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Dissertation by

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Optimal Clipped Linear Strategies for Controllable Damping

Abstract:

In the past few decades, structural control research has focused mostly on passive and semiactive vibration mitigation strategies. Among the latter, the clipped-optimal control paradigm is one of the most commonly used. With this control strategy, a primary controller is designed using an optimal linear feedback assuming the control device is a linear actuator that can exert any force. Then, a secondary controller is commanded to exert the force generated by the primary controller if it is dissipative and minimal force if it is non-dissipative. However, if the optimization to design the optimal control law cannot consider the inherent passivity constraints of controllable dampers, then the commanded forces may often be non-dissipative for some structures and some performance objectives, causing frequent clipping; the result effectively deactivates the controllable damper for most of the duration of the response.

This study presents an alternate clipped linear control strategy. The clipped LQR (CLQR) strategy is just one of a family of clipped linear strategies; herein, the optimal choice, considering the dissipative nature of the controllable damper, from among this family is denoted the “Optimal Clipped Linear Control” (OCLC). This OCLC strategy provides performance superior to all other clipped linear strategies and can be far superior to CLQR when CLQR exhibits frequent clipping.
For convenience and for physical interpretation, the closed-loop OCLC system is parameterized relative to a CLQR solution, and the parameters are chosen to minimize a response metric to a particular excitation.

This proposed approach is first applied to a single degree-of-freedom (SDOF) structure model subjected to a Gaussian white noise (GWN) excitation. To illustrate the optimality of OCLC, it is compared to both CLQR and an optimal passive linear viscous damper. Then, the SDOF model, with the OCLC and CLQR strategies, is excited by multiple historical earthquakes and Kanai-Tajimi filtered excitations. OCLC designed for one specific excitation is also evaluated with other excitations. A strategy to select the best control gain parameters for OCLC for a SDOF system is proposed and validated. Moreover, the relationship between OCLC control gain parameters and structural characteristics for SDOF systems is explored.

Next, the effectiveness of OCLC and CLQR strategies in reducing three different response metrics (absolute floor accelerations, inter-story drifts and ground-relative floor velocities) is studied for a two-degree-of-freedom (2DOF) system with a control device either in the first or second story. With a GWN ground acceleration, OCLC again reduces the cost metric and structural response better than either the corresponding CLQR or an optimal passive linear viscous damper. Then, the robustness of the proposed control strategy for both SDOF and 2DOF models is explored through evaluating the controllable damper performance when the structure model differs from the nominal ones used to design the OCLC strategy.

The proposed strategy is also tested for a physical magnetorheological (MR) damper. Real-time hybrid simulation (RTHS) tests are conducted for a set of different structural systems and OCLC shows variable levels of performance improvements over CLQR for different structures for both numerical simulation and RTHS tests.
The performance of OCLC designed for one specific excitation is evaluated when subjected to other excitations through RTHS.

Next, shake table experiments are conducted at Japan's NIED “E-Defense” laboratory, using several controllable damping strategies designed to mitigate the responses of a full-sized base-isolated structure specimen, with an MR fluid damper installed in the isolation layer. The experimental results show that OCLC can provide performance superior to CLQR in minimizing absolute acceleration while not increasing ground relative displacement significantly for the base-isolated structure, and vice versa. E-Defense results are also compared with RTHS and pure simulation results, and they have good correspondence.

Finally, numerical solutions to the Fokker-Planck-Kolmogorov (FPK) equation associated with ideal OCLC of a SDOF system excited by GWN are investigated using finite difference methods. Some special considerations are presented: the Heaviside function is approximated by a hyperbolic tangent function; variable grid spacing is applied for the finite difference discretization; a high order polynomial quadrature method was proposed to calculate the statistics. The results indicated that the mesh should be sufficiently fine for a convergent solution; a smaller time step and a lower order finite difference scheme may increase the convergence rate for the semiactive system. Moreover, a new choice of the initial guess for solving the time discretization equation is proposed and the symmetry of solutions is utilized to reduce the computational effort. Further, the implications for optimal clipped linear strategies using FPK solutions are indicated.

Keywords: controllable damping, optimization, dissipativity, Fokker-Planck-Kolmogorov (FPK) equation, structural control