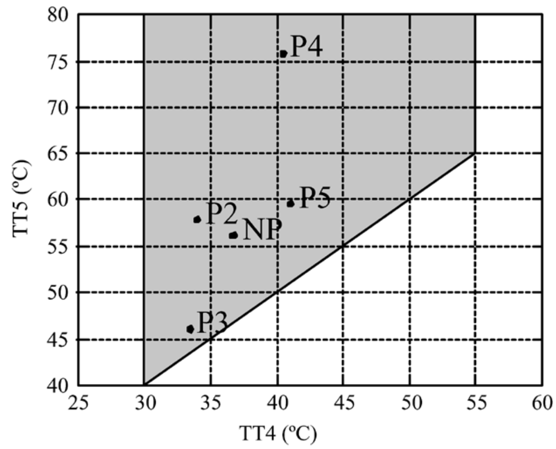


Fig. 4. Plant working space. Left: Control variables. Right: Output variables.

working points around it, NP and $\{P2, \cdots P5\}$, respectively, are shown.

The main cause of different behaviors at these operating points is due to the heat exchanger, whose efficiency may change drastically from one operating point to another. These points will be used for the estimation of the uncertainty with respect to the nominal model.

Low-order linear models for the system were obtained at the different operating points by providing experimental data to an identification algorithm, based on a multivariable ARX model with sampling period $T = 1$ s. The transfer functions obtained, corresponding to the nominal operating point, were the following

$$\begin{bmatrix} \mathrm{TT}_4 \\ \mathrm{TT}_5 \end{bmatrix} = \begin{bmatrix} G_{11}(z) & G_{12}(z) \\ G_{21}(z) & G_{22}(z) \end{bmatrix} \begin{bmatrix} FT_4 \\ R \end{bmatrix}$$

begin

$$\begin{aligned} G_{11}(z) &= \frac{1.3292z - 1.393}{z - 0.9989} \\ G_{12}(z) &= \frac{0.007\,688z + 0.1125}{z - 0.9989} \\ G_{21}(z) &= \frac{-0.1176z + 0.1125}{z - 0.9986} \\ G_{22}(z) &= \frac{0.028\,94z - 0.027\,95}{z - 0.9986.} \end{aligned}$$

These models were scaled [14] using the expected magnitudes of the maximum changes in the control signals on each input, and the maximum allowed variations of the outputs. In this experiments, the following values have been chosen as maximum variations

$$\begin{aligned} \Delta FT_{4_{\max}} &= 2\,L/m, \quad \Delta R_{\max} = 10\% \\ \Delta \mathrm{TT}_{4_{\max}} &= 2.5\,^\circ\mathrm{C}, \quad \Delta \mathrm{TT}_{5_{\max}} = 5.0\,^\circ\mathrm{C}. \end{aligned}$$

From these magnitudes, the system was scaled by means of the following expression

$$\hat{G}(z) = D_e^{-1} G(z) D_u$$

where the two scaling matrices D_u and D_e can be built as follows:

$$\begin{aligned} D_u &= \mathrm{diag}\,\{\Delta FT_{4_{\max}}, \Delta R_{\max}\} = \mathrm{diag}\{2, 10\} \\ D_e &= \mathrm{diag}\,\{\Delta \mathrm{TT}_{4_{\max}}, \Delta \mathrm{TT}_{5_{\max}}\} = \mathrm{diag}\{2.5, 5.\} \end{aligned}$$

C. Weighting Matrices and Experimental Results

Once the system has been scaled, the estimation of the multiplicative output uncertainty is carried out. From this estimation, the transfer matrix $W_T(s)$ can be designed as a diagonal matrix of the form:

$$W_T(s) = \frac{0.956(100\,\mathrm{s} + 1)}{0.1\,\mathrm{s} + 1} I_{2\times 2}.$$

The selection of this transfer function yields a value of crossover frequency $\omega_T = 0.0033$ rad/s [8]. Then, taking an initial matrix $W_{KS} = I_{2\times 2}$, the following values for the parameters κ_i were adopted in order to obtain oscillatory responses in both outputs (see Fig. 5): $\kappa_{\mathrm{TT4}} = 3$ and $\kappa_{\mathrm{TT5}} = 2.75$. Default values were used for the rest of parameters involved in W_S [8].

