Damper System Identification and Change Detection

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ABSTRACT

This paper provides an overview of the analytical and experimental studies that were undertaken as part of a Caltrans project focused on nonlinear viscous dampers. The goals of this research project were to perform a sequence of analytical and experimental studies designed to shed more light on the numerous challenging technical issues encountered in the characterization of the physical phenomena exhibited by nonlinear viscous dampers, with the aim of evaluating some structural health monitoring approaches. Specific tasks of this project included: (1) Performance of a sequence of experimental tests to gain insight into the most sensitive indicators of slight changes in the structural characteristics of the dampers; (2) Construction of a theoretical framework to develop nonlinear, reduced-order, high-fidelity mathematical models from experimental structural response measurements, that can be used to detect, quantify, and locate slight changes in the structural system parameters; (3) Investigation of the range of validity of nonparametric system identification techniques, such as neural networks, and their utility as a sensitive tool for detecting damage in a monitored structural damper, without any a priori information about the topology, or failure modes of the underlying structure.

Two typical nonlinear viscous dampers, one a 250 kip size and the other a 15 kip size, were tested at UCB, and the data were supplied to USC to perform detailed analyses using a variety of techniques for developing simplified mathematical models based on the corresponding damper response measures. A "smart" magneto-rheological (MR) damper was tested at USC to investigate the detectability of changes in the damper.

Two parametric (on-line and off-line), and two nonparametric (the Restoring Force Method, and Artificial Neural Networks) system identification approaches were found to be powerful tools for developing reduced order nonlinear models of the tested nonlinear dampers. Provided that the damper state variables and induced forces are available from measurements, high-fidelity mathematical models, of different forms and degrees of complexity, can be established and subsequently used for computational purposes, as well as for structural health monitoring applications.

The identification methods evaluated in this study provide an arsenal of powerful signal processing tools that offer the potential for being reliable indicators of small changes in the underlying physical damper characteristics, which can be detected through the application of real-time structural health monitoring methodologies based on vibration signature analysis.

INTRODUCTION

Large-scale dampers are being specified for incorporation into several California toll bridge retrofit strategies. The reasons are obvious; energy dissipative devices decrease both member design demands, thereby allowing a subsequent reduction in member sizes, and displacement demands, thereby eliminating impact forces. Dramatic weight and cost savings are realized based on mem-

ber size reductions.As such, the dampers are integral components of these structures. Failure of a damper can portend potentially catastrophic system failure, as the adjoining members have been sized based on the energy absorbed and displacements limited by the dampers.

The retrofit design of many toll bridges in California incorporated viscous dampers to dissipate the large energy anticipated from seismic events. Examples include the Vincent-Thomas Bridge, the Richmond-San Rafael Bridge, the San Diego-Coronado Bridge, and the San Francisco-Oakland Bay Bridge (SFOBB). Specification of these dampers was crucial to the success of the design in meeting the stipulated design criteria. Given the critical nature of the damper elements to the success of the retrofit strategies being implemented on these large-span structures, the development of analytical tools for evaluating their performance is imperative.

Several technical challenges play a major role in system identification applications to structural damage detection. For example, uniqueness and observability problems are inherent in many structural systems due to the presence of redundant structural members and limited sensor locations. In addition, the available physical measurements from the sensors always contain small amounts of noise superimposed on the desired signal. The presence of such noise can perturb the accuracy and reliability of various system identification algorithms. Finally, the available response measures of some structural systems are inherently insensitive to changes in structural parameters of interest, making it difficult to devise an adequate test arrangement. Further details about the numerous technical hurdles and potential approaches for structural health monitoring of infrastructure systems and components are available in the works of Housner et al. (1997), Sikorsky et al. (2001), Makris and Zhang (2004), and Masri et al. (2004).

Scope of Work

The collaborative research project under discussion was funded by the California Department of Transportation (Caltrans) and it was jointly undertaken by the University of Southern California (USC) and the University of California, Berkeley (UCB). The project involved a sequence of analytical and experimental studies to assess the utility of some promising structural health monitoring (SHM) approaches for application to individual viscous dampers of the type employed by Caltrans on several toll bridges.

The data analysis approaches employed state-of-the-art System Identification methods (Worden and Tomlinson, 2001). These methods can be broadly classified as parametric or nonparametric. Data collected from testing at UCB on two different dampers, were utilized to fully characterize the dynamics of the dampers, as a means of selection and optimization of the set of analytical tools previously developed.

Following is a brief overview of the three specific tasks that were accomplished as part of this research project. The first task was the responsibility of UCB, while the latter two tasks were the responsibility of USC.

