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Comparison between transfer path analysis methods on an electric vehicle

A. Diez-Ibarbia [a], M. Battarra [b], J. Palenzuela [c], G. Cervantes [c], S. Walsh [e,*], M. De-la-Cruz [d], S. Theodossiades [d], L. Gagliardini [f]

[a] Structural and Mechanical Engineering Department, University of Cantabria, Avda. Los Castros, s/n, 39007 Santander, Spain
[b] Engineering Department, University of Ferrara, Via Saragat, 1, 44122 Ferrara, Italy
[c] Mechanical Engineering and Energy, Miguel Hernández University, Avda. de la Universidad, s/n, 03202 Elche, Spain
[d] School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK
[e] Department of Aeronautical & Automotive Engineering, Loughborough University, Loughborough LE11 3TU, UK
[f] PSA-Peugeot-Citroen, Route de Gisy, 78943 Velizy-Vilacoublay, France

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ABSTRACT

A comparison between transfer path analysis and operational path analysis methods using an electric vehicle is presented in this study. Structure-borne noise paths to the cabin from different engine and suspension points have been considered. To realise these methods, two types of test have been performed; operational tests on a rolling road and hammer tests in static conditions. The main aim of this work is assessing the critical paths which are transmitting the structure-borne vibrations from the electric vehicle's vibration sources to the driver's ear. This assessment includes the analysis of the noise contribution of each path depending on the frequency and vehicle speed range and moreover, the assessment of the path noise impact for harmonic orders which arise due to the physical components of the electric vehicle. Furthermore, the applicability of these methods to electric vehicles is assessed as these techniques have been extensively used for vehicles powered with internal combustion engines.

1. Introduction

In the last decades, the regulatory requirements on the automotive sector have been made gradually stricter in environmental matters [25,26,27,28], in addition customers are demanding cheaper ways of transport [29,32]. These are the reasons why on the one hand, automotive companies have shown a keen interest in improving the energy efficiency in petrol and diesel engine vehicles and, on the other hand, alternative ways of producing energy that replaces or decreases the petrol and diesel fuel consumption have been looked for [2,3,7,9,10,32,33]. In this framework, hybrid vehicles (HV) and electric vehicles (EV) are two of the technological approaches adopted. These types of vehicle present the advantage that they pollute the environment less than other conventional technology-based vehicles [9,10,18,32], nevertheless one issue of concern has been the noise impact that they incur [1,4,8,11,14,19,31]. In this regard, whilst the radiated noise in the exterior of these vehicles is almost non-existent in low-speed regime, the interior noise does not fulfil high standards in terms of comfort. The former can cause accidents with pedestrians and the latter could make the potential customer reluctant to purchase the vehicle. Hence, resolving these noise issues is of crucial importance.

In this framework, the interest on Noise, Vibration and Harshness (NVH) has been growing over time, turning out to be one of the main areas related to the customer perception of quality in vehicles. In the open literature [5,4,11,17,19,21,22,30], various approaches have been reported in order to define the passive transfer paths that vibrations or acoustic signals use to propagate through the vehicle. One of these methods, the Transfer Path Analysis (TPA), was first developed in the early '80s and was seen as a tool to improve the NVH performance of several systems. This method has the main goal of reducing and improving the noise perceived in the cabin by the driver and the rest of occupants in the vehicle [1,4,8,31]. Following this procedure, it is possible to measure the effect, in terms of noise or vibration that a source is producing, on a receiver and to determine which structure/air-borne paths are utilised. As a matter of fact, this method determines the relationship between the input generated by the sources

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* Corresponding author.
E-mail address: S.J.Walsh@Lboro.ac.uk (S. Walsh).

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and the receiver output. Depending on these inputs and outputs, different TPA variations can be applied. Eventually, it becomes possible to assess in which path a modification should be implemented in order to improve the system behaviour, considering the vehicle speed and frequency conditions that have to be refined. The strengths of this approach are the ease of validating the results and the fact that cross-coupling effects between paths are always considered. Ideally, the latter should be small or even negligible, which means that the influence of a force applied on a specific point must be maximum at the application point, with the other force contributions being negligible compared to this one [17].

Classical TPA was seen as a useful method to improve the NVH performance of different systems e.g. cars, aircrafts and boats; nevertheless some weaknesses in the method and the need for quicker methods led researchers to develop new techniques entirely based upon *in-situ* measurements [4,6,11,12,17,23]. New procedures similar to this technique but following different methodologies have been developed over the last years, such as the Operational Path Analysis (OPA) and Operational Path Analysis with exogenous inputs (OPAX). Among these methods, the classic OPA is the quickest method to implement but the validity of its results is difficult to assess [4,12,23], thus the lack of reliability of this technique is one of its weaknesses. Furthermore, in order to obtain accurate results with this approach, low cross-coupling is required and all the active paths must be considered in the analysis. From the literature [6], a variation of the OPA based on the indirect application of transmissibility concepts has been developed, although its applicability on a vehicle has still to be proven. With regard to OPAX, which is a method that evolved from the TPA and OPA methods, it has the novelty of using a parametric model to estimate the operational loads [17]. This approach claims to be more accurate than other load calculation methods in TPA, such as the dynamic stiffness method. Nonetheless, this OPAX method is more expensive in terms of execution time than the OPA method.

