45º CONGRESO ESPAÑOL DE ACÚSTICA
8º CONGRESO IBÉRICO DE ACÚSTICA
EUROPEAN SYMPOSIUM ON SMART CITIES AND ENVIRONMENTAL ACOUSTICS

TRANSFER PATH ANALYSIS IN AN ELECTRICAL VEHICLE. COMPARISON WITH OPERATIONAL PATH ANALYSIS.

PACS: 43.50.Yw

Palenzuela-Andújar, Juani(1); Cervantes-Madrid, Gines(1); Diez-Ibarbia, Alberto(2); Theodossiades, Stephanos (3); Walsh, Stephen (3); Peral-Orts, Ramon(1); Campillo-Davo, Nuria(1)

1. Universidad of Miguel Hernández
Av. Universidad s/n, 03202, Elche. Spain
2. Universidad of Cantabria
Avda. de Los Castros s/n, 39005, Santander. Spain
3. Loughborough University
Epinal Way, Loughborough LE11 3TU, UK

ABSTRACT

The vibrational and acoustic behaviour of vehicles is being studied increasingly due to the high levels of comfort required by manufacturers.

Currently, the electric motor is becoming an alternative solution to the internal combustion engines, and therefore, appears a new type of vehicles, the electric car.

The aim of this work is to perform a Transfer Path Analysis (TPA) in an electric vehicle (EV), and to compare the results with those obtained previously in the same car with a different method, Operation Path Analysis (OPA), assessing the suitability of these methods for this kind of car.

RESUMEN

El comportamiento vibratorio y acústico de los vehículos se está estudiando cada vez más debido a los altos niveles de confort requeridos por los fabricantes.

En la actualidad, como una solución alternativa a los motores de combustión interna aparece el motor eléctrico, y por lo tanto, un nuevo tipo de coche, el coche eléctrico.

El objetivo de este trabajo es realizar un Análisis de los Caminos de Transferencia de ruido (TPA) en un vehículo eléctrico, y comparar los resultados con los obtenidos previamente en el mismo coche con un método diferente, el Análisis Operacional del Camino del ruido (OPA), evaluando de la idoneidad de estos métodos en este tipo de coche.

INTRODUCTION

In the NVH (Noise, Vibration and Harshness) analysis of vehicles, the most used method is the Transfer Path Analysis (TPA) [5, 6]; this method has the ability to detect different transmission paths thus allowing the intervention in the system in order to eliminate or reduce the vibration level.

The conventional classical method, Transfer Path Analysis (TPA), was first theoretically developed in the early ‘80s. TPA was seen as a useful method to improve NVH performances of several systems, e.g. cars, aircrafts and boats [7]. TPA is a method widely used because of its reliable results.

The manufacturing growth of electric cars justifies the study and the NVH analysis of EV’s and to develop a review of conventional methods used in ICE’s.

METHOD

Transfer Path Analysis is a systematic method used to understand the relation between multiple sources of noise and vibration and their effects on perceived user comfort and health. Transfer Path Analysis creates a mathematical model of the structure under test that allows:

- The quantification of source strengths.
- The ranking of contributions of the different sources along the different paths for every target receiver positions.
- The simulation that would happen if the design was changed by modifying the forces with new connection stiffness or changing transfer functions for eliminating resonances.

The TPA can be divided in four main stages; I) Operational measurements, II) Load identification, III) Frequency response function (FRF) calculation, and IV) Results and assessment [1].

I) Operational measurements

The operating loads can be identified in operation tests (e.g., run-up, run down, etc.) either on the road or on a roller bench.

This test is performed within a defined range of frequencies. In this way, the forces are introduced to the system while measuring the accelerations at the body interface and the acoustic pressure in the cabin.

II) Load identification

The load identification is the stage in which the loads are estimated. In order to obtain them, three different methods can be used (Direct measurements by transducers, Mount Stiffness Method and Matrix Inversion Method), but in this study the Matrix inversion method has been used.

This method has to be used when the transfer paths are connected with rigid connections or the mount stiffness are very stiff compared to the receiving structure since the relative displacement across the mount become too small.

The matrix inversion method combines operational and non-operational measures.

During the first step, accelerations were measured on the multiple points in operating conditions.