Task 1: Component Testing of Dampers

The component testing of a 15 kip and a 250 kip fluid dampers were conducted at UCB. The 15 kip damper was designed to deliver a nearly linear behavior of the form $F = Csgn(\dot{x})|\dot{x}|^n$, with $n \approx 1.0$ and $C \approx 0.70$ kip sec/in, whereas the 250 kip damper tested was designed to deliver a nonlinear behavior ($n \approx 0.35$ and $C \approx 60$ kip sec/in).

The imposed displacement histories included different levels of excitation and a wide spectral content capable of exciting all the relevant system parameters within the response range of interest.

The experimental tests included:

- Sinusoidal excitation as specified in seismic design codes and testing guidelines. (BSSC, 2004; HITEC, 1996).

- Broad-band stationary random excitations, one at a relatively low amplitude level and another at a higher level.

Task 2: Development of an Accurate Mathematical Model for an Individual Damper Element

Using data from the tests as defined in Task 1, parametric as well as nonparametric approaches were employed to furnish different formats of the member's identified characteristics. Four specific approaches, two parametric and two nonparametric, were used to analyze and model the physical characteristics of the damper elements:

1. The parametric phase of this study employed an efficient technique to develop suitable nonlinear model(s) of varying degree of complexity. Among the more promising parametric models that were explored are:
   (a) An off-line parametric identification approach based on the Bouc-Wen hysteretic model (Chassiakos et al., 1998; Ma et al., 2004; Masri et al., 1980; Smyth et al., 1999, 2002).
   (b) An on-line parametric identification based on the viscous damper's design model (Ioannou and Sun, 1996; Miyamoto and Hanson, 2002; Soong and Dargush, 1997).
2. The nonparametric phase of the investigation used two approaches:
   (a) The Restoring Force Method (Masri and Caughey, 1979), whereby the effective restoring force of the element is analytically represented in terms of a doubly-indexed series of orthogonal polynomials involving appropriate basis functions that depend on the element's state variables.
   (b) Artificial neural networks consisting of three-layer feedforward nets (Masri et al., 1993).

Task 3: Evaluation of Damper Modified States

Due to practical difficulties in inducing damage states of various types in real viscous dampers, it was not feasible to utilize the UCB dampers for this phase of the study. Instead, the USC researchers employed a "smart" magneto-rheological (MR) damper to investigate the detectability of relatively small changes in the physical properties of such adaptive dampers. The corresponding dynamic response was analyzed by the USC researchers in order to establish damage detection thresholds associated with the tested MR damper.

EXPERIMENTAL SETUP FOR VISCOUS DAMPERS

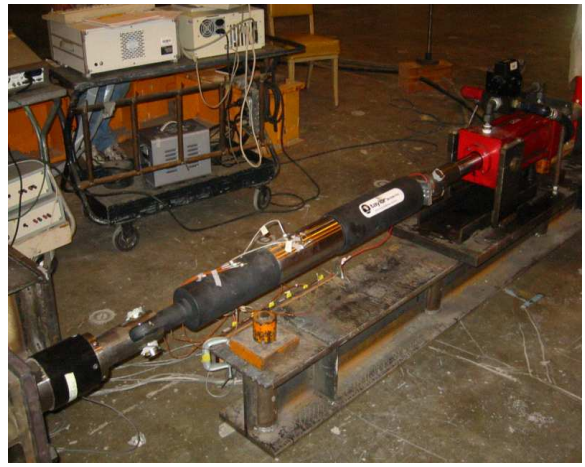
Damper Specifications

The 250 kip damper was tested at the Earthquake Engineering Research Center at the University of California, Berkeley. This damper is a sister damper of the eight dampers installed at the 91/5 overcrossing in Orange Country, California. It has a mid-stroke length of 72 in and a maximum stroke of ± 8.0 in. The 15 kip damper was also tested at the University of California, Berkeley. The 15 kip damper is a linear viscous damper with ± 6 in stroke (Chang et al., 2002). Photographs of the viscous dampers used in this study are shown in Figure 1. An MR damper test apparatus was built and tested at the University of Southern California.

Instrumentation

The 250 kip damper setup consisted of a self-equilibrating reaction frame with a 300 kip actuator equipped with a 1000 gpm proportional valve. The bolted head-piece at one end of the actuator can assume other positions to accommodate dampers with different length. In addition to the load-cell and LVDT, the damper was instrumented with six thermocouple probes along its length. The force and displacement signals were sampled at 100 Hz. The dynamic response of the 15 kip

(a) 250 kip orifice viscous fluid damper



(b) 15 kip orifice viscous fluid damper

Figure 1: The 250 kip and 15 kip orifice viscous dampers tested at the University of California, Berkeley.

Table 1: An example of test parameters for the 250 kip damper.

