Journal of Sound and Vibration 419 (2018) 337–351

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Identification of biomechanical nonlinearity in whole-body vibration using a reverse path multi-input-single-output method

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ARTICLE INFO

Article history:
Received 24 July 2017
Received in revised form 10 December 2017
Accepted 4 January 2018

Keywords:
Whole-body vibration
Biomechanics
Nonlinear dynamics
Multi-input-single-output

ABSTRACT

The study implements a classic signal analysis technique, typically applied to structural dynamics, to examine the nonlinear characteristics seen in the apparent mass of a recumbent person during whole-body horizontal random vibration. The nonlinearity in the present context refers to the amount of ‘output’ that is not correlated or coherent to the ‘input’, usually indicated by values of the coherence function that are less than unity. The analysis is based on the longitudinal horizontal inline and vertical cross-axis apparent mass of twelve human subjects exposed to 0.25–20 Hz random acceleration vibration at 0.125 and 1.0 ms^{-2} r.m.s. The conditioned reverse path frequency response functions (FRF) reveal that the uncorrelated ‘linear’ relationship between physical input (acceleration) and outputs (inline and cross-axis forces) has much greater variation around the primary resonance frequency between 0.5 and 5 Hz. By reversing the input and outputs of the physical system, it is possible to assemble additional mathematical inputs from the physical output forces and mathematical constructs (e.g. square root of inline force). Depending on the specific construct, this can improve the summed multiple coherence at frequencies where the response magnitude is low. In the present case this is between 6 and 20 Hz. The statistical measures of the response force time histories of each of the twelve subjects indicate that there are potential anatomical ‘end-stops’ for the sprung mass in the inline axis. No previous study has applied this reverse path multi-input-single-output approach to human vibration kinematic and kinetic data before. The implementation demonstrated in the present study will allow new and existing data to be examined using this different analytical tool.

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1. Introduction

The study applied a system identification procedure to analyse ‘paths’ that contributed to nonlinear dynamic behaviour of the human body during whole-body vibration (WBV). The nonlinearity in this context refers to the amount of ‘output’ response that is not linearly correlated to the ‘input’ excitation, usually indicated by values of the coherence function that are less than unity. This mathematical nonlinearity may be associated with the biomechanical nonlinearity, previously referred to

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https://doi.org/10.1016/j.jsv.2018.01.002
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as 'biodynamic nonlinearity', in which the resonance frequency increased with decreasing vibration magnitude [1,2]. Improved understanding of the mathematical nonlinearity may help to quantify the biomechanical nonlinearity that holds the key to dynamic response predictions at substantially different magnitudes.

Biomechanical nonlinearity has been reported in both the vertical and the fore-and-aft responses of the seated human body during vertical whole-body vibration [3], in both the fore-and-aft and vertical responses of the seated human body during fore-and-aft whole-body vibration [4,5], in both vertical and longitudinal horizontal responses of the recumbent person during vertical whole-body vibration [6], and in both longitudinal horizontal and vertical responses of the recumbent person during longitudinal horizontal whole-body vibration (see Fig. 1). With recumbent subjects, any voluntary or involuntary movement and muscular activity were assumed to be reduced compared to a seated person. Therefore, it provided a better condition to examine the 'linearity' of a dynamic system in comparison with other postures [2].

By measuring dual axial responses of seated subjects exposed to simultaneous dual axial excitation, Mansfield and Maeda [7] observed similar magnitude dependency of the resonance frequency. The additional axis of excitation had a similar effect of increasing the vibration magnitude in a single axis excitation, with a reduced resonance frequency characteristic in its apparent mass. Experimental studies like this would benefit from an analytical framework that could isolate effects of each axis of excitation on each axis of the response.

