15th Triennial World Congress, Barcelona, Spain

DECENTRALISED QUANTITATIVE FEEDBACK DESIGN OF LARGE-SCALE SYSTEMS

B. Labibi , B. Lohmann, A. Khaki Sedigh, P. Jabedar Maralani

Iranian Research Organisation for Science and Technology (Iran), University of Bremen (Germany), K.N. Toosi University (Iran), University of Tehran (Iran)

Abstract: In this paper a new method for robust decentralised control of large-scale systems using quantitative feedback theory (QFT) is suggested. For a given large-scale system an equivalent descriptor system is defined. Using this representation, closed-loop diagonal dominance sufficient conditions over the uncertainty space are derived. It is shown by appropriately choosing output disturbance rejection model in designing QFT controller for each isolated subsystem, these conditions are achieved. Then a single-loop quantitative feedback design scheme is applied to solve the resulting series of individual loops to guarantee the satisfaction of predefined $MIMO$ quantitative specifications. *Copyright © 2002 IFAC*

Keywords: Robust control, Large-scale systems, Quantitative feedback design, Decentralised control, Diagonal dominance.

1. INTRODUCTION

Modelling of large-scale systems by interconnected low order sub-systems is beneficial due to computational and economical difficulties in a large-scale system. In many decentralised control systems, just as in non-decentralised cases, the performance of system is heavily affected by the un-modelled dynamics, parameter changes, uncertain values, disturbances, etc. Recently, there has been a growing attention toward using robust methods in control of large-scale systems (Jamshidi, 1997).

One of the well known methods in robust control theory is quantitative feedback theory that emphasises the use of feedback for achieving the desired system performance. The quantitative feedback design robust control methodology for multi input, multi output ($MIMO$) systems introduced by Horowitz is the known technique that considers large parametric uncertainty and quantitative performance requirements simultaneously. Decentralised control with Nyquist like methods can be very effective, if one can obtain the required degree of diagonal dominance fairly easily. The first major drawback of all the existing decentralised control methods based on generalised diagonal dominance is the fact that a compensated open-loop diagonally dominant system in no way guarantees that the resulting closed-loop system is also diagonally dominant. On the other hand, closed-loop diagonal dominance is necessary for almost decoupled closed-loop response. More fundamentally, there is a need to investigate what level of open-loop dominance will guarantee a desired level of the closed-loop dominance. To do this, an appropriate measure of dominance must be defined. Secondly, if the plant is uncertain, then open-loop diagonal dominance at one parameter point does not insure the condition at any other points. In fact, decoupling at one point may result in severe open-loop and/or closed-loop interaction at another point (Nwokah, 1993). Decentralised design methods that address the above issue are therefore desirable.

In this paper, closed-loop diagonal dominance sufficient conditions over the uncertainty space are derived. It is shown by appropriately choosing output disturbance rejection model, in designing the QFT controller for each isolated subsystem, these conditions are achieved. Then a single-loop quantitative feedback design scheme is applied to solve the resulting series of individual loops to guarantee the satisfaction to predefined $MIMO$ quantitative specifications.

The paper is organised as follows: In section 2, the problem of finding suitable local dynamical controllers for the subsystems of a linear large-scale system is formulated. In section 3, by defining an equivalent descriptor system for a given large-scale system, diagonal dominance sufficient conditions are derived. In section 4, it will be shown how by appropriately choosing the output disturbance rejection model for each local QFT problem, these conditions are derived. In section 5 the effectiveness of the proposed method and its ease of application are demonstrated by a 2×2 uncertain multivariable example.

