

An Application of the Particle Velocity Transfer Path Analysis to a Hybrid Electric Vehicle Motor Sound

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ABSTRACT

A pioneering approach to implement transfer path analysis (TPA) is proposed in this paper through applying it to an automobile. We propose to use particle velocity as a measure of TPA, in addition to using sound pressure as a conventional measure for TPA. These two quantities together will give a comprehensive and complete definition of sound. Although sound pressure is a scalar, while particle velocity is a vector, it is also proposed that the same technique of the conventional sound pressure TPA should be independently applicable to each component of particle velocity vector. This has been experimentally verified with a study on our test box system. In this paper, we apply the proposed TPA to an actual vehicle to examine its applicability, advantages and limitations. The driving motor sound of a hybrid electric vehicle is chosen as the case study. A tri-axial particle velocity sensor which also measures sound pressure at the same point is utilized in the experiment. Both structure-borne and air-borne sound paths are considered, and a miniature shaker and a volume velocity source are employed for the frequency response function measurement, respectively. Our results show, for our work on the real vehicle, that our proposed particle velocity TPA works just as well as the conventional sound pressure TPA with comparable error levels. Furthermore, we discuss the details of phase effect in the path rank ordering. While the common approach employs consideration of both amplitude and phase, an alternative treatment may be exercised for sound vector. The analysis presented in this study is limited to the frequency domain. Finally, we briefly touch on the aspect of using sound intensity as a measure of TPA.

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INTRODUCTION

Transfer path analysis (TPA) has been widely performed in order to determine the main sound transmission path between the sound source and the human's (receiver) location [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. In automotive systems, one of the typical applications of TPA is the engine system. For example, TPA quantitatively rank orders the engine mounts as structure-borne sound transfer paths and predicts the mount which transmits most of the engine sound to the driver at each frequency. Consequently, the subsequent structural improvement of the mounts would become more effective with a numerical target to reduce the sound at the receiver position.

Recently, several new or modified transfer path analyses have been also developed [10,11]. The conventional TPA method postulates the linearity of the system, which often is cause of error, especially at resonance where the primary

concern exists. Thus, a motivation to develop a new TPA methodology would be to reduce the error.

In order to evaluate the sound transfer path by TPA, sound pressure has been conventionally employed as the measure. However, in general, uniquely identifying sound field requires not only sound pressure but also particle velocity. Therefore, an attempt has been made to develop a complete sound analysis for TPA which uses both sound pressure and particle velocity as the measure of TPA [1,2]. Sound pressure is a scalar quantity, while particle velocity is a vector quantity. Sound energy quantities such as sound intensity and sound power are calculated as the product of sound pressure and particle velocity. Although particle velocity is a fundamental quantity of sound, a limitation in the usage of this quantity may lie in the difficulty of measurement [12, 13, 14, 15, 16]. Particle velocity can be estimated by using several microphones with known

geometry. Alternatively, particle velocity can be directly measured by a sensor. In this study, the authors utilize a tri-axial particle velocity sensor (manufactured by Microflown Technologies). This sensor also measures sound pressure simultaneously at the same location, and is called a PU-probe.

Conventional TPA quantitatively compares the sound transfer paths using the operational path load multiplied by the frequency response function from the path to the receiver. We assume that the same approach can be applied to each component of particle velocity vector. The sound at receiver may be decomposed into each path contribution by TPA as follows.

Conventional Sound Pressure TPA:

$$P_{\text{Receiver}} = P_{\text{Path1}} + \dots + P_{\text{Path N}} \quad (1)$$

Proposed Particle Velocity TPA:

$$\vec{Y}_{\text{Receiver}} = \vec{Y}_{\text{Path1}} + \dots + \vec{Y}_{\text{Path N}}, \text{ or} \quad (2)$$

$$\begin{cases} U_{\text{Receiver}} = U_{\text{Path1}} + \dots + U_{\text{Path N}} \\ V_{\text{Receiver}} = V_{\text{Path1}} + \dots + V_{\text{Path N}} \\ W_{\text{Receiver}} = W_{\text{Path1}} + \dots + W_{\text{Path N}} \end{cases} \quad (3)$$

Here, P_{Receiver} is the sound pressure (in Pa) at the receiver location, and $P_{\text{Path n}}$ is the sound pressure contribution of Path n ($n = 1, \dots, N$. N is the total number of the paths) to P_{Receiver} . The particle velocity vector (in m/s) at the receiver location is denoted as $\vec{Y} = (U, V, W)$, where U , V and W are the particle velocity in the X , Y and Z directions, respectively. Thus, the target sound has 4 degrees of freedom; P , U , V and W , which uniquely define the sound. Note that all the quantities can be written in a complex notation in the frequency domain, such as the followings.

