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New ”light-weight” SEA software – why bother? Examples of practical applications

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Small- and mid-size companies dealing with sound and vibration issues or consulting services have never had really affordable commercial programs for statistical energy analysis (SEA). Licenses for available commercial products have gradually become very expensive and are out of reach for others than large companies extensively using the SEA method. A new software package for basic, “classic” SEA is presented. It is developed by the author mainly as an enthusiast project. It is aimed to satisfy users without the need for 3-D modelling and other extra features that are not part of the basic SEA method. It uses a simple network as graphical interface for the model development. The software is well adapted to both educational purposes and the needs of analysts with good knowledge of the fundamentals of SEA and its application limits. It is programmed in Microsoft® Visual Basic® 2005 and relies extensively on Microsoft® SQL databases for project and general data storage. It runs on all present Windows platforms, including 64-bit versions. The use is illustrated with a couple of practical examples. A small SEA model used at early concept study of a new product as well as a comprehensive model of a large built-up structure such as a ship or an off-shore platform is shown.

1 Introduction

Statistical Energy Analysis (SEA) [1, 2] has been used since the 1960s and commercial SEA software has been available since the 1980s [3, 4, 5]. Introduction of various extra features, like import of 3D CAD models etc, made the licence costs to increase rapidly during the 1990s [6, 7]. In a keynote speech at NOVEM 2000 [8], I presented a challenge to the SEA software producers to consider a “light” version of their products, omitting these advanced but not necessary features, and market it with a substantially lower licence fee. It could have a simple, user-friendly graphical network interface, suitable for building small and intermediate size SEA models and also such “Quick-SEA” examples as I presented in that speech. The software had to be affordable for small consulting companies as well as larger companies with occasional SEA modelling needs.

Since this idea was not picked up, I investigated how to develop a new, Microsoft® Windows-based program, based on my MS-DOS software GSSEACAL [9]. The development has been an enthusiast project since 2003 and resulted in completely new software architecture and code. Only the calculation algorithms from the old program were reused and in some cases improved. The GSSEA-Light software is now in its final beta testing stage to be released late in 2010.

2 SEA theory overview

Statistical Energy Analysis (SEA) [1] was mainly developed in USA in the early 1960's, as a way to predict the dynamic response of spacecraft structures to intense, high frequency acoustic excitation. SEA is used for the higher order mode analysis of complex structures. The problems and the uncertainties also when analytic or finite element methods are applied to response prediction involving a large number of higher order modes, also make a statistical approach to describe system properties a natural one. The basic theory of SEA can be found in e.g. [1, 2].

SEA is used to calculate the flow and storage of vibrational energy in complex, built-up systems with both structural and acoustic components. The energy storage elements are the subsystems, and represent parts of the system with similar vibrational modes. A component may have many subsystems (wave types) and is often easy to identify.

The components are finite linear elastic structures or acoustic cavities, with subsystems representing their uncoupled natural modes and dissipative losses. It is assumed that each mode can be modelled as a simple oscillator and that the interactions between two or more multi-modal subsystems can be represented by sets of oscillators (Figure 1).

The energy flow between two subsystems may be expressed as

$$W_{12} = \omega \cdot n_1(f) \cdot \Delta f \cdot \eta_{12} \cdot \; E_{m1} - E_{m2} \qquad (1)$$

where E_{m1},E_{m2} are the modal energies (energy/mode) of the subsystems, n_1 is modal density for subsystem 1 and η_{12} is the coupling loss factor

The energy will always flow from subsystems with higher average modal energy to subsystems with lower. This is the coupling equation in classical SEA. The coupling, excitation and dissipation for two subsystems are shown in Figure 2.

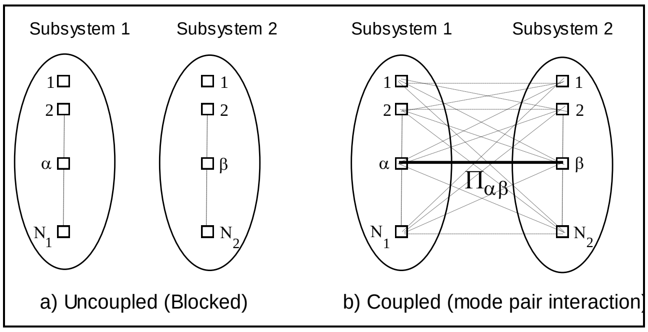

Figure 1. Coupling between multi-modal systems. The energy flow between the subsystems can be modelled as a superposition of contributions between individual modes of the blocked subsystems.