2. PROBLEM FORMULATION

Consider an uncertain large-scale system $G(s)$, with the following state-space equations

$$G(s):\begin{cases}\dot{x}(t)=(A+\Delta A)x(t)+(B+\Delta B)u(t)\\ y(t)=(C+\Delta C)x(t)\end{cases} \quad (1)$$

where $x\in R^{n}$, $u\in R^{m}$, $y\in R^{m}$, $A\in R^{n\times n}$, $B\in R^{n\times m}$, $C\in R^{m\times n}$, ΔA, ΔB, and ΔC are the uncertainties in parameters. Assuming the system is composed of N linear time-invariant subsystems $G_i(s)$, described by

$$G_i(s):\begin{cases}\dot{x}_i=(A_{ii}+\Delta A_{ii})x_i+(B_{ii}+\Delta B_{ii})u_i+\sum_{\substack{j=1\\ j\neq i}}^{N}(A_{ij}+\Delta A_{ij})x_j+\sum_{\substack{j=1\\ j\neq i}}^{N}(B_{ij}+\Delta B_{ij})u_j\\ y_i=(C_{ii}+\Delta C_{ii})x_i+\sum_{\substack{j=1\\ j\neq i}}^{N}(C_{ij}+\Delta C_{ij})x_j\end{cases} \quad (2)$$

where $x_i\in R^{n_i}$, $u_i\in R^{m_i}$, $y_i\in R^{m_i}$, $A_{ii}\in R^{n_i\times n_i}$, $B_{ii}\in R^{n_i\times m_i}$, $C_{ii}\in R^{p_i\times n_i}$, $\sum_{i=1}^{N}n_i=n$, and $\sum_{i=1}^{N}m_i=m$. The terms $\sum_{\substack{j=1\\ j\neq i}}^{N}(A_{ij}+\Delta A_{ij})x_j$, $\sum_{\substack{j=1\\ j\neq i}}^{N}(B_{ij}+\Delta AB_{ij})u_j$, and $\sum_{\substack{j=1\\ j\neq i}}^{N}(C_{ij}+\Delta C_{ij})x_j$ are due to the interactions of the other sub-systems. The objective in this paper is to design a local output feedback dynamical controller

$$U_i(s)=K_i(s)(R_i(s)-Y_i(s)) \quad (3)$$

for each isolated uncertain subsystem

$$G_i(s):\begin{cases}\dot{x}_i=(A_{ii}+\Delta A_{ii})x_i+(B_{ii}+\Delta B_{ii})u_i\\ y_i=(C_{ii}+\Delta C_{ii})x_i\end{cases} \quad (4)$$

where R_i is the i-th reference input, such that the overall closed-loop system under the decentralised QFT controller

$$K(s)=diag\{K_i(s)\},\quad i=1,\ldots,N \quad (5)$$

has the desirable QFT Performance. The systems (A,B,C) and (A_d,B_d,C_d), where $A_d=diag\{A_{ii}\}$, $B_d=diag\{B_{ii}\}$, and $C_d=diag\{C_{ii}\}$ are the nominal and the nominal diagonal systems respectively.

3. DIAGONAL DOMINANCE ACHIEVMENT

In order to derive closed-loop diagonal dominance sufficient conditions over the uncertainty space, all of the inputs and outputs are defined as state variables of the system and an equivalent descriptor system for the given large-scale by the following equations is derived

$$\overline{G}(s):\begin{cases}E\dot{\overline{x}}(t)=\overline{A}\,\overline{x}+\overline{B}u\\ y=\overline{C}\,\overline{x}\end{cases} \quad (6)$$

where

$$E=\begin{bmatrix}0_{m\times m} & 0_{m\times n} & 0_{m\times m}\\ 0_{n\times m} & I_{n\times n} & 0_{n\times m}\\ 0_{m\times m} & 0_{m\times n} & 0_{m\times m}\end{bmatrix},\ \overline{x}=\begin{bmatrix}y\\ x\\ u\end{bmatrix},$$

$$\overline{A}=\begin{bmatrix}-I_{m\times m} & C_d+C_H+\Delta C_d+\Delta C_H & 0_{m\times m}\\ 0_{n\times m} & A_d+A_H+\Delta A_d+\Delta A_H & B_d+B_H+\Delta B_d+\Delta B_H\\ 0_{m\times m} & 0_{m\times n} & -I_{m\times m}\end{bmatrix},$$

$$\overline{B}=\begin{bmatrix}0_{m\times m}\\ 0_{n\times m}\\ I_{m\times m}\end{bmatrix},\ \overline{C}=\begin{bmatrix}I_{m\times m} & 0_{m\times n} & 0_{m\times m}\end{bmatrix},\quad A_H=A-A_d$$

