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APPLICATION OF A MULTIVARIABLE ROBUST CONTROLLER DESIGN METHOD TO HARD-COAL PREPARATION

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Abstract. The paper describes an application of a robust controller design method for calculating the parameters of a controller for a multivariable hard-coal preparation process. The parameters are optimized via a sequential design method in the frequency domain, being based on a combination of the Horowitz/Sidi design (1972), Mayne's (1973) sequential design and Steinhauser/Kreisselmeier's (1979) vector performance criterion method. The design was carried out using a relatively sophisticated CAD-program. The paper shows how the parameters are calculated with this CAD-method and discusses the simulated control results. The simulation is compared with the measured results at the plant after implementation of the designed controller on a process computer AEG 80/30 with a real time software control package ARSI*.

Keywords. Multivariable robust controller design, parameter uncertainty, vector performance criterion, CAD.

I. INTRODUCTION

The plant at hand is given by two coal bunkers in a coal preparation process, which follows the underground operation of a coal mine. In order to reduce the production changes in crude coal the bunkers are used to keep an uniform coal flow. The investigated part of the whole plant is sketched in fig. 1.

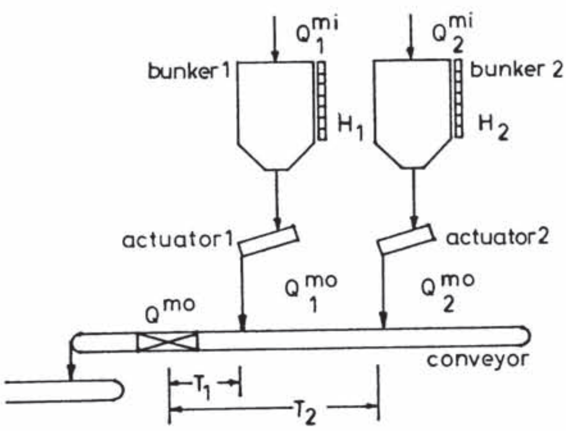

Fig. 1. Sketch of the process

The control task considered here is complicated by some special effects of the dynamic plant behaviour; such as

i. The bunkers input mass flows are not measured.

ii. The bunker volume is small compared with the mass flow.

iii. The measurement of the coal level in the bunkers is strongly disturbed (up to 50%) by several effects.

iv. The actuators behaviour depends on the grain size, the coal surface moisture and the raw coal level in the bunkers.

v. The output mass flow measurement has a considerable delay time compared to the remaining dynamic parameters.

The system can be denoted as multivariable, nonlinear and parameter uncertain. Potential solutions of such a control problem may be given by the use of adaptive algorithm and the robust controller design. As the bunker behaviour sometimes results in abruptly changing parameters adaptive control must be excluded as a control alternative:

- self adaptive control cannot provide an acceptable system performance.
- gain scheduling needs switching conditions which cannot be derived from available measurements.

That is why a robust control structure based on a systematic robust multivariable design method has been chosen.

II. THE MATHEMATICAL DESCRIPTION OF THE PROCESS AND BASIC CONTROL REQUIREMENTS

The mathematical description of the process behaviour in general can be given by a non-linear differential equation

$$\dot{\underline{X}} = \underline{f}(\underline{X},\underline{Y},\underline{U},\underline{P}) \qquad (1)$$

with
$\underline{U} \in R^{n_U}$ input vector
$\underline{Y} \in R^{n_Y}$ output vector
$\underline{X} \in R^{n_X}$ state space vector
$\underline{P} \in R^{n_P}$ parameter vector

where $\underline{P}$ represents possible changes in system parameters e.g. ρ the specific gravity of the raw coal.

Defining the workspace of the system by

$$W: = \{\underline{X}/\underline{X}_{lb} \le \underline{X} \le \underline{X}_{ub}\} \qquad \text{lb: lower bound, ub: upper bound} \qquad (2)$$

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one can assume that the system can be represented in the workspace W by a set of linearized system equations. They can also be noted as transfer functions with varying parameters $\underline{a}$

$$P(s,\underline{a}):=\{P(s,\underline{a})/P(s,\underline{a}_{ij})=L\{S_{ij}\}\ \underline{X}^j\in W\ \underline{p}^i\in R^{n_p}\ ;\quad j=1...k\ ;\ i=1...l\} \qquad (3)$$

with $L\{\ \}$ the Laplace operator

S_{ij} the linearized system equations in state space representation at the operating point $\underline{X}^j$ and the parameter set $\underline{p}^i$

$P(s,\underline{a})$ the transfer function or transfer function matrix of the linearized system in the workspace W

$\underline{a}_{ij}$ vector of parameters of the transfer function

The scalar k is the number of different fixed parameter set points $\underline{X}^j$, and its choice depends on the admissible error ϵ between the real non-linear plant and the linearized one.

