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Improving an Experimental Test Bed with Time-Varying Parameters for Developing High-Rate Structural Health Monitoring Methods

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Abstract

With the development of complex structures with high-rate dynamics, such as space structures, weapons systems, or hypersonic vehicles, comes a need for real-time structural health monitoring (SHM) methods. Researchers are developing algorithms for high-rate SHM methods, however, limited data exists on which to test these algorithms. An experimental test bed to simulate high-rate systems with rapid parameter changes was previously presented by the authors. This paper expands on the previous work. The initial configuration consisted of a cantilevered steel beam with a cart-roller system on a linear actuator to create an adjustable boundary condition along the beam, as well as detachable added masses. Experimental results are presented for the system in new configurations during various parameter changes. A clamped-clamped condition to increase the system's natural frequencies is studied, along with improvements in test repeatability and user control over parameter changes.

Keywords

Time-varying systems, Testbed, Structural health monitoring, SHM, Damage detection, High-rate state estimation

Disciplines

Civil Engineering | Structural Engineering

Comments

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Chapter 1
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Abstract With the development of complex structures with high-rate dynamics, such as space structures, weapons systems, or hypersonic vehicles, comes a need for real-time structural health monitoring (SHM) methods. Researchers are developing algorithms for high-rate SHM methods, however, limited data exists on which to test these algorithms. An experimental test bed to simulate high-rate systems with rapid parameter changes was previously presented by the authors. This paper expands on the previous work. The initial configuration consisted of a cantilevered steel beam with a cart-roller system on a linear actuator to create an adjustable boundary condition along the beam, as well as detachable added masses. Experimental results are presented for the system in new configurations during various parameter changes. A clamped-clamped condition to increase the system's natural frequencies is studied, along with improvements in test repeatability and user control over parameter changes.

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1.1 Introduction

There are a growing number of advanced structures in dynamically harsh environments, such as hypervelocity air vehicles, space structures, and weapon systems. These structures can experience high speed impacts (>4 km/s) that result in damage propagating through the structures in microseconds [1, 2]. These applications have fueled interest in developing structural health monitoring (SHM) and damage prognosis methods for rapidly changing, time-varying systems [3–8]. These methods could calculate the location and severity of damage and determine what actions are required on timescales too small for human decision making.

Sufficient data pertaining to these rapidly changing systems is limited. Such data is needed for developing these SHM techniques and gain insight into structural damage. In order to address this absence, an experimental test bed is developed that allows for examination of multiple configurations for an example system. The DROPBEAR (Dynamic Reproduction of Penetrator Ballistic Environments for Advanced Research) is an experimental test bed capable of generating data for model-based estimators of rapidly changing, time-varying systems. The test bed is shown in Fig. 1.1. The system consists of a rectangular steel beam with several mechanical parameters that can be changed during the system response. The base cantilevered beam utilizes detachable electromagnets to add additional mass to any desired location along the beam's length. The electromagnets can be disengaged quickly to simulate a sudden detachment of a system component. The DROPBEAR

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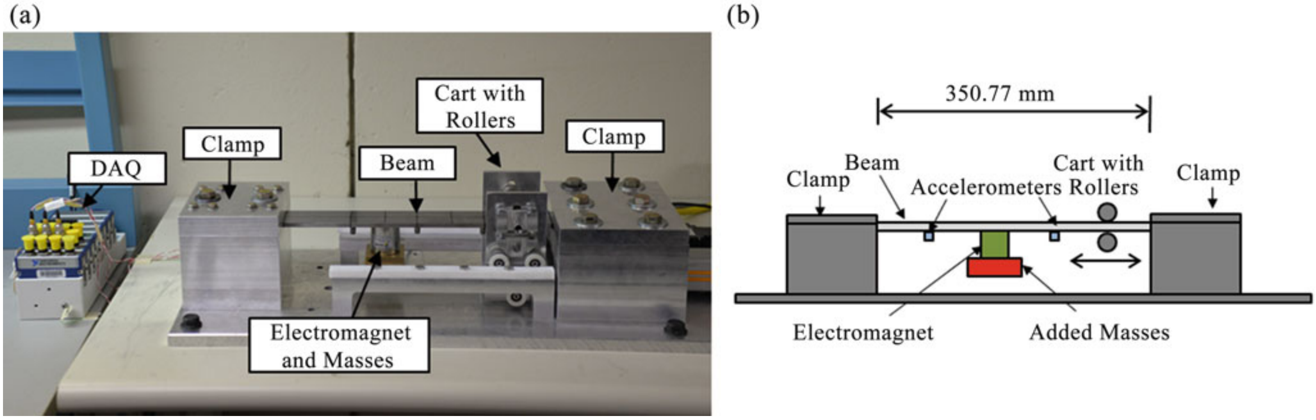

