MEMS-BASED ACTIVE STRUCTURAL STRENGTHENING TECHNOLOGY

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Introduction

Active structural strengthening is an emerging technology that adjusts the dynamic behavior of structural members to prevent buckling, thereby allowing structures to be made stronger, lighter, and more reliable than would otherwise be possible. Early experiments have achieved active stabilization of the first two modes of column buckling, yielding a strength increase of 5.6x and demonstrating that active control of buckling can allow a member to be loaded well in excess of its critical buckling load. This paper presents an overview of these early experiments and describes potential military and commercial applications of active structural strengthening technology.

Technology Overview

Although structural materials such as steel are very strong in many ways, they have one severe flaw: they are flexible. When long, thin members are loaded in compression beyond a certain critical load, this flexibility leads to buckling, in which the member suddenly flexes due to the applied load. Buckling is a sudden failure that occurs without warning and often leads to complete structural collapse, requiring that very large safety factors (load reductions of 20x-100x) be incorporated into designs in order to ensure that buckling does not occur. The key idea exploited by active structural strengthening technology is that if the onset of buckling is detected very early, while the member is still nearly straight, very small restoring forces can push the member back towards the undeflected position, thereby keeping it from buckling. Thus even very tiny control forces can yield very large strength increases by allowing members to be loaded beyond their critical buckling load.

Control of buckling is achieved by using sensors to detect the onset of buckling motion, and then applying the appropriate actuation forces to counteract the shape and velocity changes caused by buckling. For some geometries, such as a column loaded purely in compression, buckling occurs in well-defined shapes known as modes, such that only a few appropriately located sensing and actuation sites are required to counteract buckling. However, for other configurations, such as the local buckling of thin-walled cylinders, the location and shape in which buckling will occur depends on material imperfections and cannot be predicted in advance, requiring the use of a large number of independently addressable sensing and actuation sites and highly adaptive control technology.

Coordinating the actions of such a large distributed array of sensors and actuators in real time represents a challenging research problem in distributed control. The problem is further complicated by the possibility of interactions between multiple active members in a structure. For instance, will the control actions taken to stabilize one member actually induce buckling in another? MEMS technology is poised to provide a solution to this distributed communication and control problem by allowing microelectronic circuitry, along with sensors and actuators, to be embedded in materials and on surfaces.

Progress to Date

Active Control of Column Buckling

Active structural strengthening has been demonstrated using a composite column, pictured in Figure 1, that is actively stabilized against buckling through the use of piezo-ceramic (PZT) actuators [1]. This column achieves a factor of 5.6x increase in load-bearing strength by actively stabilizing the first two buckling modes. We expect that even greater strength increases can be obtained through better actuator placement, through improved sensing technology, and through the control of additional buckling modes.

The control strategy for the active column is implemented by a centralized control computer (a 486 PC), which is fed information about the column's dynamic behavior from five pairs of resistive strain gauge sensors. Actuation is provided by PZT actuators using the induced-strain method, in which actuators are mounted in pairs on each side of the column and are driven out of phase so that the actuator on one side of the column seeks to grow, while the actuator on the other side seeks to shrink, thereby applying a distributed bending moment to the column.

Active Bridge Demonstration

A small-scale railroad-style truss bridge has also been fabricated, using two of the composite steel/piezo-ceramic members developed for the actively controlled column experiments. This bridge, pictured in Figure 2, controls each active member independently of the other, using separate control computers. The sensor data recorded no significant interaction between the actively stabilized members, clearly showing that it is possible to combine multiple active members to form a compound actively strengthened structure. Further research is required to determine under what conditions the active members in a structure can be controlled independently, and what degree of communication and coordination is desirable between the controllers of different members.

Why MEMS?

In some sense, the components used in the prototype column and bridge are at about the same integration level in the smart structures domain as discrete IC logic gates are in the microelectronics domain. MEMS technology promises to integrate these components to form "Smart Matter", with technology to: provide ultra high accuracy strain sensors complete with on-board amplification/digitization electronics; provide wireless communication within a structure; fabricate interdigitated electrode arrays to produce the high electric fields required to drive PZT actuators without the need for high voltages; and implement the control computation and communication within the column material itself. In the very long run, we envision that this technology will evolve to the point where "smart paint", containing sensors, actuators, and computational elements, can be applied to actively strengthen structures.

Dual-Use Impact and Applications

From the dual-use perspective of this conference, active structural strengthening technology is attractive for two reasons. First, buckling is a fundamental barrier that affects both the military and civilian sectors. Second, the technology has a wide range of implementation scales, providing dual-use opportunities that range from office products to large military aircraft.

Strength on Demand

One of the most important applications for active control of buckling will be to supplement traditional designs, providing an added factor of safety in the form of "emergency strength" for exceptional situations. For instance, when an airplane makes an unusually hard landing, the landing struts can be given added strength by actively controlling buckling. Aircraft are particularly attractive candidates for this technology because they already have highly reliably sources of power, have hydraulic systems available for actuation, and undergo large dynamic loading only for a brief period. Active structural strengthening technology can allow designers to reduce weight and increase speed, range, and fuel economy by designing structures for typically occurring loads, while relying on active strengthening to handle unusual instances of large dynamic loading.