The plant as shown in fig. 1 has an input vector $\underline{U}$ containing the actuator set points U_1, U_2 and the unmeasureable input mass flows Q_1^{mi}, Q_2^{mi}. The output vector $\underline{Y}$ contains the elements Q^{mo} the measured output mass flow and the coal level of each bunker H^1 and H^2. The differential equations describing the process behaviour are

$$\frac{dM_j^s}{dt} = Q_j^{mi} - Q_j^{mo}$$

$$\frac{dM_j^s}{dt} = \rho_j \cdot A(H_j) \cdot \frac{dH_j}{dt} \qquad (4)$$

$$\frac{dQ_j^{mo}}{dt} = \psi_j(H_j,\alpha_j,\gamma_j)Q_j^{mo} + \phi_j(H_j,\alpha_j,\gamma_j)U_j \qquad j=1,2$$

with ψ_j and ϕ_j as non-linear functions of H_j the coal level, α_j the grain size and γ_j the surface moisture of the raw coal.

Fig. 2 shows the bar chart of the linearized process model with the above mentioned input/output parameters.

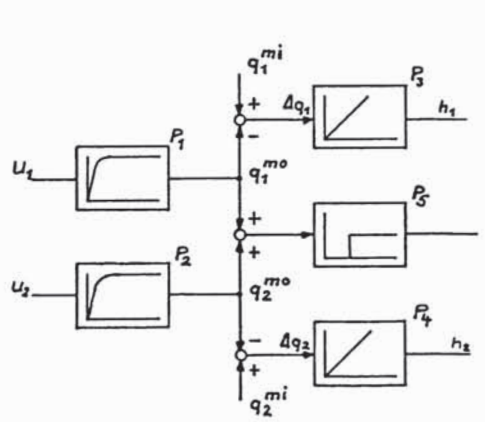

Fig. 2. Linearized process model

The transfer functions P_i are given by

$$P_i(s,\underline{a}) = \frac{K_i^A}{1+T_i s} = \frac{q_i^{mo}}{u_i} \qquad ; \quad i=1,2$$

$$P_i(s,\underline{a}) = \frac{K_i^A}{s} = \frac{h_{i-2}}{\Delta q_{i-2}} \qquad ; \quad i=3,4$$

$$P_5(s) = e^{-T_T s} \quad ; \quad T_1 \approx T_2 = T_T \qquad (5)$$

The varying parameters $\underline{a}$ of the model are summarized as:

$$K_i = K_i^A/_j$$

$$T_i = T_i^A/_j \quad ; \qquad i=1,2$$

$$K_i = 1/(\rho_i \cdot A_i/_j) \quad ; \ i=3,4 \qquad (6)$$

with $/_j$: parameter depending on different linearization points

In particular the parameter A_i represents the changing of the bunkers cross sections depending on the coal level in the bunkers. The parameter ρ_i describes the varying specific gravity of the bunkers contents. Due to coal level, grain size and coal surface moisture the actuator parameters K_i^A and T_i^A change. The variation limits of the above mentioned parameters were measured (K_i^A, A^i) or estimated (T_i^A, ρ_i). They are listed in the following table:

$20 \le K_1^A \le 33$ [t/hV]

$23 \le K_2^A \le 36$ [t/hV]

$5.36 \le A_i \le 24.97$ [m^2] with $1.5 \le h_i \le 4.8$[m]

$1.2 \cdot 10^3 \le \rho_i \le 1.4 \cdot 10^3$ [kg/m^3]

The model in fig. 2 represents the actuator and bunker behaviour. In our practical application we have two sensors for measuring the coal level in the bunkers. Due to a lot of effects we get uncertainties in the sensor signals. One can observe errors up to 50%. A controller design has to take these effects into consideration. Therefore the model in fig. 2 has to be extended by a sensoring part. The complete model including the disturbance inputs d_i and the filters F is shown in fig. 3.

