UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

A CORRECTED MODEL OF STATISTICAL ENERGY ANALYSIS (SEA) IN A NON-REVERBERANT ACOUSTIC SPACE

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AL MUNAWIR

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled ”A Corrected Model of Statistical Energy Analysis (SEA) In A Non-Reverberant Acoustic Space” is the result of my own research except as cited in the references. The Thesis has not been accepted for any degree and is not currently submitted in candidate of any other degree.

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATION

”To my beloved parents and wife”

ABSTRACT

Statistical Energy Analysis (SEA) is a well-known method to analyze the flow of acoustic and vibration energy in a complex structure. The method is based on the power balance equation where energy in the divided subsystems must be reverberant. This study investigates the application of SEA model in a non-reverberant acoustic space where the direct field component dominates the total sound field rather than a diffuse field in a reverberant space. Here, a corrected SEA model is proposed where the direct field component in the energy is removed and the power injected in the subsystem considers only the remaining power after the loss at first reflection. To validate the model, a measurement was first conducted in a box divided into two rooms where the condition of reverberant and non-reverberant can conveniently be controlled. In the case of a non-reverberant space where acoustic material was installed inside the wall of the experimental box, the signals are corrected by eliminating the direct field component in the measured impulse response. Using the corrected SEA model, comparison of the coupling loss factor (CLF) with the theory shows good agreement. Secondly, a test was conducted in a car cabin where the front and rear cabins act as two separate subsystems. A loudspeaker was first used to inject the sound energy into the subsystems and several microphones were located to measure the transfer function. The CLF and the damping loss factor (DLF) were obtained using the classical SEA model. The corrected CLF and DLF are then calculated using corrected SEA model after eliminating the direct field components. The engine was then turned on to provide the input energy into the cabin. The sound power transmitted into the cabin was measured and from here the sound pressure level (SPL) can be obtained, either using the uncorrected CLF and DLF or using the corrected CLF and DLF. The results were compared with the directly measured SPL showing that good agreement is obtained from those using the corrected SEA model.

ABSTRAK

Analisis Statistik Tenaga (SEA) merupakan satu kaedah yang terkenal untuk menganalisis aliran akustik dan getaran tenaga dalam struktur yang kompleks. Kaedah ini adalah berdasarkan persamaan keseimbangan tenaga di mana tenaga dalam subsistem dibahagikan mestilah yg bergema. Kajian ini menyiasat penggunaan model SEA di dalam ruang akustik tanpa gema di mana komponen 'direct field' dari sumber bunyi mendominasi jumlah medan bunyi berbanding dengan medan resapan di dalam ruang yang bergema. Di sini, pembetulan terhadap model SEA dicadangkan di mana komponen 'direct field' dalam tenaga dikeluarkan dan kuasa disalurkan ke dalam subsistem hanya mempertimbangkan kuasa yang tinggal selepas kehilangan pada pantulan pertama. Untuk megesahkan model tersebut, ukuran pertama dilaksanakan di dalam kotak yang mempunyai dua bilik di mana keadaan yg bergema dan bukan yg bergema supaya mudah dikawal. Di dalam kes ruang yang tidak bergema di mana bahan akustik telah dipasang di dalam dinding kotak eksperimen, isyarat diperbetulkan dengan menghapuskan komponen 'direct field' sebagai tindak balas impuls yang diukur. Dengan menggunakan model SEA yang telah diperbetulkan, perbandingan terhadap faktor kehilangan gandingan (CLF) menunjukkan persamaan yang sepadan dengan teori. Kedua, pengukuran dijalankan di dalam kabin kereta dimana kabin depan dan kabin belakang bertindak sebagai dua subsistem yang terpisah. Pembesar suara digunakan untuk menyalurkan tenaga bunyi ke dalam subsistem dan beberapa mikrofon diletakkan untuk mengukur fungsi pindah. Kemudian CLF dan faktor redaman kehilangan (DLF) diperoleh daripada model SEA terdahulu. Seterusnya model SEA yang telah diperbetulkan digunakan untuk memperbaharui CLF dan DLF yang diperoleh setelah komponen 'direct field' dihapuskan. Enjin dihidupkan untuk memberi input tenaga ke dalam kabin. Kuasa bunyi yang dihantar ke dalam kabin diukur dan tahap tekanan bunyi (SPL) boleh diperoleh, sama ada menggunakan kesemua CLF dan DLF yang diperbetulkan ataupun tidak. Perbandingan dibuat dengan SPL yang diukur secara lansung menunjukkan bahawa keputusan tersebut sepadan dengan model SEA yang diperbetulkan. Ini menunjukkan model SEA yang diperbetulkan memberi ramalan yang lebih baik terhadap tahan tekanan bunyi (SPL) di dalam kabin kereta.