The intended procedure applied in this paper is called the reverse path nonlinear multi-input-single-output (MISO) method. It was introduced by Bendat et al. [8] and later demonstrated with implementations by Bendat and Piersol [9,10]. There are two principle steps: first, one needs to define and prepare 'mathematical' inputs, usually physical output from measurement of the structural response, and 'mathematical' output, usually the physical input excitation, in the reverse path diagram shown in Fig. 2. Secondly, one produces a formulation of the MISO system including computation of frequency response functions (FRF) based on correlated and uncorrelated (or conditioned) mathematical inputs and their coherence functions (Fig. 3).

The procedure has been widely used in structural dynamics to identify nonlinear behaviour present in flexible and slender structures. An example being the nonlinear cubic stiffening effect of a two-end-clamped mid-excited beam, characterised by two nonlinear mathematical inputs in addition to the original dynamic force input [11]. The two added inputs were the square and cubed power of the input dynamic force. With the two mathematically constructed inputs, the multiple coherence function was markedly improved, enabling a more accurate prediction model to be used for the structural response when the ordinary coherence was low.

For road-induced vehicle vibration a MISO system was employed to analyse transmissibilities of multiple acceleration inputs [12]. Instead of using arbitrarily constructed mathematical inputs, the authors used multiple channels of physical inputs – up to twelve accelerations at the four corners of the seat floor and in each of the three orthogonal directions. The method identified the dominant channels for the input acceleration in predicting the seat transmissibility.

With longitudinal horizontal random excitation of a semi-supine human body, the coherence function of the apparent mass showed a drop between 6 and 20 Hz [1]. With increasing magnitude of excitation, the frequency of the coherence drop decreased – a similar behaviour to the resonance frequency of the apparent mass between 2 and 4 Hz. It was plausible to assume that at certain frequencies a part of the output force in the inline (longitudinal) direction was transferred to the cross-axis (vertical) direction, and therefore the coherence of the inline apparent mass was low at these frequencies. However, there has been no investigation to quantify the amount of 'transferred' output force from the inline axis to the cross axis.

Most biomechanical studies of whole-body vibration have allocated any nonlinear effects at the 'output' side of a transfer function, e.g. Ref. [13]. From a system linearity point of view, it was not known whether the output could have a nonlinear feedback path to affect the linear input such as that shown in Fig. 2a. At the same time, implementing a feedback loop in the frequency response functions (FRF) involves time-consuming iterative procedures and stringent assumptions about the random distribution of the output. A 'reversed path' approach would offer a more efficient computational algorithm for FRF and coherence [9].

When using correlated inputs it is difficult to obtain separately the linear FRF, in an optimum least-squares predicted sense, between the individual inputs and the output(s). The identification method applied in the present study enables firstly a primary input to be used to estimate the first linear transfer function between itself and the output. The correlated parts of the other inputs are identified separately and are expressed in terms of linear transfer functions between the primary input and the other inputs. A calculation is then made to estimate any further linear transfer function between the uncorrelated parts of the other inputs and the output. To obtain the optimum linear transfer functions for the other inputs, there is the iterative relationship relating the subsequent transfer functions between the uncorrelated components in addition to the contribution from the correlated components. In this manner the optimum linear transfer functions between each of the inputs can be evaluated. Bendat and Piersol [9] applied this procedure to the 'Duffing' oscillator model excited by a force. The

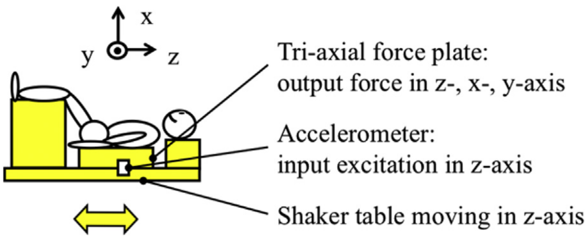

Fig. 1. Schematic experimental setup of the semi-supine human body exposed to horizontal vibration and the axes of the forces (in horizontal z-axis, vertical x-axis and lateral y-axis) and acceleration (z-axis) transducers following Huang and Griffin [1].

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