$B_H=B-B_d$, $C_H=C-C_d$ $\Delta A_d=diag\{\Delta A_{ii}\}$, $\Delta B_d=diag\{\Delta B_{ii}\}$, $\Delta C_d=diag\{\Delta C_{ii}\}$ $\Delta A_H=\Delta A-\Delta A_d$, $\Delta B_H=\Delta B-\Delta B_d$, and $\Delta C_H=\Delta C-\Delta C_d$.

Defining

$$\overline{P}_T=(sE-\overline{A}+\overline{B}K\overline{C})^{-1}, \quad (7)$$

$$\overline{A}_d=\begin{bmatrix}-I_{m\times m} & C_d+\Delta C_d & 0_{m\times m}\\ 0_{n\times m} & A_d+\Delta A_d & B_d+\Delta B_d\\ 0_{m\times m} & 0_{m\times n} & -I_{m\times m}\end{bmatrix}, \quad (8)$$

$$\overline{H}=\overline{A}-\overline{A}_d, \quad (9)$$

and

$$\overline{P}=(sE-\overline{A}_d+\overline{B}K\overline{C})^{-1}, \quad (10)$$

it is simple to show that

$$\overline{P}_T=\begin{bmatrix}\overline{P}_{T1} & \overline{P}_{T2} & \overline{P}_{T3}\end{bmatrix} \quad (11)$$

where

$$\overline{P}_{T1} = \begin{bmatrix} I-(C+\Delta C)(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1}(B+\Delta B)K \\ -(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1}(B+\Delta B)K \\ -K(I-(C+\Delta C)(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1}(B+\Delta B)K) \end{bmatrix}$$

$$\overline{P}_{T2} = \begin{bmatrix} (C+\Delta C)(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1} \\ (sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1} \\ -K(C+\Delta C)(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1} \end{bmatrix},$$

$$\overline{P}_{T3} = \begin{bmatrix} (C+\Delta C)(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1}(B+\Delta B) \\ (sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1}(B+\Delta B) \\ I-K(C+\Delta C)(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1}(B+\Delta B) \end{bmatrix}$$

and

$$\overline{P} = [\overline{P}_1 \quad \overline{P}_2 \quad \overline{P}_3] \tag{12}$$

where

$$\overline{P}_1 = \begin{bmatrix} I-(C_d+\Delta C_d)(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1}(B_d+\Delta B_d)K \\ -(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1}(B_d+\Delta B_d)K \\ -K(I-(C_d+\Delta C_d)(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1}(B_d+\Delta B_d)K) \end{bmatrix}$$

$$\overline{P}_2 = \begin{bmatrix} (C_d+\Delta C_d)(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1} \\ (sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1} \\ -K(C_d+\Delta C_d)(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1} \end{bmatrix},$$

$$\overline{P}_3 = \begin{bmatrix} (C_d+\Delta C_d)(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1}(B_d+\Delta B_d) \\ (sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1}(B_d+\Delta B_d) \\ I-K(C_d+\Delta C_d)(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K(C_d+\Delta C_d))^{-1}(B_d+\Delta B_d) \end{bmatrix},$$

With these,

$$\begin{aligned} &\overline{G}_{cl}(s) = \overline{C}\overline{P}_T\overline{B}K(s) = \\ &(C+\Delta C)(sI-A-\Delta A+(B+\Delta B)K(C+\Delta C))^{-1}(B+\Delta B)K \\ &= G_{cl}(s) \end{aligned} \tag{13}$$

and

$$\begin{aligned} &\overline{G}_{dcl}(s) = \overline{C}\overline{P}\overline{B}K(s) = \\ &(C_d+\Delta C_d)(sI-A_d-\Delta A_d+(B_d+\Delta B_d)K. \\ &.(C_d+\Delta C_d))^{-1}(B_d+\Delta B_d)K = G_{dcl}(s) \end{aligned} \tag{14}$$

