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An Overview of Reliability Assessment and Control for Design of Civil Engineering Structures

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ABSTRACT

Random variations, whether they occur in the input signal or the system parameters, are phenomena that occur in nearly all engineering systems of interest. As a result, nondeterministic modeling techniques must somehow account for these variations to ensure validity of the solution. As might be expected, this is a difficult proposition and the focus of many current research efforts. Controlling seismically excited structures is one pertinent application of nondeterministic analysis and is the subject of the work presented herein. This overview paper is organized into two sections. First, techniques to assess system reliability, in a context familiar to civil engineers, are discussed. Second, and as a consequence of the first, active control methods that ensure "good" performance in this random environment are presented. It is the hope of the authors that these discussions will ignite further interest in the area of reliability assessment and design of controlled civil engineering structures.

1. INTRODUCTION

Technological advances over the past several decades, including the dramatic increase in computing power and development of novel sensors and actuators, have made actively controlled structural systems a reality. There are several recent books and monographs on the subject. Interested readers are directed to Housner, *et al.* (1997) and the references therein for a thorough review of the field of structural control applied to civil engineering structures.

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techniques must account for these variations during both assessment and design. This is often a difficult proposition and is the focus of many recent and current research efforts.

In the context of structural control, there are two fundamental issues. The first is stability robustness. Here, uncertainty in system parameters and time delay can destabilize an otherwise stable closed-loop system. This problem was first examined from a probabilistic viewpoint by Stengel and Ray (1991) in the context of Monte Carlo simulation and by Spencer *et al.* (1992) and Kantor and Spencer (1993) using FORM/SORM procedures. Additional work is discussed in, for example, Stengel *et al.* (1995). The second issue is control design to ensure that the closed loop system attains an acceptable level of reliability. This problem has been examined by Spencer *et al.* (1993) and Spencer *et al.* (1994) through the explicit use of reliability as a control objective.

The purpose of this paper is to provide an overview of recent work done that addresses both of these issues. The probabilistic robustness problem will be addressed first, where FORM and a probabilistic μ procedure developed by the authors are discussed and contrasted. The design problem is then examined, as a synthesis of first excursion and covariance control formulations, and strengths and shortcomings are noted.

2. RELIABILITY ASSESSMENT TECHNIQUES

When modeling active structural systems, it can be important to consider the uncertainties inherently present in the controlled structure. Figure 1, for example, illustrates the stability region of a structure with two uncertain parameters and three failure modes. The probability that all eigenvalues have real part less than zero, when considering the random nature of the input and model parameters, is indicative of the stability robustness of the system. In general, active control techniques can be applied to improve this degree of stability robustness.

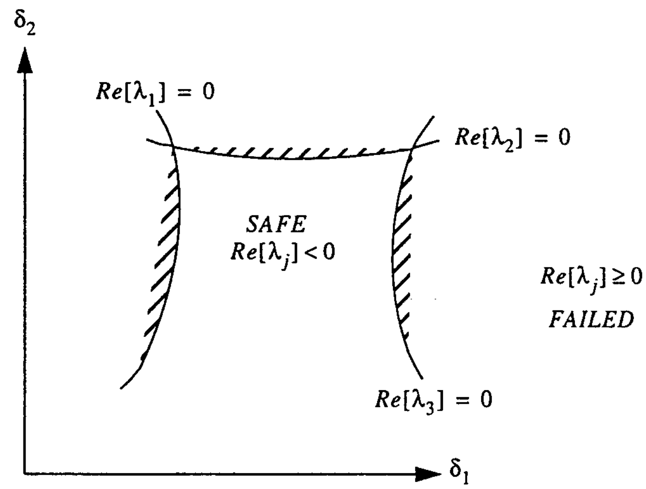

Figure 1. Stability region of three-mode system with two uncertain parameters.

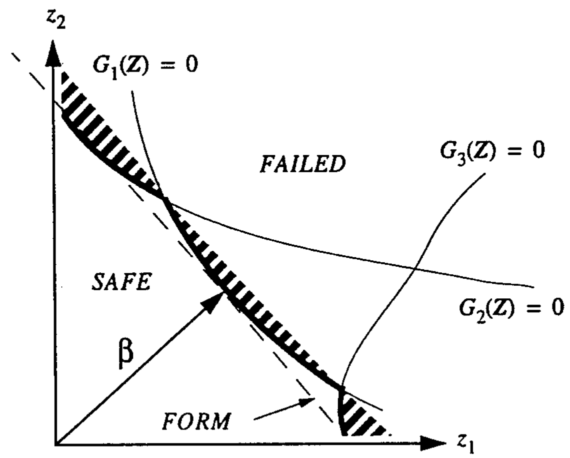

Figure 2. Illustrations of the FORM approximation.