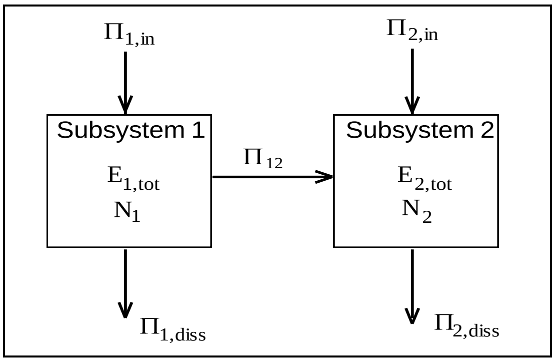

Figure 2**.** Block diagram for a two-subsystem SEA model.

A set of simultaneous energy balance equations is used to calculate the stationary energy levels of each subsystem. Response levels in engineering quantities (pressure, stress, acceleration, etc.) can then be calculated from these energies.

$$\Delta f \cdot \omega \begin{bmatrix} n_1\eta_{1tot} & -n_1\eta_{12} & \cdots & -n_1\eta_{1N} \\ -n_2\eta_{21} & n_2\eta_{2tot} & \cdots & -n_2\eta_{2N} \\ \cdots & \cdots & \ddots & \cdots \\ -n_N\eta_{N1} & -n_N\eta_{N2} & \cdots & n_N\eta_{Ntot} \end{bmatrix} \cdot \begin{Bmatrix} E_{m1} \\ E_{m2} \\ \cdots \\ E_{mN} \end{Bmatrix} = \begin{Bmatrix} W_{in1} \\ W_{in2} \\ \cdots \\ W_{inN} \end{Bmatrix} \quad \text{or in matrix notation} \quad \Delta f \cdot \omega [A] \cdot \{E_m\} = \{W_{in}\} \qquad (2)$$

Only resonant vibratory energy of the subsystems is involved in the energy balance calculations. Vibratory energy transmission via non-resonant paths, e g the mass-law sound transmission behaviour of a panel, must be included as separate couplings in the SEA model. The average response levels of well-damped subsystems may be under-estimated since non-resonant response is excluded. Total energy in each frequency band is obtained by multiplying the modal energy with the number of modes in the band. From these total energies, average response quantities are determined.

2.1 SEA Parameters.

The SEA parameters used for the subsystems and junctions in order to solve the energy balance equations are:

1) Input powers W_i to the i-th subsystem
2) Modal densities n_i for the i-th subsystem
3) Internal loss factors η_i for the i-th subsystem.
4) Coupling loss factors η_{ij} between the i-th and the j-th subsystems

Input power definition. The input power to subsystems is given directly or as a quantity from which the power may be calculated when subsystem parameters are known. More details are presented in the examples later on.

Modal density definition. The modal densities for subsystems (average number of modes/Hz), are usually calculated by the SEA computer program after input of subsystem data. The programs use well-established theoretical expressions, see e. g. [1, 2].

Internal loss factors. Describe the amount of dissipative losses in each subsystem. The data has to be supplied for each subsystem as empirical data, or as predicted loss factors of certain damped structures.

Coupling loss factors. The coupling loss factors (CLF:s) for energy transmission paths are calculated for different junction types from published formulae [1, 2]. CLFs are also related to other quantities of junctions [1, 2], like sound transmission loss (STL) for partitions that separate acoustic cavities, the radiation efficiency or radiation resistance for acoustic-structural coupling or wave transmission coefficients for junctions between plate-like subsystems. The CLFs for point structural connections may be derived from the mechanical point mobilities of the connected subsystems.

Only main parameters for components like volumes, areas, thicknesses, curvature, stiffeners etc are used to calculate these parameters. Exact details of the geometry are not necessary to define for the model. This is a benefit of SEA that allows prediction of responses also for early system concepts. Import of CAD-models or 3D-modeling is not essential.

3 The GSSEA-Light® Software

The GSSEA-Light® software was originally meant to be based on the previous GSSEACAL program. It resulted in completely new object oriented software architecture with several tiers. A graphical Windows user interface (GUI) was separated from the calculation kernel and a SQL database layer. Numerous improvements have been added incorporating ideas and experience from using other commercial SEA programs (AutoSEA®, SEADS®).

