Mechanical Systems and Signal Processing 85 (2017) 162–176

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Modeling and study of nonlinear effects in electrodynamic shakers

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ARTICLE INFO

Article history:
Received 14 June 2015
Received in revised form
10 January 2016
Accepted 17 July 2016

Keywords:
Electrodynamic shaker
Nonlinear lumped parameters
Nonlinear viscoelastic model
White box model

ABSTRACT

An electrodynamic shaker is inherently a nonlinear electro-mechanical system. In this work, we have developed a lumped parameter model for the entire electromechanical system, developed an approach to non-destructively determine these parameters, and predict the nonlinear response of the shaker. This predicted response has been validated using experimental data. Through such an approach, we have been able to accurately predict the resulting distortions in the response of the shaker and other nonlinear effects like DC offset in the displacement response. Our approach offers a key advantage vis-à-vis other approaches which rely on techniques involving Volterra Series expansions or techniques based on blackbox models like neural networks, which is that in our approach, apart from predicting the response of the shaker, the model parameters obtained have a physical significance and changes in the parameters can be directly mapped to modification in key design parameters of the shaker. The proposed approach is also advantageous in one more way: it requires measurement of only four parameters, voltage, current, displacement and acceleration for estimating shaker model parameters non-destructively. The proposed model can be used for the design of linearization controllers, prototype testing and simulation of new shaker designs as well as for performance prediction of shakers under testing conditions.

1. Introduction

The structure and working principle of an electrodynamic shaker somewhat resembles that of a loudspeaker. When the armature coil of a shaker is supplied with an electric current, a magnetic field is produced which interacts with the magnetic field attributable to a permanent magnet to exert a force on the coil and causes the armature coil to move.

Even though shakers behave linearly only in a small range of displacement, nonlinear effects in electrodynamic shakers have not been studied in detail. A few works in literature are found which mostly refer to linear models and assume the mechanical system as a simple spring-mass-damper system. These linear models cannot predict three key features of an electrodynamic shaker's response. These are: nonlinear relationship between shaker's acceleration and displacement response and applied voltage or current, harmonic distortion in the response of the shaker table, and presence of a DC offset in displacement response particularly at higher values of externally applied voltage or current. Since most of the nonlinearities are position dependent and a large displacement level is typically obtained only in case of low frequencies, this work

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http://dx.doi.org/10.1016/j.ymssp.2016.07.025
0888-3270/

Nomenclature

Bl	Electromechanical force factor (N/A)
C_1,ce:inf>?bk [?up][?tjl=1000] [?down]?>C_2, C_3	Compliance elements (m/N)
f_{em}	Electromechanical resonance frequency (Hz)
f_m	Mechanical resonance frequency (Hz)
M	Moving mass of shaker (Kg)
R_E	Effective resistance of the coil (Ω)
R_1	Mechanical resistance, i.e. inverse of primary damping coefficient of the system (m/N-s)
R_2	Inverse of damping influencing primary creep behavior (m/N-s)
R_3	Inverse of damping influencing secondary creep behavior (m/N-s)
R_{eq}	Equivalent damping at resonance (m/N-s)
THD	Total Harmonic Distortion
x	Position of shaker table

Symbols used for mobility analogy

$\mathrm{C_e}$	Electrical capacitance
$\mathrm{C_m}$	Mechanical compliance
F	Force
I	Current
$\mathrm{L_e}$	Electrical inductance
$\mathrm{M_m}$	Mechanical mass
$\mathrm{R_e}$	Electrical resistance
$\mathrm{R_m}$	Mechanical resistance
u	Velocity
V	Voltage

concentrates on the accurate prediction of displacement and acceleration response of electrodynamic shakers at very low to medium frequencies.

In an electrodynamic shaker, there are four important sources of nonlinearities which are important. These are:

(1) Dependence of stiffness on the position of the shaker table.
(2) Dependence of inductance on the position of the shaker table and current.
(3) Dependence of electromechanical force factor on the position of the shaker table.
(4) Dependence of damping on frequency.

Among these, nonlinearities due to stiffness and force factor have been studied in this work as these are the most dominant. The dependence of inductance on current and position was not considered in our work as all of our experiments were conducted in current-controlled mode and not in voltage-controlled mode. In the former approach, current is the independent input parameter and its value does not get altered due to changes in inductance. Since the mechanical force generated due to electromechanical transformation is BIl, the value of this force does not change due to variations in inductance in such a current-controlled setup. For this reason the mechanical response of shaker remains insensitive to changes in coil inductance. An advantage of this approach is that we were able immunize the influence of variations in coil inductance on shaker's mechanical response and make the study somewhat simpler. Shaker systems also exhibit viscoelastic effects and they need to be modeled accurately to predict the response particularly at low frequencies. We have covered these effects in the present work.

Most of the past work done in the field of electromechanical transducers has been for loudspeakers. The method of using lumped parameters for modeling mechanical and acoustical systems and representing them in terms of electrical components has been described in detail by Beranek [1]. The work by Lang [2,3] describes the structure of an electrodynamic shaker and its linear equivalent electrical and mechanical models. Flora and Grundling [4] have proposed an electromechanical model and used experimentally measured transfer function for linear parameter identification. Puri [5] has used lumped parameters to create a linear model of a medium sized shaker. It was found in this work that the parameters extracted at different acceleration levels resulted in different values of linear parameters and thus the author suggested a need for nonlinear modeling. Kaizer [6] and Klippel [7,8] have modelled a loudspeaker using Volterra series expansions. The use of such a method is cumbersome as it requires introduction of higher order terms, and such an approach is useful only for soft nonlinearities for which the series converges. Klippel [9] has discussed the causes of nonlinearities in different components of a loudspeaker namely stiffness, force factor and inductance. He has further discussed effects of nonlinearities on the output of a loudspeaker. Petosic et al. [10] have used Runge-Kutta method to solve a nonlinear model of loudspeaker and compared their simulation results with experimental data. In their model, they assumed stiffness, damping and mass as different sources of nonlinearity. The authors initially estimated model parameters for a linear system. Subsequently they used response error minimization method, i.e. the least squares method to get reasonable agreement between prediction and experimental data. However, such an approach does not help in developing a physical insight into the importance of each model parameters. Similarly, Mihelich [11] have also used Runge-Kutta method to solve the nonlinear system of equations of a loudspeaker.

In our approach, we focus on the modeling of an electrodynamic shaker in a way such that the model parameters have a physical significance, and any changes in these parameters can be mapped directly to changes in design parameters of the shaker. This work is an extension of the work done by the author Saraswat [12] in his Master's Thesis.