Students and Collaborators

There are currently 3 graduate students, 1 postdoctoral fellow, and 4 visiting scholars with Professor Ma. The research students are: Jaeseung Byun, Ritwik Ghosh, and Rubens Goncalves Salsa Junior.

Facilities and Equipment

Theoretical investigations are performed on the Berkeley campus, which has extensive library and computer facilities. Cyclic tests and other experimental investigations are conducted in the laboratories of the Pacific Earthquake Engineering Research Center in nearby Richmond.

Description of Current Research Projects

1. Coordinate Coupling in Damped Linear Systems

It is well known that an undamped linear dynamical system possesses classical normal modes, and that in each mode different parts of the system vibrate in a synchronous manner. The normal modes constitute a modal matrix, which defines a linear coordinate transformation that decouples the undamped system. This process of decoupling the equation of motion of a linear system is a time-honored procedure termed modal analysis. In the presence of damping, however, modal analysis provides a decoupling transformation only if the system is classically damped.

In the analysis of non-classically damped systems, a common procedure is to apply modal analysis and then to ignore the off-diagonal elements of the modal damping matrix. This procedure is referred to as the decoupling approximation, which amounts to neglecting coupling of the principal coordinates. Intuitively speaking, the errors of decoupling approximation should be small if either the off-diagonal elements of the modal damping matrix are small or the natural frequencies of the system are well separated. Contrary to these widely accepted beliefs, examples have been constructed in this project to demonstrate that neither of these two criteria are valid. In fact, within a practical range of engineering applications, coupling effects can even increase as the modal damping matrix becomes more diagonal or as the separation of natural frequencies increases.

The "classical decoupling problem" is concerned with the elimination of coordinate coupling in damped linear systems. It is a well-trodden problem that has attracted the attention of many researchers in the last century. In "The Theory of Sound" in 1894, Lord Rayleigh already expounded on the significance of system decoupling. However, a solution of this problem has not been reported to date.

This project has a two-fold objective. A primary purpose is to research into the characteristics of coordinate coupling through an analysis of the errors of decoupling approximation. Among other things, the effects of coupling in large-scale damped linear systems will be quantified. A secondary purpose is to devise a scheme to decouple any damped linear system. A great deal of progress has already been made in the past few years.

Coordinate coupling plays a central role not only in vibrations but also in such diverse areas as numerical linear algebra, quantum mechanics, and systems science. Characterization of coordinate coupling of linear systems can lead to fundamental advances in many areas of physical science.

2. Identification and Performance Prediction of Nonlinear Degrading Systems

All structures exhibit nonlinear behavior and degrade when acted upon by cyclic loads associated with earthquakes, high winds, and sea waves. If the restoring force is plotted against the structural deformation, degradation manifests itself in the evolution of hysteresis loops. In general, the restoring force depends not only on the instantaneous deformation but also on the history of deformation. Mechanical and structural systems capable of dissipating energy tend to possess large and non-repeating hysteresis loops. Indeed, it is commonly agreed that a measure of degradation at any time is the total energy dissipated through hysteresis prior to that time. However, a fundamental theory of the evolution of hysteresis loops has not been developed.

In the absence of a theory of hysteretic evolution, cyclic tests of structural joints and connections were extensively conducted in the past thirty years. These tests have generated a substantial amount of experimental data on load-displacement hysteretic traces for wood, steel, and concrete structures. A question naturally arises: can a model of degradation of a structure be deduced from its experimental load-displacement traces by system identification?

System identification in the time domain requires an empirical model. Empirical models are not derivable from the fundamental postulates of mechanics; they are simply constructed to match experimental observations. Many empirical models of hysteresis have been proposed in the past few decades. One of the most widely accepted empirical models of hysteresis is the generalized Bouc-Wen differential model. In this model, the restoring force and structural deformation are connected through a nonlinear differential equation containing 13 unspecified parameters. By choosing the parameters suitably, it is possible to match practically any hysteretic trace. Using techniques of nonlinear optimization, it is highly feasible to estimate the 13 control parameters of differential hysteresis from the extensive base of experimental data. A fundamental objective of this project is to do just that.

Three specific tasks will be addressed in this project. First, a robust identification algorithm will be devised to generate empirical models of degradation from experimental load-displacement data. This algorithm will be based upon the generalized differential model and the theory of genetic evolution, streamlined through sensitivity analysis. Second, it will be verified by experimentation that a model of degradation of a structure, obtained by identification, can be used to predict the future performance of the same structure. Third, a method will be developed to decompose a complex structure into a number of elementary joints and connections. Through such a decomposition, the relationship between degradation of a complex structure and the degradation of its constituent joints and connections will be explored.

The practical significance of this project cannot be over-emphasized. Through brute-force identification of hysteretic evolution or degradation, it becomes possible to assess, for the first time, the performance of a real-life structure that has previously been damaged. There is not any other method capable of predicting the response of a nonlinear degrading structure well beyond its linear range.

Selected Publications

1. F. Ma, H. Zhang, A. Bockstedte, G. C. Foliente and P. Paevere, Parameter analysis of the differential model of hysteresis, *ASME Journal of Applied Mechanics* **71**(3), 342-349 (2004).

2. F. Ma, A. Imam and M. Morzfeld, The decoupling of damped linear systems in oscillatory free vibration, *Journal of Sound and Vibration* **324**(1-2), 408-428 (2009).

3. F. Ma, M. Morzfeld and A. Imam, The decoupling of damped linear systems in free or forced vibration, *Journal of Sound and Vibration* **329**(15), 3182-3202 (2010).

4. D. T. Kawano, R. G. Salsa, F. Ma and M. Morzfeld, A canonical form of the equation of motion of linear dynamical systems, *Proceedings of the Royal Society of London A* **474**: 20170809, 14 pp. (2018).

5. R. G. Salsa and F. Ma, *Advances in the Theory of System Decoupling*, Springer, Cham, Switzerland, 169 pp. (2021).