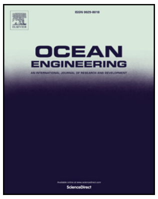
Ocean Engineering 161 (2018) 136–153

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Computation of dominant energy transmission paths for ship structure using a graph theory algorithm

Mehmet Avcu*, Ahmet Güney

Department of Mechanical Engineering, Istanbul Technical University, Gumussuyu, Beyoglu, 34437, Istanbul, Turkey

ARTICLE INFO

Keywords:
Graph theory
Energy transmission path
SEA
Ship structure
Structure-borne
Vibration

ABSTRACT

When solving a vibroacoustic problem in a physical system, a fundamental goal is to determine how energy is transmitted from a given source to any part of the system. This enables the modifications needed to reduce noise or vibration levels in each system component. Numerical techniques such as Finite Element Method (FEM) and Statistical Energy Analysis (SEA) can predict the vibroacoustic behavior of the system; yet, they do not directly reveal which part of the system shall be modified. The energy transmitted via the path that connects a source and a target subsystem component can be determined numerically. Finding the dominant paths that contribute the most to the total energy transmitted between a source and target is more art than science; finding the dominant paths usually depends on an engineer's expertise and judgement. Thus, a systematic approach to automatically identify those paths would be beneficial. Graph theory provides a solution to this problem, because powerful path algorithms for graphs have already been developed. In this study, a systematic procedure for ranking the dominant energy paths in a vibroacoustic model is developed by using existing graph theory and SEA graph approaches. To extend the use and performance of this application-specific approach which investigates the vibroacoustic behavior of a ship structure, a research ship has been modelled via a SEA model for mid- and high-frequency ranges. Then, the structure-borne energy transmission paths from a vibration source to the keel bottom (underwater hull) plates are determined and ranked by their energy output. Next, the process identifies the structural elements that need to be modified to reduce the overall energy levels. A parametric approach is then used to modify these ideal candidates using a representative FEM model. Finally, the modelling results verify that the path-modified ship structure has reduced the structural vibration energy levels. Thus, by using and extending the pre-existing graph theory algorithm, the vibroacoustic behavior of complex ship structures is predicted, the energy output of each path is found and the problematic paths are modified during the ship design phase to ensure that vibration and noise levels are minimized.

1. Introduction

The vibroacoustic behavior of a physical system can be modelled using several numerical methods. One of the most common measures used to categorize them is the frequency range, i.e., low-frequency, mid-frequency and high-frequency. Since each frequency range has its own characteristics and has a limited scope of validity (Deckers et al., 2014), modelling strategies to resemble the vibroacoustic response of a system depends on the frequency range used. In the low-frequency range, deterministic approaches like Finite Element Method (FEM) and Boundary Element Method (BEM) can be used to determine the vibration modes; this is likely because there are few modes and they are well-separated. Nevertheless, in the high-frequency range, modal density and modal overlap are high and the physical system's vibroacoustic behavior is more sensitive to slight changes in the physical parameters due to the range's short wavelengths. Therefore, since these variations must be considered, predicting the response of a single system via deterministic techniques becomes meaningless. Instead, calculating the average responses of a physical system is more rational. Consequently, statistical approaches like the Statistical Energy Analysis (SEA) are the commonly used techniques for this frequency range.

Because there is a large frequency gap between low- and high-frequency ranges, the mid-frequency range is too diverse for an exact description of the system's vibroacoustic response. The vibroacoustic characteristics of the system may fall in between low- and high-frequency ranges, or the system may not present uniform dynamic behavior. To tackle this mid-frequency range problem, several numerical methods and strategies like the Wave Based Methods (WBM) in Deckers et al. (2014), Desmet (1998), the Asymptotical Scaled Modal Analysis (ASMA) in De Rosa and Franco (2008), the Energy Distribution

---

* Corresponding author.
E-mail addresses: avcum15@itu.edu.tr, mehmetavcu@ymail.com (M. Avcu), guney@itu.edu.tr (A. Güney).

https://doi.org/10.1016/j.oceaneng.2018.05.002
Received 13 August 2017; Received in revised form 28 April 2018; Accepted 2 May 2018

Methods in Mace and Shorter (2000), the Statistical modal Energy distribution Analysis (SmEdA) in Maxit and Guyader (2001a, 2001b, 2003), the MODal Energy Analysis (MODENA) approach in Totaro and Guyader (2013), the radiative energy transfer methods in Le Bot (2005), the dynamic energy analysis in Chappel and Tanner (2012, 2014) and the FEM-SEA hybrid methods in Langley and Cordiali (2009), Shorter and Langley (2005) have been developed.

Numerical methods can also be used to solve noise and vibration problems seen in the automotive and marine industries. Usually, these problems consist of a vibroacoustic source that generates an extreme energy level in the other part of the system, normally named as target or receiver (Guasch and Aragonès, 2011). For instance, in a ship's structure, the diesel engine may interfere with the comfort levels of the crew's living and working spaces on the upper level decks. To resolve these quality issues, some parts of the system will need to be modified to decrease the energy level of the target to an adequate level. Analysis methods like FEM, BEM and SEA are used to predict the vibroacoustic response of a system at a given frequency band. Depending on the method used to model the vibroacoustic response, quantities such as acoustic pressure or, structural vibration velocity can be determined. The results yield information about the vibroacoustic behavior of the system, but does not directly provide a solution for the part of the system that needs to be modified. By investigating the system response during postprocessing, a general overview (of the modifications) is provided, reviewed and applied. This procedure does not guarantee the best modification to reduce energy levels of the targeted system component.