From these responses, the following values of the oscillation frequencies were estimated: $\omega_{d_{\mathrm{TT4}}} = 0.0262$ rad/s and $\omega_{d_{\mathrm{TT5}}} = 0.0209$ rad/s. These values were employed to design a new weighting matrix $W_{KS}(s)$ as in (1). Regarding to the parameters ρ_{ij} in this same expression, the following analysis is performed.

From the time responses in Fig. 5, the oscillation amplitudes can be measured. When a step is given to the reference of TT_4, the amplitudes of the oscillations in $\mathrm{TT}_4, \mathrm{TT}_5, FT_4$, and R are approximately 1 °C, 1.7 °C, 0.5 L/m, and 20%, respectively. Similarly, when the step is given to the reference of TT_5, the oscillation amplitudes are 1.5 °C, 4 °C, 1 L/m, and 70%, respectively.

The *scaled* or normalized influence among these variables may be estimated by means of the following ratios:

- In the case of reference change in TT_4

$$\frac{\frac{\Delta \mathrm{TT}_4}{\Delta \mathrm{TT}_{4_{\max}}}}{\frac{\Delta FT_4}{\Delta FT_{4_{\max}}}} = \frac{1/2.5}{0.5/2} \simeq 1.6$$

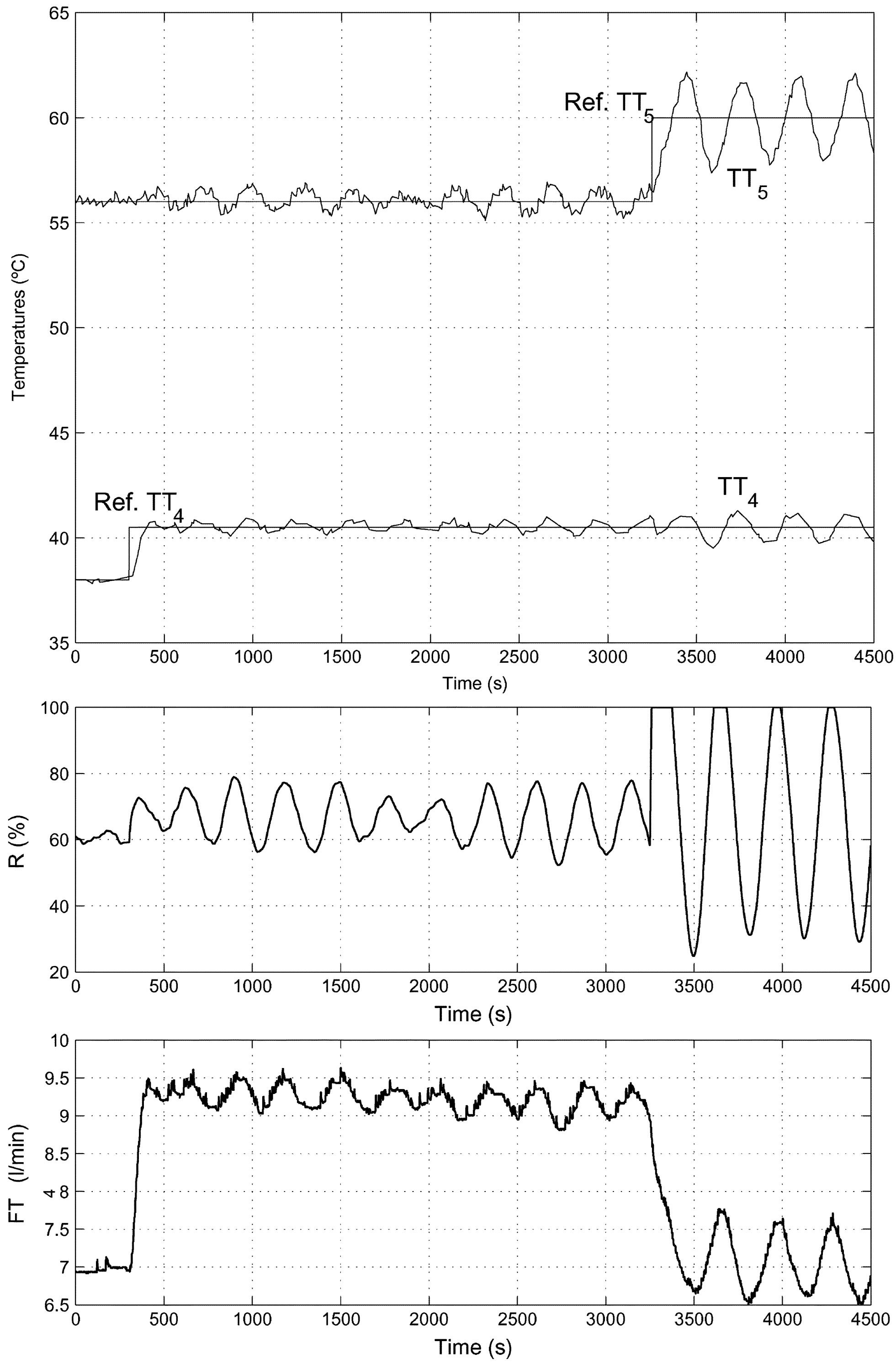


Fig. 5. Experimental results with $W_{KS} = I_{2\times 2}$.

$$\frac{\frac{\Delta \mathrm{TT}_5}{\Delta \mathrm{TT}_{5_{\max}}}}{\frac{\Delta FT_4}{\Delta FT_{4_{\max}}}} = \frac{1.7/5}{0.5/2} \simeq 1.36$$

$$\frac{\frac{\Delta \mathrm{TT}_4}{\Delta \mathrm{TT}_{4_{\max}}}}{\frac{\Delta R}{\Delta R_{\max}}} = \frac{1/2.5}{20/10} \simeq 0.2$$

$$\frac{\frac{\Delta \mathrm{TT}_5}{\Delta \mathrm{TT}_{5_{\max}}}}{\frac{\Delta R}{\Delta R_{\max}}} = \frac{1.7/5}{20/10} \simeq 0.17.$$

- In the case of reference change in TT_5

$$\frac{\frac{\Delta \mathrm{TT}_4}{\Delta \mathrm{TT}_{4_{\max}}}}{\frac{\Delta FT_4}{\Delta FT_{4_{\max}}}} = \frac{1.5/2.5}{1/2} \simeq 1.2$$

$$\frac{\frac{\Delta \mathrm{TT}_5}{\Delta \mathrm{TT}_{5_{\max}}}}{\frac{\Delta FT_4}{\Delta FT_{4_{\max}}}} = \frac{4/5}{1/2} \simeq 1.6$$

