Mechanical Systems and Signal Processing 95 (2017) 106–121

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Influences of system uncertainties on the numerical transfer path analysis of engine systems

A. Acri [a,b,*], E. Nijman [a], A. Acri [c], G. Offner [d]

[a] Virtual Vehicle Research Center, Inffeldgasse 21A, A-8010 Graz, Austria
[b] Dipartimento di Ingegneria Meccanica, Politecnico di Milano, Italy
[c] Dipartimento Ingegnerie Meccanica Energetica e Gestionale, Università della Calabria, Italy
[d] AVL List GmbH, Austria

ARTICLE INFO

Article history:
Received 1 December 2016
Received in revised form 14 February 2017
Accepted 24 March 2017

Keywords:
Wishart model
Random matrix theory
Numerical transfer path analysis
Engine multi-body dynamics

ABSTRACT

Practical mechanical systems operate with some degree of uncertainty. In numerical models uncertainties can result from poorly known or variable parameters, from geometrical approximation, from discretization or numerical errors, from uncertain inputs or from rapidly changing forcing that can be best described in a stochastic framework. Recently, random matrix theory was introduced to take parameter uncertainties into account in numerical modeling problems. In particular in this paper, Wishart random matrix theory is applied on a multi-body dynamic system to generate random variations of the properties of system components. Multi-body dynamics is a powerful numerical tool largely implemented during the design of new engines. In this paper the influence of model parameter variability on the results obtained from the multi-body simulation of engine dynamics is investigated. The aim is to define a methodology to properly assess and rank system sources when dealing with uncertainties. Particular attention is paid to the influence of these uncertainties on the analysis and the assessment of the different engine vibration sources. Examples of the effects of different levels of uncertainties are illustrated by means of examples using a representative numerical powertrain model. A numerical transfer path analysis, based on system dynamic substructuring, is used to derive and assess the internal engine vibration sources. The results obtained from this analysis are used to derive correlations between parameter uncertainties and statistical distribution of results. The derived statistical information can be used to advance the knowledge of the multi-body analysis and the assessment of system sources when uncertainties in model parameters are considered.

1. Introduction

Transfer Path Analysis (TPA) is a test-based method, which allows to trace the flow of vibro-acoustic energy from a source, through a set of known structure- and air borne pathways, to a given receiver location. This methodology is commonly implemented for the study of vibrating active systems in connection with passive structures [1]. Recently TPA was associated with noise, vibration and harshness (NVH) engineering, with particular interest in the automotive industry driven by the increasing customer expectations on acoustic comfort [2,3]. The TPA technique is adopted in automotive industry since

* Corresponding author at: Virtual Vehicle Research Center, Inffeldgasse 21A, A-8010 Graz, Austria.
E-mail addresses: Antonio.Acri@v2c2.at, antonio.acri@polimi.it (A. Acri).