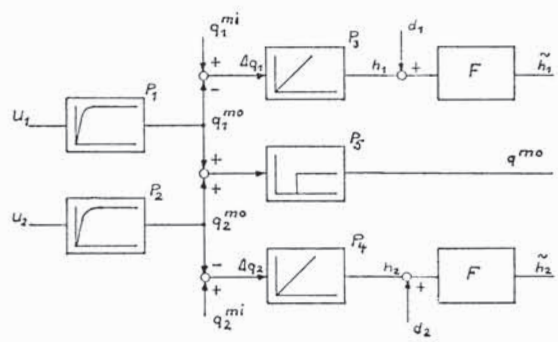

Fig. 3. Linearized process model including measurement units

The basic requirements for the design are:

i. A nearly constant mass flow q^{mo} should be reached, because the process units following the bunkers work in a much better way when the mass flow is constant over a time intervall which is as long as possible.

ii. The control loop should work in such a way that the measurement disturbancies of all the h_i-values do not affect the mass flow q^{mo}.

iii. The control loop should prevent an overflow of the bunkers.

iv. The bunkers should not become empty.

III. STRUCTURE OF THE MULTIVARIABLE CONTROL LOOP

The variables which could be used for feedback are the coal level $\tilde{h}_1$, $\tilde{h}_2$ and the output mass flow. The actuator set points are u_1 and u_2. In a preanalysis some controller structures using the above mentioned input/output variables had been tested and compared on the real process. As a result of the preanalysis we chose the structure which is depicted in fig. 4.

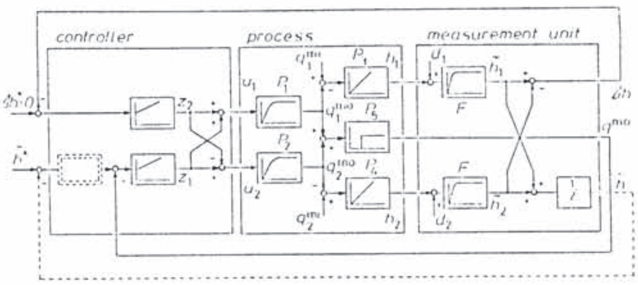

Fig. 4. Control structure

The control structure contains PI-algorithms as sufficient in most applications in process industries. The measured difference of $\tilde{h}_1$ and $\tilde{h}_2$ is one of the controlled variables. The other two are given by q^{mo} and the average coal level $\bar{h}$ which is controlled via a so called master loop. The $\Delta\tilde{h}$-loop comes into consideration because both bunker volumes should be used symmetrically. The q^{mo}-loop controlls the main variable q^{mo} in order to produce a nearly constant mass flow. However, the output mass flow must be connected with the input mass flows otherwise the bunkers might become empty or full. Therefore a third control loop has to be designed. This master regulator which is not considered in this paper sets the commanded output mass flow. However, to fulfill the controll demands one has to design the multivariable inner loop in order to control $\Delta\tilde{h}$ and q^{mo} in a robust way at first. The required multivariable design was carried out by a CAD method described in section IV.

IV. ROBUST MULTIVARIABLE DESIGN METHOD

The plant description indicates that the applied design method must allow to deal with the following restrictions:

i. The plant is multivariable and parameter uncertain.

ii. One loop contains a considerable delay time compared to the remaining dynamic parameters.

iii. The process has very strong limitations for the actuator signal range.

In order to handle the multivariable aspects we used the sequential design method proposed by Mayne (1973). As in most multivariable design methods using the frequency domain the m-input, m-output multivariable system is split down by this method into m-single input/single output systems for design. Frequently used and well-known design procedures can now be applied for the SISO design. To handle the parameter variations and especially to guarantee stability in spite of them the quantitative design method proposed by Horowitz/Sidi (1972) for SISO systems is combined with Mayne's method, as suggested by Shaked/MacFarlane (1977). For the iii-th design restriction and a comfortable way of work with the Horowitz/Sidi method (Gräser, Neddermeyer, Tolle 1982) a vector performace criterion in analogy to the Kreisselmeier/Steinhauser's (1979) design method was defined and optimized.

The whole procedure which makes use of sequentiell design, robust design and a vector performance criterion can only work in a computer aided way.

The following sections introduce to Mayne's method (IV.1) and the robust design very briefly. The use of the vector performance criterion and the CAD package which were discussed already by Gräser, Neddermeyer, Tolle (1982) will be explained in section IV.2 and IV.3.