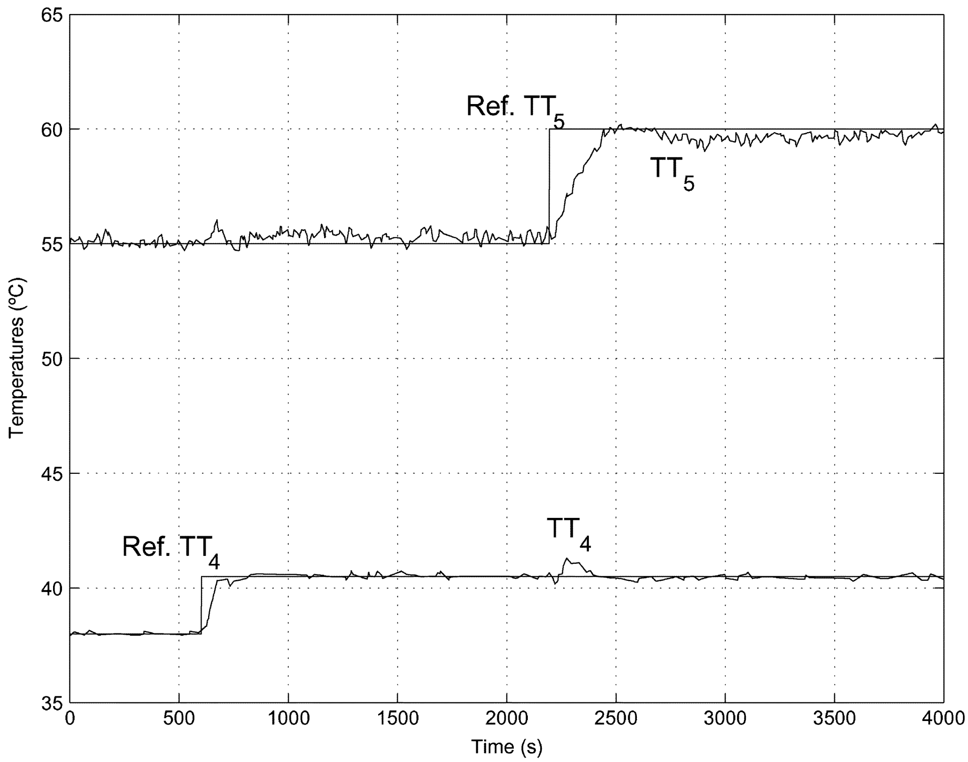


Fig. 6. Experimental results with $\rho_{\mathrm{FT4,TT4}} = \rho_{\mathrm{FT4,TT5}} = 1, \rho_{R,\mathrm{TT4}} = 0.85, \rho_{R,\mathrm{TT5}} = 0.25$.

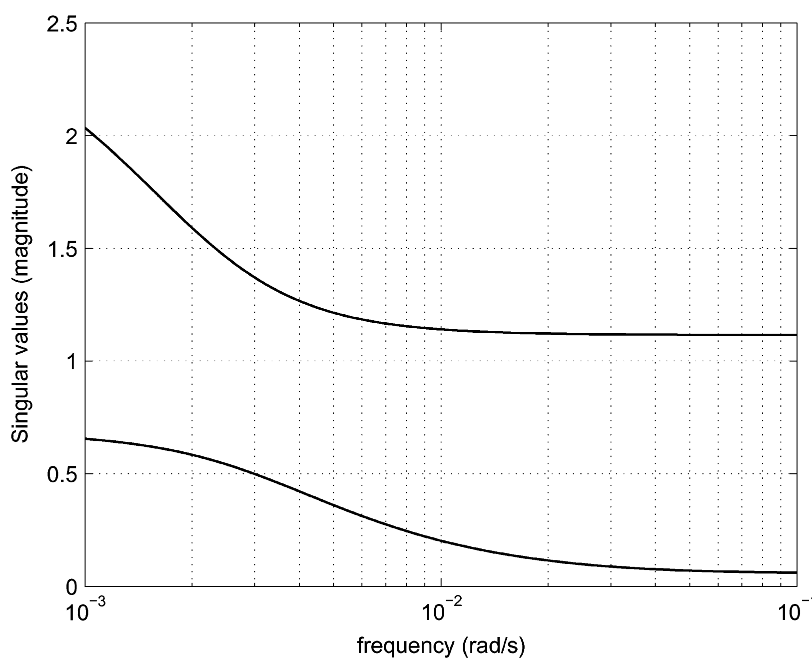


Fig. 7. Magnitude of the singular values.

$$\frac{\frac{\Delta \mathrm{TT}_4}{\Delta \mathrm{TT}_{4_{\max}}}}{\frac{\Delta R}{\Delta R_{\max}}} = \frac{1.5/2.5}{70/10} \simeq 0.086$$
$$\frac{\frac{\Delta \mathrm{TT}_5}{\Delta \mathrm{TT}_{5_{\max}}}}{\frac{\Delta R}{\Delta R_{\max}}} = \frac{4/5}{70/10} \simeq 0.11.$$

From these indexes, it is clear that the scaled influence of a variation in FT_4 is greater than the one of R at these frequencies. Therefore, the penalty coefficients related to FT_4 (i.e., $\rho_{\mathrm{FT4,TT4}}$ and $\rho_{\mathrm{FT4,TT5}}$) should be greater than those related to R (i.e., $\rho_{R,\mathrm{TT4}}$ and $\rho_{R,\mathrm{TT5}}$).