$$\begin{aligned} P &= |P(\omega)| e^{i\phi_P(\omega)}, \quad U = |U(\omega)| e^{i\phi_U(\omega)}, \\ V &= |V(\omega)| e^{i\phi_V(\omega)}, \quad W = |W(\omega)| e^{i\phi_W(\omega)} \end{aligned} \quad (4)$$

We have examined the particle velocity TPA by applying it to a test box system in our previous study [1]. The total sound quantity listed on the left-hand side of Eqs. (1), (2), (3) were compared with the measured (actual) sound at the peak frequencies. It was found that the particle velocity TPA is just as accurate as the sound pressure TPA with comparable error levels. In this paper, the proposed particle velocity TPA is examined by applying it to an actual vehicle. A hybrid electric vehicle (HEV) was selected as a real-life application in consideration of the recent popularity in the automobile industry. The specific objectives are:

1. To examine the applicability of the particle velocity TPA to an automobile, and compare it with the conventional sound pressure TPA.

2. To investigate how to deal with the four independent sound measures (P , U , V and W) in the combined TPA for the path rank ordering with specific emphasis to explore the partial sound phase.

The scope of this study is limited to the frequency domain analysis of linear time-invariant systems. Hence, the dependency on frequency ω (rad/s) is not explicitly denoted. Both the structure-borne and air-borne sound paths are considered. Only the vertical translational motion (of the mount) is considered for the structure-borne paths.

FORUMULATION OF PARTICLE VELOCITY TRANSFER PATH ANALYSIS

The fundamental concept and the technical formulation of the particle velocity TPA is first described in detail. Subsequently, a generic procedure of TPA is introduced with the frequency dependent calibration for the sensor (triaxial PU-probe).

Basic Approach and Formulation

First, the conventional TPA in terms of sound pressure may be generally formulated as follows [3,5,6,7].

$$\begin{aligned} P_{\text{TPA}}^{\text{Op}} &= P_{\text{Structure-borne Sound}}^{\text{Op}} + P_{\text{Air-borne Sound}}^{\text{Op}} \\ &= \underbrace{\sum_s \sum_{d=x,y,z} \left(\frac{P}{F_{s,d}} \right) F_{s,d}^{\text{Op}}}_{\text{Structure-borne Sound}} + \underbrace{\sum_a \left(\frac{P}{Q_a} \right) Q_a^{\text{Op}}}_{\text{Air-borne Sound}} \end{aligned} \quad (5)$$

Here, $F_{s,d}$ is force (in N) at the structure-borne path s in the d -direction ($d = x, y, z$). Q_a is volume velocity (in m^3/s) at the air-borne path a . $(P/F_{s,d})$ and (P/Q_a) are the corresponding frequency response functions (FRF) from the path to the receiver. The superscript Op explicitly indicates the quantity in the actual operating condition of the system, which may be omitted when it is apparent. Each term in the summation may be called partial sound pressure. The first summation represents the structure-borne sound, while the second represents the air-borne sound.

We propose to extend the sound pressure TPA formulation (5) to particle velocity. By replacing P in Eq. (5) with $\vec{Y}$, or each component U , V and W ,

$$\vec{Y}_{\text{TPA}}^{\text{Op}} = \sum_s \sum_{d=x,y,z} \left(\frac{\vec{Y}}{F_{s,d}} \right) F_{s,d}^{\text{Op}} + \sum_a \left(\frac{\vec{Y}}{Q_a} \right) Q_a^{\text{Op}}, \text{ or} \quad (6)$$

$$U_{\text{TPA}}^{\text{Op}} = \sum_s \sum_{d=x,y,z} \left(\frac{U}{F_{s,d}} \right) F_{s,d}^{\text{Op}} + \sum_a \left(\frac{U}{Q_a} \right) Q_a^{\text{Op}}$$

$$V_{\text{TPA}}^{\text{Op}} = \sum_s \sum_{d=x,y,z} \left(\frac{V}{F_{s,d}} \right) F_{s,d}^{\text{Op}} + \sum_a^{\text{Air}} \left(\frac{V}{Q_a} \right) Q_a^{\text{Op}} \quad (8)$$

$$W_{\text{TPA}}^{\text{Op}} = \sum_s \sum_{d=x,y,z} \left(\frac{W}{F_{s,d}} \right) F_{s,d}^{\text{Op}} + \sum_a^{\text{Air}} \left(\frac{W}{Q_a} \right) Q_a^{\text{Op}} \quad (9)$$

Each summation term shown in Eqs. (6), (7), (8), (9) may be referred to as partial particle velocity. Sound pressure P can be related with particle velocity $\vec{V}$ through velocity potential Φ .

$$P = -\rho \frac{\partial \Phi}{\partial t}, \quad \vec{V} = \nabla \Phi \quad (10)$$

Here, $\nabla = (\partial/\partial x, \partial/\partial y, \partial/\partial z)$, and ρ is mass density (in kg/m^3). Based on this relation (10), it is assumed that the same TPA formulation may be employed for sound pressure and particle velocity.