IV.1 MULTIVARIABLE DESIGN PROCESS

The structure of the considered control loop with two degrees of freedom is shown in fig. 5.

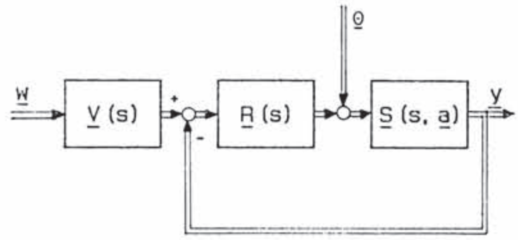

Fig. 5. Multivariable control loop

In our special application a one degree of freedom structure is sufficient because a prescribed disturbance behaviour is required only. According to Mayne an additional input vector $\underline{\theta}$ is used for the derivation of the equations (see fig. 5). The dynamic behaviour of the closed control loop depending on the two inputs is given by

$$\underline{y} = \underline{\tilde{T}}\,\underline{V}\,\underline{w} \quad \text{with} \qquad (7)$$

$$\underline{\tilde{T}} = (\underline{I} + \underline{S}\,\underline{R})^{-1}\,\underline{S}\,\underline{R}$$

$$\underline{y} = \underline{T}\,\underline{\theta} \quad \text{with} \qquad (8)$$

$$\underline{T} = (\underline{I} + \underline{S}\,\underline{R})^{-1}\,\underline{S}.$$

For the sequential design in connection with a non-diagonal dominant MIMO system, the i-th design step depends on all the controllers determined previously and it is necessary to mark the different transfer function matrices with a superscript. According to Mayne, the following notation is used

$$\underline{S}^{o}(s) = \underline{S}(s), \quad \underline{R}^{o}(s) = \underline{O}, \quad \underline{R}^{m}(s) = \underline{R}(s)$$

$$\underline{S}^{q}(s) = (\underline{\Delta}^{q})^{-1}\cdot\underline{S} = (\underline{I} + \underline{S}\,\underline{R}^{q})^{-1}\underline{S}$$

$$\underline{\Delta}^{q}(s) = (\underline{I} + \underline{S}(s)\,\underline{R}^{q}(s))$$

$$\underline{R}^{q}(s) = \mathrm{diag}(r_{11},\ldots,r_{qq},0\ldots0) \qquad (9)$$

In general, after closing the q-th control loop we find for the elements of the system transfer matrix

$$S^{q}_{ab} = \frac{S^{q-1}_{ab} + R_{qq}\,(S^{q-1}_{qq}S^{q-1}_{ab} - S^{q-1}_{aq}S^{q-1}_{qb})}{\delta_q} \qquad (10)$$

δ_q denotes the characteristic equation of the q-th-SISO-control loop.

$$\delta_q = 1 + S^{q-1}_{qq}\,R_{qq} \qquad (11)$$

For the sequential method, there are only m stable controller designs necessary for S^{q-1}_{qq}; q = 1,2...m and all methods used for SISO design can be taken for that.

IV.1.1 ROBUST CONTROLLER DESIGN

The Horowitz/Sidi design method is based upon the plant transfer function of the process (here $S^{q-1}_{qq}(s,\underline{a})$) and the Nichols chart for controller design.

For SISO systems the Horowitz/Sidi-design is normally divided into three design areas according to growing frequencies.

In area one, high accuracy and small effects of the parameter variations are demanded. The relative sensitivity of the closed loop compared with the one of the open loop has to be less than one. For control systems with an excess $e \geq 2$ of poles over zeros the Bodeintegral

$$\int_0^\infty \log |E(j\omega)| \, d\omega = 0 \qquad (12)$$

is valid. As a consequence $|E|$ can not be less than one over the whole range of frequencies. So in the second design area $|E|$ can only be limited to an magnitude $1 \leq |E| \leq \gamma$. In area three, the controller gain is very small and the sensitivity of open and closed loop are almost the same $|E| \approx 1$. For quantitative design of SISO-systems within area one, the sensitivity of the closed loop

$$|\Delta T_{qq}(j\omega, \underline{a})| \leq \alpha(j\omega) \qquad 0 \leq \omega \leq \omega_w \qquad (13)$$