“Light” in this respect means that the package does not have a 3D modelling interface, but uses a network for creation and presentation of the SEA models, similar to AutoSEA® (version 1), SEADS®, and VisiSEAM®. “Light” means also that only basic classic SEA theory is used. Some add-on extensions, like modelling of vibration isolated sources, are available. Since programming and support effort is not invested for such additional features, and also since the programming is a personal, non-profit venture, license prices are also expected to be comparatively “light”. It does thus not intend to compete with the abovementioned more advanced commercial programs.

The package is developed in Microsoft® Visual Basic 2005 and uses Microsoft® SQL Server 2005 databases for all project specific and general utility data. It is fully object oriented and modularized to simplify future additions of features. The software runs on Windows XP, Vista and Win 7, also the 64-bit versions. Installation is straightforward.

The following GUI will open when GSSEA-Light is started. The small window is for selecting a stored project from the active project database.

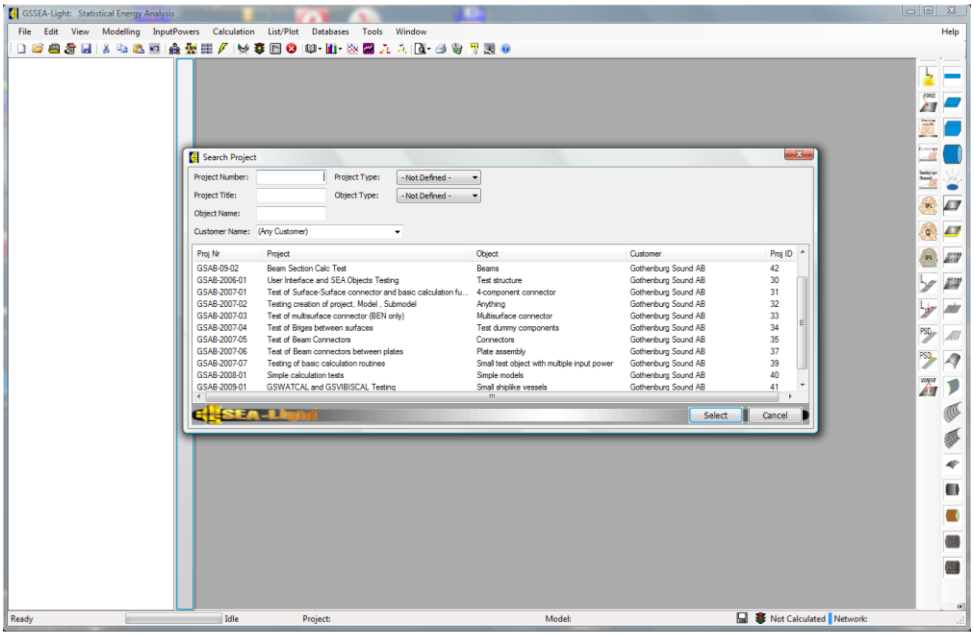

Figure 3. The graphical user interface of GSSEA-Light, with the project selection window open.

When a project is selected, a network diagram as well as an object tree will open for model editing and presentation of various results, see Figure 4. The icons in the network are full components, not subsystems. A component may include several subsystems, e.g. a plate can have three subsystems defined for the wave types (Figure 4). In a similar way, connectors between components are defined. These connectors connect many components that in turn may consist of several subsystems and all subsystem-subsystem couplings are managed in one connector. This leads to a much simpler network building and a much cleaner network than the one used in version 1 of AutoSEA®.

User input data for sources, material properties, internal loss factors, transmission losses, beam and sandwich sections, resilient elements etc. must be inserted into general utility databases used for all projects. Avoiding *ad-hoc* input to the SEA objects by the user results in traceability of used data to stored database records, see the examples in Figure 5.

