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Robust control for a tracking electromechanical system

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ABSTRACT

A strategy for the design of robust control of tracking electromechanical systems based on H_∞ synthesis is proposed. Proposed methods are based on the operations on frequency characteristics of control systems designed and developed using the MATLAB robust control toolbox. Determination of the singular values for a transfer matrix of the control system reduces the disturbances and guarantees its stability margin. For selecting the weighted transfer functions, the basic recommendations are formulated. The efficiency of the proposed approach is verified by robust control of an elastically coupled two-mass system whose parameter values are adjusted by matching them with the parameters of one of the supplied robots. The simulation results confirm that the proposed strategy of design of robust control of two-mass elastic coupling system using the H_∞ synthesis is very efficient and significantly reduces the perturbation of parameters of the controlled plant.

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1. INTRODUCTION

Many modern approaches for the design of control systems pay much attention to robust features, in particular, robust stability and robust performance of control systems in conditions of existing uncertainties. These approaches primarily consider the fact that the real physical systems and the environmental conditions in which they operate cannot be modeled precisely, the values of their parameters can be changed unpredictably and can be perturbed from the external environment. As it is known, a system can be considered robust if it has sufficient reliability, roughness, and flexibility. The requirements for the robust systems are the following: i) possessing a low sensitivity, ii) remaining stable, and iii) keeping its quality features insufficiently large intervals of their parameters.

The robustness of control systems is related to the sensitivity of the systems to conditions not considered during analysis and synthesis. For example, they can be sudden disturbances, sensor noises, and extra parameters affecting their dynamics. In such conditions, the system must be capable to reduce the influence of these affections during its performance and achieve the stated objectives. External disturbances and parametric perturbations caused by internal uncertainties are going to be easily eliminated using robust control. The main idea of robust control is that a feedback controller should ensure that the requirements for a closed-loop system are satisfied for a set of objects with fixed deviations from the nominal regime.

H_∞ control theory is widely used for control design problems [1]–[5]. The usefulness of the H_∞ norm as an optimality criterion for the synthesis of multidimensional systems is based on its relationship with the powerfulness of the systems. The H_∞ norm of the transfer function is the energy quantity of the system's output when a signal with unit energy is directed to its input. When we represent the output as an error and input as the perturbation, we minimize the H_∞ norm of the transfer function and minimize the energy of the error for the most difficult case of perturbation of the system's input. In the scalar case, the norm of such a function is bounded and equal to the maximal value of the frequency response. Due to these properties, H_∞ control has various applications in various fields such as electric motors, manipulators, spacecraft, control of aircraft and other vehicles.

Research [1], [2], [5] present a design and development of a robust control as a part of a complete automatic landing system proposed by ONERA and AIRBUS. Reliable synthesis methods, for example, the standard and structured H_∞ construction) provide an effective basis for solving these problems. In the study [3], a robust automatic landing controller based on proposed stable inversion (SI). The SI algorithm is applied to increase the accuracy of output signal tracking in the system's architecture, and the H_∞ synthesis is used to increase the robust resistance to uncertainties caused by wind disturbances. In the study [4], the vertical speed control of the aircraft before landing is based on the structured H_∞ control, and minimizes the influence of wind shear, ground effects, and changes in airspeed.

In the study [6], vibrational control of composite panels that contain indeterminate parameters in a hypersonic flow is analyzed on non-probabilistic reliability. Its simulation results show the high efficiency of the applied control method under the influenced reliability. The performance indicator H_∞, and the approximation speed suppresses all panel vibrations in the entire range of uncertain parameters.

In the study [7], a morphing aircraft multi-circuit control system is developed. It provides stability of the transition process in the form of a wing. The designed control uses a set of gain factors in the internal loop and ensures stability by standard methods, while the self-tuning controller H_∞ of the external loop is designed to provide a certain stability level and performance indices for time-varying dynamics. Work [8] describes an analytical method that generalizes the parameters of robust lateral control of an aircraft using auxiliary damping in automatic devices (ADAD). The design of the proposed controller is based on the application of the H_∞ and μ methods.