In the second step, the relation between the interface force and the movement/deformation is obtained during controlled conditions, non-operational (impact-hammer test in the case of study).

This relation between force and deformation is characterized by an acceleration matrix form by multiple transfer functions in the frequency domain (H).

With F_v calculated operational force through path v, $H_{vn}(\omega)$ local transfer function between the transfer path locations in the point *n*, and indicator point *n* and a_n the operational accelerations at indicator location *n*.

So, the *H* matrix describes the local relation between a known force input at the transfer path location and a measured response acceleration output due to this known input.

To calculate the force, there were inverted the *H* matrix and multiplied it by the operational accelerations [2].

$$\begin{bmatrix} F_1(\omega) \\ F_2(\omega) \\ \vdots \\ F_v(\omega) \end{bmatrix} = \begin{bmatrix} H_{11}(\omega) H_{12}(\omega) \cdots H_{1n}(\omega) \\ H_{21}(\omega) H_{22}(\omega) \cdots H_{2n}(\omega) \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ H_{v1}(\omega) H_{v2}(\omega) \cdots H_{vn}(\omega) \end{bmatrix}^{-1} * \begin{bmatrix} a_1(\omega) \\ a_2(\omega) \\ \vdots \\ a_n(\omega) \end{bmatrix} \tag{1}$$

Calculating the inverse of the acceleration matrix in practice requires taking some numerical stability issues into account.

III) FRF calculation

To calculate the FRF (T_{ik}) the forces at the body interface and the acoustic pressures in the cabin are required, equation (2) is obtained by hammer testing. It can be noted that if the load identification method uses the stiffness or matrix approach, the FRF can be performed at the same stage, measuring the acoustic pressure as well as the accelerations.

$$P_i = \sum T_{ik} \cdot F_k \tag{2}$$

Where P_i is the receiver operational response at point *i* as a function of frequency, $T_{ik}$is the FRF between the point *i* and the input signal applied to path *k*, and F_k is the operational force applied to path *k* [3].

IV) Results and assessment

The simulated acoustic pressure can be calculated by the operational forces and the transfer function (third stage). Finally, the comparison between the calculated acoustic pressure and the experimental one is done in order to assess the validity of the results.

OPERATIONAL MEASUREMENTS

Technical aspects of the measurements were defined in previous paper of the authors [4].

The tested car is a small fully electric car. The most important is that the powertrain is over the rear axis.

There are five measurement points. The first three correspond to the powertrain mounts. Each of them was measured in the vertical and longitudinal axes of the vehicle. The last two points were located where the rear suspension is supported, in the vertical axe, see figure 1.

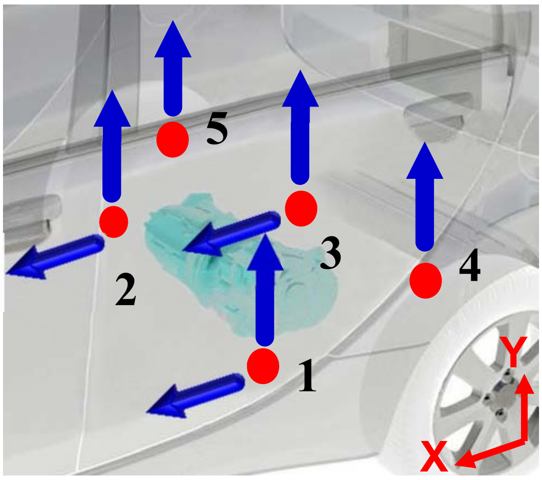

Figure 1: Measurement points

The microphone inside the car was placed in the same position as was placed in the OPA tests [4], as close as possible of the driver's ear. Once the vehicle was installed in the roller bench, many tests were carried out to ensure sufficient measurements were in place for the post process part.

Also, like the OPA test [4], a LabVIEW application was developed that records the data and then generates a file for export to Matlab with the eight accelerations in m/s^2, the acoustic pressure in Pa and in dBA, and vehicle speed in km/h.

LOAD IDENTIFICATION

To obtain the relation between the interface of force and the movement/deformation, there was performed an impact-hammer test (figure 2).

It was a deceptively repetitive process. The measurement points were individually hit with the hammer and the changes in accelerations and acoustic pressure were recorded.