where $\overline{G}_{cl}(s)$, $\overline{G}_{dcl}(s)$, $G_{cl}(s)$, and $G_{dcl}(s)$ are the transfer matrices of the descriptor system with and without considering the interactions, and the original system with and without considering the interactions. With these equations, it can be concluded that designing appropriate QFT controller for the equivalent descriptor system given by the equations (6) is equivalent to designing QFT controller for the original system given by the equations (1). The equation (13) can be written as

$$\begin{aligned} &\overline{G}_{cl}(s) = \overline{C}(s\overline{E}-\overline{A}-\overline{B}K(s)\overline{C})^{-1}\overline{B}K(s) = \overline{C}\overline{P}_T\overline{B}K(s) = \\ &\overline{C}\overline{P}\overline{H}(I-\overline{P}\overline{H})^{-1}\overline{P}\overline{B}K(s)+\overline{C}\overline{P}\overline{B}K(s) = \\ &\overline{C}\overline{P}\overline{H}\overline{P}_T\overline{B}K(s)+\overline{C}\overline{P}\overline{B}K(s). \end{aligned} \tag{15}$$

and

$$(\overline{C}-\overline{C}\overline{P}\overline{H})\overline{P}_T\overline{B}K(s) = \overline{C}\overline{P}\overline{B}K(s). \tag{16}$$

In the above equation if the norm of the difference $\overline{C}-(\overline{C}-\overline{C}\overline{P}\overline{H})$, i.e. $\|\overline{C}\overline{P}\overline{H}\|_\infty$ is small, the matrix $(\overline{C}-\overline{C}\overline{P}\overline{H})$ can be approximated by the matrix $\overline{C}$ (Stewart, 1973). Then the equation (16) can be written as

$$\overline{C}\overline{P}_T\overline{B}K(s) \cong \overline{C}\overline{P}\overline{B}K(s), \tag{17}$$

Theorem 3.1: The closed-loop uncertain system under decentralised controller is diagonal dominant over the uncertainty space if

$$\|\overline{C}\overline{P}\overline{H}\|_\infty < 1 \tag{18}$$

Proof: The overall closed loop system has the following transfer function

$$\begin{aligned} &\overline{G}_{cl}(s) = \overline{C}\overline{P}_T\overline{B}K(s) = \overline{C}(I-\overline{P}\overline{H})^{-1}\overline{P}\overline{B}K(s) = \\ &\overline{C}\overline{P}\overline{H}(I-\overline{P}\overline{H})^{-1}\overline{P}\overline{B}K(s)+\overline{C}\overline{P}\overline{B}K(s) = \\ &\overline{C}\overline{P}\overline{H}\overline{P}_T\overline{B}K(s)+\overline{C}\overline{P}\overline{B}K(s) \end{aligned} \tag{19}$$

Defining $\overline{C}^+$, the generalised inverse of $\overline{C}$, as defined by

$$\overline{C}^+ = \overline{C}^T(\overline{C}\overline{C}^T)^{-1} \tag{20}$$

(Skogestad, 1996),

$$\overline{G}_{cl}(s) \cong (I-\overline{C}\overline{P}\overline{H}\overline{C}^+)^{-1}\overline{C}\overline{P}\overline{B}K(s). \tag{21}$$

Then

$$\|\overline{C}\overline{P}\overline{H}\overline{C}^+\|_\infty < \|\overline{C}\overline{P}\overline{H}\|_\infty \|\overline{C}^+\|_\infty \tag{22}$$

since

$$\|\overline{C}^+\|_\infty = \frac{1}{s_{min}(\overline{C})} \tag{23}$$

(Skogestad, 1996), and from the definition of the matrix $\overline{C}$, in the equations (6),

$$s_{min}(\overline{C}) = 1. \tag{24}$$

Then the relation (22) may be written as

$$\|\overline{C}\overline{P}\overline{H}\overline{C}^+\|_\infty < \|\overline{C}\overline{P}\overline{H}\|_\infty \tag{25}$$