Note that the particle velocity degrees of freedom (U, V, W) and the path motion degrees of freedom (F_x, F_y, F_z) should not be confused in TPA. The peak amplitude of oscillating quantity, such as $|P|$, $|U|$ and $|F|$, may be simply called amplitude, while the 3-dimensional particle velocity vector length ($\sqrt{U^2 + V^2 + W^2}$) may be called magnitude.

Procedure of Particle Velocity TPA

The basic procedure of the particle velocity TPA is the same as the sound pressure TPA up to the point of TPA model validation. The four sound quantities, P , U , V , and W , may be independently processed in the same manner implemented in the conventional TPA method. The difference starts at the point of processing the path rank order (step 5 and beyond shown below). The procedure of TPA applied to each sound quantity is as follows.

Step 1. Define the sound source, its transmission paths, and the receiver point (target sound evaluation location). The paths must all be parallel. Also, it is necessary to define the degrees of freedom that will be dealt.

Step 2. Carry out measurements in the system operation (vehicle driving test) under the conditions of interest. Measure the response at the paths and receiver(s). Define the frequency (and order, if necessary) range.

Step 3. Measure the frequency response functions (FRF) from each path to the receiver. (This step may be before step 2.)

Step 4. Compare the measured target sound with the TPA-synthesized sound by Eqs. (5), (6), (7), (8), (9). This is a TPA model validation.

Step 5. Quantitatively rank order the paths in terms of the partial sound on the right-hand side of Eqs. (5), (6), (7), (8), (9).

Step 6. Modify the dominant path(s) for an effective target sound reduction. (This step is not illustrated in this paper.)

In the steps 2 and 3, frequency dependent calibrations have to be applied for the PU-probe. The calibration curves are given in Figure 1 [16]. The amplitude calibration is division, while the phase calibration is subtraction. Steps 4 and 5 mentioned above are the key aspects of this paper which correspond to the objectives 1 and 2, respectively, defined in the introduction.

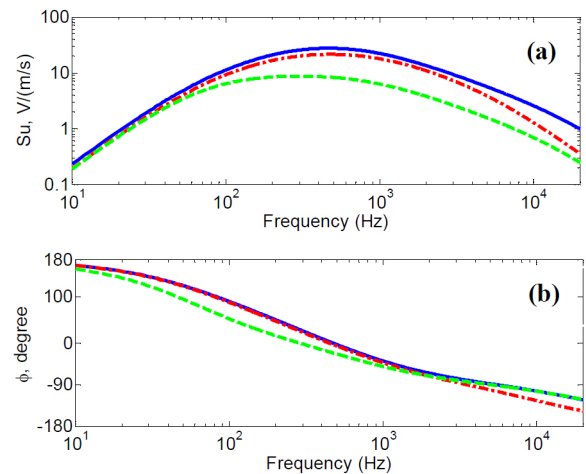


Figure 1. Frequency dependent calibration curves for the particle velocity sensor. (a) Amplitude calibration curve, (b) Phase calibration curve. Key: —, U ; - - - , V ; - - - , W .

MEASUREMENTS FOR THE PROPOSED TPA METHOD APPLIED TO A HYBRID VEHICLE

Definition of Source-Paths-Receiver Network

In order to obtain a good result from TPA, the source, paths and receiver network has to be properly defined at the beginning. Specifically, an appropriate definition of parallel paths is essential. For our test vehicle, the source or target sound is the driving motor sound of an HEV. This vehicle is driven by only the motor at low speed, which is called EV-mode. At higher speed, the engine starts and helps to propel the vehicle. In this study, TPA is applied only in the EV-mode so as to avoid the engine sound.

The motor is located in the transmission (TM) unit box which is attached behind the engine. The engine-TM combined unit is mounted on the vehicle chassis by the 3 mounts; we call them left, right and back mounts. These constitute the structure-borne paths. On the other hand, the motor sound is directly radiated from the TM case surface. We divide the surface into two areas and designated them as left and right surfaces. These constitute the air-borne paths.

The sound evaluation point of TPA is defined at the passenger's right ear position in the front-right seat where the tri-axial PU-probe is installed as the receiver. The source-paths-receiver network is summarized in Table 1.

Table 1. Definition of the Source-Paths-Receiver network for the TPA application to the HEV.