The difficulty lies on the necessity of being accurate blowing of the hammer to have a good coherence between the impact caused and the response measured in the sensors.

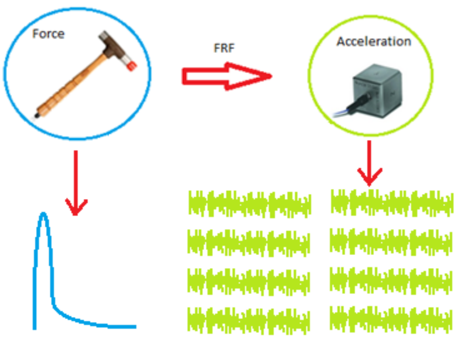

Figure 2: Obtaining H matrix with the impact test

It has beaten up with the impact hammer in all metering points while maintaining an average coherence between the impact and response greater than 0.9 (figure 3).

Once all measuring point was hit, another application in LabVIEW records the data and incorporates this data into a file for exporting to Matlab.

Figure 3: Example of coherence after ten impacts.

CALCULATION

When the measurements data were prepared for the post processing, there were developed the data processing in the Matlab environment.

To calculate the H, the data were obtained in the impact test and then data were arranged in the matrix so that each column corresponds to the eight accelerations caused by the same impact.

$$FRF\ matrix = \begin{bmatrix} \frac{acc_{11}}{F_1} & \frac{acc_{12}}{F_2} & \cdots & \frac{acc_{18}}{F_8} \\ \frac{acc_{21}}{F_1} & \frac{acc_{22}}{F_2} & \cdots & \frac{acc_{28}}{F_8} \\ \vdots & \vdots & & \vdots \\ \frac{acc_{81}}{F_1} & \frac{acc_{82}}{F_2} & \cdots & \frac{acc_{88}}{F_8} \end{bmatrix}$$

When the matrix was finished, it was inversed and operational forces were obtained by applying the equation 1.

Once the operational forces were calculated the H could be obtained from the impact test dividing the acoustic pressure recorded by the force applied in each case.

RESULTS AND ASSESSMENT

Once the operational forces and the sound pressure H were calculated to obtain results, the partial contributions of sound pressure of each path could be obtained (figure 4).