Fig. 1.1 Cantilever configurations for the DROPBEAR test bed. (**a**) and (**b**) show a photo and a schematic of the clamped-clamped beam with detaching electromagnet and rolling cart

also features a sliding cart on an actuator capable of acting as a pinned condition at a specific position on the beam. The sliding cart can be utilized in the same manner as a stationary pin or a moving pin after beam excitation. The electromagnet's attachment and the cart's position can be used as fixed parameters or as variable parameters at any time during testing. The versatility of both components coupled together provides an array of repeatable, fixed or variable testing configurations. Previous results have been presented on the beam in a clamped-free (cantilever) boundary condition [9]. The primary motivation for changing the boundary condition of the experiment is to increase the natural frequency of the system, and then illustrate faster changes in mechanical responses when the time-varying parameters occur. This extended abstract discusses the beam setup in a clamped-clamped boundary condition, which increased the natural frequencies of the system.

This paper focuses on the experimental setup, testing, and data analysis of the DROPBEAR in the clamped-clamped condition employing the lumped mass characterization. The frequency response functions of the beam are collected and analyzed in different experimental configurations to ultimately compare the response to analytical and finite element models. Comparison to these models verifies that the test bed is repeatable and reliable while providing a reference for any discrepancies experienced in the system's response. The objective is to capture data from the time-varying, rapidly changing configurations to analyze the response and develop models that can estimate system parameters and lead to damage detection.

1.2 Added Mass Experimental Setup and Test Procedure

The basic structure of the test bed features a large, rectangular aluminum plate fastened to a tabletop. This plate serves as the mounting base for the clamp housing in which the steel beam is secured. For these tests the cart with rollers was removed. The steel beam is 51 mm (2 in.) wide with a free length of 350.77 mm (13.81 in.) at a thickness of 6.3 mm (0.25 in.). Two single-axis PCB 353B17 accelerometers were attached to the beam at 87.63 mm (3.45 in.) and 219.2 mm (8.63 in.), from the primary clamp, as highlighted in Fig. 1.1b. The accelerometers were connected to a NI-9234 IEPE analog input module seated in a National Instruments (NI) cDAQ-9172 eight-slot chassis. The chassis was connected to a computer to acquire the generated signals via NI LabVIEW. A PCB 086C01 modal hammer was used to excite the beam at a desired location along the beam length. The hammer was equipped with various options for strike tips ranging from soft rubber to steel to vary the impulse provided to the beam. The hammer was connected to the chassis through the same NI-9234 module enabling impulse input data to be collected and analyzed. A LabVIEW program acquired and saved response data from all three sensors. MATLAB was employed for post-processing and generating frequency response functions (FRF).

The clamped-clamped configuration was tested in multiple configurations including pinned and added mass configurations. The clamped-clamped configuration with no added mass and with added mass near the tip of the beam is presented here. The added mass consisted of the electromagnet (weighing 0.259 kg). The beam was struck by the modal hammer in five locations measured from the beam base at the primary clamp at 87.6 mm (3.45 in.), 131 mm (5.16 in.), and 175.3 mm (6.9 in.), 219.2 mm (8.63 in.), and 262.9 mm (10.35 in.). For brevity, only the results from the impact at 262.9 mm (10.35 in.) and the tip accelerometer are used here. The beam was struck five times per test with ample time between each strike to observe the full decay in the response.

1.3 Added Mass Results

For mass configuration, the natural frequencies predicted by an analytical model and a finite element model are validated against natural frequencies calculated frequency response functions (FRFs) derived from experimental data. The natural frequencies were estimated against a finite element model capturing the clamped-clamped conditions of the beam.

A finite element of the beam with mass and variable cart position was derived from Euler's beam equation of motion using cubic Hermite polynomials [10]. A MATLAB script forms the mass and stiffness matrices, computes the natural frequencies and mode shapes, and calculates the frequency response functions for various impact and measurement locations. The finite element model accounts for the magnet as additional masses and rotational inertia terms at the degrees of freedom of the beam where the magnet attaches.

The experimental, time-domain data was processed in MATLAB to compute the FRF using the H_v estimation and the coherence [11, 12]. Figure 1.2 plots the FRFs and coherence near the first natural frequencies from experimental data alongside the FRF determined by the finite element model. The FRFs from the model and the data show good agreement. Adding mass decreases the natural frequencies as expected.

