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Excitation design for damage detection using iterative adjoint-based optimization—Part 2: Experimental demonstration

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ABSTRACT

The iterative, adjoint-based excitation optimization technique developed in Part 1 is evaluated on an experimental structure consisting of a non-linear cantilever beam. The developed technique is shown to be effective at producing excitations which significantly improve the detectability of damage relative to two different "naive" excitations (a random input and a chirp). The technique is also demonstrated to be effective across multiple damage levels. In addition, by formulating a second-order version of the adjoint problem, it is shown that the terms needed to solve the associated adjoint equation are readily available from many commercially available finite element packages, which further enhances the usability of the technique.

1. Introduction

In Part 1 [1] of this two-part paper, a technique was developed to optimize the excitation to a system for the purpose of making damage most visible. In this second part, the focus is on experimental validation of the developed technique on a structural system. In addition, a second-order version of the adjoint problem is formulated. Through this formulation, it is easily seen that the mass, damping, and tangent stiffness matrices are the only terms needed for the solution of the adjoint system. These matrices are calculated automatically by most commercial finite element codes, which enhances the usability of the developed technique.

One of the conjectures made in Part 1 was the robustness of the technique to modeling errors. The specific topic of robustness is not directly addressed in this paper. However, the experimental validation of the developed techniques is very important, because it lends support to this conjecture and demonstrates that the technique can be used in the real world, where modeling errors are inevitable.

The remainder of this paper describes the experimental setup, develops the appropriate adjoint problem for the excitation optimization, and presents the experimental results.

2. Experimental setup

The experimental setup consists of a non-linear cantilever beam, shown in Fig. 1. The beam, made from 6061 aluminum, is 381 mm long, 50.8 mm wide, and 2.29 mm thick. The nonlinearity is introduced through a set of neodymium magnets at the free end of the beam (region 1 in Fig. 1). A close up view of the magnets, with polarity annotations, is shown in Fig. 2.

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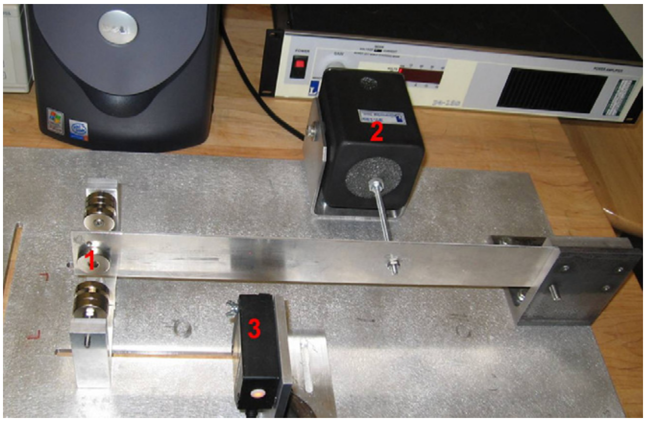

Fig. 1. Experimental setup.

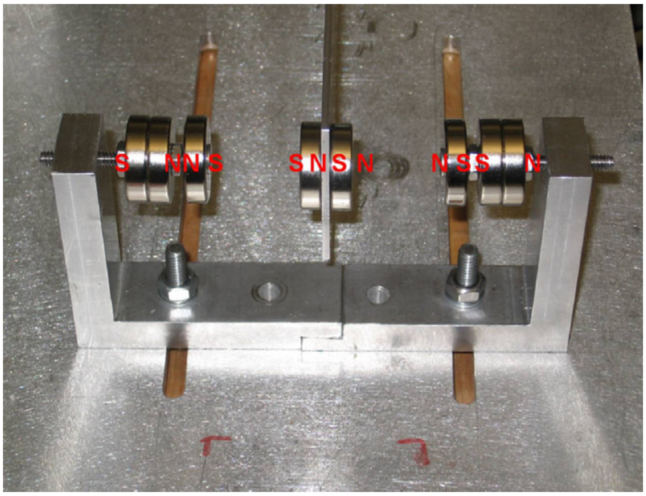

Fig. 2. Magnet configuration and orientation.

The magnets are arranged such as to create the effect of a stiffening spring between the free end of the beam and ground. As is discussed below, the magnets introduce a linear stiffness term in addition to non-linear terms. The purpose of the two magnets furthest from the beam and their associated orientation is to minimize this linear term. Damage is simulated by moving the magnets connected to ground further away from the beam. This has the effect of decreasing the stiffening effect. Excitation to the beam is provided by an electrodynamic shaker (region 2 in Fig. 1) located 130.5 mm from the clamped end. Beam deflection approximately half way in between the point of excitation and the free end of the beam is measured with a laser displacement sensor (region 3 in Fig. 1). The reason for choosing this location for measuring the displacement is due to the range and resolution of the laser displacement sensor. Thus, the goal of the excitation design is to provide an excitation that causes the undamaged and damaged measured displacements to be as different as possible.

3. Adjoint model development

The beam is modeled as an Euler–Bernoulli beam, and is governed by the familiar equation

$$\frac{d^2}{dx^2}\left(EI\frac{\partial^2 u}{\partial x^2}\right) + \rho A\frac{\partial^2 u}{\partial t^2} = 0$$

$$u(0,t) = \frac{\partial u}{\partial x}(0,t) = 0$$

$$\frac{d}{dx}\left(EI\frac{d^2 u}{dx^2}\right)\bigg|_{x=x_s} = f(t)$$

$$\frac{d}{dx}\left(EI\frac{d^2 u}{dx^2}\right)\bigg|_{x=L} = k_{nl_1}u(L,t) + k_{nl_3}u(L,t)^3 + k_{nl_5}u(L,t)^5$$