is limited. In area two, limits for the sensitivity

$$|E_{qq}(j\omega)| \leq \gamma_1 \qquad (14)$$

or of the maximum peak of

$$|T|, \quad |T_{qq}(j\omega)| \leq \gamma_2 \qquad (15)$$

with $\gamma_1, \gamma_2 < 1$ are given, respectively, guaranteeing in this way also stability in spite of parameter variations. With the Nichols chart and parameter areas for different values $s = j\omega_i$; $i = 1...n$ of the transfer function $S_{qq}^{q-1}(j\omega, \underline{a})$, Horowitz/Sidi transforms the requirements as formulated in Eq. 13, 14 or Eq. 13, 15 into boundaries for the nominal open loop

$$L_{qq}(j\omega, \underline{a}_o) = R_{qq}(j\omega) \, S_{qq}^{q-1}(j\omega, \underline{a}_o)$$

frequency response.

For the design of a multivariable control system two problems have to be distinguished:

- robustness of the stability under the presence of parameter variations,
- quantitative design.

The first case demands stability of the characteristic equations of the m-SISO-systems sequentially designed. A SISO-system is stable for all parameter sets $\underline{a}$ when the open loop nominal frequency response plot does not penetrate into the closed curves (boundaries in the Nichols chart) which are derived from Eq. 14 or Eq. 15. Additionally the Nyquist criterion has to be fulfilled.

For quantitative design of the multivariable system the sensitivity $|\Delta T_{qq}(j\omega, \underline{a})|$ should be limited within the frequency range $0 \leq \omega \leq \omega_w$. In the SISO-case one holds the design requirements Eq. 13 exactly if the controller brings the magnitude of the nominal open loop on the boundaries (Horowitz 1973) in the Nichols chart. For the multivariable case these relations are not easy to describe. In the sequential design method the q-th design step may also influence all transfer functions designed previously

$$S_{aa}^{q} \neq S_{aa}^{q-1}; \; a < q.$$

Up to now, it is not possible to formulate an exact interrelation between the design requirements Eq. 13 and the sequential design steps. Only for the last row of the transfer function matrix T(s) a direct correlation can be derived (Gräser, Tolle 1982). But due to the relatively high gains normally used in region 1, the already designed closed loops are very often changed only marginally by closing additional loops so that one can live with this design method in general also in the multivariable case.

IV.2 OPTIMIZATION OF A VECTOR PERFORMANCE CRITERION

Section IV.1 reduces the multivariable robust design problem to the following task: Find a regulator which holds the boundaries for the nominal open loop frequency responses.

A most convenient way to find the denominator and nominater parameters $\underline{r}$ of $R_{qq}(s, \underline{r})$ is to make use of a vector performance criterion $\underline{G}(\underline{r})$ which was very succesfully applied bei G. Kreisselmeier and R. Steinhauser (1979, 1984) for some other problems. Therefore the constraints for $L_{qq}(j\omega, \underline{a}_o, \underline{r})$ and/or the controller have been formulated as such a vector performance criterion $\underline{G}(\underline{r})$. The robust design requirements derived from the boundaries in the Nichols chart are normally representable by the following six elements of the vector criterion:

- $g_1(\underline{r})$: Sum of the deviations of the frequency response points $L_{qq}(j\omega_i, \underline{a}_o)$ from the boundaries B_i to higher gains;
- $g_2(\underline{r})$: Sum of the deviations of the frequency response points $L(j\omega_i, \underline{a}_o)$ from the boundaries B_i to lower gains;
- $g_3(\underline{r})$: Component resulting from the violation of the high frequency boundaries;
- $g_4(\underline{r})$: Gain of the controller $(j\omega \to 0)$;
- $g_5(\underline{r})$: High frequency gain K^∞ of the controller;
- $g_6(\underline{r})$: Stability of the controller.

In a practical application one has not only requirements which can be easily represented by the frequency domain methods. Such demands are time domain spezifications as noted under section IV (strong limits for the actuator signal range).

