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Vibration fatigue tests by tri-axis shaker: design of an innovative system for uncoupled bending/torsion loading

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Abstract

An innovative system for bending-torsion fatigue tests by tri-axis shaker is designed and presented. The system mounts a cylindrical specimen with eccentric tip mass, excited by horizontal and vertical base accelerations. A lateral thin plate prevents specimen horizontal displacement and allows torsional and bending deformations to be controlled independently. A lumped-mass model is first used to verify if input accelerations and resultant dynamic forces, required in testing, comply with shaker specifications. A finite element model is then used to perform both modal and harmonic analyses, necessary to determine the system natural frequencies and the dynamic response under horizontal and vertical accelerations. Experimental measures on a prototype are finally used to gather preliminary information for validating the numerical model and to verify that the proposed testing system can control bending and torsion loadings independently.

Keywords: tri-axis shaker; vibration testing; uncoupled bending/torsion loading; multiaxial fatigue; system design

1. Introduction

Multiaxial random fatigue loadings are very common in vibrating structures and components. Fatigue life can profitably be estimated by spectral methods defined in frequency domain (Benasciutti and Tovo (2005), (2006)). Over the last decades, a number of methods has been proposed to analyze Gaussian and non-Gaussian stationary uniaxial and multi-axial random loadings, with narrow-band or wide-band frequency content (Benasciutti and Tovo

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(2005), (2006), (2016)). Despite great improvements in theoretical and numerical investigations, experimental laboratory tests still remain an important step to check the accuracy of spectral methods against experimental data, as well as to perform full-scale durability tests that resemble actual service conditions very closely.

Laboratory tests with multiaxial random loading generally apply an imposed force or displacement (e.g. by a servo-hydraulic machine), or a base acceleration by a shaker (thus allowing for higher testing frequencies). Various testing methodologies that differ by testing machines, specimen geometry and type of excitation have been proposed in the literature. Servo-hydraulic machines usually adopt cylindrical specimens, whereas shakers range from simple (plate, cylindrical) to more elaborated specimens (Y-geometry), which are usually fixed to the shaker table and excited by a base acceleration.

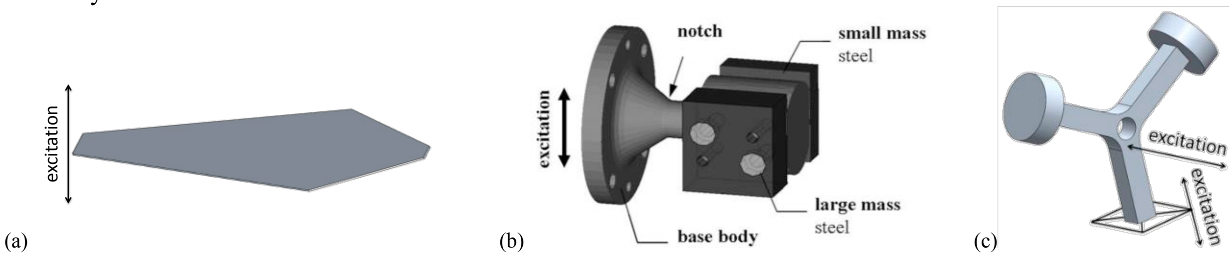

Fig. 1. (a) trapezoidal plate specimen; (b) cylindrical specimen with eccentric tip mass; (c) Y-specimen

Plate specimen with square or rectangular shape (often with lateral notches), excited at resonance by base vertical acceleration, represent the simplest and cheapest layout to realize a bending loading (uniaxial stress) (Ghielmetti et al. (2011), Khalij et al. (2015), Ellyson et al. (2017)). A “trapezoidal” plate specimen (Fig. 1a) was used, instead, for in-phase biaxial bending (with stress ratio $\sigma_y/\sigma_x \cong 0.59$) to simulate turbine blades response at resonance (George et al. (2004)). The stress ratio depends on the specimen geometry and cannot be changed. A biaxial normal stress was also obtained by a thin cruciform specimen used in (Łagoda et al. (2000)). With plate specimens, obtaining a torsion loading is yet not possible.

Cylindrical specimens (smooth, notched or with transverse holes) were adopted in different studies (Łagoda et al. (2005), Niesłony et al. (2012), Kim et al. (2011)). The layout in Kim et al. (2011) allows for simple bending when the specimen mounted on a shaker is excited by a base vertical acceleration. Two shakers controlled independently are used in Łagoda et al. (2005) to apply bending, torsion or both (with any correlation), their relative intensities being controlled by the amount of load eccentricity with respect to the specimen axis. Instead, in Niesłony et al. (2012), a servo-hydraulic multiaxial testing machine was used to apply bending-torsion loading.

An interesting layout for bending-torsion loading by shaker was proposed in Nguyen et al. (2011): a cantilever cylindrical specimen with two tip masses, and resonating under a base vertical (uniaxial) acceleration. The free specimen extremity mounts two unequal masses (i.e. an eccentric net mass), whose barycenter is not aligned with the specimen axis (Fig. 1b). This eccentricity then allows for torsion loading, even when the specimen is excited by uniaxial vertical acceleration. The intensity of bending loading is controlled by the mass value, the intensity of torsion loading by the eccentricity value (zero eccentricity would give simple bending, with no torsion). The only restriction is that torsion is always coupled with bending, i.e. it is not possible to have only torsion without bending.

A certainly more elaborated, yet less cheap, testing layout is the Y-specimen designed in Česnik et al. (2012). The specimen has a central hole and two tip masses and it develops a multiaxial stress when subjected to horizontal and vertical base excitation. The relative amount of shear-to-normal stress ratio is, however, predetermined by the specimen geometry and cannot be changed arbitrarily.

Among all those surveyed above, the layout proposed by Nguyen et al. (2011) sounds very promising, as it allows for bending-torsion random loading by vertical acceleration imposed by a uniaxial shaker. The only limitation is that torsion cannot be uncoupled from bending. The aim of the present paper is to design a testing system that, when excited by a tri-axis shaker, induces a fully uncoupled bending and torsion loading. The system can apply either bending or torsion, or both with any prescribed phase shift. Starting from the layout in Fig. 1b, the idea is to introduce a thin plate at the specimen free extremity to prevent the bending deformation when the specimen is loaded in torsion (see Fig. 2).