Works [9]–[11] are dedicated to the design of robust control of aircraft motion using the H_∞ technique. Lyapunov functions are used in [12]–[14] to increase the robust stability of control systems to uncertainties caused by internal and external perturbations. The Lyapunov function is constructed in the form of a vector function, the anti-gradient of which is given by the components of the velocity vector of the system. In [15]–[18], the problems of constructing robust aircraft control under the conditions of uncontrolled disturbances are considered, where the so-called weight functions are introduced.

In the study [19], the robust control of an electromechanical drive system's (EMF) thrust vector in a spaceship is designed. During the spaceship's motion, the EMF system overcomes the load perturbation and changes the operating point to improve the strength characteristics of control. Considering this problem and taking into account the high inertia and low load stiffness of the EMF system, the robust control of the EMF system is developed using the H_∞ control based on operating on degrees of freedom (DOF) of the system. Works [20], [21] describe the robust control technique for the EMF system using the H_∞ control that allows to neglect perturbation of parameters and the load very efficiently.

In this paper, a methodology has been developed for designing a robust control system for H_∞ synthesis tools. The considered methods use the robust control toolbox, a part of the MATLAB software platform. These methods are based on operations with the frequency characteristics of systems. There are singular values for the transfer matrix of the control system that determine the attenuation of disturbances and provide a margin of stability of the control system. One of the most important steps of robust structural design is the determination of weight transfer functions using the heuristic approaches. Recommendations on choosing the weight matrices are proposed. In particular, we apply robust control for an elastically coupled two-mass system with parameter values corresponding to the parameters of one of the robots. The considered system is a significant simplification in comparison to the existing control systems. The proposed approach makes it possible to neglect the perturbation of parameters and the perturbation of the load in control systems very efficiently. Further, section 2 presents a problem statement and mathematical model of the control system, properties of the robust structural synthesis procedure H_∞. Section 3 contains the results of the H_∞ synthesis method for an elastically coupled two-mass system, recommendations for the choice of weight matrices. In section 4, we interpret obtained results and conclude.

2. METHOD OF ANALYSIS

2.1. Mathematical model of the control system

A rotating mechanical system consists of two inertial masses J_1, J_2 connected by an elastic coupling [22], [23] as shown in Figure 1. This is a significant simplification of the actual elastic design of the control system. The moment M_y transmitted by the clutch is the resistance moment to the first and the driving time for the second inertial mass. It is proportional to the difference between angular displacements of both masses with a coefficient of proportionality C. The controller in this system is the drive moment of the first mass (typically, a torque of a drive motor) M_d. The output is the speed of its rotation ω_d. The speed sensor is usually installed on the shaft of the drive motor. For more simplicity, the moment of resistance is assumed to be zero. System equations shown in (1) to (3).

$$\frac{d\omega_d}{dt} = \left(M_d - M_y\right)/J_1 \quad (1)$$

$$\frac{dM_y}{dt} = C(\omega_d - \omega_m) \quad (2)$$

$$\frac{d\omega_m}{dt} = M_y/J_2 \quad (3)$$

If $x = (\omega_d, M_y, \omega_m)^T$, $u = M_d$ then the system under consideration can be written with matrices:

$$A = \begin{bmatrix} 0 & -1/J_1 & 0 \\ C & 0 & -C \\ 0 & 1/J_2 & 0 \end{bmatrix}, B = \begin{bmatrix} 1/J_1 \\ 0 \\ 0 \end{bmatrix}, C = [1 \quad 0 \quad 0], D = 0$$

In this case, the system equations have the next form:

$$\frac{dx}{dt} = Ax + B_1 w + B_2 u$$

$$y_1 = C_1 x + D_{11} w + D_{12} u$$

$$y_2 = C_2 x + D_{21} w + D_{22} u$$

The system in this form is denoted as in (4),

$$sys = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix} \quad (4)$$

where input and output variables are split in the system as the following: inputs are split to external influences w and controlled signals u, and outputs are split to controlled y_1 and measured y_2.