With the reduction of the design problem to an optimization of a vector performance criterion such constraints can easily be considered by defining additional vector elements. In our practical application such elements can be given by

$$g_{6+i} = \int_0^{T_E} (y(t,\underline{a}_i) - y_{max})^2 \, dt$$

$$\forall \; t \text{ with } y(t,a_i) \geq y_{max} \qquad i = 1,2...n. \qquad (16)$$

IV.2.1 OPTIMIZATION TECHNIQUE

As the above performance vector elements indicates each design aspect is to be rated quantitatively by means of a suitable positive design criterion in such a way, that reducing the value of a criterion always means improvement of a corresponding design aspect. In a second step the design is achieved iteratively as follows. In the γ-th design step a target vector $\underline{c}^\gamma$ is chosen within the range given by

$$\underline{G}(\underline{r}^{\gamma-1}) < \underline{c}^\gamma < \underline{c}^{\gamma-1} \qquad (17)$$

Here $\underline{r}^{\gamma-1}$ denotes the controller poles and zeros which resulted from the previous design step, and $\underline{c}^{\gamma-1}$ denotes the associated target vector. In the above choice of $\underline{c}^\gamma$, it is advisable to take $c_j^\gamma = c_j^{\gamma-1}$ for those design criteria, which have been made sufficiently small in earlier design steps, whereas $c_i^\gamma = g_i(\underline{r}^{\gamma-1})$ may be chosen for design criteria, which are to be reduced in value further. This determines the direction in which the design proceeds. Then $\underline{r}^\gamma$ is defined as the solution of a scalar optimization problem

$$\min_{\underline{r}} \{-\frac{1}{\beta} \ln \sum_{i=1}^{L} \exp(\beta g_i(\underline{r})/c_i^\gamma)\}. \qquad (18)$$

Using the definition

$$\alpha(\underline{r}) := \max_{1 \leq i \leq L} (g_i(\underline{r})/c_i^\gamma) \qquad (19)$$

the optimization problem can be rewritten in the form

$$\min_{\underline{r}} \{\alpha(\underline{r}) + \frac{1}{\beta} \ln \sum_{i=1}^{L} \exp[\beta(\frac{g_i(\underline{r})}{c_i} - \alpha(\underline{r}))]\} \qquad (20)$$

and the minimization is essentially reduced to the minimization of the value of $\alpha(\underline{r})$. With Eq. 19 we have

$$g_i(\underline{r}) \le \alpha(\underline{r}) \cdot c_i^{\gamma} \quad i = 1,2...L \tag{21}$$

that means minimizing $\alpha(\underline{r})$ is the same task as reducing the value of all design criteria simultaneously. In the program package described below the optimization task is realized with the Hook-Jeeves method.

IV.3 CAD PACKAGE

The program package used here is written in FORTRAN 77 as a multitasking dialog system which runs on a VAX 11/780. Some detailed program descriptions are given by Ersü, Neddermeyer, Tews (1983). However, the global structure is shown in fig. 6.

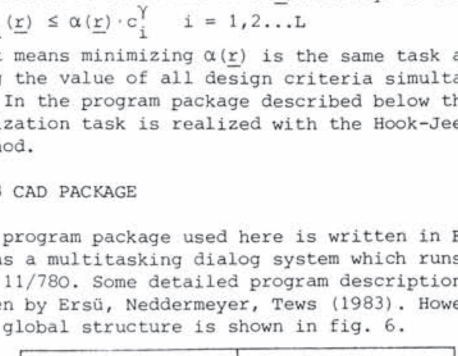

Fig. 6. Global software structure

On the higest level we have the multivariable frequency domain design and time domain requirements for the multivariable system. As shown in IV.1 and IV.2 the multivariable design problem reduces to m-single loop designs which are carried out by an optimization of a vector performance criterion. During this process a grafical output supports the user choosing the target vectors for the optimization and for inspection of the design results.

V. APPLICATION OF THE INTERACTIVE COMPUTER AIDED CONTROLLER DESIGN

At first the plant is rewritten in a P-kanonical system representation. Fig. 7 shows the input/output variables and the location of the transfer functions $S_{ij}(s, \underline{a})$.

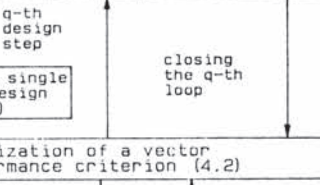

Fig. 7. P-kanonical plant model

They are given by

$$S_{11}(s,\underline{a}) = P_5(s) \cdot (P_1(s,\underline{a}) + P_2(s,\underline{a}))$$
$$S_{12}(s,\underline{a}) = P_5(s) \cdot (P_1(s,\underline{a}) - P_2(s,\underline{a})) \tag{22}$$
$$S_{21}(s,\underline{a}) = F(s) \cdot (P_3(s,\underline{a})P_1(s,\underline{a}) - P_4(s,\underline{a})P_2(s,\underline{a}))$$
$$S_{22}(s,\underline{a}) = F(s) \cdot (P_3(s,\underline{a})P_1(s,\underline{a}) + P_4(s,\underline{a})P_2(s,\underline{a}))$$

Fig. 8 contains the corresponding Bode plots of the parameter uncertain transfer functions S_{ij}.

