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Improved results on stability of linear systems with time-varying delays via Wirtinger-based integral inequality

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Abstract

In this paper, the problem of stability analysis for linear systems with time-varying delays is considered. By the consideration of new augmented Lyapunov functionals, improved delay-dependent stability criteria for asymptotic stability of the system are proposed for two cases of conditions on time-varying delays with the framework of linear matrix inequalities (LMIs), which can be solved easily by various efficient convex optimization algorithms. The enhancement of the feasible region of the proposed criteria is shown via three numerical examples by the comparison of maximum delay bounds.

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1. Introduction

Stability analysis for dynamic systems is one of the basic research in control society and a pre-requisite job before designing controllers. Specially, stability analysis of time-delay systems has been one of the hot issue since physical and industrial systems naturally have time-delays such as transport, communication, or measurement delays [1]. In other words, since the occurrence of time-delays causes undesirable dynamic behaviors such as performance degradation, instability or oscillation, it is strongly needed to investigate the stability problem for time-delay systems before implementing various control strategies. In line with this view, in order to check the conservatism of stability criteria, an important index is to obtain maximum delay bounds for guaranteeing asymptotic stability of time-delay systems as large as possible. Therefore, in the field of stability analysis, how to construct a Lyapunov–Krasovskii functional, augmented vectors and the derivation of a stability condition from the time-derivative of such a functional with some appropriate techniques play key roles in enhancing the feasible regions of stability criteria. For more details, see [2–10] and references therein.

Moreover, the field of stability analysis of time-delay systems can be classified into two categories, i.e., delay-dependent stability criteria and delay-independent ones. Also, it is well known that delay-dependent stability criteria, which make the use of the information on the size of time-delays, are less conservative than delay-independent ones. Thus, more attention has been paid to the derivation of delay-dependent stability criteria for time-delay systems. Naturally, in order to improve results for this problem, various methods were introduced. Simply put, the integral inequality lemmas [11–13], Jensen's inequality [14], the reciprocally convex approach [15], the augmented model [16,17], new cross-term bounding technique [18], triple integral terms [16,19–21], parameterized neutral model transformation method [22] and free weighting matrices technique [23,24] had contributed to enhance the feasible regions of stability criteria for systems with time-delays. Specifically, since estimating a lower bound of the quadratic integral term such as $\int_{t-h}^{t} x^T(s)Qx(s)\,ds (Q>0)$ is one of the major topics studied in research field on time-delay systems, Jensen's inequality has been used in plenty as a key lemma in obtaining delay-dependent stability criteria during the last decade. Very recently, the Wirtinger-based integral inequality which reduced the conservatism of Jensen's inequality was introduced in [25] and its advantage was shown via the comparison of maximum delay bounds for various systems such as systems with constant and known delay, systems with a time-varying delay, and sampled-data systems. However, the work [25] focused on the application of the Wirtinger-based integral inequality and some new Lyapunov–Krasovskii functionals were not considered as mentioned in [25]. Therefore, there is still room for a further improvement on the reduction of conservatism in stability analysis for a system with time-varying delays, which motivated this research.

In this paper, the problem of delay-dependent stability analysis is investigated by utilizing the Wirtinger-based integral inequality [25]. Unlike the method [25], some new Lyapunov–Krasovskii functionals will be introduced and utilized in stability analysis for systems with different conditions on time-varying delays. The obtained stability criteria are derived in terms of LMIs which can be solved efficiently by using standard convex optimization algorithms such as interior-point methods [26]. Finally, three numerical examples are included to illustrate the effectiveness of the proposed methods.

Notation: Throughout this paper, the used notations are standard. $\mathbb{R}^n$ is the n-dimensional Euclidean vector space, and $\mathbb{R}^{m\times n}$ denotes the set of all $m \times n$ real matrices. $\mathbb{C}_{n,h} = \mathbb{C}([-h, 0], \mathbb{R}^n)$ denotes the Banach space of continuous functions mapping the interval $[-h, 0]$ into $\mathbb{R}^n$, with the

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