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LIST OF ABBREVIATIONS

CLF	**C**oupling **L**oss **F**actor
DLF	**D**amping **L**oss **F**actor
FFT	**F**ast **F**ourier **T**ransform
FRF	**F**requency **R**esponse **F**unction
PIM	**P**ower **I**njection **M**ethod
SEA	**S**tatistical **E**nergy **A**nalysis
SPL	**S**ound **P**ressure **L**evel
TL	**T**ransmission **L**oss

LIST OF SYMBOLS

E_i	Energy in the subsystem-i
E_j	Energy in the subsystem-j
E_{dir}	Energy travelling directly from the sound source
E_{rev}	Energy reflected from the surface
f	Frequency
F	Force
I	Sound intensity
$j = \sqrt{-1}$	Imaginary unit
k	Acoustic wavenumber
n	Modal density of the subsystem
p	Sound pressure
P_{in}	Input power
S_{xx}	Auto-spectra from the reference microphone and the response microphone
S_{xy}	Cross-spectra between the reference microphone and the response microphone
T_{60}	Reverberation time
V	Volume
W	Sound power
Y_p	Point mobility of the structure
Z	Impedence
α_i	Absorption coefficient in subsystem-i
σ	Perforation ratio
τ	Transmission coefficient
ω	Angular frequency
η_i	Damping loss factor in the subsystem-i
η_j	Damping loss factor in the subsystem-j
η_{ij}	Coupling loss factor from subsystem-i to subsystem-j
η_{ji}	Coupling loss factor from subsystem-j to subsystem-i

LIST OF PUBLICATIONS

A. Putra, Al Munawir and W.M.F.W. Mohamad (2014). The effect of the direct field component on a statistical energy analysis (SEA) model, *Applied Mechanics and Materials Journal*, Vol. 471, pp 279-284.

Al Munawir, A. Putra and W.M.F.W. Mohamad. A corrected model of Statistical Energy Analysis (SEA) in a non-reverberant acoustic space, *Engineering Noise Control Journal* (under review).

A. Putra, Al Munawir and W.M.F.W. Mohamad . Prediction of sound pressure level in a motor vehicle cabin using corrected SEA model, *Advances in Acoustics and Vibration* (under review).

CHAPTER 1

INTRODUCTION

1.1 Background

In recent years, noise and vibration performance is always a major issue for manufacturers around the world. Vibration is a phenomenon existing in a machine, such as vibrating pumps, motors and washing machines as well as in a flexible structure of a car or an airplane body. The level of noise and vibration has become one of the subjective performance indicators of a system. The problem of noise and vibration in vehicles for example, requires more attention due to competitive marker and increasing customer awareness on low noise emission either for quality comfort inside the vehicle or noise pollution to the environment. Therefore, reduction of noise and vibration becomes important.

There are many methods to analyze the noise and vibration problem. The choice of the right method is important to find a required result with minimum attempt and cost. Energy-based methods can be considered as an effective method due to their techniques of using energy quantities that is energy and power rather than quantities such as force and displacement used by the classical analysis of vibration (Sarradj, 2004). Energy-based methods have some advantages:

(a) The power-energy relation is not so sensitive to small parameter changes.

(b) Energy quantities can be averaged more easily.

Apart from the energy-based methods, Finite Element Analysis (FEA) and Boundary Element Analysis (BEA) are very well known and are usually implemented for analysis of noise and vibration at low frequency range. However, at high frequency range these methods are not efficient for several reasons:

(a) Finer discretization in the model to cope with very small wavelength requires long computational time.

