Back Story

For several decades, one of the most popular themes in control research has been the desire to use feedback to suppress vibrations. Within an idealized linear range of motion, structures without rigid-body modes are open-loop stable and thus need not be actively stabilized. This property holds regardless of the components that make up the structure, such as beams, plates, or membranes. But these systems are extremely challenging to control for several reasons. First, structures typically have lightly damped eigenvalues and thus can be inadvertently destabilized. Next, the frequencies of vibration, damping levels, and mode shapes are typically uncertain despite the elegance of textbook models. And third, the density of modes typically increases at high frequency, where density refers to the number poles per frequency range. All of these issues apply to active noise (that is, acoustic) control as well since air vibrates in compression as a kind of three-dimensional structure. Active vibration control has thus served as a motivation for developing new control techniques as well as a testbed for determining the limitations

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Contributors

Diego Regruto with his wife Consuelo and daughters Giorgia (left) and Lorenza (right).

Mats Larsson with solar panel.

Jim Spall at Johns Hopkins University.

Jim, Kathy, Daniel, and Sarah Spall.

Ian Petersen with his daughter Charlotte and son Edward in San Francisco.

of methods developed for other applications. To get a feel for some of the challenges of active vibration control, see the article by Fuller and Flotow in the December 1995 issue of this magazine.

Early research on structural control focused on the obvious fact that these structures are distributed and thus are naturally modeled by partial differential equations. The technical issues that arise in accounting for an infinite number of eigenvalues, especially under asymptotically vanishing damping at high frequency, entail serious mathematical challenges. When these models lead to infinite-dimensional control algorithms, the next challenge then becomes determining how to best arrive at an implementable algorithm. Model and controller reduction techniques become necessary, and spillover, which is a manifestation of the Bode sensitivity integral, is inevitably observed. When realistic, finite-bandwidth implementation issues are imposed, these issues become less of a concern.

The simplest approach to using feedback to suppress vibration is to measure velocity and implement a force of the opposite sign at the same location, thereby enhancing damping. This approach, called negative velocity feedback or direct velocity feedback (Googling the latter term leads to Mark Balas's 1979 paper), is the tip of a huge iceberg of control theory, involving the full power of passivity and dissipativity theory pioneered by Jan Willems and its specialization in terms of positive-real control techniques. Negative velocity feedback has some attractive features; for example, it is robust to uncertainty in damping, modal frequencies, and mode shapes. Yet, despite its powerful underpinnings, simplicity, and robustness, negative velocity feedback can be challenging to implement. For starters, obtaining a good measurement of velocity is difficult for various subtle reasons; suffice it to say that angular rate is an inertial measurement obtainable by a gyro, whereas few sensors (and certainly none that are inertial) are available for measuring translational velocity. If the measurement is imperfect in the sense that it is

Vito Cerone climbing the north face of the Ciarforon, in the Alps.

Ian Petersen in Harbin, China.

Harpreet Singh of Wayne State University.

Alexander Lanzon, his wife Laura Sbaffi, and their daughters Nicole (left) and Dominique.

corrupted by phase shift, then instability can occur. The need to apply the force at the same location—the requirement for colocated sensing and actuation (note the spelling of *colocated*)—is harder than it sounds; even a small transmission path from sensing to actuation can lead to instability.

Beyond these practical difficulties, direct velocity feedback is largely limited to adding damping to the structure but not changing its shape. The ability to modify the shape of a structure is a more challenging task than improving its settling time and increasing its ability to withstand external disturbances. To modify and maintain shape, what matters is whether the shape variables are controllable and observable and whether the desired equilibrium shape is in the range of the actuation matrix so that it can be sustained. Shape control is facilitated by the use of a position sensor to compare the desired displacement with the measured displacement.

Which brings me to my main point: How can a position sensor be used to add damping to a structure? Within the paradigm of direct velocity feedback, the obvious answer would be to differentiate the measurement; but online differentiation is something that we may be tempted to do but know that we should avoid due to sensor noise. Indeed, if we could differentiate measurements enough times, then virtually every control task would be made easier. We'll differentiate when we must and hope that it works, but in the long run we recognize that differentiation is not a "real" solution.

The story I've told to this point would be neat and tidy except for one thing: In the 1980s, a control algorithm was developed by Goh and Caughey for flexible structures based on position sensing. This method, called positive position feedback (PPF), has been avidly used for structures with significant actuator dynamics. Notice the duality in names: positive position feedback versus negative velocity feedback. Interestingly, PPF is missing one of the sensing derivatives needed for damping augmentation and yet mysteriously compensates by reversing the sign of the feedback gain.

That was, until David Angeli published a paper on counterclockwise dynamics in 2004, where he demonstrated a conceptual framework that can explain the effectiveness of PPF. The fleshing out of these ideas for feedback control of structures is the subject of the feature article by Ian Petersen and Alexander Lanzon. In this issue, Ian and Alexander develop a theory of negative imaginary systems as a kind of rotated version of positive-real theory and show that control based on negative imaginary transfer functions affords the same robustness as negative velocity feedback. In a nutshell, a control theory for negative imaginary systems expands our understanding of what is needed to control structural vibration as another crucial piece of the feedback puzzle.

This issue also includes a feature article by James Spall on factorial design for experiments. Using systems language and concepts, this article explains how a judicious choice of inputs can decrease the number of trials needed to identify a system relative to one-at-a-time strategies. This approach is demonstrated on applications in which experiments are costly and data are limited.

For "People in Control," we speak with Maria Domenica ("Marika") Di Benedetto and Sandor Veres, both of whom have wide-ranging interests in systems and control. Harpreet Singh remembers Andrzej Olbrot in a short historical note. We also bring you one book review, the usual hearty collection of new book announcements, and a report on HarrisFest in honor of former IEEE Control Systems Society President Harris McClamroch. With sadness we publish obituaries of two luminaries in our field. We end with yet another commentary on the merits of television.

We invite your letters on any aspect of this magazine. Submissions on all aspects of systems and control technology are encouraged.

See you in December!

Dennis Bernstein

Winning Tools

Ms. Steinkuehler, an assistant professor of educational communication and technology at the University of Wisconsin at Madison, studies video gamers. In one recent case study, she noted how players in a chat room had used complex mathematics to argue for a certain plan of attack against some unruly beast.

"People were actually—no kidding—gathering data on things like the game monster's behavior, putting it in an Excel spreadsheet, and building little mathematical models to try to beat the monster," she told me recently. The game teaches complex problem solving and collaborative learning, Ms. Steinkuehler argues.

—Jeffrey R. Young, *The Chronicle of Higher Education*, January 29, 2010, p. A15.