Applied Acoustics 133 (2018) 144–156

Contents lists available at ScienceDirect

Applied Acoustics

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

Modal approach to obtain the coupling loss factors between structural systems and the surrounding fluid

Esther Jorge[a,b,*], Asier Alonso[b,c], Nere Gil-Negrete[a,b]

[a] *Ceit, Manuel Lardizabal 15, 20018 Donostia/San Sebastián, Spain*
[b] *Universidad de Navarra, Tecnun, Manuel Lardizabal 13, 20018 Donostia/San Sebastián, Spain*
[c] *CAF I+D, José Miguel Iturrioz 26, 20200 Beasain, Spain*

ARTICLE INFO

Keywords:
Sound radiation
Sound transmission
Statistical energy analysis
Hybrid method
Coupling loss factors
Complex structures

ABSTRACT

Air radiation caused by vibrating structural systems is a fundamental problem in acoustic engineering with a wide application range. Exact analytical solutions are possible for some simple structures but for complex ones analytical expressions are not easily established. In this paper a methodology for computing the acoustic radiation caused by any type of flat structural system is presented. A general equation is established in modal terms, including the interaction between the structure and the surrounding fluid through pressure fluctuations. These are defined using a potential function, whose description is based on Hankel or Green baffled functions depending on the radiating surface dimension. Solving the obtained equation modal displacements caused by a specific excitation are known. Through these displacements the radiated power by the structure as well as the energy stored are quantified. Relating both the coupling loss factors between the structural system and the surrounding fluid are determined. In order to achieve the statistical diffuse field assumption coupling loss factor values are averaged both in frequency and in space. Some examples are analysed and it is shown that accurate results can be obtained applying the developed methodology in simple structures. In complex configurations it is validated using the computed coupling loss factors to estimate the transmission loss values and compare them with the experimental ones.

1. Introduction

The vibroacoustic behaviour of structural systems is an important issue in many applications such as building constructions, vehicles and aircraft. Over the years, sound radiated by a vibrating structure into the surrounding fluid has been analysed by different formulations such as the Finite Element Method (FEM) or the Boundary Element Method (BEM) and power flow approaches. Calculation consists basically in establishing the movement equations of the structure [1] along with the wave propagation equations in the acoustic medium [2].

FEM/BEM methodologies [3,4] are appropriate for the low frequency range, in which components present large wavelengths compared to their size. They provide results at discrete points and frequency values, being their main drawback the computational cost. In order to solve the problem a discretization of the system (or boundary) into a set of contiguous and disjointed regions, known as elements, is made. The fundamental equations are established at each defined element. The solution accuracy is sensitive to the discretization size, which is related to the wavelength of the wave propagating through the structure. It is usually suggested to use between 6 and 10 elements per wavelength to get accurate enough results [5,6]. As the frequency increases the wavelength decreases and hence the number of elements needed to perform the computation grows, meaning a higher computational cost. In the high frequency range energy flow approaches are usually employed. These methods quantify the exchange of vibrational energy in a system, being the stored energy the primary variable of interest. Unlike FEM/BEM computations, energy flow methods provide space average and broadband solutions with a lower computational cost.

One of the most widely used energy flow approaches is the Statistical Energy Analysis (SEA). It consists in dividing the system under study into different subsystems [7]. The general system of equations is obtained establishing a power balance in each defined subsystem, relating input power to dissipated and transmitted powers. The dissipation within a subsystem is characterized by a parameter known as loss factor (LF) while the transmission between them is associated to a variable known as coupling loss factor (CLF). One of the SEA advantages is that the resulting system of equations is algebraic; the main difficulty in applying the methodology is the evaluation of needed parameters, particularly coupling loss factors. CLF values depend on the analysed subsystems (for instance beam, plate or cavity)

---

[*] Corresponding author at: Ceit, Manuel Lardizabal 15, 20018 Donostia/San Sebastián, Spain.
E-mail address: ejorge@ceit.es (E. Jorge).

https://doi.org/10.1016/j.apacoust.2017.12.014
Received 8 September 2017; Received in revised form 2 November 2017; Accepted 12 December 2017

and the type of junction between them (such as point, line or area). In case junctions between vibrating structures and the surrounding fluid are of interest, the CLF value is evaluated from the power radiated by the structural system.

