

Source-Path-Contribution Methodologies across a Wide Range of Product Types

Todd Freeman and Gabriella Cerrato
Sound Answers Inc.

ABSTRACT

Source-path-contribution (SPC) analysis, or transfer-path-analysis, is a test based method to characterize noise and vibration contributions of a complex system. The methodology allows for the user to gain insight into the structural forces and acoustic source strengths that are exciting a system, along with the effects of the structural and acoustic paths between each source and a receiver position. This information can be utilized to understand which sources and/or paths are dominating the noise and vibration performance of a system, allowing for focused target cascading and streamlined troubleshooting efforts. The SPC process is widely used for automotive applications, but is also applicable for a wide range of product types. For each unique application the basic SPC principles remain constant, however best practices can vary for both measurement and analysis depending on the type of system being evaluated. In this paper the application of the SPC process is described across a range of different applications including automotive, agricultural, small engine, and smaller component-level applications.

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INTRODUCTION

Source-Path-Contribution (SPC) analysis, or Transfer-Path-Analysis (TPA), has been utilized for many years, particularly in the automotive industry. These methods allow for the calculation of partial contributions from multiple sources and systems back to a receiver position, as well as for providing estimations of both acoustic and structural source strengths for each system/sub-system under evaluation. The output of the SPC analysis can be utilized in several different ways including NVH troubleshooting efforts [1] in which the structural/acoustic source strengths, local path terms, and global sensitivities can be examined to determine root cause and identify the most efficient potential countermeasure for the noise and vibration concern.

To facilitate the SPC calculations, information from the system under test must be gathered from CAD drawing, physical testing, analytical models, or a combination of all of the above. An initial inspection of CAD drawing and pictures is always useful to identify sources and paths and to define the most appropriate instrumentation strategy. The underlying assumption is that noise sources are well separated (both spatially and in terms of their features) among each other and in relation to the receiver (typically the driver/operator or an exterior pass-by microphone for a passenger vehicle) and that they can be represented by an ensemble of discrete microphone signals. While this is true for passenger vehicles and for larger equipment such as off-highway, agricultural and commercial vehicles, it becomes a challenge when dealing with smaller, utility-type products such as lawnmowers, appliances, vacuum cleaners, etc., where the sources are not only close to each other but also close, in a relative sense, to

the receiver (user). In these cases, the SPC tests need to be carefully designed and adapted to deal with the compact nature of sources and paths to receiver.

In the SPC procedure, structural and acoustic source strengths can be calculated using operational sound pressures and vibrations along with the local frequency response functions (FRF's), as seen in Equations (1) and (2).

$$\begin{pmatrix} Q_1 \\ \vdots \\ Q_n \end{pmatrix} = \begin{bmatrix} \frac{P_{11}}{Q_1} & \cdots & \frac{P_{1n}}{Q_n} \\ \vdots & \ddots & \vdots \\ \frac{P_{m1}}{Q_1} & \cdots & \frac{P_{mn}}{Q_n} \end{bmatrix}^{-1} \begin{pmatrix} p_1 \\ \vdots \\ p_m \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} f_1 \\ \vdots \\ f_n \end{pmatrix} = \begin{bmatrix} \frac{\ddot{x}_{11}}{F_1} & \cdots & \frac{\ddot{x}_{1n}}{F_n} \\ \vdots & \ddots & \vdots \\ \frac{\ddot{x}_{m1}}{F_1} & \cdots & \frac{\ddot{x}_{mn}}{F_n} \end{bmatrix}^{-1} \begin{pmatrix} \ddot{x}_1 \\ \vdots \\ \ddot{x}_m \end{pmatrix} \quad (2)$$

The inversion of the transfer function matrices is facilitated by having redundant (indicator) transducers for each source under consideration. Additionally source strengths can be calculated using mount stiffness methods, as seen in Equations (3) and (4).

$$f = K^* \Delta X$$

Where K^* is the dynamic stiffness, and ΔX is the displacement across the mount (defined below).

$$\Delta X(t) = \iint (\ddot{X}_A(t) - \ddot{X}_P(t)) dt \quad (4)$$

Partial contributions to a receiver position can then be calculated using the individual source strengths and the respective global transfer functions, as seen in [Equations \(5\) and \(6\)](#).