Let us involve the load moment M_c to the system (1) to (3) and assume the purpose of control is to reduce the speed deviations of the mechanism ω_m under the action of M_c. Let us write (3) will be written as:

$$\frac{d\omega_m}{dt} = M_y/J_2 - M_c/J_2$$

and denote $w = M_c$, $y_1 = \omega_m$, $y_2 = \omega_d$, $B_1 = \begin{bmatrix} 0 \\ 0 \\ -1/J_2 \end{bmatrix}$, $B_2 = \begin{bmatrix} 1/J_1 \\ 0 \\ 0 \end{bmatrix}$,

$$C_1 = [0 \quad 0 \quad 1], C_2 = [1 \quad 0 \quad 0]$$

Thereby we obtain system (4) for all $D_{ij} = 0$.
The mathematical model (4) can be used as the basis for robust structural optimization procedures.

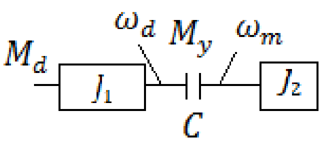

Figure 1. The mechanical system with elastic coupling

2.2. H_∞ synthesis

One of the last famous approaches to the structural design of robust control is H_∞ design. Its basic fundamentals are known, for example, from [15]–[18]. The standard architecture of a system with applied H_∞ design is shown in Figure 2.

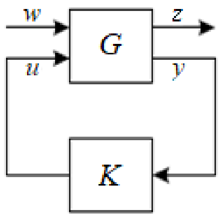

Figure 2. Standard H_∞ configuration

This system consists of a controllled plant G and a control K, and can be characterized by an output parameter vector z, be vector of external inputs w, by a vector of control outputs y, and entered inputs of control [18]. The statement of the optimization problem of robust structural control can be described as in (5) [18]:

$$K_{opt} = arginf_{K_{opt} \in K_{add}} J(G, K) \quad (5)$$

where

$$J(G, K) = \left\| \begin{bmatrix} (I + GK)^{-1} \\ K(I + GK)^{-1} \\ GK(I + GK)^{-1} \end{bmatrix} \right\|_\infty \quad (6)$$

The modern approach for solving the optimization problem (5) forms the desired frequency characteristics with additional weight transfer functions obtained from the control plant as shown in Figure 3.

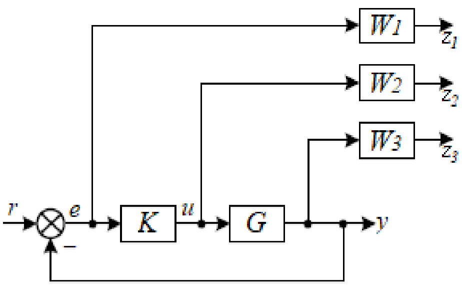

Figure 3. Block diagram of designed control system with additional weight transfer functions

After new representation of the control system, the problem can be solved using the mixed sensitivity method. In this case, instead of the expression from formula (6), the H_∞ norm for extended system [17], [18]:

$$J(G, K) = \left\| \begin{bmatrix} W_1(I + GK)^{-1} \\ W_2K(I + GK)^{-1} \\ W_3GK(I + GK)^{-1} \end{bmatrix} \right\|_\infty = \left\| \begin{bmatrix} W_1S \\ W_2R \\ W_3T \end{bmatrix} \right\|_\infty \quad (7)$$

where W_1, W_2, and W_3 are the weight transfer functions and S, R, T are the sensitivity functions for a given signal and control, and simultaneously, acomplementary sensitivity functions.

The procedure of H_∞ design by the mixed sensitivity method is based on solving two Riccati equations. It tests certain conditions and minimizes the H_∞ norm of mixed sensitivity functions of the system (7). Automated solutions to this problem are included to the corresponding package of MATLAB software.