Acoustic radiation from simple structures such as beams and plates has been a subject of deep research. One of the first works focused on studying the structure behaviour through an energy flow approach was developed by Lyon [8]. In this work a simply supported beam was excited by a diffuse incident acoustic field, with the same incidence probability in all directions and random enough in time so that its power spectrum was a fairly smooth function of frequency; thus fulfilling the excitation requirements in an energy flow approach. Maidanik [9] considered the radiation resistance of simple and ribbed finite plates and compared results of campled versus simply supported boundary conditions. Both investigations [8,9] were focused on studying the effects in the structure response due to the excitation by incident acoustic fields. They neglected fluid-structure interaction when calculating plate deflection, and thus radiation to fluid; i.e. the structure was assumed to be in vacuum and response effects due to coupling were neglected. Fahy [10] went a step further and analysed the radiation of a system consisting of one flexible plate of a rectangular rigid box to the sound field inside the box. The study showed a lower limiting frequency above which the radiation efficiency falls below free field values, while at high frequencies the radiation efficiency value was stated to be half of a freely radiating panel. Fahy's study considered the fluid-structure interaction and his analysis of the effects on the coupling of modal resonance frequency proximity leaded to corrections to the normal statistical energy response equations. Nevertheless, the study was conducted under conditions where diffuse field assumptions do not necessarily apply. The importance of fluid-structure interaction was again addressed by Skudrzyk [11]. He stated that, although only one plate mode was excited, the interaction produces response in non-excited modes. This behaviour was also analysed by Cremer et al. [12] in the case of a simply supported beam. Keltie and Pend [13] studied the importance of inter-modal coupling effect between simply supported excited panels and the acoustic medium. The analysis showed that if the driving force is high frequency, effects due to inter-modal coupling are negligible and only resonant excitation influences the response value; i.e. effect of modes whose natural frequency is in the frequency band of interest are contributing to the response. However, at the low frequency range contributions due to the inter-modal coupling may be important, i.e. off-resonant excitations should also be considered. A similar study was carried out by Davies [14] and Pope et al. [15] for clamped plates in the low frequency range. In these studies, the inter-modal coupling coefficients described the interaction of the plate with the fluid half-space above it. The coefficients were quantified in terms of the in vacuum plate modes. This methodology leaded to an infinite set of coupled algebraic equations representing the solution (as opposed to the uncoupled set of equations obtained in the absence of fluid loading). In an independent study, Leppington et al. [16,17] proposed improved statistical expressions taking into account resonant and non-resonant contributions to the acoustic radiation from a simply supported plate over the whole frequency range. The asymptotic results achieved were different according to the computation frequency being above or below the coincidence value. In the latter case, account was taken of both resonance and non-resonance contributions to the power flow and near coincidence frequency a transition formula was given.

The use of new materials and manufacturing processes has led to an increase of complexity in structures as systems are not only composed of simple plates and beams. Radiation of complex structures can be evaluated by experimental procedures measuring impulse responses [18–21]. The difficulty of the experimental methods lies in the number of measurements needed and the evaluation of the spatially averaged energy from some measurement points. These procedures are useful to evaluate the radiated power but they are not prediction tools as it is necessary to have the structure physically to carry out measurements. In order to solve this problem FEM/BEM methods can be used to compute the response of the coupled subsystems and to determine the radiation between them [22–26]. Their main drawback lies in the necessity of repeating simulations many times to average results, for example by a Monte Carlo methodology, with the added computational cost of including the fluid cavity. Another approach to analyse complex structures theoretically is to use specific equations developed to characterize the acoustic radiation of particular configurations [27–33]. Finally, to study general structural systems hybrid methodologies are applied, which combine FEM/BEM with statistical computations [34–37].

Some examples of models proposed to analyse particular configurations are the wave propagation approach to study sandwich panels (Nilsson [27]), the approximate model to analyse aluminium extrusions used in railway vehicles (Xie et al. [28]), the wave finite element method to compute the vibroacoustic response of arbitrarily thick layered panels (Chronopoulos et al. [29]), the transfer matrix, periodic cell and Rayleigh-Ritz procedures to calculate transmission and radiation properties of typical rail and aerospace structures (Orrenius et al. [30]), the transfer matrix method of periodic planar media (Parrinello and Ghiringhelli [31]), the wave finite element method extension to the predict radiation from infinite panels (Yang et al. [32]) and deformation theories (first and third order) to analyse laminated composite cylindrical and curved shells (Talebitooti et al. [38–41]). Moreover, the latter contributions by Talebitooti et al. [38–41] provide a methodology to calculate the Transmission Loss theoretically and investigate the influence of parameters in the results for different configurations.

As stated above, these approaches only allow studying particular structure configurations. In order to analyse any type of structural configuration different hybrid methodologies have been developed. One of the most widely known was presented by Shorter and Langley [34]. By that procedure the system response is divided into two components, corresponding to long wavelength, modeled by a FEM/BEM procedure, and short wavelength deformations, modeled using SEA. The fundamental idea of the method is a reprocity result regarding the forces exerted on the boundaries of the long wavelength subsystems [42]. The wave field in statistical subsystems is decomposed into direct and reverberant field components and the reverberant field component is described in terms of a random diffuse field. The reciprocity relationship couples direct field radiation with diffuse reverberant loading at the interfaces between FEM/BEM and statistical subsystems. The challenge of this method is the proper computation of direct field dynamic stiffness matrices. This matrix can be found from numerical evaluation by a boundary element analysis at long wavelength boundaries, by the Fourier transform approach [43], or using the wavelet approach based on JINC functions [44]. A similar hybrid method was established by Ji et al. [35], who used a free-interface component mode synthesis model of the system. Through this model each component is described in terms of its free-interface uncoupled modes and coupled using basis functions defined on the interface. This work concerns the interaction of a long-wavelength source substructure with a short-wavelength receiver substructure. Sadoulet-Reboul et al. [36], proposed a method to predict radiated noise using the radiative energy transfer method which is an energy boundary integral method.

Hybrid methods described so far couple FEM/BEM with SEA responses. Nevertheless, it would be convenient to avoid modeling and calculating all FEM/BEM components. Instead it would be preferred, if possible, to model the whole system by SEA and calculate the statistical parameters of each subsystem. Accordingly, Cotoni et al. [45] described a SEA subsystem formulation based on a combination of finite elements,