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Linear Parameter-Varying Anti-windup Control For Active Microgravity Isolation

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Abstract

Researchers apply anti-windup methodology to provide anti-windup protection for adaptive active microgravity vibration isolation. For such systems, anti-windup protection is required because of the possibility of actuator saturation in response to inertially based forces acting on the isolated platform. This report addresses the design of a static anti-windup compensator that applies a correcting signal only when the control is saturated. The performance of the overall closed-loop system is demonstrated by simulations.

ACTUATOR SATURATION EXISTS IN ALMOST ALL ENGINEERING control systems. Due to saturation, the actual plant input is different from the controller output. This discrepancy is called controller windup (Aström and Wittenmark). Since actuator saturation is ignored in linear control design, controller windup could result in degradation from expected linear performance, large overshoot or possible instability (Campo and Morari). Because of the complexity of the anti-windup problem, early anti-windup schemes were mostly heuristic in nature. Only in the last decade has the problem been addressed in a more formal way with stability guarantees and clear performance specifications.

One systematic approach to the anti-windup problem is to embed it within a larger linear parameter-varying (LPV) problem; see Wu, Grigoriadis, and Packard for details. This methodology allows standard LPV stability and performance methods to be applied to the problem. However, this approach may result in conservative designs. An alternative approach to saturating control is the anti-windup method that employs a two-step design procedure. The idea here is to first design the linear controller by ignoring the saturation nonlinearities and then add anti-windup compensation to minimize the adverse effects of saturation on closed-loop performance. In Grimm, Hatfield et al., LMI-based anti-windup compensator synthesis with quadratic stability and performance guarantees for a stable system is presented. Wu and Lu extend the methodology to unstable systems as well.

In this report, an anti-windup technique is applied to a linear parameter-varying (LPV) controller, designed to provide adaptive microgravity vibration isolation performance; see Mehendale, Fialho, and Grigoriadis for details. The anti-windup control structure is shown in Fig. 1. The designed LPV controller provides improved isolation and position control over the range of operating conditions via the use of parameter-dependent weighting functions. Because the controller is linear and aggressive, disturbances such as inertial based forces applied to the isolated platform cause the controller to command values to the actuator that exceed its saturation limits. During such events, isolation performance is degraded and modifications of the nominal control algorithm are necessary to keep the system well-behaved.

SOLVING SATURATION—Dr. Karolos Grigoriadis, Assoc. Professor in Mechanical Engineering (UH), leads a research team that seeks to improve automatic response to controls. To compensate for saturation in linear control design that leads to instability, team members suggest a two-step process that first ignores saturation nonlinearities and, next, minimizes the adverse effects of saturation on closed-loop performance.

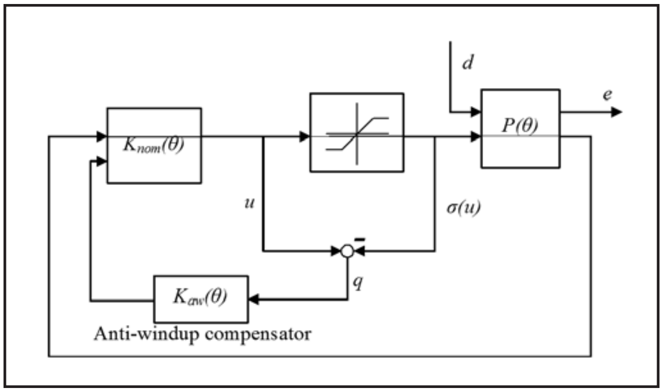

Figure 1. Anti-windup Controller Structure

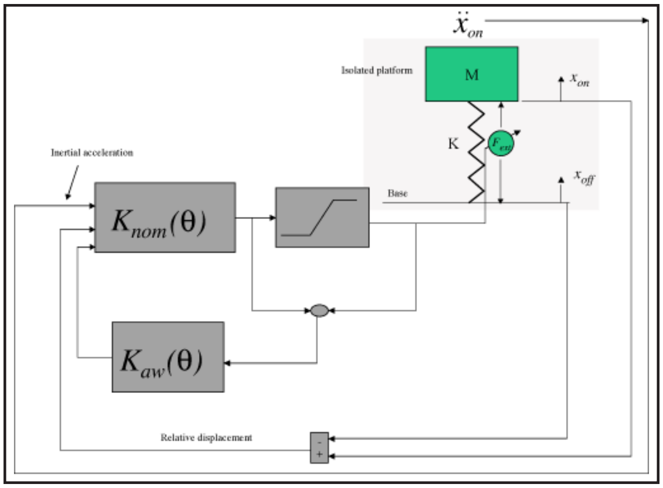

Figure 2. Schematic of the Isolation System

Anti-Windup Compensator Design for Active Microgravity Isolation Control

Mehendale, Fialho, and Grigoriadis report the fabrication of an adaptive LPV controller with parameter dependent performance requirements designed for an active microgravity isolation system. A schematic of the system is shown in Fig. 2.