For designing a robust control system, let's consider the methods used in the MATLAB robust control toolbox. These methods are based on the operations with the frequency characteristics of the systems. The role of maximum frequency response for assessing the robustness of the system is the following: the smaller the maximum, the greater the change of the parameters of the controlled plant can be assumed for maintaining the stability of the system [24]–[26]. One of the indicators that indirectly characterize the value of the maximum frequency response is so-called H_2-norm which is defined for the matrix of transfer functions $F(S)$ as (8):

$$\|F\|_2 = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty} Sp|F^*(j\omega)F(j\omega)|d\omega} \tag{8}$$

where the symbol * means a transposed matrix with complex conjugate elements. A more direct approach for estimating the robustness of the system is based on finding the singular values of the transfer matrix of the system and minimizing the$\|F\|_\infty$ norm based on those singular values.

The singular values depend on the frequency for transfer matrices $F(j\omega)$, including the largest singular value σ_1. The upper bound of this value during changing ω within $0 < \omega \leq \infty$ is called H_∞ the norm of the transfer matrix:

$$\sigma_{F1}(\omega) = max_i\sqrt{eig_i(F^*(j\omega)F(j\omega))}, \tag{9}$$

$$\|F\|_\infty = sup_{0<\omega<\infty}\sigma_{F1}(\omega).$$

Since the singular value $S(j\omega)$ attenuates the perturbations, the required attenuation can be represented by (10):

$$\sigma_1\big(S(j\omega)\big) \leq |W_1^{-1}(j\omega)|. \tag{10}$$

Based on obtained above, the interval for the remaining sensitivity functions is represented by (11):

$$\sigma_1\big(R(j\omega)\big) \leq |W_2^{-1}(j\omega)|.$$

$$\sigma_1(T(j\omega) \leq |W_3^{-1}(j\omega)|. \tag{11}$$

Thus, the following condition has to be satisfied

$$\sigma_1\big(W_1^{-1}(j\omega)\big) + \sigma_1\big(W_3^{-1}(j\omega)\big) > 1 \tag{12}$$

where W_1, W_2, W_3 are the weight transfer functions [25].

All the requirements for the system for reducing the disturbances and keeping margin stability can be reduced to the following single requirement:

$$\|T_{y1u1}\|_\infty \leq 1 \tag{13}$$

where T_{y1u1}, accordance to (7), is equal to:

$$T_{y1u1} = \begin{bmatrix} W_1S \\ W_2R \\ W_3T \end{bmatrix}.$$

3. RESULTS

The proposed approach of robust synthesis is applicable for the previous two-mass system with elastic coupling in Figure 1, which is a significant simplification of the actual elastic control design. An elastically coupled two-mass system [22], [23] as shown in Figure 1 with parameter values corresponding to the parameters of one of the robots is considered and $C = 90\ Nm$, $J_1 = 0.008\ kgm^2$, $J_2 = 0.008\ kgm^2$. Let us assume that the speed or position sensors are located not on the engine, but on the mechanism. The task of synthesis is to design a robust system that has a first matching time t_c of equal or less than $0.5\ s$ for a step-by-step task, with equal or less than 20% re-adjustment for a speed-controlled system and, respectively, 1 second and 25% for the robot's position control system. The characteristics must be maintained as the moment of inertia of the second mass increases three times.

One of the most important steps of the robust structural design is the determination of appropriate weight transfer functions. The approach is based on heuristic approaches. First of all, it considers the position of control system and needs to form the weight frequency characteristics. The characteristic W_2 is assumed to be a small constant. The characteristic W_3 is taken as:

$$W_3 = K_{f1}s^2/100$$

where K_{f1} - is a configurable parameter, and the characteristic W_1 is in the form:

$$W_1 = \frac{K_f b(as^2+2z_1\omega_0\sqrt{a}s+\omega_0^2)}{bs^2+2z_2\omega_0\sqrt{b}s+\omega_0^2}$$

Such expression for the frequency response can be considered as more general. Figure 4 shows these characteristics for the specified parameters.