The first four natural frequencies are listed for no added mass in Table 1.1 and for the electromagnet mass in Table 1.2. For the bare beam with no added mass, the models show a good agreement (less than 2% error) with the experimentally obtained natural frequencies of the beam. Adding the electromagnet decreases all of the natural frequencies as expected. For the first three modes, the added mass model still had good agreement (less than 3% error), but there quickly started to be discrepancies at the higher modes (greater than 9% error). In the finite element model, the added mass is distributed along the elements of the beam occurred by the magnet (a diameter of 40 mm). The natural frequency estimates from the distributed mass of the finite element model produces a closer estimate to the experimental values compared to the results from the analytical model with lumped mass at the tip. It should be noted that model updating could be used to refine parameters and produces more accurate estimates of the natural frequencies. The small errors between the experimental and finite element natural frequencies indicate the model captures the behavior of the baseline system with fix parameters and could predict the beam's response once the mass detaches.

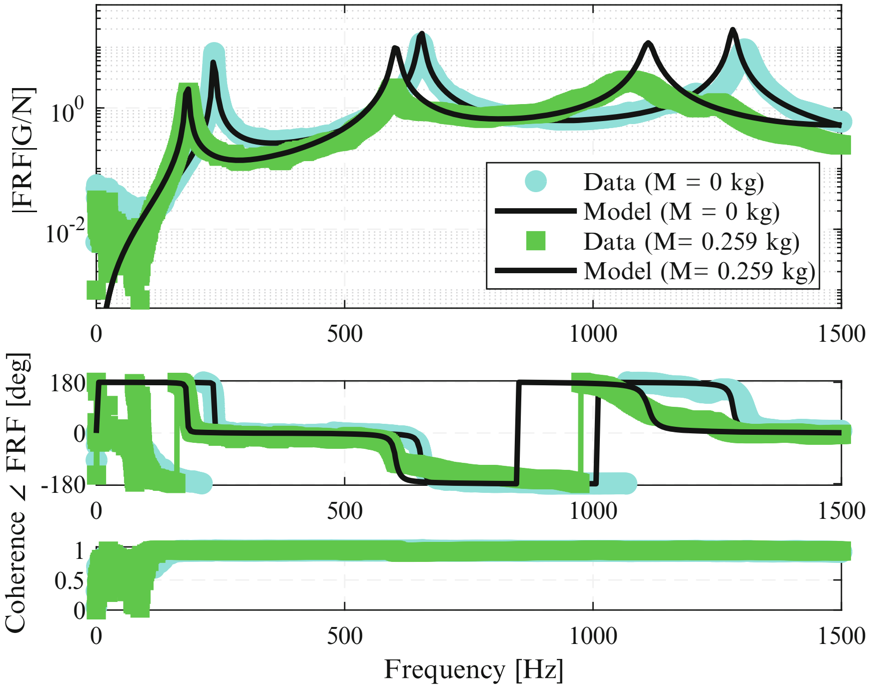

Fig. 1.2 Comparison of frequency response functions (FRF) between the beam without added mass ($M = 0$ kg), and with the mass of the electromagnet ($M = 0.259$ kg). Data is from the accelerometer at 87.63 mm (3.45 in.) and impacts at 262.89 mm (10.35 in.) from the base. The model FRFs are from the finite element model

Table 1.1 Comparison between theoretical and finite element frequencies for the bare beam with no added mass ($M = 0$ kg)

	Experimental	Finite element	
Mode	Natural frequency [Hz]	Natural frequency [Hz]	Percent error (%)
1	237.3	237.2	0.04
2	654.7	653.8	0.14
3	1306	1281.7	1.86
4	2255	2118.8	6.04

Percent errors are relative to the experimentally obtained natural frequencies

Table 1.2 Comparison between theoretical and experimental frequencies for the beam with the electromagnet near the beam tip with mass ($M = 0.259$ kg)

	Experimental	Finite element	
Mode	Natural frequency [Hz]	Natural frequency [Hz]	Percent error (%)
1	186.1	182.9	1.72
2	589.5	602.7	−2.24
3	1070	1111.1	−3.84
4	1922	1744.7	9.22

1.4 Static Cart Experiments

The cart with rollers was re-attached to the beam, as seen in Fig. 1.1a, b. The As the rollers moves along the beam, they create a moving pinned condition along the span of the beam. The beam was tested with several static configurations of the cart with rollers.

1.5 Conclusions and Future Work

There is a need for an experimental test bed for developing and demonstrating high-rate damage detection methods for the advancement of structural health monitoring. The DROPBEAR serves as a unique test bed capable of producing repeatable, time-varying system conditions that can assist in evolving state estimators for a highly dynamic environment. The finite element model showed good agreement to the experimentally obtained natural frequencies of the system with clamped-clamped boundary conditions and varying masses.

Future results presented will discuss the clamped-pinned-clamped conditions and the time varying conditions (mass drop and rolling pin) for the clamped-clamped boundary condition. This array of future experiments will capture response data for a multitude of conditions and parameter changes. This data will guide developing and testing algorithms for state estimation, system identification, and damage detection. The test bed's future in testing new, variable configurations offers encouraging potential for the progression of high-rate state and parameter identification methods.

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