The goal of the control design is to achieve a level of iso-

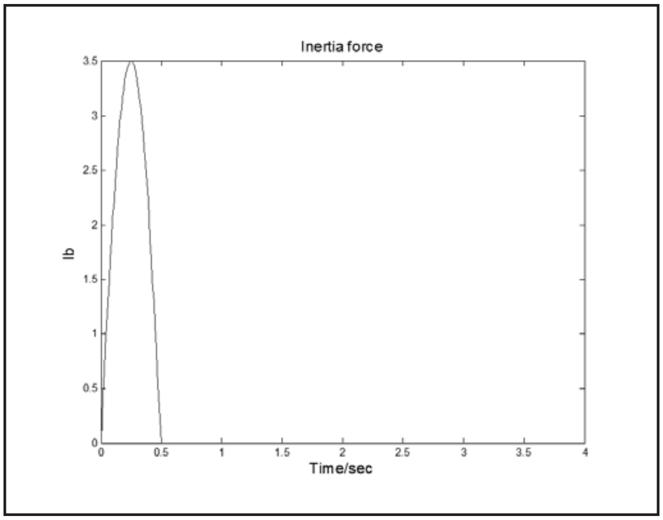

Figure 3. Inertial Force Profile

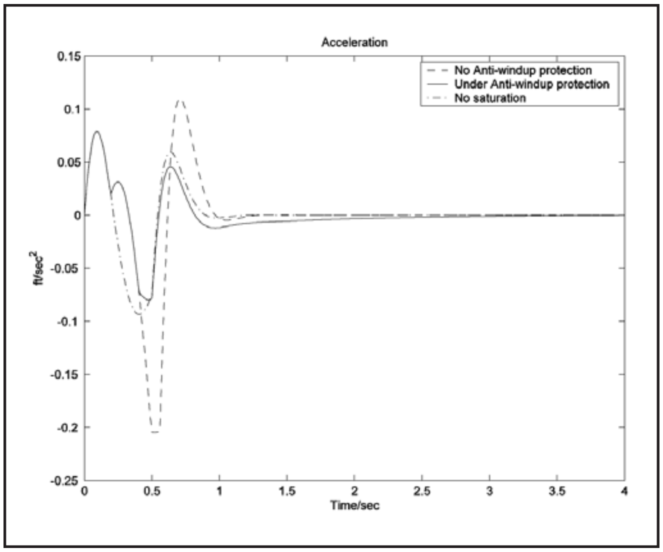

Figure 4. Acceleration Performance

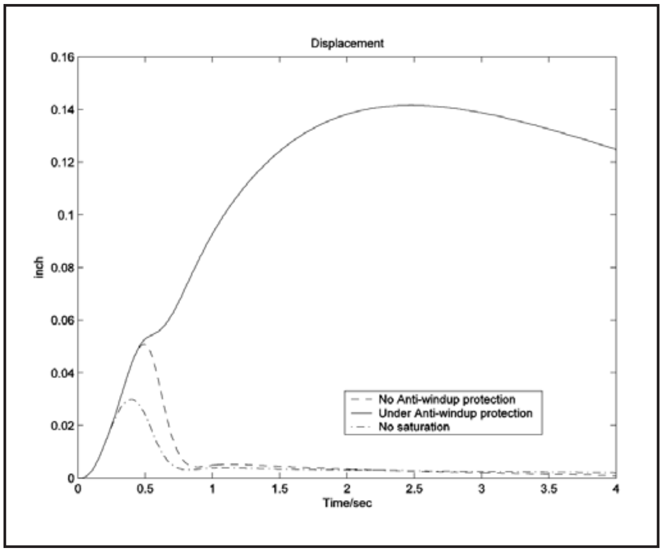

Figure 5. Relative Displacement

lation between the base acceleration $\ddot{x}_{off}$ and the inertial acceleration $\ddot{x}_{on}$ of the isolated platform. The isolated platform must operate in a limited rattlespace; hence, an additional design constraint is that the relative displacement $x_{on} - x_{on}$ does not exceed the 0.5 inch rattlespace limit in order to prevent the platform from bumping into its hardstops. In order to achieve these objectives, the LPV controller is scheduled on two parameters. The first parameter θ_d is the relative displacement while the second parameter θ_r is an additional scheduling variable that is chosen to quantify the harshness of the operating environment. By scheduling on relative displacement, the LPV controller is able to shift its focus from a "soft" setting to a "stiff" setting depending on the need for acceleration minimization or relative displacement reduction to prevent bumping. Scheduling on the second parameter that quantifies base motion harshness allows the controller to adjust the way in which the system transitions between the "soft" and "stiff" settings. In order to achieve the design objectives, weights that depend parametrically on the scheduling variables $[\theta_d, \theta_r]$ are appended to the basic LTI plant to create the control design generalized LPV plant. The LPV controller is then designed for this generalized interconnection. This approach allows the controller to achieve excellent isolation performance over the range of base motion environments, while, at the same time, preventing the isolated platform from exceeding its hard rattlespace limits. Since the controller is linear and aggressive, there are disturbances, such as inertially-based forces acting on the isolated platform that cause actuator saturation. This saturation leads to degradation in isolation performance. Adding an anti-windup protection loop is necessary to ensure good isolation performance. The anti-windup method, presented in Zhang, Fialho, and Grigoriadis, is used for the anti-windup compensator design.

In this work, both the LPV controller and anti-windup compensator designs are carried out for a simplified model of a microgravity isolation system. The mass of the payload is assumed to be a M = 15 slug, and the spring constant K is assumed to lie between 0 and 20 lbf/ft.

Anti-Windup Design Results

