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A novel fast model predictive control with actuator saturation for large-scale structures

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ABSTRACT

One of the most critical issues faced in the application of active control to engineering structures is actuator saturation. In this paper, a novel fast model predictive control with actuator saturation for large-scale structures is proposed. First, based on the second-order dynamic equation, the explicit expression form of the Newmark-β method is derived. Then, according to the parametric variational principle, the explicit structure of the model predictive control (MPC) saturation controller is obtained. A linear complementary problem for the proposed fast MPC saturation controller is developed, replacing the quadratic programming problem for the original MPC saturation controller. The optimal control input can be achieved by solving one linear complementarity problem and one transient analysis problem. Particularly, the physical meaning of the explicit expression form of the Newmark-β method is discovered and applied for increasing computational efficiency and saving memory. Finally, numerical simulations of a plane adjacent frame building subjected to earthquake ground motion demonstrate that the proposed fast MPC saturation controller is highly efficient and can be applied under a large step-length, especially for large-scale structural dynamic control problems.

1. Introduction

Structural active control is one of the most important research fields in civil engineering [1–5], particularly with relevant applications within the wind engineering and seismic engineering fields. Although passive control and/or semi-active control do not have a large power demand and offer high reliability at the expense of reducing control effectiveness, active control has still been a hot topic in recent years. In the past several years, great progress has been made in advancing the theory and practice of structural active control methods, such as classic control methods, including PID control [6], positive position feedback (PPF) [7], and velocity feedback control (VFC) [8], and modern control methods, including linear quadratic optimal control [9,10], $H\infty$ theories [11,12], sliding mode control [13,14], and neural networks [15,16], which were developed to reduce building vibration under earthquake or wind excitation. However, when designing a controller for the active vibration control of structures, besides the control performance that must be considered, some practical issues should be considered in the controller design process as well [17].

In practical cases, actuator saturation [18,19], unavoidable input time delay [20,21] and parameter uncertainties of controlled structures [22,23] can cause a controller designed for structures without considering these factors to lose stability and even fail to work [24]. In this paper, the case of actuator saturation is one of most important factors and will be paid more attention. Saturation of the control input often occurs because the expected control input is unrealistic. Physical inputs such as force and torque are ultimately limited, and unexpected large amplitude disturbances can also push a system's actuators into saturation [25]. Therefore, control actuators are usually designed and implemented in such a way to operate below their physical limits. However, this approach is not acceptable from an economic viewpoint and can become unsafe under extreme loading conditions. A more rigorous approach should directly consider the system's limitations in the control algorithm [26]. Control actuators designed based on system limitations can be roughly classified into two categories: those that attempt to a priori prevent the system from reaching its limits and those that allow the system to reach its limits in a controlled manner [19]. For the former set of methods, a set of variable feedback gains is designed as a function of a single variable that indicates a trade-off between the reduction of the building response and the amplitude of the auxiliary mass stroke [27]. The on-off nonlinear velocity feedback control, as the natural evolution of the linear

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velocity feedback control, is employed when high gains and/or significant vibration levels are present together with saturation in the control law [28]. For the latter methods, control functions are considered to be piecewise constants and switching points are taken as decision variables, and then the bang-bang control problem is converted into a mathematical programming problem [29]. The model predictive control (MPC) is employed and transforms the control saturation problem into a parameter optimization problem [30]. The advantage of MPC is that the control saturation can be directly considered and designed in a simple manner.

With the rapid development of computer technology, MPC is becoming a reality in many engineering applications [31], such as civil engineering [32], mechanical engineering [33] and aerospace engineering [34]. The primary advantage of MPC over other control strategies is that it can handle process constraints that arise from natural requirements on an algorithmic level [35]. Despite the success of MPC in many engineering applications, there is still much room for improvement. For example, the time required to compute the control law in MPC cannot exceed the sampling time of the controller. In other words, the time necessary to evaluate the control law must be smaller than the sampling period [2]. Thus, multi-parametric explicit MPC [36,37] methods transfer much online computational work into offline operations. The main drawback of this method is the complexity of the controller, with its increased dimensions and long horizons. The Newton-Raphson-based MPC [38,39] methods proposed as alternate formulations of the MPC problem usually imply a loss of optimality.