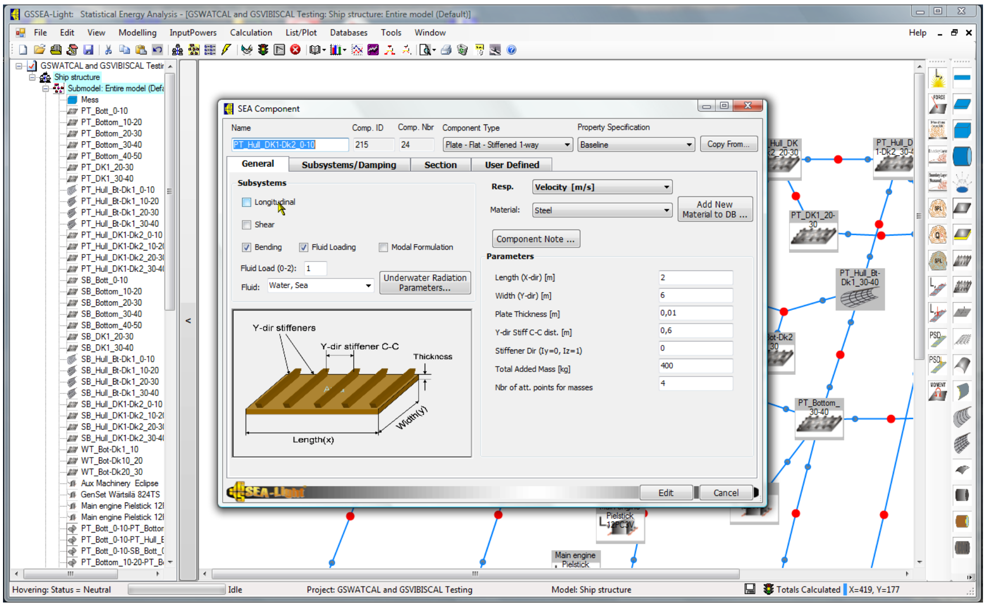

Figure 4. GSSEA-light with a model open. Part of the network and the object tree are shown. A property dialog for one component, selected is open on top. Note that a plate-like component may include up to three subsystems.

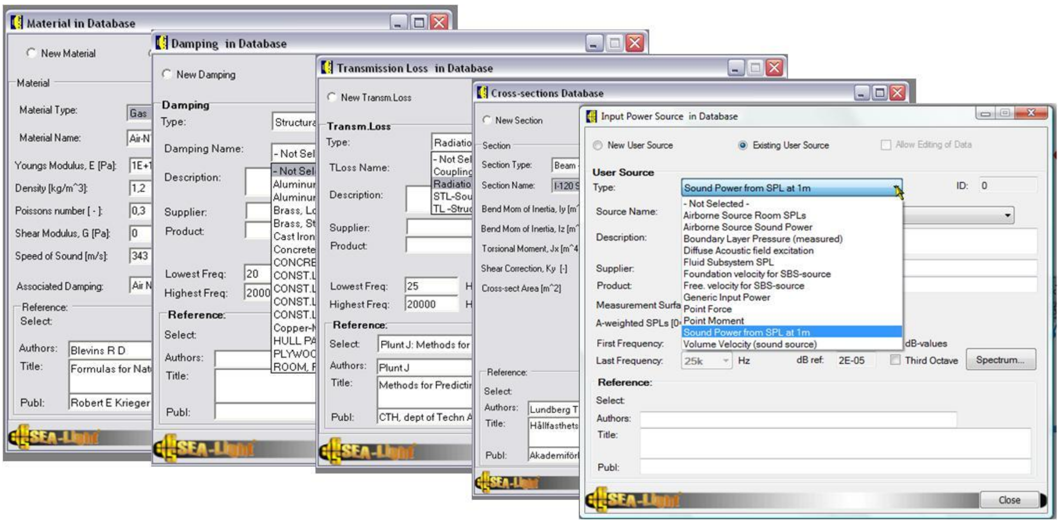

Figure 5. Examples of the utility databases for GSSEA-Light. These are tables in a SQL utility database, separate from the project SQL database. All input data to components and connectors have to reference to these databases.

Figure 6 shows a few immediate results that can be plotted for subsystems of a component. These parameters are calculated immediately when the component is created and recalculated whenever the component property window is opened. Figure 7 shows a similar example for a connector, allowing the plotting of transfer functions as well as coupling loss factors.