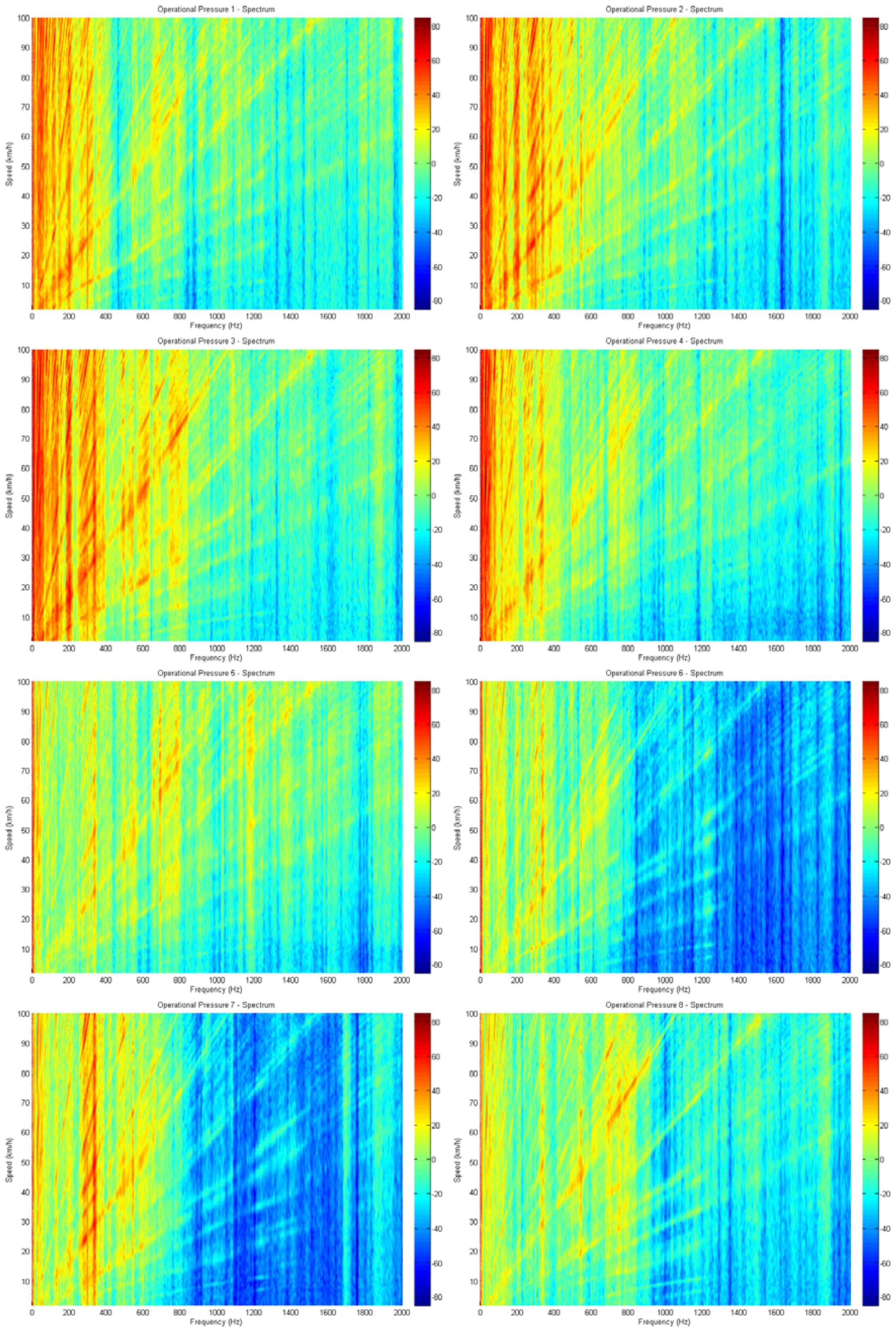

Figure 4: Partial sound contribution from each path, in dB

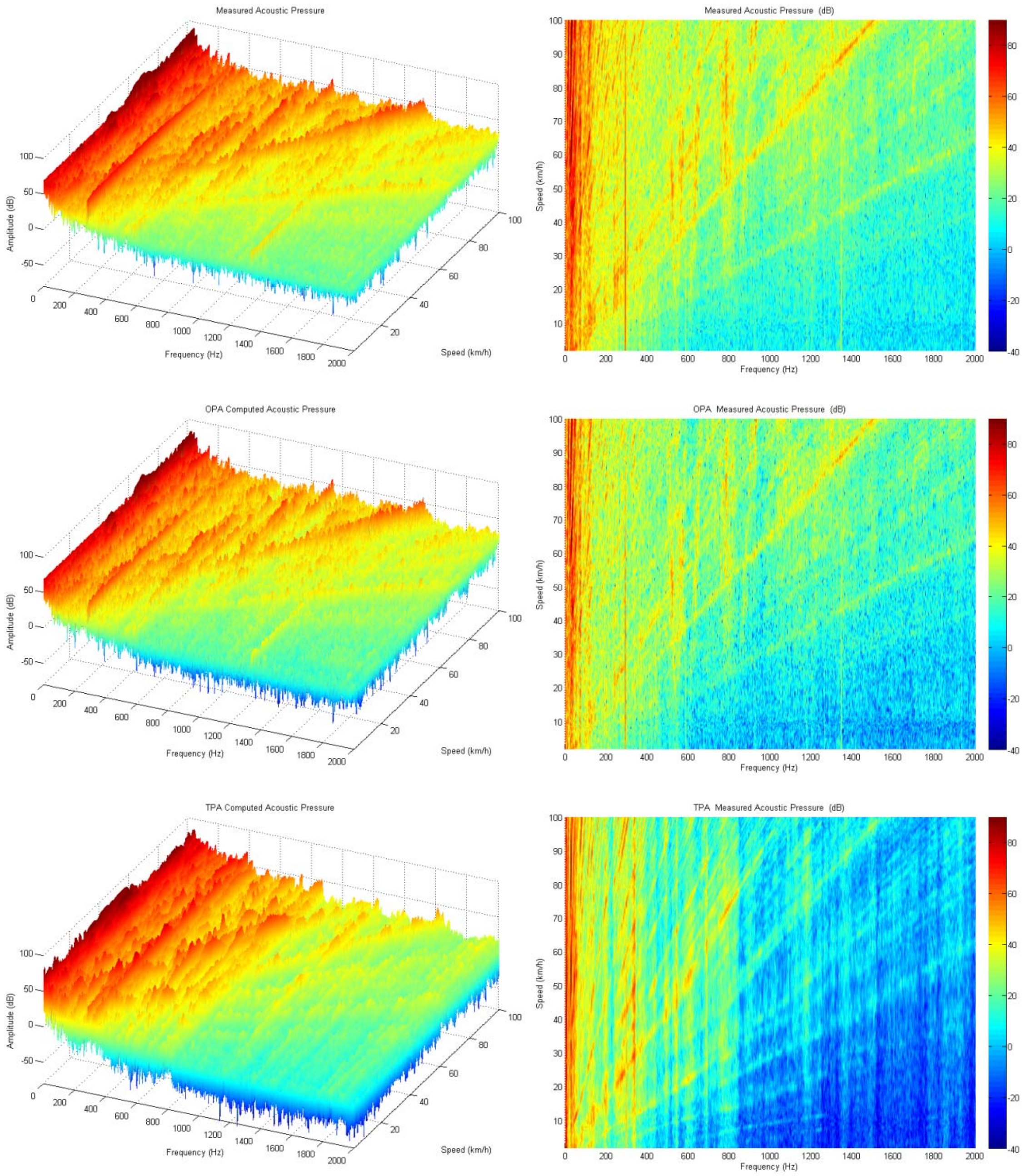

Figure 5: Comparison between TPA, OPA and Measured Acoustic Pressure

The results assessment demonstrated that the TPA results are similar to those obtained in the OPA method, as shown the Figure 5.

On the other hand, comparing the three figures of Total Sound Pressure, Measured, OPA and TPA (Figure 6) it can be seen that there is great similarity between them. It is noteworthy that the most reliable method is still the TPA because it calculates the operational forces independently and is not influenced by the environment, as does happen in OPA.

The different mathematical treatment ensures that the OPA interprets all sound register. Alternatively, the TPA only takes into account the sound that actually traverses these paths.

Therefore, both methods are applicable to electric vehicles, but it is important understand the scope of each of them.

The OPA is a method that provides appropriated results, faster and easier. The TPA is a more accurate method, but it requires more time, more resources, being a more complex process.

CONCLUSIONS

- Interior noise and accelerations in specified operating conditions were measured.
- Operational forces were calculated by local transfer functions.
- The sound pressure calculated has good agreement with the sound pressure measured.
- The TPA method has been completely performed.