http://dx.doi.org/10.1016/j.ymssp.2017.03.037
0888-3270/

Nomenclature

$\boldsymbol{D}_b$	damping matrix of body b
$\boldsymbol{G}$	symbol for system matrix, $\boldsymbol{G} \equiv \{\boldsymbol{M}, \boldsymbol{D}, \boldsymbol{K}\}$
$\boldsymbol{K}_b$	stiffness matrix of body b
$\boldsymbol{M}_b$	mass matrix of body b
$\boldsymbol{M}$, $\boldsymbol{D}$ and $\boldsymbol{K}$	are mass, damping and stiffness random matrices whenever a probabilistic approach is adopted
$\bar{\boldsymbol{M}}$, $\bar{\boldsymbol{D}}$ and $\bar{\boldsymbol{K}}$	are the best known information regarding the system matrices and may be close to the mean of the fundamental matrix ensemble of $\boldsymbol{M}$, $\boldsymbol{D}$ and $\boldsymbol{K}$
$\boldsymbol{f}_b(t)$	vector of external forces applied on body b in time domain
$\boldsymbol{g}_b(t)$	vector of contact forces applied on body b in time domain
a_p, a_k, a_{tot}	respectively projected contribution, amplitude of investigated contribution and magnitude of the overall acceleration vector
cc	Pearson correlation coefficient
cv	coefficient of variation
m	the total number of external excitations applied on a substructure
n	the total number of excitations that can be applied on a substructure
$p, \Sigma, \alpha_G, \theta_G$	scalar and matrix parameters of Wishart distribution
$\boldsymbol{q}_b(t), \dot{\boldsymbol{q}}_b(t)$ and $\ddot{\boldsymbol{q}}_b(t)$	are respectively displacement, velocity and acceleration vectors of body b in time domain
s	symbol for the target substructure
$cov(A, B)$	covariance of the random variables A and B
$\det(\cdot)$	determinant of a matrix
$E(\cdot)$	the mathematical expectation
$Trace(\cdot)$	sum of diagonal elements of a matrix
$\Vert \cdot \Vert_F$	Forbenius norm of a matrix
φ_k, φ_{tot}	respectively the phase of the investigated contribution and the phase of the overall acceleration vector
σ_A, σ_B	standard deviations of random variables A and B
σ_G	dispersion parameter characterizing the variability of the random matrix $\boldsymbol{G}$
ω	pulsation frequency

1970s and so far it is still a useful tool for the NVH assessment of vehicles and mechanical structures. The first examples of techniques nowadays denoted as *classical TPA* are often attributed to the work of Verheij around 1980 s who studied the transmission of ship machinery vibrations through resilient mounts [4]. Starting from his work, many other authors studied in this direction and extended transmissibility concept applications. To be cited are the works of Magrans and Guasch [5–9], followed by Liu, Ewins, Varoto, McConnell, Riberio, Maia, Fontul and Silva that investigated the properties of transmissibility matrices for structural vibration problems [10–14]. Extensions of the *classical* TPA are represented by the *Operational* TPA [15], the so-called *blocked forces* method [16], the *in situ* method [17], the *pseudo-forces* method [18], and also the combination of TPA with energy methods and graph theory [19–21]. Recent works combine the TPA methodology with the novelty of numerical simulations. The Hybrid TPA formulation (HTPA) uses simulated excitation forces as input for TPA analysis, where the vibro-acoustic transfer functions are measured [22], while the Numerical TPA (NTPA) proposed in [23,24] is based on the Dynamic Substructuring (DS) of flexible multi-body systems.

Flexible multi-body systems are non-linear systems that exhibit large rigid body motion together with flexible deformations of the bodies. In industrial automotive applications, it is widely implemented during the development process of internal combustion engines and power unit systems. Crankshaft and engine dynamics, radial slider bearing dynamics or noise, vibration and harshness are examples of problems that can be investigated with this methodology.

Mechanical models may exhibit modeling errors or uncertainties that arise naturally due to incomplete knowledge of the system (e.g. Refs. [25–28]). Joint clearances, friction, lubrication, load estimation, material non-uniformities, manufacturing and assembly errors are examples of factors influencing the model uncertainties of internal combustion engines. As any model contains such uncertainties, the question of their effect on the quality of results, obtained when using such a model becomes relevant.

In literature, several methods can be found that can be used to formally assess uncertainties in mechanical systems [29–44]. Among them, the Monte Carlo approach is maybe the most extensively used method in dynamic models. It consists in repeated random sampling of a set of system parameters to obtain the uncertainty distribution via numerical simulation results [45–47]. Being computationally demanding, Latin Hypercube Sampling [48] and Bayesian methods [49,50] were introduced to overcome classical Monte Carlo limitations.

In this paper, a methodology is proposed to deal with uncertainties in source assessment and ranking problems. A Monte Carlo methodology is implemented to determine the influence of model uncertainties on numerical results of multibody dynamic simulation, with particular emphasis on the application of DS techniques for NTPA on internal combustion engines.