Fig. 6 shows the experimental results achieved with the proposed method, when the following values of the parameters ρ_{ij} were adopted: $\rho_{\mathrm{FT4,TT4}} = \rho_{\mathrm{FT4,TT5}} = 1, \rho_{R,\mathrm{TT4}} = 0.85, \rho_{R,\mathrm{TT5}} = 0.25$.

On the other hand, some insight, useful for the selection of these parameters, can be obtained from a simple controllability analysis of the system [14].

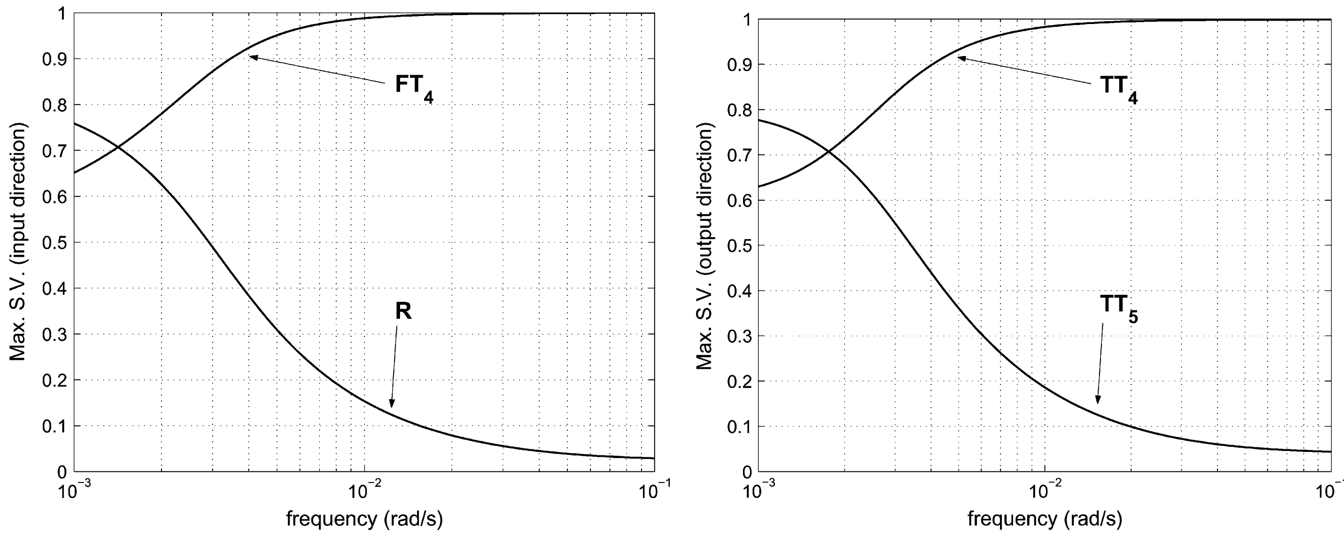


Fig. 8. Input (left) and output (right) directions of the maximum singular value.

