Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A full-spectrum analysis of high-speed train interior noise under multi-physical-field coupling excitations

Xu Zheng [a], Zhiyong Hao [a], Xu Wang [b,a], Jie Mao [a]

[a] Department of Energy Engineering, Zhejiang University, Hangzhou, China
[b] School of Aerospace, Mechanical & Manufacture Engineering, RMIT University, Melbourne, Australia

ARTICLE INFO

Article history:
Received 12 February 2015
Received in revised form
28 November 2015
Accepted 2 December 2015

Keywords:
High-speed train
Full-spectrum noise
Statistical acoustic energy flow
Multi-physical-field coupling excitation

ABSTRACT

High-speed-railway-train interior noise at low, medium, and high frequencies could be simulated by finite element analysis (FEA) or boundary element analysis (BEA), hybrid finite element analysis–statistical energy analysis (FEA–SEA) and statistical energy analysis (SEA), respectively. First, a new method named statistical acoustic energy flow (SAEF) is proposed, which can be applied to the full-spectrum HST interior noise simulation (including low, medium, and high frequencies) with only one model. In an SAEF model, the corresponding multi-physical-field coupling excitations are firstly fully considered and coupled to excite the interior noise. The interior noise attenuated by sound insulation panels of carriage is simulated through modeling the inflow acoustic energy from the exterior excitations into the interior acoustic cavities. Rigid multi-body dynamics, fast multi-pole BEA, and large-eddy simulation with indirect boundary element analysis are first employed to extract the multi-physical-field excitations, which include the wheel–rail interaction forces/secondary suspension forces, the wheel–rail rolling noise, and aerodynamic noise, respectively. All the peak values and their frequency bands of the simulated acoustic excitations are validated with those from the noise source identification test. Besides, the measured equipment noise inside equipment compartment is used as one of the excitation sources which contribute to the interior noise. Second, a full-trimmed FE carriage model is firstly constructed, and the simulated modal shapes and frequencies agree well with the measured ones, which has validated the global FE carriage model as well as the local FE models of the aluminum alloy–trim composite panel. Thus, the sound transmission loss model of any composite panel has indirectly been validated. Finally, the SAEF model of the carriage is constructed based on the accurate FE model and stimulated by the multi-physical-field excitations. The results show that the trend of the simulated 1/3 octave band sound pressure spectrum agrees well with that of the on-site-measured one. The deviation between the simulated and measured overall sound pressure level (SPL) is 2.6 dB(A) and well controlled below the engineering tolerance limit, which has validated the SAEF model in the full-spectrum analysis of the high speed train interior noise.

Abbreviations: FEA, finite element analysis; BEA, boundary element analysis; FEA–SEA, hybrid finite element analysis–statistical energy analysis; SEA, statistical energy analysis; SAEF, statistical acoustic energy flow; HST, high speed railway train; NVH, noise, vibration, and harshness; RMBD, rigid multi-body dynamic; BIW, body-in-white; DOE, degrees of freedom; STL, sound transmission loss; CLF, coupling loss factor; ILF, internal loss factor; FMBEA, fast multi-pole boundary element analysis; LES, large-eddy simulation; IBEA, indirect boundary element analysis; SPL, sound pressure level; TGV, les Trains à Grande Vitesse

http://dx.doi.org/10.1016/j.ymssp.2015.12.010
0888-3270/

1. Introduction

The incremental coverage of high speed railway train (HST) lines in China brings not only the convenience and economical benefit, but also the environmental noise to civilian. According to a survey of the noise alongside railway lines between major cities in China, the noise pollution in the cities near the railway lines is much more serious than that of the other Chinese cities [1]. Besides, interior noise, vibration, and harshness (NVH) of HST degrade riding comfort of passengers, generate bad sound quality concerns caused by booming and tonal noise [2]. Therefore, low-noise design method is significantly demanded in the HST research and development area.

Common approaches for evaluating the HST interior noise mainly include on-site experiment and numerical calculation and analysis. Since the vibro-acoustic measurement cost is high due to the limitation of manpower and material resources and measurable opportunities, the numerical calculation and analysis are preferred.