No	Filename	Vel (in/s)	Disp (in)	# cycles	No	Filename	Vel (in/s)	Disp (in)	# cycles
1	UCB1_10_4	10.0	4	6	9	UCB1_15_5	15.0	5	6
2	UCB1_10_5	10.0	5	6	10	UCB1_15_6	15.0	6	10
3	UCB1_10_6	10.0	6	6	11	UCB1_15_7	15.0	7	6
4	UCB1_12_4	12.5	4	6	12	UCB1_17_4	17.5	4	6
5	UCB1_12_5	12.5	5	6	13	UCB1_17_5	17.5	5	6
6	UCB1_12_6	12.5	6	6	14	UCB1_17_6	17.5	6	6
7	UCB1_12_7	12.5	7	6	15	UCB1_17_7	17.5	7	6
8	UCB1_15_4	15.0	4	6	-	-	-	-	-

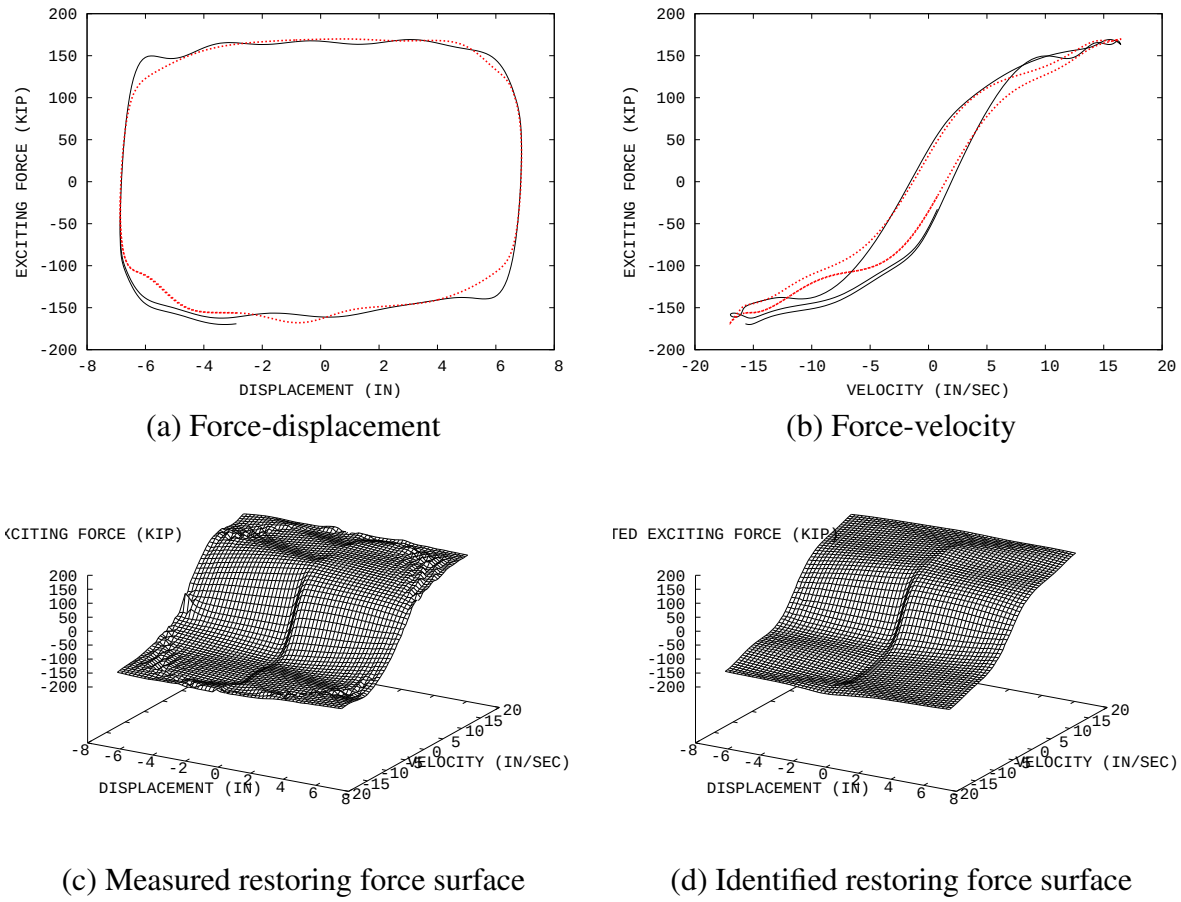
damper was instrumented with twelve transducers, measuring force, displacement, acceleration, actuator command signal, damper oil temperature, and damper surface temperature. The signals were sampled at 1000 Hz. The MR damper was instrumented with an LVDT, LVT, accelerometer, pressure gage, and a thermocouple. The signals were sampled at 500 Hz.

Test Specifications
A series of test specifications were designed for each damper. An example of the test specifications is shown in Table 1. Sinusoidal excitation tests were performed on the 250 kip damper, and broadband excitation tests were performed on the 15 kip damper and the MR damper.