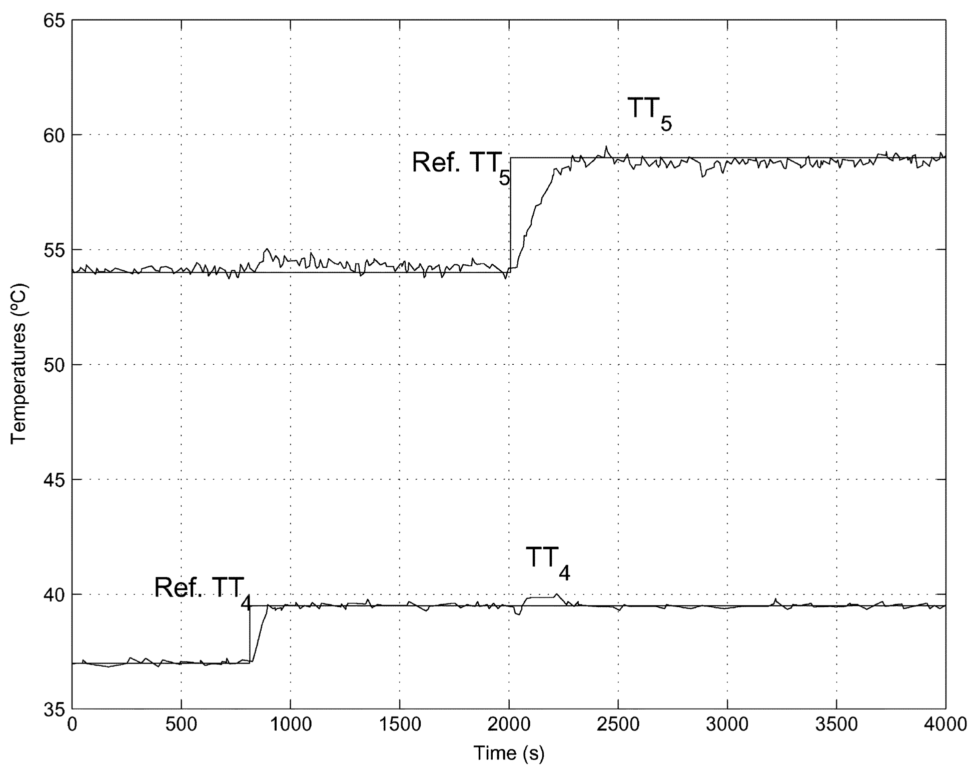


Fig. 9. Experimental results with W_{KS} diagonal: $\rho_{\mathrm{FT4,TT4}} = 2, \rho_{R,\mathrm{TT5}} = 0.75$.

In this particular case, an analysis of the singular values of the *scaled system model* has been made. Fig. 7, shows the magnitude of these singular values versus frequency, while the input and output directions (absolute values) corresponding to the maximum singular value[1] are depicted in Fig. 8.

From Fig. 8 it may be concluded that the system is almost decoupled at the bandwidth frequencies (around 0.01 rad/s). Thereby, temperature TT_4 can be controlled at these frequencies using the control input FT_4 with a high gain (see maximum singular value in Fig. 7), while temperature TT_5 can be controlled by means of R with a small gain. Notice that at low frequencies this matching is just the opposite. An analysis of the time constants of the model reveals that its poles are around 0.001 rad/s (a decade before the bandwidth frequency). At this point, it is important to remind that, as low-order models are intended to be used, the conclusions from this analysis may not completely hold at bandwidth frequencies.

Assuming that this relation is valid, the elements of the weighting matrix $W_{KS}(s)$ relating FT_4 with TT_5 and R with TT_4 (in this case, the nondiagonal elements) can be neglected. This implies that only two parameters ($\rho_{\mathrm{FT4,TT4}}$ and $\rho_{R,\mathrm{TT5}}$) must be adjusted. Besides, taking into account the magnitude and directions of the singular values (see Figs. 7 and 8), the parameter $\rho_{\mathrm{FT4,TT4}}$ should be greater than $\rho_{R,\mathrm{TT5}}$. Fig. 9, shows the experimental results attained with a diagonal weighting

[1]The input and output directions corresponding to the minimum singular values are perpendicular to the respective directions of the maximum singular values.