Numerous studies have been conducted in simulating the HST interior noise of low, medium, and high frequency where the mainstream methods of finite element analysis/boundary element analysis (FEA/BEA) [3], hybrid finite element analysis–statistical energy analysis (FEA–SEA) [4], and statistical energy analysis (SEA) [5], are respectively used. Xiao and Kang [6] constructed a rigid multi-body dynamic (RMBD) model, an FE body-in-white (BIW) model, and a BE model of a locomotive. Standard BEA method was employed to calculate the interior noise distribution excited by the contact patch roughness between wheels and rail. However, their work neglected the air borne wheel–rail noise and aerodynamic noise, as well as the acoustic attributes of trim parts. Sapena et al. [7] adopted hybrid FEA–SEA method to build a model and calculate the interior noise of a driver's carriage cabin. The trim parts were considered to contribute constant acoustic absorption coefficients, and the mechanical and aerodynamic excitations were also considered, however the wheel–rail noise was not considered. Liu et al. [8] extracted pressure fluctuations from exterior unsteady flow field to calculate interior aerodynamic noise in the medium-to-high frequency range. Unfortunately, this work could only be used to study the aerodynamic noise contribution for the interior noise. Furthermore, all the above results have not been validated by experiment.

From the previous literature study, the gaps of HST interior noise study are embodied in three main aspects:

(1) For the low frequency FEA/BEA, the upper limit of the analytic frequency or wavelength range is determined by the acoustic element dimension, that is, the minimal wavelength contains at least 6 elements. Thus, the degrees of freedom (DOE) of the acoustic carriage cabin model are too enormous to calculate the acoustic response for high frequencies.
(2) For the medium-to-high frequency hybrid FEA–SEA or SEA, a body-in-white (BIW) geometry model is converted into SEA subsystems where material acoustic properties such as acoustic absorption coefficients are defined to represent sound packages of trim parts [9]. However, the SEA subsystems are simplified with plates and singly curved shells based on equivalent area density or equivalent intensity method [8], which is unable to ensure the same sound transmission loss (STL) of the original and equivalent structures.
(3) The interior noise research is mainly based on the BIW model, and the multi-physical-field coupling excitations have not been fully taken into account. However, the parameterization of the trim parts neglects the restraint between the BIW and trim parts, which affects the modeling accuracy of the global carriage cabin modes and local composite board STLs, especially for the BIW–floorboard composite board.

To solve these problems, first, a new method named statistical acoustic energy flow (SAEF) is proposed, which can be applied to the full-spectrum HST interior noise simulation (including low, medium, and high frequencies) with one model. SAEF only considers main exterior acoustic excitations flowing into the interior acoustic cavities by the sound insulation attenuation of the composite boards from different carriage cabin areas; and the acoustic energy flow between the interior cavities is predicted through coupling loss factor (CLF) of statistical acoustics. Second, a full-trimmed carriage model is constructed for the HST interior noise simulation, while the corresponding multi-physical-field coupling excitations are fully considered. Fig. 1 shows the research flowchart of SAEF. The excitations inducing the HST interior noise fall into two categories of mechanical and acoustic excitations.

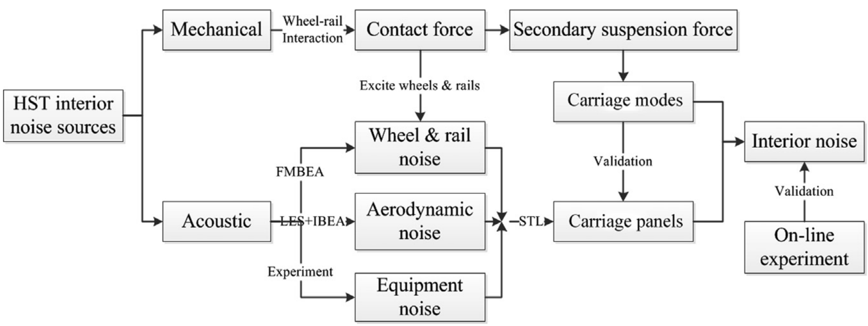

Fig. 1. The SAEF-based research procedure for HST full-spectrum interior noise.

Please cite this article as: X. Zheng, et al., A full-spectrum analysis of high-speed train interior noise under multi-physical-field coupling excitations, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2015.12.010