- The methodology is valid to use in EV's.
- The comparison of the two methods allows appreciating the advantages and weaknesses of each of them.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the logistical support of the COST action TU1105.

REFERENCES

[1] Padilhaa F, Arrudab R. Comparison of estimation techniques for vibro-acoustic transfer path analysis, Shock and Vibration,
Vo. 13 (2006) 459-467.

[2] Juha P. Finding and fixing vehicle NVH problems with transfer path analysis. Sound Vib Vol 11, (2005) 12-16.

[3] Sakhaei B, Durali M. Vibration Transfer Path Analysis and Path Ranking for NVH Optimization of a Vehicle Interior. Shock and Vibration, vol. 2014.

[4] Cervantes-Madrid G, Palenzuela-Andújar J, Diez-Ibarbia A, Battarra M, Theodossiades S, Walsh S. An application of operational path analysis (OPA) on an electric car. Tecniacustica 2014, Murcia, Spain.

[5] Plunt J. Examples of Using Transfer Path Analysis (TPA) together with CAE-Models to Diagnose and Find Solutions for NVH Problems Late in the Vehicle Development Process. Proceedings of the 2005 SAE Noise and Vibration Conference.

[6] Putner J, Fastl H, Lohrmann M, Kaltenhauser A, Ullrich F. Operational transfer path analysis predicting contributions to the vehicle interior noise for different excitations from the same sound source, Internoise 2012, New York City, USA.

[7] Klerk D, Lohrmann M, Quickert M, Foken W. Application of Operational Transfer Path Analysis on a Classic Car, DAGA 2009, Rotterdam, 2009.