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A mathematical model for coupled vibration system of road vehicle and coupling effect analysis

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ABSTRACT

A mathematical model describing the dynamics of road transport vehicle is proposed in this paper. The system consists of a cab, a carriage, a chassis, the road, and mounts/suspensions between them. The coupled correlations between substructures are studied using the state space theory. A factor, coupling coefficient, for describing the coupling effect in the subsystem and a factor, vibration attenuation coefficient, for characterizing the vibration reduction of the substructures are derived. The joint location, the stiffness, and the damping of the mount/suspension, as well as the mass and inertia moment of the substructures are considered as design variables affecting system vibration coupling and reduction. The contribution of design variables is analyzed using Latin hypercube sampling and quadratic regression, top ten contributing variables are obtained, and their effects on the subsystem coupling are analyzed and discussed. The back propagation neural network is employed to investigate the nonlinear correlation between subsystem coupling and substructure vibration reduction. The results show the cab vibration reduction achieves optimum when the cab–chassis coupling is high and the carriage–chassis coupling is low. However, the optimal carriage vibration reduction requires the exact opposite coupling correlations.

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1. Introduction

Vibration of cab and carriage has great influence on ride comfort and goods safety, as well as vehicle reliability. The vibration on cab floor, seat, backrest, and steering wheel has been reduced as low as possible to enhance driver's comfort. On the other hand, however, the vibration of carriage is usually considered as an unimportant factor in the ride comfort. For some specialized purpose, such as medical purpose delivery or special equipment delivery, the vibration of carriage requires a much higher level of concern.

Transport vehicle is a very complex system consisting of cab, carriage, chassis, wheel, and kinds of joints between them such as mounts, suspensions, and tires. The excitation of road roughness acts on the tires and is transmitted to the wheel and suspension, then the chassis or frame, finally the cab and carriage through the mounts. Taking the sprung mass of vehicle as a multi-supported system, the coupling effects between the substructures strongly affect the vibration transmission and vehicle response. An inappropriate coupling intensity might lead to a significant magnification of vibration response of cab or carriage to some operating conditions (road pavement, frequency range or speed). However, it is difficult to investigate or design the coupling effect in those subsystems. The relation between vibration reduction and coupling intensity is also difficult to establish for complex interactions and large number of factors.

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Nomenclature

Symbol

$\boldsymbol{A}$	interaction matrix of the substructure state
$\boldsymbol{B}$	input matrix of system
$\boldsymbol{C}$	damping matrix
$\boldsymbol{D}$	state matrix
$\boldsymbol{E}$	displacement transform matrix
$\boldsymbol{F}$	force matrix
$\boldsymbol{G}$	transfer function
$\boldsymbol{H}$	inspection matrix
$\boldsymbol{I}$	identity matrix
I	moment of inertia
$\boldsymbol{K}$	stiffness matrix
L	distance from joint to reference point
$\boldsymbol{M}$	mass matrix
$\boldsymbol{q}$	global coordinate
$\boldsymbol{Q}$	state variable
$\boldsymbol{R}$	position vector
$\boldsymbol{T}$	coordinate transform matrix
x, y, and z	translational displacement in x, y, and z directions
α, β, and γ	rotational displacement in x, y, and z directions
ψ, θ, and ϕ	precession angle, nutation angle, and rotation angle
μ	coupling coefficient of subsystem
η	vibration attenuation coefficient of substructure

Superscript and subscript

B	basis
S	sprung mass
M	mount
sus	suspension
cab	cab
car	carriage
cha	chassis
f	front
r	rear

The fundamental purpose of a vehicle suspension/mount system is to act as a vibration isolation among the road, wheel, chassis, frame, driver and passenger, and cargo. Many researchers have done a lot of effective work on the suspension and mount design, improvement and optimization. In vehicle suspensions, most investigations focus on multi-body dynamic modeling and optimization design of semi-active and active dampers and control model [1–7]. In powertrain/engine mounts, optimizations of passive mount in shape and arrangement, and design and development of active/semi-active dampers are the two main interests. Refs. [8–13] investigated optimal designs of passive engine mounts by parameterizing mount factors which influence the shock/vibration isolation and reduction, and the optimization procedures were carried out using analytical method, finite element method, or genetic algorithm. In order to control the vibration transmissibility from engine to chassis and cabin, great designs or optimizations have been accomplished on semi-active engine mount [14,15] and active mount systems [16–18]. In addition to the isolation of vibration sources (road roughness and engine vibration), to reduce the vibration transmitted into cab and carriage of road transport vehicle, mount system of the cab and carriage have been studied as well [19–29].

Although many valuable investigations on vehicle suspension, cab mount, engine mount, and body mount have been presented, the objective of the optimal designs usually focused on only one substructure, such as cab ride comfort or noise, vibration transmitted from the powertrain or road excitations, and body vibration. However, a vehicle includes many subsystems and substructures, and the correlations between them are so complicated that an adjustment of one subsystem or substructure may introduce several uncertain or unexpected influences on the others. For example, an improvement of cab mount that can reduce cab vibration effectively, however, may increase the acceleration of carriage at the same time, which is not considered in most studies. As a result, to identify the coupling correlations between the subsystems clearly would be a precondition of vehicle component optimization. It is important to find out the effect of design parameters on the coupling relationships between components, substructures, and subsystems.

In this paper, a dynamic model of vehicle, which is taken as a coupled vibration system consisting of the cab, the carriage, the chassis, mounts, suspensions, wheels and tyres, is developed. The equations of motion are derived and described in the state space form in order to find out functions representing the coupling effect and the vibration reduction of the subsystem.

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