(b) Require more details of structural pattern for a more complex structure.

One possible solution to solve the noise and vibration problems at mid to high frequency is Statistical Energy Analysis (SEA). It describes a complex system in terms of a network of connected subsystem, each of which has a resonant multi-modal response or, equivalently, reverberant wave field. In SEA, no attempt is made to recover the detail displacement pattern of the structure like FEA or BEA, but rather the structure is modelled as an assembly of subsystems. The aim is to predict the 'average' vibrational energy level of each subsystem. This is done by establishing a set of power balance equations which are based on the key assumption that the energy flow between two connected subsystems is proportional to the difference in the subsystem modal energies (Fahy, 1994). Such 'average' can be achieved when the structural or acoustic wavelength is much smaller than the dimensions of the corresponding structure or cavity.

Subsystems in SEA is defined as part of a system separated by boundaries across which distinct discontinuities in physical properties exist, e.g thickness, mass density or volume. Figure 1.1 shows division of car structure into three subsystems to predict the sound pressure level in the cabin due to force applied on the bulkhead. The subsystems can be divided into car cavity, windshield, and bulkhead. The noise in the cabin is expected to directly radiate from the vibration of the bulkhead. Meanwhile, there is also propagating vibration wave from the bulkhead to the windscreen causing the screen to vibrate and eventually radiate noise into the cabin.

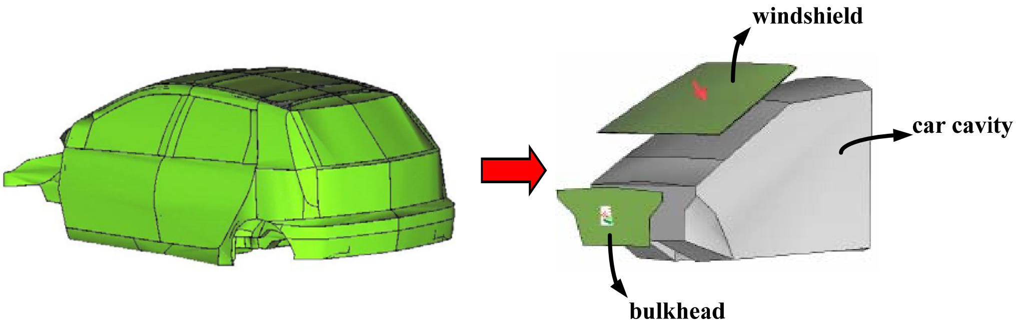

Figure 1.1 Illustration of subsystem division in the SEA model.

Because SEA is based on the statistical behaviour of the responses, therefore several assumptions apply:

(a) Behaviour of the subsystem is dominated by resonances

A larger number of resonant modes in a frequency band smoothes the response spectra and the spatial variation in the responses (provided that the damping in the subsystems is not too large).

(b) Weak coupling between subsystems

This is to allow 'control' of energy flow among the subsystems. In this case, the damping in both subsystems should be much larger than the coupling between subsystems. This means that almost all power dissipates in the excited subsystem and one subsystem does not affect the other subsystems.

Figure 1.2 shows example of a frequency response function (FRF) compared with the SEA prediction. At low frequency, the SEA can be seen to have large discrepancy with the FRF. This is because at low frequency, the FRF has very low modal density noted by the

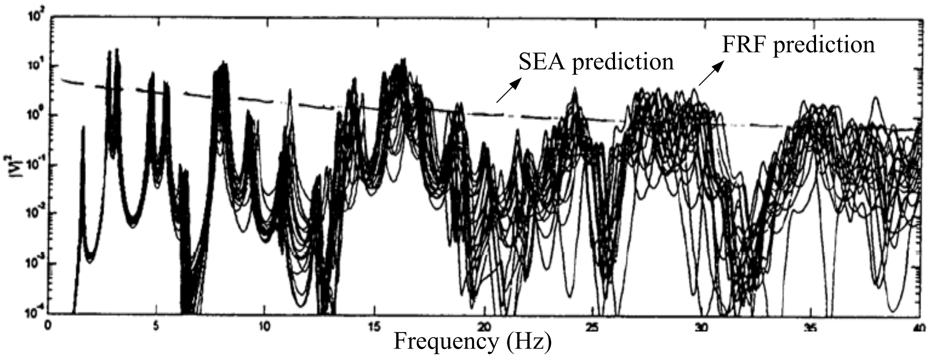

Figure 1.2 Comparison between FRF and SEA predictions.