Monte Carlo numerical experiments may be employed to find components that need modifications. The experiment defines thousands of unique scenarios with random and slightly modified parameters; each parameter is kept within acceptable values and the best parameters that yield the best results are kept (Dinsmore and Unglenieks, 2005). This technique has a high computational cost without guaranteeing the best or optimal solution for the system. One of the other approaches is to combine known optimization algorithms with sensitivity analyses. Then the optimization is achieved in two-stages; the objective function is minimized or maximized in the first stage and the parameters which are the most influential in the variation of the results are determined in the second stage. This procedure has been applied to SEA models by several researchers (Bartosch and Eggner, 2007; Büssow and Petersson, 2007; Chavan and Manik, 2005).

These optimization approaches look for solutions that provide the best results, but they do not attempt to discover the origin of the problem. One of the key issues when modelling the vibroacoustic behavior of a system is specifying how energy is transmitted from a source, where the external energy is known, to a target, where the resulting energy is determined and needs to be reduced. The experimental methods traditionally used to solve these type of vibroacoustic energy minimization problems are known as Transmission Path Analysis (TPA) and Operational Transfer Path Analysis (OTPA) techniques (Bendat, 1976a, 1976b; Dodds and Robson, 1975; Potter, 1977; Stahel et al., 1980; Tschudi, 1991; Verheij, 1982; Guasch, 2009; Guasch and Magrans, 2004; Toome, 2012). In the automobile industry, this experimental technique is used extensively (Toome, 2012; Cremer, 2005; Klerk, 2009a, 2009b; Klerk and Ossipov, 2010; Plunt, 2005; Wang, 2000; Kurado and Yamazaki, 2013); but for the marine sector, the relatively large number of parameters and complexity of the ship structure result in many measurement difficulties.

Additionally, the energy transmission paths can be found numerically and the SEA method is at the core of the path determination strategy. The first description of the contribution of an energy transmission path between two subsystems was made in Craik (1979, 1996). Additionally, later works showed that the energy level in a subsystem can be recovered by adding the contribution of all the paths heading such subsystems (Craik, 1996; Magrans, 1993). Using graph theory to obtain the energy transmission paths in a SEA model was first proposed in Guasch and Cortés (2009). A graph is a set of elements that share pairwise connections. Furthermore, a SEA model consists of subsystems and the interactions of power flow between them. Therefore, the theoretical similarities between a graph and a SEA system can be found in the premise of each method. As mentioned in Guasch and Aragonès (2011) and in Guasch and Cortés (2009), the problem of reducing the energy of a set of target subsystems in a SEA model could be solved in the general framework of graph theory as in Gross and Yellen (1999), Carré (1979), Diestel (2005). The work done in Guasch and Cortés (2009) shows that a SEA model can obtain more information by establishing the connection between graph theory and the SEA method via a SEA graph[1] for noise and vibration control purposes. As a possible application of graph theory to vibroacoustics, a graph cut algorithm strategy that computes cuts in the graph separating source and target subsystems is implemented to achieve energy reduction at a target subsystem with the sole modification of a reduced set of loss factors (Guasch et al., 2011).

While determining the vibroacoustic behavior and energy transmission paths for a system, another issue related to noise and vibration control arises when ranking source-to-target energy transmission paths. Ranking the energy transmission paths, i.e., determining the relative importance of these paths, is significant because a small set of dominant paths can carry a high percentage of the overall energy (Guasch and Aragonès, 2011).

Ranking energy transmission paths requires a systematic path search in a vibroacoustic system model and a systematic dominant-energy path-ranking approach. As mentioned in Guasch and Aragonès (2011), the association between SEA and graph theory was established in Guasch and Cortés (2009) by defining a generating matrix of the SEA system series solution with the adjacency matrix of a graph, designated as a SEA graph. A systematic procedure to determine the set of K-ranked dominant energy paths in a SEA model was addressed in Guasch and Aragonès (2011) using graph theory tools found in (Guasch and Cortés, 2009).

The graph theory-based systematic procedure for ranking the dominant energy paths developed in Guasch and Aragonès (2011) will be combined with a SEA graph approach using the path-detection algorithm in Guasch and Aragonès (2011). Adapting this procedure for optimizing vibroacoustic behavior will be one of the main goals of this paper. Another goal is to extend the use and performance of this approach for investigating the vibroacoustic behavior of a ship's structure. For this purpose, the component in a ship's structure with the most impact on ship acoustics (underwater noise) will be modelled as a SEA model for mid- and high-frequency ranges. Then, the structure-borne energy transmission paths are found. Each path extends between the effective vibration source of the gearbox system and the target of keel bottom (underwater hull) plates. Each path will be identified and ranked according to the energy contribution to the target. The paths that yield the highest contribution are then determined as ideal candidates of ship structural elements to be modified to reduce the structural vibration on keel bottom and underwater noise accordingly. Finally, a parametric FEM model, which represents a limited version of the analyzed ship structure, is built. This reduced parametric FEM model is used to analyze the structural design modifications using the ideal parameters. The SEA model of the ship structure is then modified using the best acoustically-improved structural modification parameters; the modified ship structure is used to verify that the modified structural elements have reduced the energy levels in terms of structural vibration. Moreover, the structure-borne energy transmission paths for the modified ship structure are (independently) determined to comprehend how the structural modifications impact their behavior.

Ships reveal problems when they provide both a workplace and a living environment for onboard personnel. These personnel are often

---

[1] A graph that represents the SEA system.