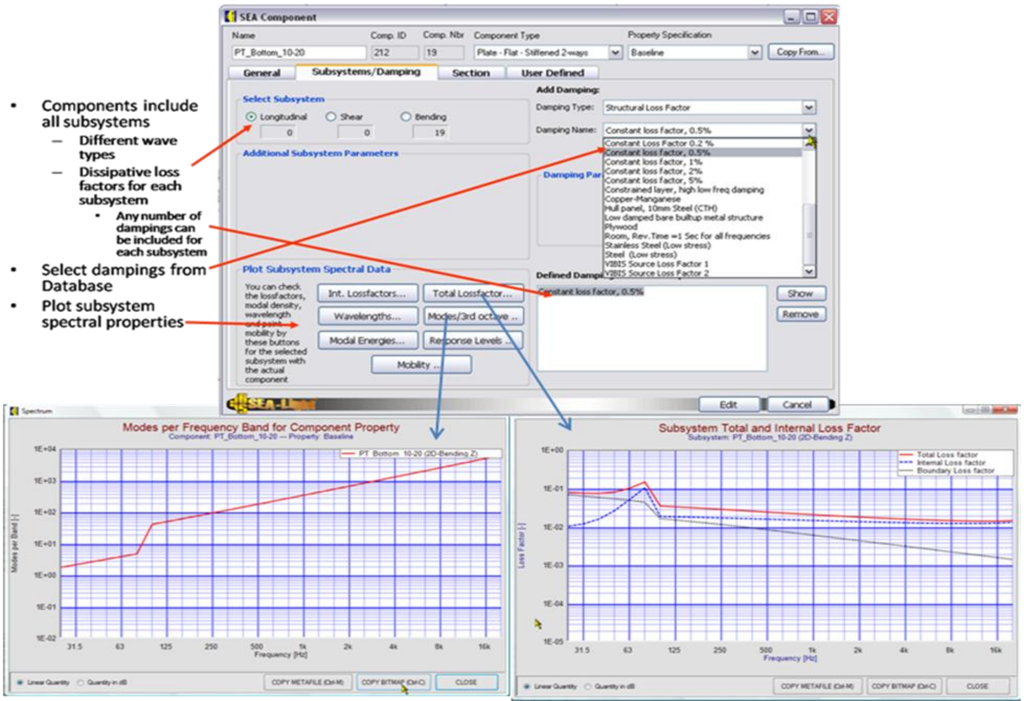

Figure 6. Example of subsystem data input and plotting of different subsystem properties

The calculation effort by the software and time needed is quite moderate, at least for models up to 200-300 components (≈ 300-800 subsystems), even on good laptops. Since more processing power is needed for the graphical interface, it is recommended to run the software on stationary computers with good graphic cards and preferably using a large monitor screen if large models are built and used.