DATA ANALYSIS

Identification Procedures
A variety of parametric and nonparametric modeling approaches were used to perform system identification of the tested dampers based on their experimental measurements. Specifically,

- Parametric identification approaches used (1) nonlinear optimization approaches in conjunc-



(a) Force-displacement

(b) Force-velocity

(c) Measured restoring force surface

(d) Identified restoring force surface

Figure 2: Comparison of the measured and identified (restoring force method) restoring forces of the 250 kip damper (solid line for the measured force and dashed line for the identified force).

tion with the Bouc-Wen hysteresis model, and (2) on-line identification approaches based on adaptive least-squares estimation methods, in conjunction with the conventional viscous damper design model;

- Nonparametric identification approaches used (1) the restoring force method, and (2) artificial neural networks.

Sample Identification Results

Analysis of all the available data was performed by applying the modeling techniques discussed above. The advantages and limitations of the various identification approaches were evaluated, and the different formats of the identification results were compared and contrasted in order to establish guidelines to assist users of nonlinear dampers in assessing the merits of alternative data-based modeling approaches.

Sample results of one of the data sets that was analyzed by using the restoring force method are shown in Figure 2. An example of the identification results with parametric (on-line and off-line) and non-parametric (the restoring force method and the artificial neural networks) identification techniques for the 250 kip damper are also shown in Table 2.

Table 2: The normalized mean-square fit errors (%) of different identification techniques for the 250 kip damper.

No	Test name	Identification Technique			
		On-line (%)	Off-line (%)	RFM (%)	ANN (%)
1	UCB1_10_4	11.05	7.28	5.52	1.19
2	UCB1_10_5	8.29	3.76	2.82	3.57
3	UCB1_10_6	7.03	8.03	7.63	4.04
4	UCB1_12_4	12.42	8.60	4.84	9.36
5	UCB1_12_5	6.89	5.64	7.76	7.94
6	UCB1_12_6	2.66	5.63	2.27	7.28
7	UCB1_12_7	3.52	5.75	6.86	4.16
8	UCB1_15_4	11.70	6.46	9.75	1.32
9	UCB1_15_5	6.97	4.95	2.22	8.51
10	UCB1_15_6	3.48	6.48	7.19	8.01
11	UCB1_15_7	0.76	4.09	3.17	2.21
12	UCB1_17_4	9.84	3.86	4.97	5.47
13	UCB1_17_5	4.55	2.27	2.34	6.42
14	UCB1_17_6	3.38	1.45	3.58	0.00
15	UCB1_17_7	1.65	3.00	4.76	4.76

SUMMARY AND CONCLUSIONS

The goals of the project reported herein were to perform a sequence of analytical and experimental studies designed to shed more light on the numerous challenging technical issues encountered in the characterization of the physical phenomena exhibited by the viscous damper's structural components. Specific tasks of this research project included:

1. Performance of a sequence of experimental tests to gain insight into the most sensitive indicators of slight changes in the structural characteristics of the dampers.
2. Development of a theoretical framework for processing the experimental structural response measurements to obtain nonlinear, reduced-order, high-fidelity mathematical models which can be used to detect, quantify, and locate slight changes in the structural system parameters.
3. Investigate the range of validity of nonparametric system identification techniques, such as neural networks, and their utility as a sensitive tool for detecting damage in a monitored structural damper, without any a priori information about the topology or failure modes of the underlying structure.

To accomplish the goals of the project, two typical nonlinear viscous dampers, one a 250 kip size, and the other a 15 kip size, were tested at UCB, and the data were supplied to USC to perform detailed analyses using a variety of techniques for developing simplified mathematical models based on the corresponding damper response measurements.

USC also used an adaptable ("smart") magneto-rheological (MR) damper to generate vibration measurements corresponding to modified damper characteristics, which were used to mimic changes in the damper vibration signature. The nonparametric data analysis tools that were evaluated in conjunction with the nonlinear viscous dampers, were subsequently used to detect and quantify the level of observed changes in the MR damper vibration signature.

Findings

Two parametric (one on-line and the other off-line), and two nonparametric (the Restoring Force Method, and Artificial Neural Networks) system identification approaches are found to be powerful tools for developing reduced order nonlinear models of the tested nonlinear dampers. Provided that the damper state variables and induced force are available from measurements, high-fidelity mathematical models, of different forms and degrees of complexity, can be established and subsequently used for computational purposes, as well as for structural health monitoring applications.

Due to the fact that the class of dampers under investigation consists of essentially a uniaxial member whose force-deformation characteristics can be accurately and completely defined once the underlying state variables are obtained, the uncertainty bounds on the detected changes in such measurements are quite small. Hence, the methods provide an arsenal of powerful signal processing tools that offer the potential for being reliable indicators of small changes in the underlying physical damper characteristics, which can be detected through the application of real-time structural health monitoring methodologies based on vibration signature analysis.

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