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Covariance matrix adaptation evolution strategy based design of fixed structure robust H_∞ loop shaping controller

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ABSTRACT

This paper proposes the application of Covariance Matrix Adaptation Evolution Strategy (CMA-ES) in fixed structure H_∞ loop shaping controller design. Integral Time Absolute Error (ITAE) performance requirement is incorporated as a constraint with an objective of maximization of stability margin in the fixed structure H_∞ loop shaping controller design problem. Pneumatic servo system, separating tower process and F18 fighter aircraft system are considered as test systems. The CMA-ES designed fixed structure H_∞ loop-shaping controller is compared with the traditional H_∞ loop shaping controller, non-smooth optimization and Heuristic Kalman Algorithm (HKA) based fixed structure H_∞ loop shaping controllers in terms of stability margin. 20% perturbation in the nominal plant is used to validate the robustness of the CMA-ES designed H_∞ loop shaping controller. The effect of Finite Word Length (FWL) is considered to show the implementation difficulties of controller in digital processors. Simulation results demonstrated that CMA-ES based fixed structure H_∞ loop shaping controller is suitable for real time implementation with good robust stability and performance.

1. Introduction

Modern industries have been demanded a robust controller for the need of safe and reliable closed loop system [1]. A robust controller delivers a stable closed loop system even under uncertain environment while satisfying the performance specifications (i.e., Risetime, Settling Time, ITAE, etc.). In 1960s, Linear Quadratic Gaussian (LQG) controller was successfully used in the industries, but it was not able to give guaranteed robustness [2]. Hereafter, in 1980s, H_∞ controller synthesis was very popular for designing robust controller for both Single Input Single Output (SISO) and Multi Input Multi Output (MIMO) systems [3]. But, this iterative method loses some important system dynamics due to pole zero cancellation [4]. In order to overcome the pole zero cancellation, H_∞ loop shaping method was proposed for designing robust controller [5–9]. In this method, two pre and post compensators (i.e., weights) are used to represent performance specifications and measurement noise respectively. The controller is designed based on the stability and performance information in the weights. However, this method gives higher order controller which makes difficult in controller implementation in digital processors. Also, this method does not support re-tuning in the designed controller in case of plant model changes [10]. To overcome these drawbacks, fixed structure controller has been preferred for industrial applications [11].

Many research works have been proposed for designing fixed structure H_∞ loop shaping controllers. Linear Matrix Inequality (LMI) approach was extensively applied in fixed structure H_∞ loop shaping controllers [12–14]. However, these LMI approaches require clear understanding of robust control theory and Semi Definite Programming (SDP). Due to this, it may not be easy for most engineers to employ these LMI approaches [15]. Also, LMI solver gives only local optimal solution for non-convex, disconnected parameter space fixed structure H_∞ loop shaping controller design problem [16]. To overcome the limitations of LMI approaches, evolutionary computing (EC) techniques are very popular in solving the non-convex, non-smooth, multi-modal and badly scaled problems [17]. Many, EC techniques such as Genetic Algorithm (GA) [18,19], Particle Swarm Optimization (PSO) [20,21] and Heuristic Kalman Algorithm (HKA) [16], Hybrid PSO [22] are used for designing the fixed structure H_∞ loop shaping controller.

The methods discussed above focus on the maximization of stability margin as an objective and the performance specifications are represented in the pre-tuned weights. However, tuning of the weights is not an easy task [23]. It is tuned based on performance specifications as well stability conditions. But, the performance and stability are conflicting with each other. Due to this, a time consuming trial and error method is required for tuning the weights.

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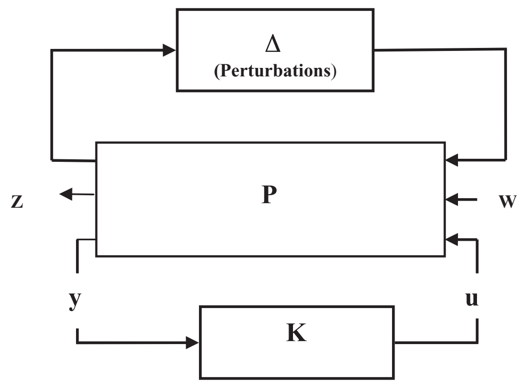

Fig. 1. Standard robust control system. *P* is the augmented plant to be controlled; *K* is the stabilizing controller; *w* is input vector that contains reference signals and disturbances; *z* is the output vector which contains error signal and output; *y* is the measurement vector; *u* is the control action vector and Δ represents the perturbation on the system.

This paper proposes a new problem formulation by incorporating a performance requirement as a constraint in the fixed structure H_∞ loop shaping controller design problem. From the proposed formulation, the weights can be tuned only based on stability conditions and the desired performance can be obtained using the constraint. Also, in this disconnected surface problem, the performance requirement constraint helps to find the better stability margin than the existing work of [16,18].