$$\begin{Bmatrix} f_1 \\ \dots \\ f_n \end{Bmatrix} \begin{Bmatrix} \frac{P}{F_1} & \dots & \frac{P}{F_n} \end{Bmatrix} = \begin{Bmatrix} p_1 \\ \dots \\ p_n \end{Bmatrix}_{SB} \quad (5)$$

$$\begin{Bmatrix} Q_1 \\ \dots \\ Q_n \end{Bmatrix} \begin{Bmatrix} \frac{P}{Q_1} & \dots & \frac{P}{Q_n} \end{Bmatrix} = \begin{Bmatrix} p_1 \\ \dots \\ p_n \end{Bmatrix}_{AB} \quad (6)$$

As mentioned previously, these methods have been used for many years in the automotive industry to aid in troubleshooting efforts, perform vehicle, sub-system, and component-level target setting, and evaluate alternate design options or new components/systems and their effects on overall NVH performance. These methods, however, can be applied to many different applications and product types, such as agricultural products [2], small engine applications, and component-level applications.

SPC APPLICATION CASE STUDIES

The following discussion will focus on the application of SPC methodologies for several automotive and non-automotive applications. The fundamental principles of the analysis will remain the same for each application, however each situation can require unique best practices for measurement and analysis for successful implementation.

Automotive SPC Typical Application

A common application of SPC analysis for an automotive vehicle is for the study of powertrain noise, with the goal of gaining insight into the key sources and paths affecting the acoustic experience of the end customer. To accomplish this, the acoustic signature of the powertrain (engine and transmission) can be quantified with microphone inside the engine bay, along with accelerometers at key points including the mounting locations [1].

The number of transducers (microphones and accelerometers) required to facilitate accurate characterization of the system can be dependent on the size of the system as well as the boundary conditions. For measurements within an engine bay, the boundary conditions can produce a diffused field condition in which the acoustic signature within the engine bay can be similar at multiple points around the powertrain. To resolve the unique acoustic properties at multiple positions around the powertrain, the number of microphones typically needs to increase and the position of each microphone typically needs to be very close to the powertrain, particularly to resolve higher frequency content.

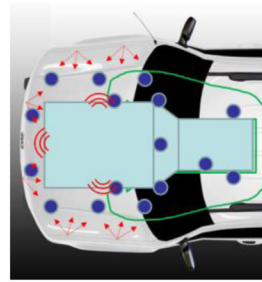


Figure 1. Engine Bay Diffused Field

The number and position of the transducers can have a direct impact on the characterization of both the acoustic source strength estimations, as well as the characterization of the local transfer functions.

The mount stiffness method ([equations 3 and 4](#)) also works well for structural characterization of the powertrain mounts as their dynamic stiffness can be characterized via shaker testing by the mount supplier. A word of caution is necessary, though, as lab-tested dynamic stiffness is measured under fixed pre-load conditions that represent only a fraction of real world boundary conditions to which the mount is subjected to in vehicle. To compensate for this uncertainty, dynamic stiffness can be estimated from [equation 3](#) with forces estimated from the matrix inversion method and measured displacement across the mount.

Agricultural SPC Application

Source-Path-Contribution (SPC) methods can be applied to agricultural applications in similar fashions as automotive applications. For agricultural applications the physical size of the systems under test, however, are typically much larger and the boundary conditions between sources and receivers can often times be unique.

Number of Transducers

The physical size of the application and its sources has a significant impact on the required number of transducers to adequately characterize the system. The larger size of the sources (large diesel engine with cooling fan, as an example) translates into more surface area from which acoustic energy can radiate, thus requiring many more microphones (source and indicator) to sufficiently map the system. This is specifically true if the goal is to determine which specific components (turbo charger, pump, hydraulic hose, fan, etc.) are radiating the key energy. Each component/area must be monitored sufficiently, increasing the number of transducers required.

If knowledge of the specific components radiating noise is not critical then the number of transducers can often be minimized. This can be true for situations in which it is sufficient to assign the energy to general areas of the system, for example the left side of the engine, as opposed to assigning the energy to a more specific area, for example a particular panel of the engine block.

If the number of transducers is too low, or the placement of the transducers does not capture all of the critical energy sources, the result can be an under-estimation of the total energy in the system. In this case, as highlighted in [Figure 2](#), some of the frequency content