distinct peaks in the graph (in this example below 15 Hz). The FRF can be seen to approach the SEA prediction at mid to high frequency as the modal density grows rapidly at higher frequency.

Figure 1.3 shows the typical frequency response of a structural-acoustic system, indicating frequency range of applicability for Finite Element Analysis (FEA), Boundary Element Method (BEM) and Statistical Energy Analysis (SEA). The SEA is best to predict the ensemble average at mid to high frequencies (Kenny, 2002).

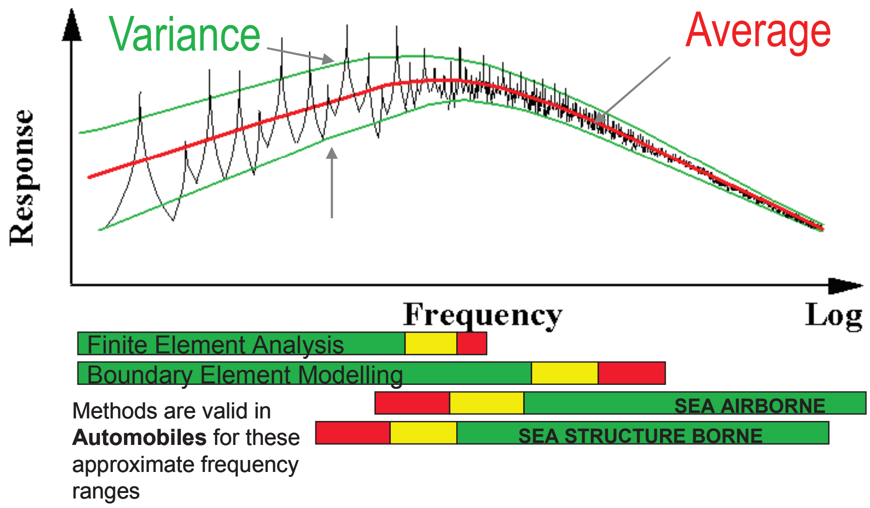

Figure 1.3 Frequency range response of FEA and SEA (ESI Group, 2010).

1.2 Past researches on the SEA model development and its application

Statistical Energy Analysis (SEA) was developed in 1960 by Lyon (1967) to predict the response of launch vehicles to rocket noise and to overcome the limitations of computational methods. He found that the power flow was proportional to the difference in uncoupled energies of the resonators and that it always flow from the resonator of higher to lower resonator energy. A complex structure was breached into subsystems and then stored and exchanged vibrational energy between these subsystems were analyzed.

The coupling loss factor (CLF) is the most important SEA parameter to be obtained from the SEA method. It represents how the energy flows from one subsystem to other subsystems. Good predictions of CLF is therefore critically important to obtain good estimation of the noise and vibration in a system. Price and Crocker (1969) formulated the CLF between room and cavity, assuming that transmission from room to cavity is the same as transmission from room to room. Cushieri and Sun (1994) presented a method for determinating the dissipation and CLF from SEA model of a fully assembled machinery structure. The method is based on the experimental measurements of the total loss factors and the energy ratios between the subsystems of the machine structure when they are fully assembled. Yap and Woodhouse (1996) investigated the effects of damping on energy sharing in coupled systems. The approach taken is to compute the forced response patterns of various idealised systems, and from these the parameters of the SEA model for the systems are calculated.

Mace (1998) predicted the coupling loss factor using SEA theory for systems consisting of rectangular plates. It is found that if the damping is large enough (weak coupling) the response is independent of the shape of the plates and for lighter damping (strong coupling) the response depends significantly on the specific geometry of each plate. Skeen and