The first-order approximation to the classical reliability problem (abbreviated FORM) is illustrated in Fig. 2 for a three-mode system with two uncertain parameters. Each of the three curves represents a single failure mode. The global failure condition is then the union of the three curves, represented by the hash marks. The reliability of the system is proportional to the index β, because this is the distance from the origin to the closest point on the failure boundary.

In Field *et al.* (1994), the authors use FORM to examine the robustness of state feedback control for an actively-controlled single degree-of-freedom (SDOF) structural system. Real, parametric uncertainty in the mass, damping, and stiffness terms was modeled with various continuous probability distributions common in reliability engineering. In addition, the feedback control signal was subject to a nondeterministic time delay, which proved to be the principle factor in determining the robustness of the closed-loop system. All analytical techniques used therein were validated through the use of Monte Carlo simulation. Similar analytical methods were applied to a distributed parameter system in Field *et al.* (1995a).

The work contained in Field *et al.* (1995b, 1996a) adopted the use of the structured singular value (μ), a method borrowed from robust control theory, to assess the robustness of the SDOF closed-loop system under this same state of real, parametric uncertainty. Much effort went into posing the small gain condition, a design technique commonly used in the robust control literature that incorporates μ into a probabilistic framework. In addition, the robustness characteristics of more advanced active control schemes, such as output feedback using the H_2 and H_∞ norms, were investigated. Results were compared with reliability estimates using the classical FORM method, and good agreement was obtained for the SDOF system. Monte Carlo simulation was again used to verify the analytical methods.

In Field *et al.* (1996b, 1996c), multiple degree-of-freedom (MDOF) structures were studied. The two reliability assessment techniques previously discussed were each found to have limitations. The FORM methodology, in which one must search a failure hypersurface of dimension equal to the number of closed-loop modes of vibration, sometimes yielded poor reliability estimates. In addition, there is no guarantee that the estimate will be conservative; it is dependent upon the sign of the curvature of the failure hypersurface at the design point. In contrast, the new method using the structured singular value is always conservative, but so much so that it may sometimes provide no useful information at all, as when it gives a unity upper bound to the probability of failure.

At the conclusion of this effort, it was apparent that efforts to design the control law to perform in the presence of these uncertainties would be the most logical direction for this work to proceed. The concept of μ-synthesis control was investigated for this very purpose. While successful (see Field *et al.* (1996b)), the controller proved to be very large and simply unimplementable for larger systems. In addition, these techniques are not optimized for civil engineering applications, where it is most common to view the problem in a probabilistic framework. As a result, alternative techniques for control design in the presence of uncertainty were investigated.

3. RELIABLE CONTROL TECHNIQUES

Control design involving eigenvalue assignment and quadratic optimization have arguably been the most popular methods for actively-controlled civil engineering systems. However, some of these methods do not explicitly address uncertainty in the input or in the model, "real world" phenomena that cannot be ignored when performing design. In addition, traditional robust control methods do not easily conform to the reliability format, perhaps the most useful framework for civil engineering applications.

Covariance control theory, introduced by Skelton and co-workers (1989, 1997), is a well-established design technique to be applied when considering systems subject to stochastic excitation. Specifically, it can be used to assign a particular covariance structure to the closed-loop state vector, where the target covariances are chosen to satisfy specified output performance requirements.

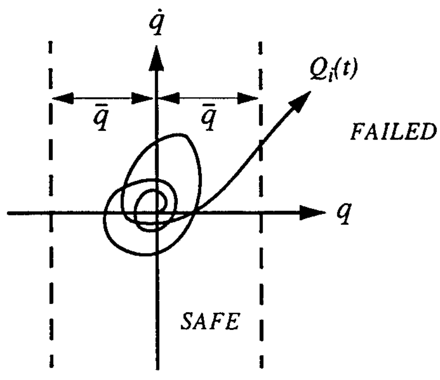

Figure 3. One realization of Q(t) outcrossing the safe domain.

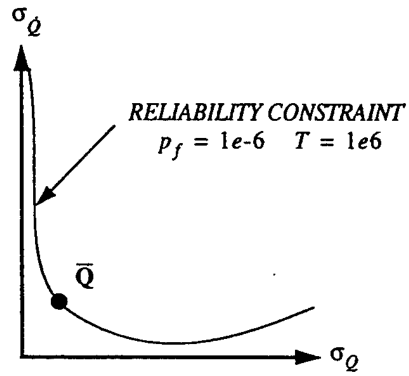

Figure 4. Design space of SDOF problem.