Source	Driving Motor (in the EV-mode)		Abbrev
Path	Structure-borne path	Engine Left Mount	St-Left
		Engine Right Mount	St-Right
		TM Back Mount	St-Back
	Air-borne path	TM Case Left Surface	Air-Left
		TM Case Right Surface	Air-Left
Receiver	Passenger's right ear position at the front right-side seat	Sound Pressure	P
		Particle Velocity in X	U
		Particle Velocity in Y	V
		Particle Velocity in Z	W

The driver's right direction, the vehicle movement direction and the vertical direction are defined as X, Y and Z directions respectively, which also correspond to the particle velocity components U , V and W , respectively. The response of the structure-borne paths is measured only in the vertical Z-direction. Thus, the subscript $d = z$ in Eqs. (5), (6), (7), (8), (9) will not be explicitly written hereafter.

Vehicle (HEV) Driving Measurements in the EV-Mode

The HEV was driven at low speed to measure the operational responses in a driving motor run-up. Here, an accelerometer was installed at each path location to estimate the path force and the path volume velocity. The motor speed, vehicle speed and engine speed from the CAN system are shown in Figure 2. The driving motor speed is synchronized with the vehicle speed. The triaxial PU-probe, accelerometers (manufactured by PCB) and CAN interface were used with a data acquisition system (manufactured by of LMS International).

The measured particle velocity in the z-direction (W) at the receiver location is shown in Figure 3. The order lines 28 and 60 of the motor sound can be observed clearly up to about 1 kHz. (There is another motor which is operated together with the driving motor.) TPA is implemented and examined for these orders, mainly for the order 28.

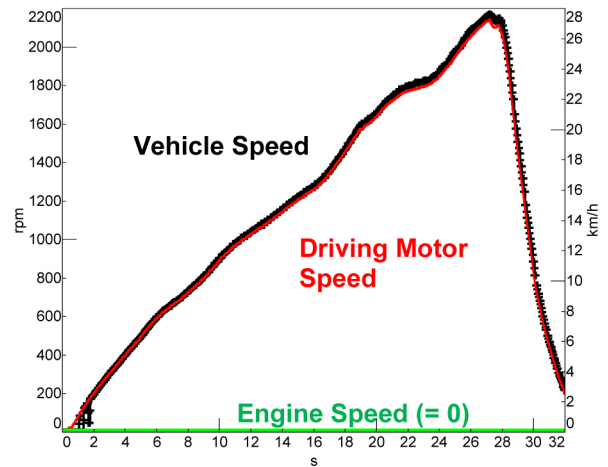


Figure 2. Measured CAN signals. Key: —, Motor speed; + + +, Vehicle speed; —, Engine speed (=0).

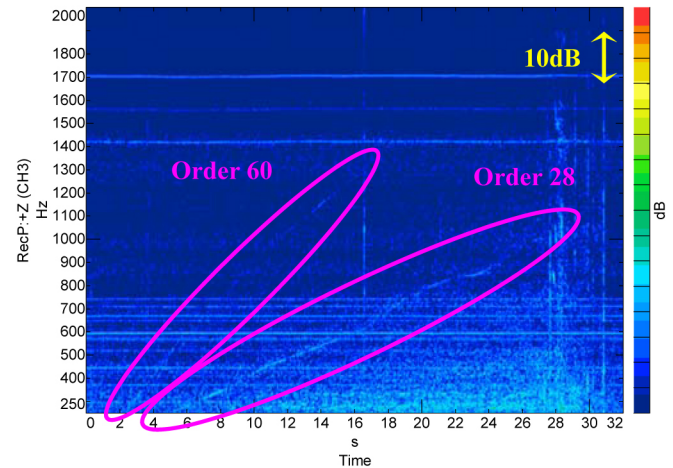


Figure 3. Target sound in STFT colormap: particle velocity in the z-direction (W) measured at the receiver location during the HEV run-up driving.

The measured particle velocities U , V and W at the order 28 are shown in Figure 4 (a). It is found that particle velocity W is much larger than the other directions U and V . The driving tests were carried out with all the window completely rolled up which caused sound reflection. Some peaks are likely to have been caused by the acoustic resonance or standing wave.

It should be noted here that there are phase differences among the particle velocity components U , V and W . Recall the complex notation in Eq. (4) where $\varphi_U(\omega)$, $\varphi_V(\omega)$ and $\varphi_W(\omega)$ are all different in general. Figure 4 (b) shows the difference between the simple or pseudo magnitude $\sqrt{U^2 + V^2 + W^2}$ and the maximum magnitude of $\sqrt{\text{Re}[U]^2 + \text{Re}[V]^2 + \text{Re}[W]^2}$ at each frequency. Note that