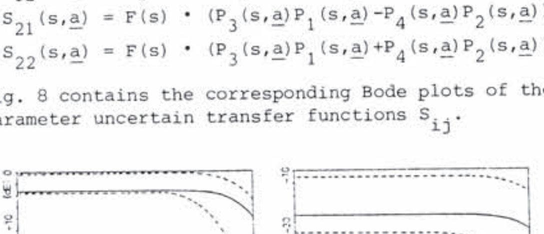

Fig. 8. Bode plots of the uncontrolled plant

The design requirements for the MIMO problem can be summarized as:

i. $|\Delta T_{qq}(j\omega,\underline{a})|$ as small as possible for $0 \le \omega \le \omega_w$

ii. $|T_{qq}(j\omega,\underline{a})| \le 2\,\text{dB} \quad \forall \underline{a},\omega$

iii. The overshooting of the step response of the q^{mo}-loop should be limited to 10%.

iv. An abrupt measurement disturbance of the coal level (o.5 m is a typical value) should not disturbe the bunkers output mass flow.

For the first item i. it makes no sense to require absolute bounds on $|\Delta T|$. Due to the non-minimum phase behaviour of the plant the bandwidth and as a consequence the realizeable robustness are limited. However, the Horowitz/Sidi-boundaries for the first open loop $R_{11}(S,\underline{r})\ S_{11}^{o}(s,\underline{a}_o)$ are noted in fig. 9.

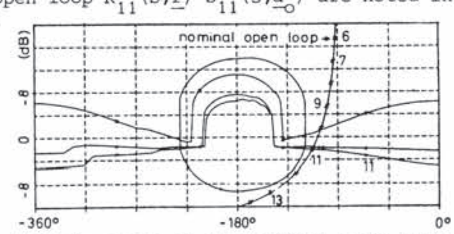

Fig. 9. Nichols chart of the nominal open loop frequency response

The chosen vector performance index contains the terms $g_1...g_6$ mentioned under IV.2 and the time domain requirements

$$g_{6+i} = \int_o^{T_E} (q^{mo}(t,\underline{a}_i) - w^{q^{mo}})^2 dt$$
$$\forall\ t \text{ with } q^{mo}(t,\underline{a}_i) \ge w^{q^{mo}} \qquad i=1,2...n \tag{23}$$

The optimized nominal open loop (see fig. 9) does not penetrate the closed boundaries and frequency point 11 (ω=o.6[1/min]) is on a line of constant $|\Delta T|$ with $|\Delta T|$=2.7dB. Additionally in fig. 12d the response of a q^{mo} set point step for the linearization point L_1 is shown. The q^{mo}-trajectory fulfills the overshooting restriction.

The controller parameters are computed as

$$R_{11}(s) = 0.228|1 + \frac{1}{11.4s}| \tag{24}$$

With this regulator we obtain for the frequency response of the first closed loop $\tilde{T}_{11}^1 = S_{11}^1 R_{11}$ the Bode plot noted in fig. 10.

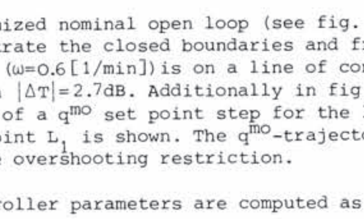

Fig. 10. Bode plot of $\tilde{T}_{11}^1$

The frequency plot of S_{22}^1 with the boundaries according to item (ii.) and the frequency plot of the nominal open loop $R_{22}(s,\underline{r})S_{22}^1(s,\underline{a}_o)$ are not shown, since they are in principle similar to fig.9. The second regulator was optimzied with the vector performance criterion containing $g_1 \ldots g_6$ and

$$g_{6+i} = \int_{o}^{T_E} (q^{mo}(t,\underline{a}_i) - w^{q^{mo}})^2 dt$$

$$\forall\ t \text{ with } w^{q^{mo}} = \text{const.} \qquad i=1,2\ldots n$$

The resulting regulator parameters are

$$R_{22}(s,\underline{r}) = 1.46\left(1+\frac{1}{460s}\right)$$

Fig. 13d shows a simulated disturbance of 0.5 m at the linearized plant (L_2). One can see that the output mass flow is not disturbed.

