ENHANCING SENSITIVITY OF VIBRATION-BASED METRICS FOR
DAMAGE DETECTION IN SMART STRUCTURES

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OVERVIEW
The efficacy of modal analysis in detecting and localizing damage is debated based on sensitivity concerns – modal frequencies are extremely insensitive to small changes in local parameters and geometry. Convincing evidence of sensitivity issues is vast, and here we cite a single field study of a 163 ft. long, 10 ft. deep experimental test girder from an I40 bridge in Bernalilo County New Mexico. In-situ modal analysis of the span for four substantial damage cases shows small changes in the first three modal frequencies. Three of the damage cases, which range from a 2 ft. long, 3/8 in. wide cut in girder web to a 6 ft. cut in the web plus cuts halfway through each side of the bottom flange, produce measured frequency shifts of less than 2% in the first three modes. Only when the structure is nearly cut through, are frequency shifts significant.

We propose using feedback control to systematically enhance sensitivity of modal frequencies to small changes in structure parameters and local geometry. Under closed-loop control, characteristic structure dynamics can be modified such that modal frequencies are more sensitive to parameter variations induced by damage. Since feedback control is required, the method applies to smart structures that are instrumented with both sensors and actuators. Our research integrates the disciplines of control and autonomous health monitoring of structures, such that in structures instrumented for other tasks, (e.g., vibration damping or acoustic noise cancellation) the same hardware can be used for damage detection.

DEMONSTRATION OF SENSITIVITY ENHANCEMENT IN SMART STRUCTURES
Our initial exploratory research has demonstrated sensitivity enhancement concepts through computer simulation and proof-of-concept lab-scale experiments. A simple demonstration of sensitivity issues and enhancement can be made using a single degree-of-freedom structure. Here, the sensitivity of the natural frequency \( \omega_n = \sqrt{k/m} \) to small changes in stiffness \( k \) and mass \( m \) is \( \frac{\partial \omega_n}{\partial k} = \frac{\omega_n}{2k}, \) and \( \frac{\partial \omega_n}{\partial m} = -\frac{\omega_n}{2m} \). Hence, sensitivity is fixed by the magnitudes of \( k \) and mass \( m \). However, state feedback control modifies the dynamics, and the closed-loop natural frequency \( \omega_{n,cl} = \sqrt{(k + K_1)/m} \) depends on a selectable control gain \( K_1 \). Accordingly, closed-loop natural frequency sensitivities \( \frac{\partial \omega_{n,cl}}{\partial k} = \frac{\omega_{n,cl}}{2(k + K_1)}, \) and \( \frac{\partial \omega_{n,cl}}{\partial m} = -\frac{\omega_{n,cl}}{2m} \) depend on the control gain. Thus, for the single degree-of-freedom system, one should reduce \( \omega_n \) (make \( K_1 \) negative) to enhance sensitivity to change in stiffness, and to enhance sensitivity to change in mass, one should increase \( \omega_n \) (make \( K_1 \) positive). The fact that effects of each control law on sensitivity to specific parameter variations are opposite suggests that multiple control laws enhance sensitivities of different damage mechanisms, providing the ability to distinguish between some damage types by successive application of different control laws during structure maintenance.

These concepts apply equally well to distributed parameter systems, although the relationship between the control gains and sensitivity is not as readily apparent. Figure 1 summarizes
simulation results of applying a control law designed to enhance sensitivity to stiffness reduction in a 0.5 m long cantilevered beam under transverse vibration. A Rayleigh-Ritz model of the beam is used, and damage is modeled by a 5% reduction thickness at longitudinal location \( x/L \). A single piezoceramic actuator is assumed available, and the first three modes of the beam are controlled. For these modes, the increase in sensitivity to local damage is substantial. Figure 1 shows small open-loop sensitivities – under 0.5% when damage is located at the root of the beam, and smaller as damage location moves towards the tip. Under closed-loop control, sensitivities increase more than an order of magnitude (mode 1) to a factor of 2 (mode 3).

**SUMMARY OF RESEARCH TO-DATE**

Our initial research includes simulations such as that summarized above, a proof-of-concept experiment, a brief investigation of enhancing mode shape sensitivity, and investigation of using feedback control within commercial FEM software packages. We have made the following key findings:

- Sensitivity enhancing control can be implemented using commercially available piezoceramic sensors and actuators. Bandwidth and control authority provided by typical amplifiers is sufficient to control structures for sensitivity enhancement.

- Mode shape sensitivities also can be enhanced through feedback control, but the control law that should be used to enhance mode shape sensitivities is not obvious. Identifying shifts in mode shapes due to damage aids in damage localization.

- ABAQUS, commercial software in which specific damage cases, such as fatigue cracks and composite delamination are efficiently modeled, is useful for creating numerical models to which control laws can be applied. By developing this capability, we have been able to perform sophisticated numerical simulation experiments in applying feedback control to structures with fatigue crack damage. These experiments are difficult to perform in the laboratory.

**RESEARCH TASKS**

In order to advance the concept of using feedback control for damage detection, we have identified the following research issues:

- **Design of control laws for sensitivity enhancement**

In our work to date, heuristics have been used to design control laws for sensitivity enhancement. The control laws that we have developed are by no means optimized for the task. Research is
required to develop methods of optimizing control laws and placing sensors and actuators for the purpose of enhancing sensitivity of damage metrics. Included in this task are accuracy requirements for the model that is used for control law design, and study of spillover effects, or the effects of the compensator on unmodeled modes.

Effect of nominal uncertainty and damage localization
All modal-based damage metrics will fail at the point where effects of nominal uncertainty on modal properties (thermal expansion, humidity, and boundary conditions) or measurement noise are as significant as the damage. Research is required to answer the following questions. How large must damage-related parameter variations be compared to nominal parameter uncertainty to differentiate between damage and nominal uncertainty that occurs simultaneously? Can damage be localized? Can distributed damage be distinguished from local damage? Can quantitative information regarding damage be provided from closed-loop vibration-based metrics? What is the effect of measurement noise on damage isolation?

Enhancing sensitivity of other damage metrics
Other researchers have found other modal information (e.g., eigenvectors, mode shapes) or other metrics (e.g., electromechanical impedance) useful in detecting and localizing damage, though these metrics are also subject to sensitivity concerns. We have considered sensitivity enhancement of other modal measures under damage, such as mode shape changes, local strain energy, or the traditional amplitude sensitivity function used in classical controls. In particular, research is required to isolate and enhance metrics that are less dependent on nominal uncertainty and boundary conditions than the lowest modal frequencies of a structure. Examples of such measures may include characteristic electromechanical impedance or acoustic properties.

Applications of sensitivity enhancing control
Our proof-of-concept simulation and laboratory experiments have focused on isotropic, one-dimensional structures. Extension to other structures (plates, shells) and materials (composites) is necessary to fully understand the principles of sensitivity enhancing control.

RESEARCH RELEVANCE
The proposed research aims to enhance sensitivity of vibration-based non-destructive evaluation methods to structural damage through closed-loop control. The long-term impact will be real-time, autonomous damage detection methods that use preexisting sensors and actuators available on smart structures. In addition to the direct goal of enhancing autonomous damage evaluation methods for structures, the research includes extrinsic goals. Model-based damage detection is essentially a method of system identification. Whereas traditional system identification methods rely on input shaping, persistent excitation, and output signal processing to enhance performance, introducing feedback control specifically to aid the identification process, initiates a new approach to system identification.