Since $\|\overline{C}\overline{P}\overline{H}\|_\infty < 1$, from the relation (25), $\|\overline{C}\overline{P}\overline{H}\overline{C}^+\|_\infty < 1$, and the equation (21) may be written as (Stewart, 1973),

$$\overline{G}_{cl}(s) \cong \overline{C}\overline{P}\overline{B}K(s)+\overline{C}\overline{P}\overline{H}\overline{C}^+\overline{C}\overline{P}\overline{B}K(s) \tag{26}$$

In the equation (26), $\overline{C}\overline{P}\overline{B}K(s)$ and $\overline{C}\overline{P}\overline{H}\overline{C}^+\overline{C}\overline{P}\overline{B}K(s)$ may be considered as the diagonal and off diagonal parts of $\overline{G}_{cl}(s)$, respectively. Since the matrix $\overline{C}\overline{P}\overline{B}K(s)$ is non-singular, then $\overline{G}_{cl}(s)$ has a dominant principal diagonal if

$$\|\overline{C}\overline{P}\overline{H}\overline{C}^+\overline{C}\overline{P}\overline{B}K(s)(\overline{C}\overline{P}\overline{B}K(s))^{-1}\|_\infty = \|\overline{C}\overline{P}\overline{H}\overline{C}^+\|_\infty < 1 \tag{27}$$

(Yeung & Bryant, 1992). Since $\|\overline{C}\overline{P}\overline{H}\|_\infty < 1$, results in $\|\overline{C}\overline{P}\overline{H}\overline{C}^+\|_\infty < 1$, it can be concluded that the closed loop system is diagonal dominant and the proof is complete.

It is simple to show that

$$\begin{aligned} &\overline{C}\overline{P}\overline{H} = S_d(C_d+\Delta C_d)(sI-A_d+\Delta A_d)^{-1}. \\ &.[0 \quad A_H+\Delta A_H \quad B_H+\Delta B_H]+[0 \quad C_H+\Delta C_H \quad 0] \end{aligned}, \tag{28}$$

From the relations (18), and (28) it can be seen by minimising S_d, the sensitivity matrix of the diagonal uncertain system $(A_d+\Delta A_d, B_d+\Delta B_d, C_d+\Delta C_d)$, as given by the relation

$$\|S_d\|_\infty < \frac{a}{\max_{\Delta} \left\| (C_d + \Delta C_d)(sI - A_d + \Delta A_d)^{-1} \left[(A_H + \Delta A_H) \quad (B_H + \Delta B_H) \right] + \left[(C_H + \Delta C_H) \quad 0 \right] \right\|_\infty} \quad (29)$$

where $0 \le a \le 1$, is a designing factor, the closed-loop diagonal dominance for the system (1) is achieved. Since

$$S_d = diag\{S_i\} \quad (30)$$

where S_i is the sensitivity function of the i-th isolated uncertain subsystem, the closed-loop diagonal dominance condition (29) can be written as given by the relation

$$\|S_i\|_\infty < \frac{a}{\max_{\substack{\Delta \\ i=1,\ldots,N}} \left\| (C_d + \Delta C_d)(sI - A_d + \Delta A_d)^{-1} \left[(A_H + \Delta A_H) \quad (B_H + \Delta B_H) \right] + \left[(C_H + \Delta C_H) \quad 0 \right] \right\|_\infty}, \quad (31)$$

4. DECENTRALISED QUANTITATIVE FEEDBACK DESIGN

Quantitative feedback theory is a unified theory that emphasises the use of feedback for achieving the desired system performance tolerance despite plant uncertainty and plant disturbance. QFT quantitatively formulates these two factors in the form of (a) sets $\Im_R = \{T_R\}$ of acceptable command or tracking input-output and $\Im_D = \{T_D\}$ acceptable disturbance input-output relations, and (b) a set $\Pi = \{P\}$ of possible plants. The objective is to guarantee that the control ratio $T_R = \frac{Y}{R}$ is a member of $\Im_R = \{T_R\}$ and $T_D = \frac{Y}{D}$ is a member of $\Im_D = \{T_D\}$, for all P in Π (Horowitz, 1991).