Assessing the reliability of a dynamic system requires one to determine the probability that the response process, $Q(t)$, here assumed to be Gaussian and stationary, will cross out of a safe region into a failure region for the first time during a finite time interval, $t \in [0,T]$. This notion of reliability is shown graphically in Fig. 3, where system failure is defined as any excursion of $Q(t)$ beyond $\bar{q}$. In Field and Bergman (1997, 1998a), it was shown that the concept of reliable control can be accomplished by exploiting the covariance structure of the state vector. This provides an ideal framework in which to apply the covariance control techniques. Previously addressed independently, their interrelationship forms the foundation of this work.

The desired degree of reliability can be shown to map to a manifold of state covariances. As an example, Fig. 4 illustrates the set of covariances that correspond to a desired level of reliability for a SDOF system; any pair of covariances on the constraint line satisfy the reliability conditions. Covariance control techniques can then be applied to determine the control law that guarantees the specified level of reliability. The technique was successfully applied to a SDOF structural system in Field and Bergman (1997, 1998a). Figure 5 shows the controlled and uncontrolled response in a framework consistent with that of Fig. 3. Note that the uncontrolled response immediately exits the safe region, whereas the controlled response remains clear of the failure boundary for the time window considered.

These methods were then applied to a MDOF system in Field and Bergman (1998a), but the algorithm proved overly restrictive. Specifically, the reliability model employed assumes classical damping, and the resulting control required an actuator for every state variable.

The most recent work, discussed in Field and Bergman (1998b), investigates an alternative reliability model for MDOF systems. Initial efforts proved to be unsuccessful because there was no intersection between the set of covariances that guarantee the specified degree of reliability and the set of covariances that satisfy the admissibility conditions for a corresponding control law. Note that this is not true in general but, unfortunately, it was for the particular example considered. One possible solution is to apply the covariance upper bound control schemes introduced in Skelton *et al.* (1997). Here, instead of prescribing specific closed-loop performance, bounds on the response are utilized. As a result, the admissibility conditions on the state covariance matrix are

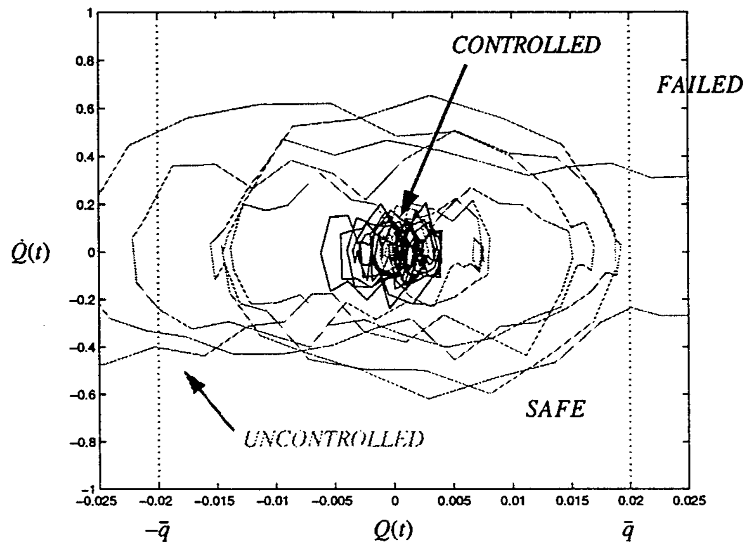

Figure 5. Phase plot of response process for SDOF example.

relaxed and a feasible solution to this problem may be attained. To proceed in this manner, however, the map between system reliability and an upper bound on the response covariance must be attained. Our efforts along these lines continue.

This method of designing a reliable control scheme exhibits certain limitations. Beyond those already mentioned, the choice of reliability model is crucial to the success of the method. For example, in Field and Bergman (1997, 1998a, 1998b), two different reliability models were investigated, but neither facilitated the use of acceleration feedback control, the most realistic output when considering civil engineering structures. In addition, the reliability models are only valid for Poisson outcrossings of the safe domain (extremely improbable events), which places huge limitations on the set of admissible covariances. As a result, an alternative reliability model which reduces or eliminates these limitations must be found. In particular, one that facilitates a convex representation of the "safe region" would be most useful.

4. CONCLUSIONS AND FUTURE WORK

The use of probabilistic methods to assess the robustness of a closed-loop structural system and to design a reliable controller has been discussed. In the case of the former, real time delay was shown to be a controlling factor, and the FORM approach was shown to be superior to probabilistic μ despite not being uniformly conservative in its reliability estimate. In the latter, state covariance assignment was utilized in conjunction with a simple first passage problem formulation to design a reliable controller for a second order system. Extension of the procedure to problems of greater complexity was shown to be difficult.

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