In fig. 11 the frequency response of the closed loop $\tilde{T}^2_{22} = S^2_{22} R_{22}$ is given.

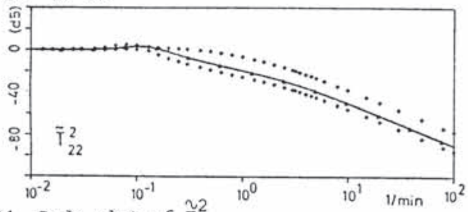

Fig. 11. Bode plot of $\tilde{T}^2_{22}$

The couplings are not very strong. That is why the frequency response of $\tilde{T}^1_{11}$ is nearly the same as $\tilde{T}^2_{11}$. Due to that it is not shown again here. The optimized controller parameters have been tested at the real plant. The results are given below.

VI. REALIZED CONTROL LOOP

The here interesting units of the hard coal preparation plant at hand are controlled by a AEG 80-30 process computer system.

The application software used for the realization of the feedback control is ARSI80 and AS80 for the logic/sequence control. Both systems provide operating procedures to run the plant automatically from start up to normal operation and to manage emergency and shutdown operations. Custom tailoring of the modular program packages has been made mainly off-line while necessary modifications of control structures could be done during on-line operation.

The control structure and the control algorithm has been realized in a quasi continuous way.

Fig. 12,13,14 show the simulation results together with the measured traces.

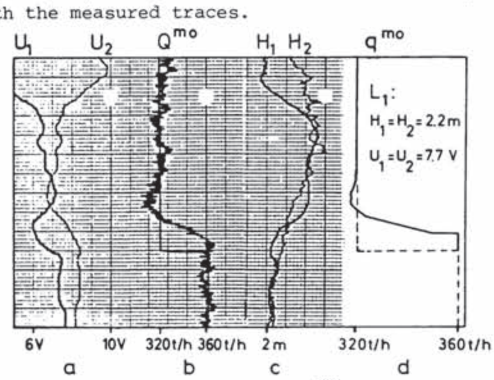

Fig. 12. Step response of the q^{mo}-loop

Fig. 12 compares the simulated to the real step responses of the q^{mo} loop.

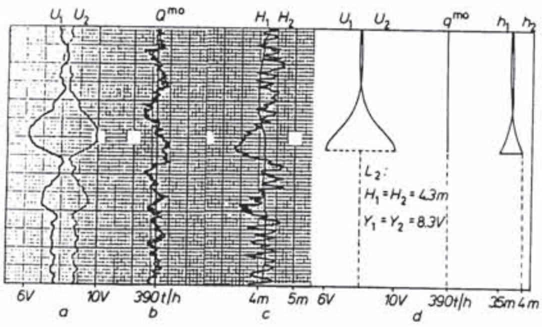

Fig. 13. Disturbance response (0.5 m)

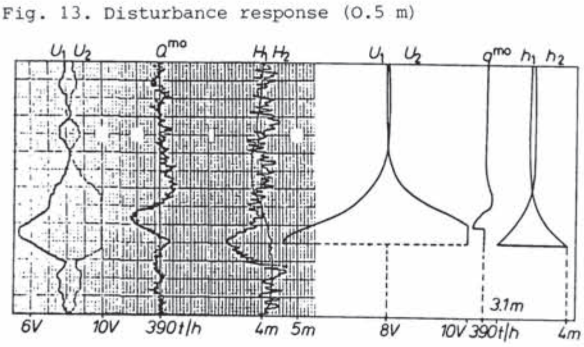

Fig. 14. Disturbance response (0.9 m)

Fig. 13 and 14 show the influence of the disturbed coal level measurement. Looking at the measured and simulated trajectories one finds that they are very similar.

In a more general way one can say that the controller fulfills the design requirements in the simulation as well as on the real plant.

VII. CONCLUSIONS

The paper describes a multivariable, robust design process. The design was carried out with an interactive CAD-system. The optimized controller parameters are applied to the real process. The process behaviour fulfills the required system performance in an impressive way.

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