The design approach for the output disturbance rejection problem, is based upon the performance specification that the disturbance has no effect on the steady state output; also, the resulting transient must die out as fast as possible with a limit a_p on the maximum magnitude of the output. There are some methods to minimise, the effect of a disturbance input on the output of a control system, such that

$$\|S\|_\infty = \left\| \frac{Y(s)}{D_2(s)} \right\|_\infty < \|T_{D_2}(s)\|_\infty \quad (32)$$

where $T_{D_2}(s)$ is the output disturbance rejection model, and $D_2(s)$ is the output disturbance. In section 3, it is shown by minimising the sensitivity function of each isolated subsystem as given by the relation (31), the closed-loop system is diagonal dominant. Considering the relations (31), if for each isolated subsystem the output disturbance rejection model is selected as given by the relations

$$\|T_{D_i}\|_\infty < \frac{a}{\max_{\substack{\Delta \\ i=1,\ldots,N}} \left\| (C_d + \Delta C_d)(sI - A_d - \Delta A_d)^{-1} \left[(A_H + \Delta A_H) \quad (B_H + \Delta B_H) \right] + \left[(C_H + \Delta C_H) \quad 0 \right] \right\|_\infty},$$

(33)

the closed-loop system is diagonal dominant. Then an appropriate QFT controller with this output disturbance rejection model for each isolated $SISO$ subsystem will be designed.

5. ILLUSTRATIVE EXAMPLE

The 2×2 benchmark problem in $MIMO - QFT$ design (Yaniv, 1993), $P = \frac{1}{s}\begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}$, where $k_{11}, k_{22} \in [2 \quad 4]$, and $k_{12}, k_{21} \in [1 \quad 1.8]$, is used as the example. A tracking model for the upper bound based upon the given desired performance specifications, is tentatively identified by $T_{R_u} = \frac{0.6584(s+30)}{(s^2 + 4s + 19.753)}$. A tracking model for the lower bound, based upon the desired performance specifications, is tentatively identified by $T_{R_l} = \frac{60}{(s+2)(s+3)(s+10)}$. The specifications for all off diagonal terms are ideally zero. However, it is impossible because of parameter uncertainty. The state space realisation of the system may have the following matrices

$$A + \Delta A = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, B + \Delta B = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}, C + \Delta C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The system is in output decentralised form. The system is consisted of two isolated subsystems

$$A_{11} = 0, B_{11} = k_{11}, C_{11} = 1, \quad k_{11} \in [2 \quad 4],$$

$$A_{22} = 0, B_{22} = k_{22}, C_{22} = 1, \quad k_{22} \in [2 \quad 4]$$

and the interaction matrices $A_H + \Delta A_H = 0_{2\times 2}$, $B_H + \Delta B_H = \begin{bmatrix} 0 & k_{12} \\ k_{21} & 0 \end{bmatrix}$, $k_{12}, k_{21} \in [1 \quad 1.8]$, and $C_H + \Delta C_H = 0_{2\times 2}$.

Since $\frac{1}{\max_{\Delta} \left\| (C_d)(sI - A_d)^{-1}(B_H + \Delta B_H) \right\|_\infty} = \frac{w}{1.8}$, the output disturbance rejection models for both of the subsystems is selected as $T_{D_{2i}} = \frac{s}{5}$, $i = 1,2$. Therefore the closed-loop diagonal dominance condition (33) are satisfied. Designing local QFT controllers for two isolated subsystems, the decentralised controller and pre-filter are given by $K(s) = \begin{bmatrix} \frac{18.13}{s+9.8} & 0 \\ 0 & \frac{18.13}{s+9.8} \end{bmatrix}$, and

$$F(s)=\begin{bmatrix}\frac{3.18}{s+3.18} & 0\\ 0 & \frac{3.18}{s+3.18}\end{bmatrix}$$ respectively. Figure 1 shows the frequency responses of $|t_{ij}|$ the diagonal and off diagonal elements of the closed-loop system in some operating points. From this figure it can be observed that the desirable tracking and closed-loop diagonal dominance over the uncertainty space are achieved.

