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General framework for transfer path analysis: History, theory and classification of techniques[☆]

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ABSTRACT

Transfer Path Analysis (TPA) designates the family of test-based methodologies to study the transmission of mechanical vibrations. Since the first adaptation of electric network analogies in the field of mechanical engineering a century ago, a multitude of TPA methods have emerged and found their way into industrial development processes. Nowadays the TPA paradigm is largely commercialised into out-of-the-box testing products, making it difficult to articulate the differences and underlying concepts that are paramount to understanding the vibration transmission problem. The aim of this paper is to derive and review a wide repertoire of TPA techniques from their conceptual basics, liberating them from their typical field of application. A selection of historical references is provided to align methodological developments with particular milestones in science. Eleven variants of TPA are derived from a unified framework and classified into three categories, namely classical, component-based and transmissibility-based TPA. Current challenges and practical aspects are discussed and reference is made to related fields of research.

1. Introduction

Transfer Path Analysis (TPA) has been a valuable engineering tool for as long as noise and vibrations of products have been of interest. A TPA concerns a product's actively vibrating components (such as engines, gearing systems or turbochargers) and the transmission of these vibrations to the connected passive structures. TPA is particularly useful when the actual vibrating mechanisms are too complex to model or measure directly, as it allows us to represent a source by forces and vibrations displayed at the interfaces with the passive side.

In this way the *source excitations* can be separated from the structural/acoustic *transfer characteristics*, allowing us to troubleshoot the dominant paths of vibration transmission. The engineer can then anticipate by making changes to either the source itself or the receiving structures that are connected to it.

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Nomenclature

DoF	degree of freedom
FRF	frequency response function
$\mathbf{u}$	dynamic displacements/rotations
$\mathbf{f}$	applied forces/moments
$\mathbf{g}$	interface forces/moments
$\mathbf{Y}$	admittance FRF matrix
$\mathbf{Z}$	impedance FRF matrix
$\mathbf{T}$	transmissibility matrix
$\star^{AB}$	pertaining to the assembled system
$\star^{A}, \star^{B}$	pertaining to the active/passive component
$\star^{R}$	pertaining to the test rig
$\star_1$	source excitation DoF
$\star_2$	interface DoF
$\star_3$	receiver DoF
$\star_4$	indicator DoF
$\star_{ps}$	pseudo-force DoF

A TPA often rises from the need to reduce some sort of undesired noise or vibration, for instance to improve product comfort or lifetime, ensure safety or preserve stealthiness. Aside from automotive development, applications are also seen in industries such as marine and aeroplane engineering, building acoustics and acoustic modelling of musical instruments. A TPA is generally motivated by one of the following desires:

1. *Secrecy*: perhaps the earliest TPA studies were triggered by the need to reduce the transmission of engine vibrations in military ships and submarines in order to make them stealthy. Many publications in the 1950s and 1960s document on isolation of ship engines by means of absorbers and decoupling mechanisms [1–5] to minimise the transmission through the interfaces.
2. *Safety*: along with the rapid development of aeroplanes and spacecraft in the 1960s, TPA concepts started to be of use to study fatigue and stability (flutter) problems due to active or induced vibrations. As sources of vibrations are much more persistent in aeronautics – think of vortex-induced vibrations – focus was on characterising the passive transfer paths by means of modal analysis [6,7].
3. *Comfort*: over the last decades TPA tends to be particularly associated with noise, vibration and harshness (NVH) engineering as commonly encountered in the automotive industry. The majority of recent developments and commercial solutions have been tailored towards this engineering society or related industries, driven by the increasing customer expectations on acoustic comfort [8–12].

In response to the evolving demands, TPA methods have been under continuous development and their family members have grown numerous. Some designations that found their way into the literature include Operational TPA (OTPA), Operational Path Analysis with exogenous inputs (OPAX), blocked-force TPA, Gear Noise Propagation, in situ Source Path Characterisation and Virtual Acoustic Prototyping. Very often those methods are presented from highly case-specific derivations. Not surprisingly, as the underlying physical concepts are similar, some of the above-mentioned show strong similarities or are even identical.

A TPA work flow can typically be subdivided in the following steps: (a) operational measurement on the active component; (b) determination of the passive (sub)system characteristics (commonly by means of FRFs); (c) identification of interface loads; (d) calculation of path contributions. The steps are shown schematically in Fig. 1. Depending on the TPA method at hand, some or all of these steps may be performed in arbitrary order. The optimisation actions that follow from such an analysis are generally not considered part of the work flow.

This paper presents a unified framework for derivation of a large range of TPA methods. It is chosen to present and classify the methods separate from their typical fields of application, such that the underlying physical concepts are exposed and can be compared. Section 2 presents an account of some early developments and their relation to currently established TPA methods. This should by no means be regarded as a complete historical overview; rather it was chosen to highlight some key publications that have inspired the methodological developments in different ways. In Section 3 a general framework for TPA is introduced, starting by depicting the transfer problem using the Dynamic Substructuring paradigm [13]. Hereafter the TPA methods are derived and classified along three families, namely the *classical* (Section 3.2), *component-based* (Section 3.3) and *transmissibility-based* (Section 3.4) TPA methods, as depicted vertically in Fig. 1.

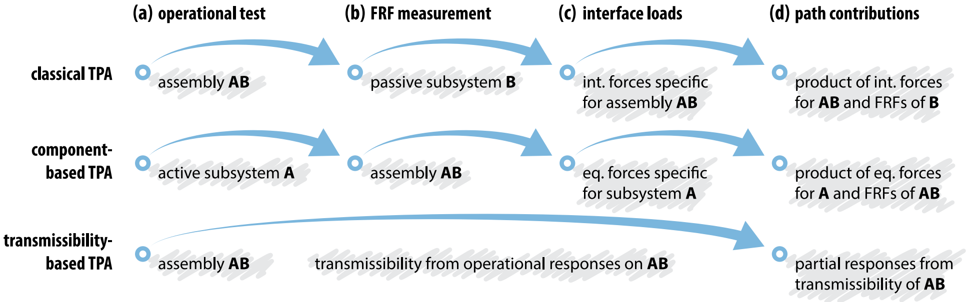

Fig. 1. The TPA work flow, depicted stepwise for the three TPA families.

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