The anti-windup compensator design, as discussed above, was verified through time-domain simulations. The saturation limit for the actuator force is set to be [-33] lbs. An inertial force profile (see Fig. 3) is applied to the isolated payload when the payload is located at the center of its rattlespace to test the isolation performance when displacement is small. In this regime, the LPV controller is focusing on minimizing acceleration. The dashed lines in Figs. 4, 5, and 6 show the acceleration, actuator force, and relative displacement responses of the nominal closed-loop system without anti-windup protection under actuator saturation. The solid lines in the figures show the same variables, but with anti-windup protection. The dashdot lines in the figures are the responses of the nominal closed-loop system in the absence of saturation. They serve as the benchmark nominal performance for comparison purposes. It is apparent that the anti-windup improves the acceleration performance significantly. The response under anti-windup protection almost converges to the nominal performance. Figure 4 shows that the anti-windup compensator helps the controller get out of saturation early, and also avoids large over-shoot. Figure 5 shows that the relative displacement for the anti-windup protected case is larger. This is expected since the payload is centered in its rattlespace and, hence, the controller is focused upon minimizing acceleration. However, it is still significantly below the displacement limit. We conclude that the anti-windup compensator improves the performance of the nominal controller under actuator saturation when the relative displacement is small.

In order to evaluate the anti-windup performance when the relative displacement is large, a representative base motion displacement profile (see Fig. 7) was applied to cause large relative displacement. The same inertial force profile as before was next applied at 30 secs, when the relative displacement was large. Once again, it is apparent that the acceleration performance is significantly improved using the anti-windup compensator; see Figs. 8, 9, and 10.

Conclusion

In this technology, an anti-windup control scheme has been successfully applied to saturation protection for an adaptive LPV controller for active microgravity isolation. The design extends our previous adaptive LPV microgravity vibration isolation control and follows a two-step anti-windup approach, resulting in the solution of a convex Linear Matrix Inequality (LMI) optimization problem. Numerical simulations have been used to demonstrate the effectiveness of the anti-windup design.

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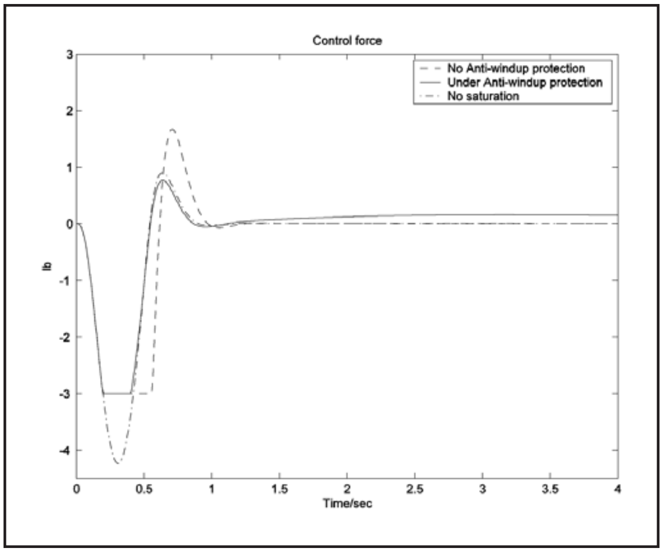