6. CONCLUSION

In this paper a new method for robust decentralised control of large-scale systems using quantitative feedback theory (QFT) is suggested. For a given large-scale system an equivalent descriptor system is defined. Using this representation, closed-loop diagonal dominance sufficient conditions over the uncertainty are derived. It is shown by appropriately choosing the output disturbance rejection model in designing the controller for each isolated subsystem, these conditions are achieved. Then a single-loop quantitative feedback design scheme is applied to solve the resulting series of individual loops to guarantee the satisfaction of predefined $MIMO$ quantitative specifications. An example is carried out to show the effectiveness of the proposed methodology. The results clearly show the achievement of desirable performance by proposed robust decentralised design.

REFERENCES

Jamshidi, M., (1997). *Large - scale systems: Modelling, Control, and fuzzy Logic*, Prentice-Hall.

Horowitz, I. M. (1991). Survey of quantitative feedback theory. *International Journal of Control*, **53**, 255-291.

Nwokah, O. D., and C. H. Yau. (1993). Quantitative feedback design of decentralised control systems. *Journal of Dynamic Systems, Measurement, and Control*, **115**, 452-464.

Skogestad, S. & Postlethwaite, I. (1996). *Multivaribale Feedback Control, Analysis and Desig.* John Wiley & Sons.

Stewart, G. W (1973). *Introduction to matrix computations*. Academic Press.

Yaniv, O. (1993). Robust feedback synthesis for margins at the plant input. *Automatica*, **31**, (2), 333-336.

Yeung, L. F. & Bryant, G. F. (1992). New dominance concepts for multivariable control system design. *International Journal of Control*, **55** (4), 969-88.

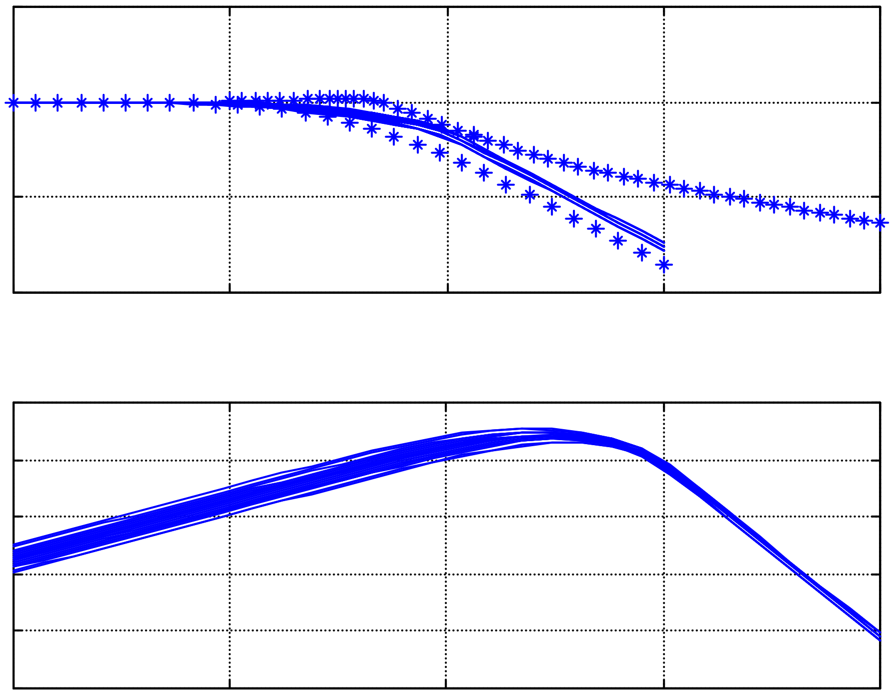

Fig. 1. Frequency responses of $|t_{ij}|, i, j = 1,2$ and the frequency responses of upper and lower tracking models ('*').