From the above references, we can see that although MPC has shown to be effective in accounting for physical constraints and can provide satisfactory control performance, the application of MPC to the large-scale structure actuator saturation problem requires to carry out expensive computations in real time. To obtain a MPC controller including physical limits, the MPC saturation controller is newly proposed in this paper for satisfying the requirement of real-time large-scale computation. The proposed saturation controller is designed and constructed based on the two main aspects. One factor is an explicit expression form of discrete recursive dynamic equation for large-scale structures. Another factor is a linear complementarity problem obtained by the parametric variational principle. In the next section, two kinds of discretization scheme of the standard MPC (i.e. MPC1 and MPC2) will be presented for comparisons. The main contributions of this paper lie in two factors. First, the explicit structure of the MPC saturation controller can be obtained by the parametric variational principle. Meanwhile, the explicit MPC saturation controller is made up of one transient response analysis problem and one linear complementary problem. However, the original standard MPC1 and MPC2 saturation controller entirely rely on the on-line numerical solutions of parameter optimization. Second, based on the explicit expression form of the Newmark-β method, the optimal control input can be derived from the second-order dynamic equation without forming an expanded state-space equation. The essential advantages of employing explicit expression form are reflected at the high efficiency and low memory requirements. Specifically, the computation of the matrix exponential is avoided and replaced by two off-line transient response analyses. Thus, the computational efficiency of the proposed fast MPC method has been improved a few orders of magnitude than that of the original standard MPC1 and MPC2. At last, a similar control performance is obtained between the proposed fast MPC and the original standard MPC1. But compared with the original standard MPC2, the control performance of the proposed fast MPC has been increased by 5–30% under the same sampling steps and predictive horizons.

The remainder of this paper is organized as follows: in Section 2, the standard MPC for large-scale structures with actuator saturation is briefly reviewed and reformulated; in Section 3, the fast MPC for large-scale structures with actuator saturation is proposed based on the explicit expression form of the Newmark-β method and parametric variational principle; in Section 4, the comparison between the standard MPC and the proposed fast MPC is discussed; in Section 5, numerical examples are carried out to verify the validity and high efficiency of the proposed fast MPC; finally, some conclusions are presented in Section 6.

2. Standard MPC with input saturation

2.1. Problem formulation

The finite element method (FEM) is often used to build the dynamical model of large-scale structures for high-fidelity numerical simulation. In this paper, a linear time-invariant structure that is subjected to an external force and protected by means of a control system with saturation is considered, and the dynamic equation can be written as

$$\mathbf{M}\ddot{\boldsymbol{q}}(t) + \mathbf{C}\dot{\boldsymbol{q}}(t) + \mathbf{K}\boldsymbol{q}(t) = \mathbf{D}_1\mathbf{u}(t) + \mathbf{D}_2\mathbf{p}(t) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the $n \times n$ mass, damping and stiffness matrices, respectively; $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ are the $n \times 1$ displacement, velocity and acceleration vectors, respectively; $\mathbf{D}_1$ and $\mathbf{D}_2$ are the location matrix with $n \times m$ dimensions control inputs and the $n \times \bar{m}$ dimensions external force, respectively; $\mathbf{u}$ and $\mathbf{p}$ are the m-dimensional vector of the control forces and the $\bar{m}$-dimensional vector of the external forces, respectively.

Eq. (1) is obtained by FEM, while for controller design, it is usually transformed into an equation in state space form

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{G}\mathbf{p}(t) \tag{2}$$

and

$$\mathbf{x} = \begin{Bmatrix} \boldsymbol{q} \\ \dot{\boldsymbol{q}} \end{Bmatrix}, \quad \mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I}_1 \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{D}_1 \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{D}_2 \end{bmatrix} \tag{3}$$

where $\mathbf{I}_1$ is an $n \times n$ identity matrix, and the control variable $\mathbf{u}$ is not free, but constrained by the inequality

$$\boldsymbol{\mu}_{\min} \leqslant \mathbf{u} \leqslant \boldsymbol{\mu}_{\max} \tag{4}$$

where $\boldsymbol{\mu}_{\min} \in R^{m\times 1}$ and $\boldsymbol{\mu}_{\max} \in R^{m\times 1}$ are the lower and upper limits of the control variable $\mathbf{u}$, respectively.

Remark 1. Control actuation devices are subject to saturation. Force, torque, thrust, stroke, voltage, and every conceivable physical input in every conceivable application of control technology are ultimately limited. For instance, a double pusher magneto-rheological fluid damping device can generally provide a maximal damping force of 20 tons.

In real civil engineering, we can only obtain the information of some limited measured points of the structure. Meanwhile, the measured point distributions have much influence on the effect of MPC control. In this paper, we assume that the number and distributions of observation points have been given and the research of observation points and their distributions are out of the subject of the present study. Therefore, the output equation with known observation can be written as

$$\mathbf{y} = \bar{\mathbf{C}}\mathbf{x} \tag{5}$$

where $\mathbf{y}$ is the $p \times 1$ output vector, and $\bar{\mathbf{C}}$ is the $p \times 2n$ observation output coefficient matrix; p is the number of output variables. Finally, substitute the above output equation into the performance index