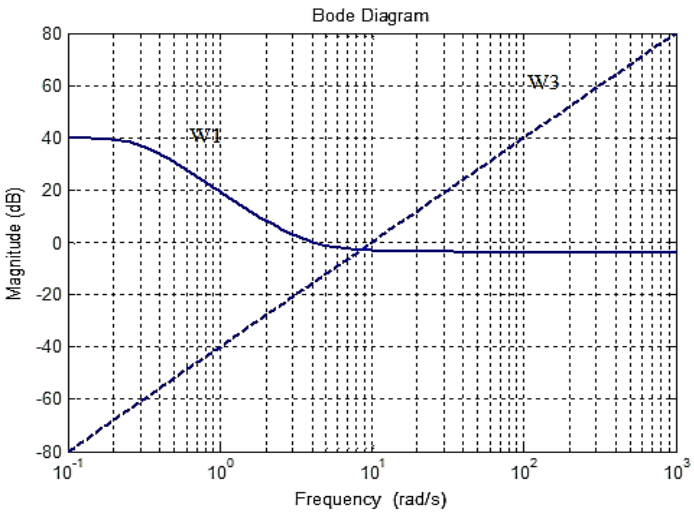

Figure 4. Weight frequency functions for a two-mass robot model

The characteristics of a system with a full-order controller while minimizing the H_∞ norm are shown in Figure 5. First, the reactions of closed-loop systems (nominal and perturbed) to the step signal are calculated. Then the Bode diagram is built from the control to the first output for the extended closed controlled object. This characteristic is shown on a logarithmics in the upper-left part of Figure 5. In the upper right sub window, it shows the sensitivity function with the reciprocal of the frequency characteristic $1/W_1$. The frequency response of closed-loop system with the inversed $1/W_3$ itself is depicted in the lower left window.

The bottom-right window shows the transients for the nominal and perturbed systems. It is seen that the design requirements are satisfied. The module of the transfer function T_{y1u1} in a significant frequency range is equal to 1. This characteristic is called 'all-pass'.

Now consider the speed control system. The resulting curves are shown in Figure 6. It is seen that the system requirements are satisfied. As a result of H_∞ control, the characteristics are maintained. While the moment of inertia of the second mass is increasing three times. Thus, robust control using H_∞ synthesis tools effectively work on the perturbation of parameters and the perturbation of the load in control systems.

The synthesized control minimizes the norm $\|z_1, z_2, z_3\|_\infty$. At the same time, it has to have a small error e within the range of low frequencies for neglecting the disturbances and for providing the stability. For suppressing the high-frequency interference, it needs to have a small y-value within the range of high frequencies. For achieving that, the error e within the range of low frequencies should be "weighed" greater than for the high frequencies, i.e. the magnitude of the frequency response W_1 should decrease along with increased frequency. In contrast to that, the magnitude of the frequency response W_3 should increase with increased frequency. Frequency response W_2 can be useful for limiting the control power, as well as a parameter that can be configured for speed control. In addition, in some cases, the inclusion of W_2 is necessary for given problems to make them solvable. In this case, the simplest choice $W_2 = \varepsilon I$ can be sufficient, where ε is a small value and I is a unit matrix of the corresponding size. Therefore, it is clear that the determination of weight matrices is a quite challenging task that requires sufficient experience for the developers, as well as the trial-and-error method. The robust control toolbox does not provide a method for selecting these frequency characteristics but only tells whether solving a problem with the selected characteristics makes it possible to complete the task.