Despite the fact that the classical OPA method (direct transmissibility concept) has shown some limitations due to the requirement of considering all the paths and using low-coherence among the signals, the automotive industry is strongly interested in implementing it because of the possibility of obtaining TPA-like results much quicker. The main advantage that OPA presents with respect to the other methods is that there is no need to identify the interface loads. Therefore, as the Frequency Response Functions (FRFs) are not necessary, the classical OPA is a quicker and less complex method based on the measurement/calculation of the transmissibility functions in operational tests (static tests are not required).

In this paper, a comparison between classic TPA and OPA methods in an EV has been made, taking into account the structure-borne noise introduced to the cabin from the motor mounts and the suspension points. The strengths and weaknesses of each method are presented. The hypothesis that the motor and suspensions (road) generate most of the acoustic noise in the cabin is also examined. Moreover, these TPA methods which are typically used for vehicles with internal combustion engines are now applied to an electric vehicle in this work. Hence, the versatility of these methods in an EV is assessed, which is the main novelty of this work.

The paper is divided in five sections. Section 2 provides the necessary background for the comprehension of the methods used in this study. In this section, the methodologies to develop the transfer path analysis are presented. In Section 3 the facilities and equipment used during the experimental tests as well as the description and layout of the different kinds of tests carried out in the study are described. In Section 4 the results of the two methods are assessed and compared, whilst in Section 5 the main conclusions are highlighted.

2. Methodology

The theoretical fundamentals of the TPA and OPA approaches are described in this section. With regard to these methods, the system to analyse is usually divided into a passive and an active part. The passive part contains the means that transmit the vibration and noise (paths) and the objects/people that absorb these vibrations (receivers), whilst the active part generates these fluctuations (sources) [12]. Hence, the system could be divided on three different elements depending on their behaviour; sources, paths and receivers. The definitions of these three elements according to [35] are:

- Source: internal DoFs belonging to the active components that cause the operational excitation but are unmeasurable in practice.
- Interface/passive paths: coupling DoFs residing on the interface between the active and the passive components.
- Receiver: response DoFs at locations of interest on the passive component, possibly including acoustic pressures and other physical quantities.

Particularly in this work, the electric vehicle (Fig. 1) is therefore composed of: (1) sources, which generate the vibrations (the electric motor and the road); (2) receivers, which accept the noise (driver); and (3) transfer paths, as the structure-borne paths that the oscillations use to propagate themselves (mainly chassis and bodywork).

2.1. Transfer path analysis

Transfer Path Analysis is the classic method used to determine the relationship between the inputs, generated by the sources, and the receiver outputs. Depending on these inputs and outputs, different TPA approaches can be followed. In this study, as only structure-borne paths impact on the cabin is considered, the inputs are forces and the outputs are acoustic pressures. Since static tests are required to characterise the behaviour of each path, the model performance does not depend on the outcome of operational tests as in other approaches (such as OPA). Therefore, the key is to select the most important paths so that the behaviour of the model is close to reality. The validity of the results is determined by comparison between the real acoustic pressure values and the simulated ones. Another interesting aspect is that the cross-coupling effects, introduced when the engine is mounted, are always considered. Nonetheless, the execution time is higher than the OPA because many impact hammer tests (static tests) have to be performed in order to determine the FRFs.

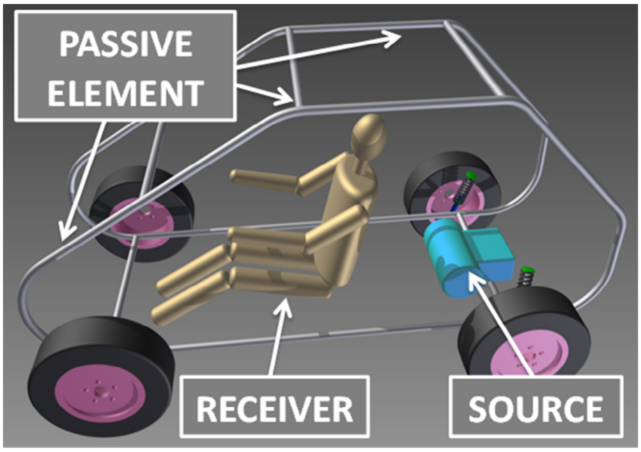

Fig. 1. Illustration of the source-path-receiver system for an electric vehicle.