Figure 6. Control Force

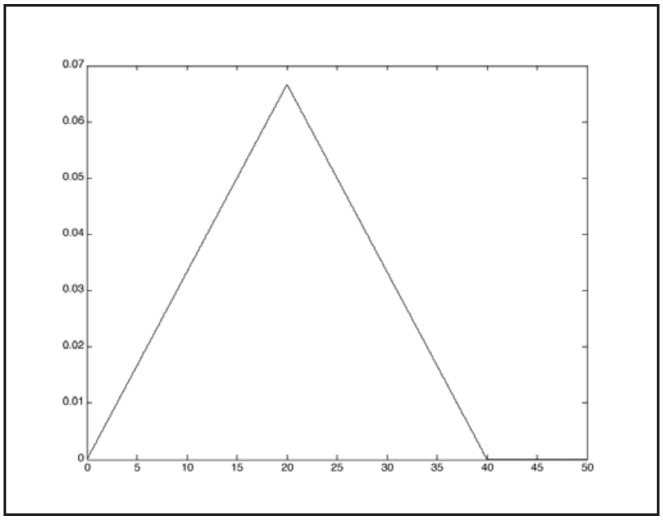

Figure 7. Base Motion Disturbance Profile

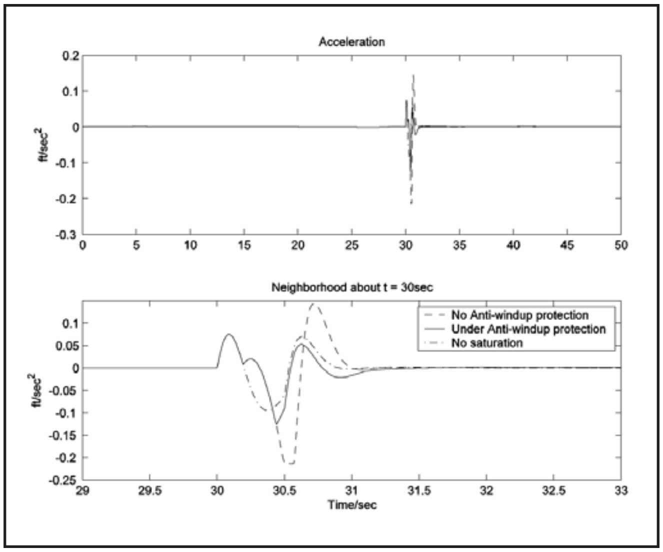

Figure 8. Acceleration Performance

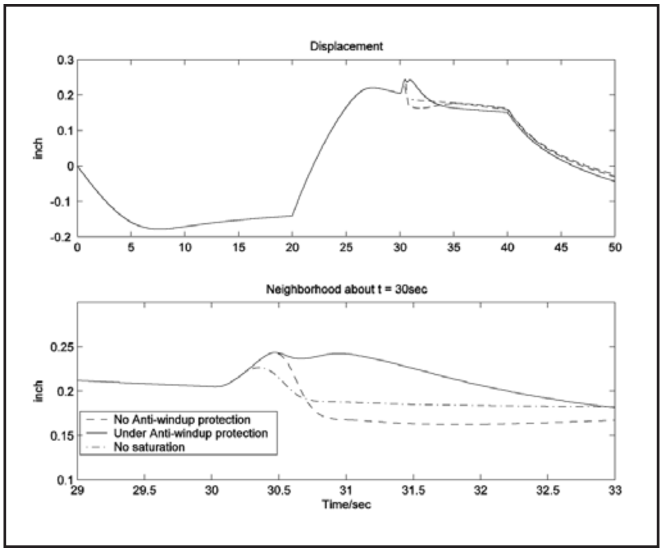

Figure 9. Relative Displacement

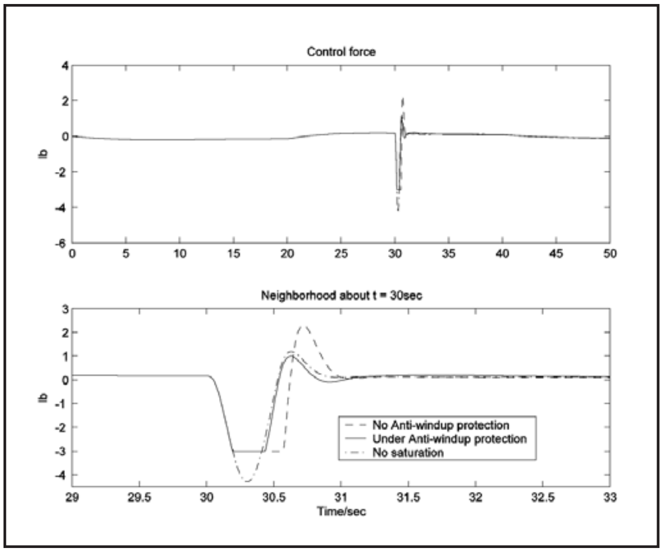

Figure 10. Control Force

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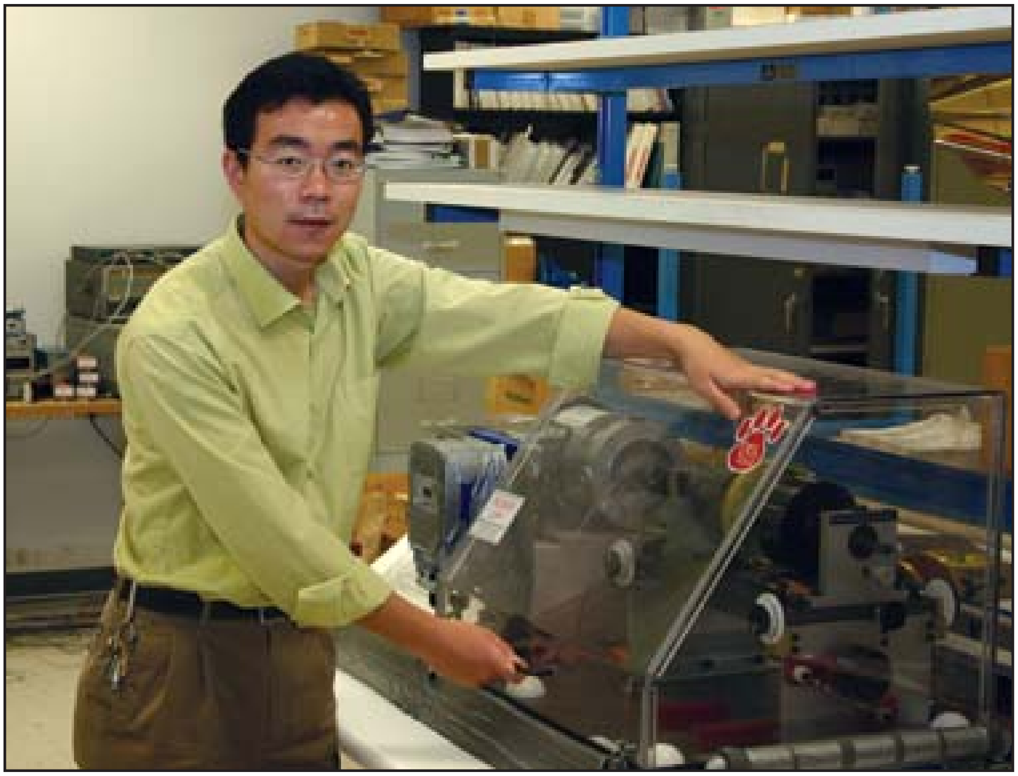

ANTI-WINDUP CONTROL—Dr. Feng Zhang earned his baccalaureate degree and M.S. degree in engineering from the Tsinghau University in Beijing, China. He earned his Ph.D. degree in mechanical engineering at the University of Houston. With Dr. Grigoriadis, Dr. Zhang published his study on "Active Microgravity Isolation Using Linear Parameter-Varying Techniques," in the *Proceedings* of the 2003 IASTED International Conference on Intelligent Systems and Control, in Salzburg, Austria. He is co-author of "Linear Parameter-Varying Anti-Windup Control for Active Microgravity Isolation," presented to the 2004 IEEE Conference on Decision and Control (Paradise Island, Nassau, 14-17 December 2004), which has been submitted for publication.