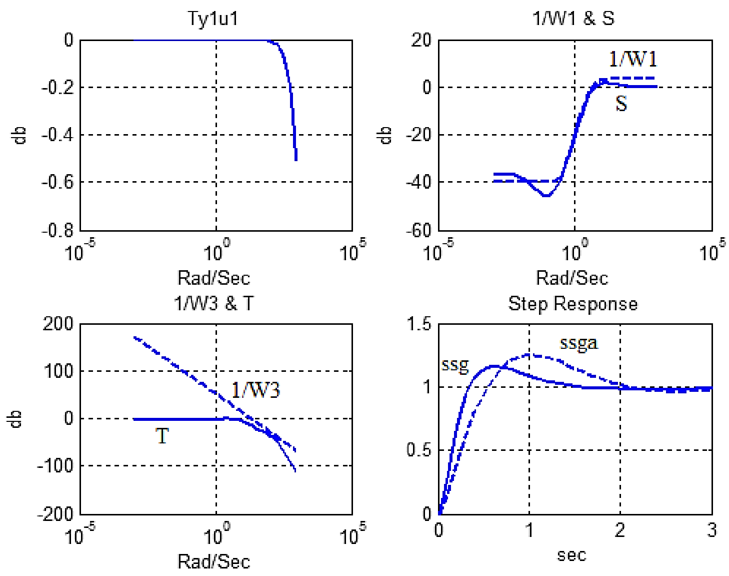

Figure 5. Characteristics of a system with a full-order controller with minimizing the H_∞ norm (position controller)

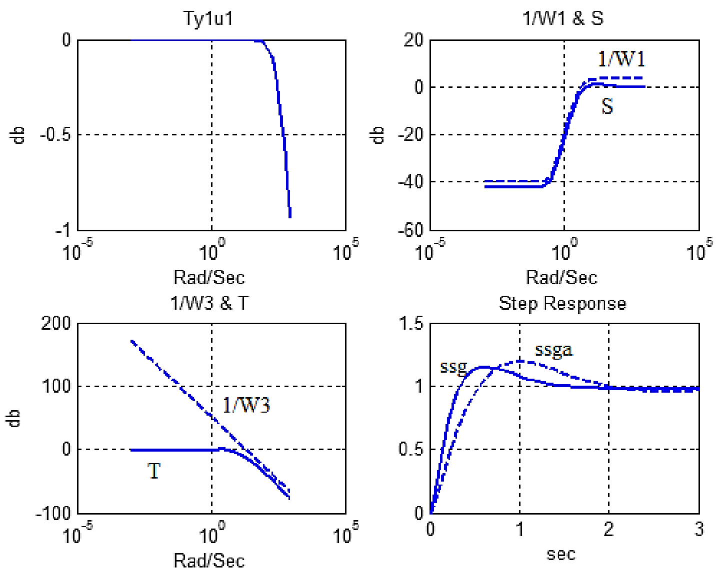

Figure 6. Characteristics of a system with a full-order controller with minimizing the H_∞ norm (speed controller)

4. CONCLUSION

An approach for the design of a robust control system is proposed using H_∞ synthesis tools on the example of an elastically coupled two-mass system. The analyzed two-mass system with elastic coupling with parameter values corresponding to the parameters of one of the robots is a significant simplification of the actual elastic design of the control system. The methods of design of robust control are based on operations on frequency characteristics of the systems. There are singular values for the transfer matrix of the control system that determine the attenuation of disturbances and provide the margin of stability of the control system. In the process of design of the control system, the expressions for weight transfer functions are obtained with heuristic approaches. By implemented modeling and synthesis of the control system, the characteristics of the system with a full-order regulator and the nominal control plant, with a reduced-order regulator and the nominal control plant, and with a reduced-order regulator and a perturbed control plant are obtained. As a result of the synthesis, all the requirements for the system are satisfied. Obtained results confirm the proposed approach that allows neglecting the perturbation of parameters and load in the given control systems. There are many prospects for further research dedicated to the design of robust control for elastically coupled two-mass systems with varied stiffness coefficients, and electromechanical systems with a more complex mathematical model using the proposed approach and based on the H_∞ synthesis.

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