Co-variance Matrix Adaptation-Evolutionary Strategy (CMA-ES) [24–27] is used to validate the proposed problem. Recently, in EC literature, it is reported that CMA-ES has better efficiency in solving different kind of engineering problems due to its self learning behavior as compared to other ECs [28–34]. The CMA-ES based fixed structure H_∞ loop shaping controller is compared with the traditional H_∞ loop shaping controller, non-smooth optimization and HKA based fixed structure H_∞ loop shaping controllers. The statistical performance of the algorithms such as CMA-ES, non-smooth optimization algorithm and HKA are compared in terms of giving consistent solutions. The implementation difficulties of higher order controllers are also discussed.

The rest of the paper is organized as follows. Section 2 discusses H_∞ loop shaping robust controller design. Section 3 describes the Co-variance Matrix Evolutionary Strategy. Section 4 describes the steps for designing CMA-ES based fixed structure H_∞ loop shaping Controller. Section 5 discusses the simulation results. Finally, conclusions are given in Section 6.

2. Robust control

Robust control is concerned to design a stabilizing controller that achieves desired feedback performance in terms of stability and accuracy against plant uncertainty, parameter variations and external disturbances.

A standard robust controller synthesis and analysis are done in the unified Linear Fractional Transformation (LFT) framework as shown in Fig. 1.

Large number of robust control design methods have been developed over the past decades including Linear Quadratic Gaussian controller [35], H_∞ optimization method [3], H_2/H_∞ Mixed Sensitivity [36], μ-Synthesis [37], etc., Among these robust controller design methods, H_∞ loop shaping method [5] has the advantages as follows: (i) no restriction on the number of right-half plane poles (ii) no pole-zero cancellations occur between the nominal model and controller (iii) no problem dependent weight selection. Also, this method has the systematic procedure to handle the stability margin constraints for MIMO systems. Moreover, H_∞ loop shaping controller has been successfully implemented in many industries [7–9]. This interesting and efficient method is illustrated in the following section.

2.1. H_∞ loop shaping control

H_∞ loop shaping method was developed by McFarlane and Glover. Loop shaping concept is used to shape singular values of the nominal plant so as to give the desired open loop properties at low and high frequencies. The desired responsiveness and noise suppression properties are described by weighing the plant transfer function in the frequency domain [23]. The design of H_∞ loop shaping controller has the following steps.

1. Shaping the singular values of the nominal system using selected weights.
2. Designing the stabilizing controller which satisfies robust stabilization condition.

2.1.1. H_∞ loop shaping design procedure

H_∞ loop shaping method inherits the properties of conventional loop shaping and incorporates it in H_∞ synthesis [23].

(a) Weight selection

Using a pre compensator W_1, and post compensator W_2, the nominal system G is modified to give a desired loop shaped system, $G_s = W_2GW_1$. Let the shaped plant is represented by the state space of the form as shown in Eq. (1),

$$G_s(s) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad (1)$$

Maximum achievable stability margin ($\varepsilon_{\max}$) is determined by using Eq. (2) suggested by Glover and McFarlane [5].

$$\varepsilon_{\max} = (1 + \lambda_{\max}(ZX))^{-1/2} \quad (2)$$

where, $\lambda_{\max}$ is the maximum Eigen value of ZX. Z and X are the unique positive definite solutions of algebraic Ricatti equation [5,23]. The weights are adjusted based on $\varepsilon_{\max}$ as in Eq. (2). If margin is too small, $\varepsilon_{\max} \ll 0.25$, i.e. the specified loop shape is incompatible, then weights are readjusted until $\varepsilon_{\max} > 0.25$ is met [23].

After the desired loop shape is achieved, the shaped plant is represented by left (or right) co-prime factors of the plant with no poles in the closed right-half complex plane, such that.

(b) The shaped plant (G_s) is represented in Eq. (3)

Let matrices $(\tilde{M}_s, \tilde{N}_s) \in H_\infty^+$ where, H_∞^+ denotes there is no pole in closed right half complex plane.

$$G_s = W_2GW_1 = \tilde{M}_s^{-1}\tilde{N}_s \quad (3)$$

M_s is square and $\det(M_s) \neq 0$

$$\tilde{M}_s\tilde{M}_s^* + \tilde{N}_s\tilde{N}_s^* = I \quad (4)$$

there exist $(\tilde{V}_s, U_s) \tilde{\in} H_\infty^+$ such that

$$\tilde{M}_s\tilde{V}_s + \tilde{N}_s\tilde{U}_s = I \quad (5)$$

Fig. 2 shows the shaped plant in terms of Normalized Co-prime Factorization and described in Eq. (6).

$$G_s = (N_s + \Delta_{N_s})(M_s + \Delta_{M_s})^{-1} \quad (6)$$

where, Δ_{N_s} and Δ_{M_s} are stable and unknown, representing the uncertainty and satisfying $\left\| \Delta_{N_s}, \Delta_{M_s} \right\|_\infty < \varepsilon$. By using small gain