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Phase influence of combined rotational and transverse vibrations on the structural response

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ABSTRACT

The planar dynamic response of a cantilever metallic beam structure under combined harmonic base excitations (consisting of in-plane transverse and rotation about the out-of-plane transverse axis) was investigated experimentally. The important effect of the phase angle between the two simultaneous biaxial excitations on the beam tip displacement was demonstrated. The experiments were performed using a unique six degree-of-freedom (6-DoF) electrodynamic shaker with high control accuracy. The results showed that the beam tip displacement at the first flexural mode was amplified when the phase angle between the rotational and translational base excitations was increased. The beam nonlinear stiffness, on the other hand, simultaneously: (i) decreased due to fatigue damage accumulation, and (ii) increased due to an increase in the phase angle. The results were compared to the uniaxial excitation technique, where the principle of superposition was applied (mathematical addition of the structural response for each uniaxial excitation). The principle of superposition was shown to overestimate the structural response for low phase angles. Thus, the application of the superposition vibration testing as a substitute for multiaxial vibration testing may lead to over-conservatism and erroneous dynamic and reliability predictions.

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1. Introduction

The reliability of mechanical systems exposed to complex vibration environments depends primarily on the structural dynamic response of the systems internal components. Designers rely on the use of vibration isolators, stiffeners and dampers to reduce the propagation of stresses from the system level to the component level, without full understanding of the dynamic loads being transmitted through the system. Uninformed use of vibration isolators, stiffeners, and dampers is inadequate for sustaining the desired life-cycle of the structure. There are two major reasons for applying these conventional strategies during the design process. First, the cost and time limitations often drive designers to employ linear modeling tools to estimate the durability of products [1]. Linear models produce inaccurate estimates of the structural dynamics of nonlinear systems exposed to sufficiently high amplitude oscillations [2,3]. Realistically, flexible bodies such as aircraft

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wings, helicopter blades, and robotic limbs are inherently nonlinear structures and consequently, linear models are of limited value. Second, designers often have limited understanding of how the nonlinear response of a component is worsened in a complex multiaxial vibratory environment [2–4].

Systems exposed to multiaxial vibration conditions experience synergistic dynamic nonlinearities due to cross-axes coupling, which can be challenging to reproduce a laboratory environment [4,5]. The dynamic response predictions under multiaxial dynamic loading have been shown to be complex and financially less tractable than uniaxial models [2–5]. Multiaxial shakers can be difficult to develop and use, thus, engineers apply sequential uniaxial vibration testing to a component along three orthogonal axes then superimpose the responses [6]. In fact, military and commercial standards have adopted sequential uniaxial testing as a compromise for simultaneous multiaxial excitation [3]. One of the highly used methods in the electronics industry for identifying product weaknesses is to simulate multiaxial environments using 'High Accelerated Life Testing' (HALT©) chambers [7–10]. The HALT method simulates random vibration spectrums by inducing random repetitive shocks on the shaker table, using multiple pneumatic impact actuators with various orientations located at different locations beneath the shaker table [7]. The vibration spectrum shape is unique to each shaker design and is not fully controllable. The shaker table total RMS spectrum is usually the only input parameter that can be adjusted [8]. The response along the other axes therefore varies in some proportional manner but is not independently controllable [3,7].

In spite of the challenges stated above, the multiaxial vibration field has gained significant attention over the past few years. Peer-reviewed journal publications have surged from an average of two articles per year from 1988 to 2005 to more than ten articles per year after 2010, as shown in Fig. 1, based on the data obtained from the Web-of-Science™ Core Collection, the Korean Journal Database, and the Institute of Engineering and Technology (IET) Inspec™. The annual citations have surged in recent years, as shown in Fig. 2. The top publishing journals for multiaxial vibrations are listed in Fig. 3.