In military applications it may prove feasible to rely on active control even for typical loads. For example, the speed and range of a missile could be extended by reducing its weight through the removal of material from its fuselage or engine housing, and compensating for the resulting strength reduction by using active structural strengthening to withstand periods of high load. Similarly, the engine housings of fighter aircraft could be actively stabilized against buckling during the high compressive loads encountered during full power dives, perhaps using aerodynamic appendages or fuel jets as actuators.

Interestingly, the first proposed use for active buckling control was in the civilian sector, when in 1970 an architect, William Zuk, predicted that some day mankind would learn to control the buckling of columns and would use this technology to build a city on top of an existing city, supported by very tall and slender actively stabilized columns [8]. Although the civilian economy is probably not yet ready for the idea of buildings that fall down when you switch them off, there are potential application of active structural strengthening in civilian buildings. One possibility would be to increase the strength of compressive members so as to make them better able to resist earthquake-induced dynamic loads. However, a potentially more important aspect of active control of buckling is that it provides a structural designer with a new option: a compressive member that can actively be made strong during normal operation to provide resistance to wind-induced vibration, but which can be allowed to flex during an earthquake to allow the structure to sway in response to the quake.

Extended Lifetime

Another potential dual-use application for active structural strengthening is in extending the lifetime of equipment by reducing fatigue. For instance, in a phenomenon known as wave-induced whipping, compressive members supporting the hulls of large ships buckle in heavy sea conditions due to wave action pounding on the hull [6]. Fortunately, the duration of the forces applied by a wave is (usually) short enough that buckling does not progress to the point of causing the immediate failure of the member. However, after repeated loading cycles, the buckling motion causes metal fatigue which damages the member over time, leading to very high maintenance costs. Active control would counteract the buckling motion induced by the wave action, thereby preventing buckling-induced metal fatigue. Industrial equipment that undergoes periodic large compressive loads is another potential target for active fatigue reduction.

Portable/Deployable Structures

Active control of buckling can be used to create structures that are both stronger and lighter than would otherwise be possible. One possible military application would be to create ultra lightweight structures, such as a portable bridge that could be carried in the back of a jeep or truck and yet be strong enough to carry heavy loads. On the civilian side, potential applications include portable telescoping supports for temporary reinforcement in the aftermath of disasters such as earthquakes and hurricanes.

Moving Flexible Objects

Industrial applications that require the high speed precision movement of flexible objects are frequently plagued by the buckling of the objects being manipulated. A potential industrial application of this technology would be to use remote sensing and actuation approaches, such as MEMS-based actuators, to actively sense the dynamical state of the object being manipulated and then apply control forces that prevent it from buckling.

Conclusions

The ability to provide strength on demand by embedding sensors, actuators, and computational elements in materials has the potential to reduce fatigue-related maintenance costs, increase safety factors, and lead to truly portable structures and devices that are both stronger and lighter than would otherwise be possible. The breadth of ways to achieve active structural strengthening, ranging from large hydraulic rams stabilizing the hulls of naval vessels to tiny actuators moving around flexible objects, positions active structural strengthening to have broad impact in both military and civilian applications.

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Acknowledgments

Dorit Berlin, Gregor Kiczales, and the members of the embedded computation area at the Xerox Palo Alto Research Center provided insightful comments and suggestions. This work benefited greatly from conversations and collaborative work with Gerry Sussman, Hal Abelson, Elmer Hung, Rajeev Surati, Ron Whiken, Erik Vaaler, and others at M.I.T.

Portions of the technology and demonstrations described in this paper were developed while the author was a graduate student at the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology. Support for that laboratory's research was provided in part by the Advanced Research Projects Agency of the Department of Defense, under contract number N00014-92-J-4097.

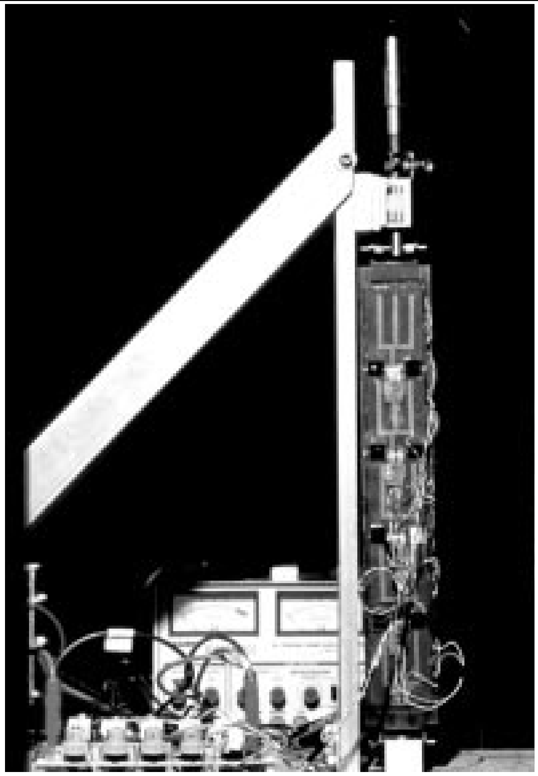

Figure 1: Actively controlled composite steel/piezo-ceramic column. Active structural strengthening enables this column to support 5.6x more load than would otherwise be possible. The column is 12.6" high, 1.78" wide, and has a steel substrate of thickness 0.010". Five pairs of 0.010" thick PZT actuators supply the control forces required to stabilize the first two buckling modes of the column.

Figure 2: . Acively Stabilized Truss Bridge. This bridge incorporates two compressive members that are actively stabilized against buckling. The bridge span is 25 inches in length.