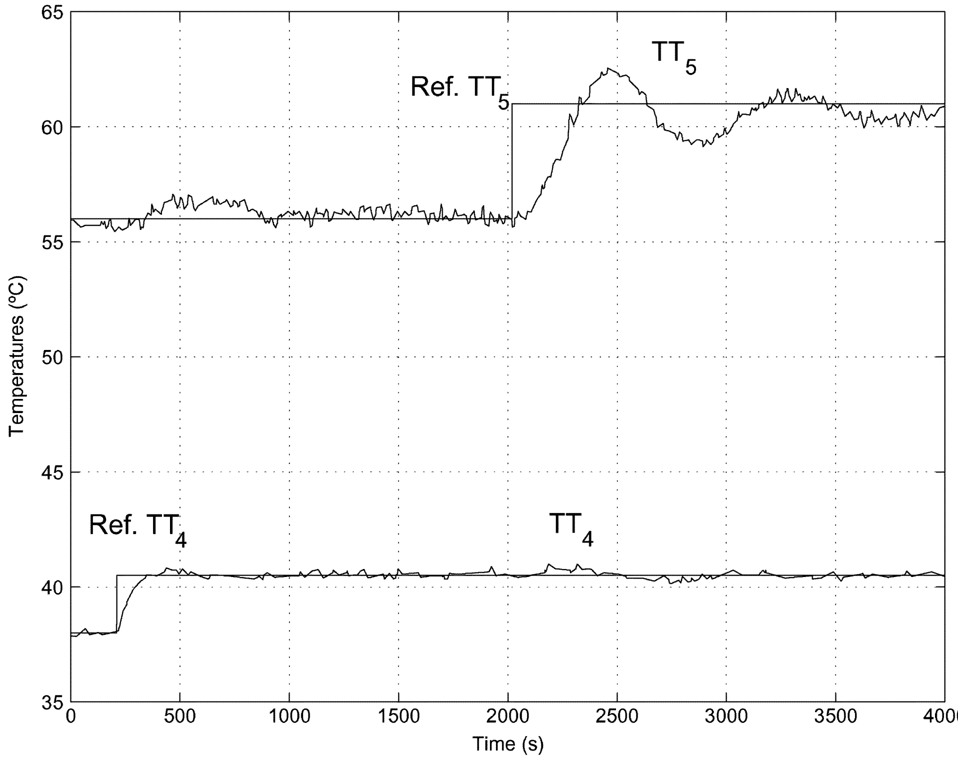


Fig. 10. Experimental results with the original S/T methodology.

matrix $W_{KS}(s)$, using values of $\rho_{\mathrm{FT4,TT4}}$ and $\rho_{R,\mathrm{TT5}}$ equal to 2 and 0.75, respectively. It can be seen that the behavior of the responses is quite similar to that obtained with the previous full matrix $W_{KS}(s)$ (see Fig. 6). In both cases, the time responses have no apparent overshoot, with a rise time about 100 s. in the case of TT_4 and 300 s. in the case of TT_5.

Finally, in order to check the improvement in the control performance, experimental results obtained with the original S/T methodology [8] are shown in Fig. 10. The followed tuning procedure was such that similar rise times to those in Fig. 6 were achieved.

It can be seen that in the case of temperature TT_4, the speed of the step response (about 130 s.) is slightly lower than that obtained in the previous experiments, but a small overshoot can be appreciated (about 4%). However, the improvements are much clearer in the case of TT_5. The rise time in this case is quite similar to that obtained in the previous experiments (about 300 s), but an overshoot of about 24% is present. This comparison experimentally confirms the accomplishment of the purpose of the proposed method: the improvement of a previous design methodology in order to achieve a significant reduction of the time response overshoots, without degrading the speed of these responses.

VI. Conclusion

An improved design methodology for the weighting matrices of the $S/KS/T$ mixed sensitivity problem has been presented in this paper. Taking as a starting point the methodology stated in a recent work, a new design of the weighting matrix for the control sensitivity function has been proposed. The inclusion of this weight allows time responses become less oscillatory, without significantly affecting the speed in the response. The design of this weighting matrix is proposed in such a form that it depends on very few parameters. Some of them (e.g., oscillation frequencies) are obtained by a previous experiment and the others by means of an intuitive rule: *the greater the influence of the scaled increments of the control signals at the bandwidth frequencies is, the greater the values of the related parameters should be*. The application of this method to a multivariable thermodynamic process, such as an experimental pilot plant, has been described. Some comparison experiments with respect to the original method has been included in order to check the improvements attained with the proposed methodology.

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