Our literature review was focused on multiaxial vibration testing using multiaxial electrodynamic shakers. Studies evaluating the merits of multiaxial excitation using electrodynamic shakers are limited [2,4–6,11–19]. These studies have shown evidence of different failure modes for structures exposed to uniaxial and multiaxial vibration loading using multiaxial shakers. Whiteman and Berman performed sequential uniaxial random vibration experiments in three orthogonal axes on notched aluminum cantilever rods and compared the results to simultaneous triaxial excitation [11]. French et al. performed durability experiments on notched aluminum beam specimens using both sequential uniaxial and simultaneous biaxial testing on a hydraulic triaxial shaker [12]. Both Whiteman and Berman, and French studies showed that sequential uniaxial and simultaneous multiaxial vibration experiments produced different damage accumulation rates and different failure modes.

To the best of our knowledge, Gregory et al. were the first to publish a detailed evaluation of a multi-(six) degrees-of-freedom (MDoF) electrodynamic shaker. In their study, they utilized an MDoF shaker to perform dynamic characterizations of a short vertical cantilever beam with a large tip mass [13]. The beam was subjected to uniaxial and multiaxial broadband random excitations with a bandwidth of 20–2000 Hz at low acceleration spectrum density (ASD) input level of 0.0032 g^2/Hz. The experimental results showed significant differences in the beam response for uniaxial and multiaxial excitations. Smallwood used the study performed by Gregory et al. to propose a methodology for generating a spectral density matrix for multiple inputs and multiple outputs (MIMO) vibration test and specification guidance for multiaxial vibration testing [14,15]. Kim et al. improved the accuracy of vibration fatigue testing of automotive components by generating the driving profiles using multiaxial vibration table [16]. Aykan et al. observed improvements in the accuracy of vibration fatigue analysis of a rotorcraft structure when they included the effects of MDoF testing [17]. Dimitrov developed a probabilistic model based on multiaxial dynamic load combinations obtained from a wind turbines which appeared to deviate from the superposition models [18]. Jacobs et al. experimentally compared the structural response of a plate exposed to six-axis and single axis random vibration tests [6]. It was observed that the plate principle axis orientation was the single largest factor influencing the dynamic response. Ernst et al. experimentally and computationally investigated the synergy between axial and transverse excitation on the reliability of heavy electronic components with high standoffs [4,5]. The study revealed the presence of nonlinear dynamic coupling among high-energy modes due to simultaneous biaxial transverse random vibration base excitation. The combination of inertial nonlinearity due to the component heavy mass and fatigue damage accumulation in the system produced dynamic softening [4]. Thomas et al. observed similar softening behavior in cantilever beams exposed to nonlinear rotational vibrations [19].

The limited understanding of the structural dynamic response of increasingly complex electro-mechanical systems and the growing demand for unmanned systems for military and civilian applications instigated our MDoF research effort. The dynamic responses of those highly nonlinear systems are influenced by the phase relationship in multiaxial vibratory loading conditions. Thus, the main focus of the study is to understand the effect of the phase angle variation between the different axial excitation in MDoF environments on the structural dynamic response and fatigue accumulation. To the best of our knowledge, this study is the first to ascertain the differences in the response of a cantilever beam structure exposed to three types of harmonic excitations: (1) single transverse base vibration, (2) single rotation base vibration, and (3) combined rotation and transverse with varying phase angle. Thus, a state-of-the-art fully controllable electrodynamic multiaxial excitation shaker was utilized for conducting the experiments. Several isotropic short metallic slender cantilever beam specimens were exposed to the three harmonic excitations. The main concern in this investigation was the beam first mode response (flexural mode). Thus, the combined rotation and transverse harmonic vibration base inputs were controlled to ensure that only the beam's flexural mode (in-plane bending) was excited. The flexural mode frequency was identified experimental using sine sweep prior to each test. In the combined multiaxial loading, the phase angle between the rotation and transverse base excitations was varied from 0° to 135°. The experimental results revealed the importance of the phase