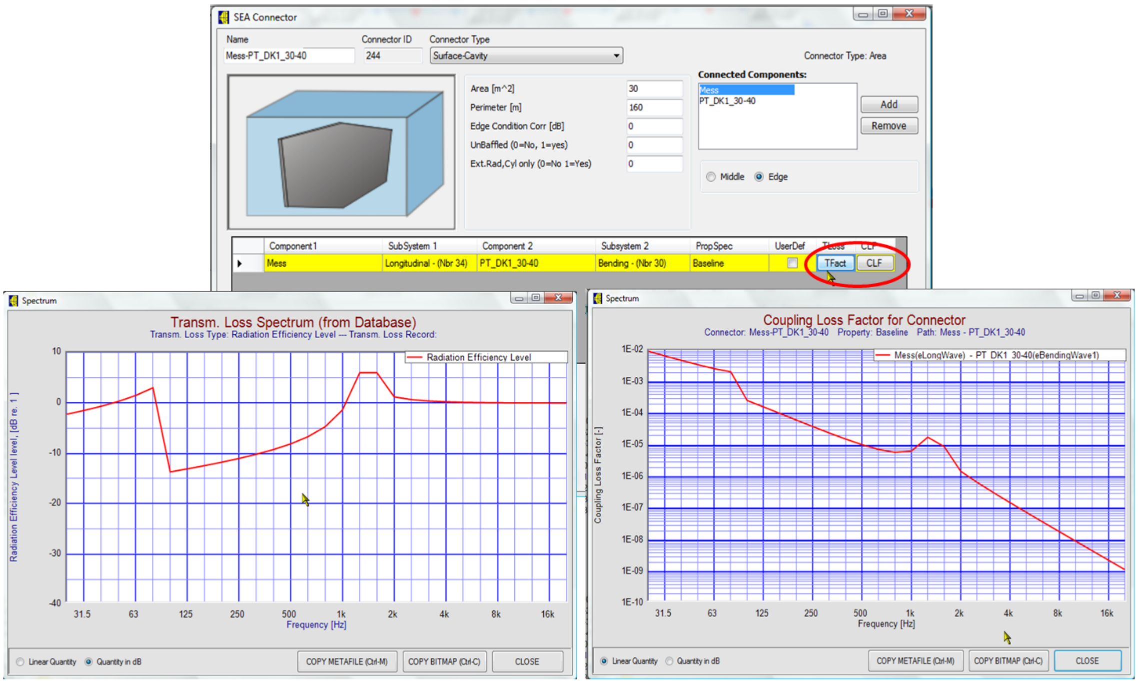

Figure 7. Example of connector data input and plotting of different transmission factors (radiation efficiency in this case) and coupling loss factor for a surface-cavity type of connector.

The software has numerous options for printing input data lists and plot calculated results. One may of course plot response levels for any subsystems of the components. It is also possible to compare the responses of the same subsystem for different property specifications for the SEA model. A property specification includes a specific set of parameters for the components and connectors. In addition to that, source contributions (Figure 8a) and path contributions (Figure 8b) to a subsystem response can be plotted.

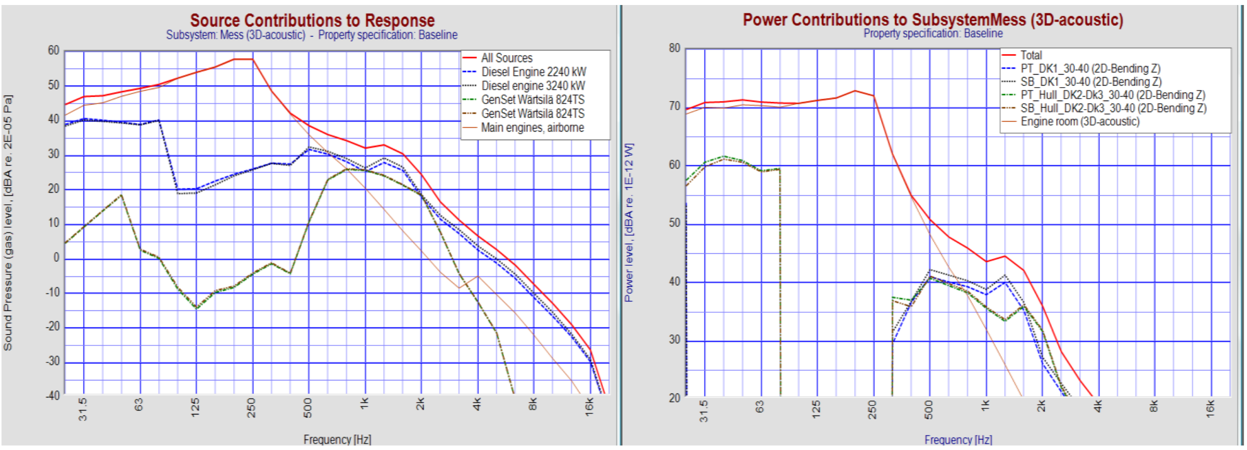

Figure 8. a) Example of source contributions to a mess space in a small ship model; b) path contributions (from coupled subsystems) to the same space. Negative, net power flow may be present which is shown as “drop-outs” for some paths.

4 Examples of quick and “lightweight” use

The real strength of SEA models are their use in the early concept or systems design stages, when the product is still described on sketches rather than detailed drawings. An experienced analyst with good vibro-acoustics knowledge can then use simplified SEA models to predict responses and select between concepts. A “lightweight” SEA program will be sufficient as a tool, provided that it allows reasonably rapid creation and successive modification of the models, uses proven SEA theory, has databases for source data, loss factors etc. and safely stores the versions of models used.

4.1 Concept design stage, example of extreme simplification

This example illustrates a very successful use of simplified SEA-modelling for a major concept design decision. It was a confidential defence project and no data can be revealed here. It was necessary during early system design of a radar unit for a fighter aircraft to decide if vibration-sensitive components had to be individually vibration isolated or if the entire unit could be resiliently mounted in the aircraft fuselage. This was before any aircraft or radar hardware was available. The components were sensitive to high-frequency vibrations (kHz range).

The vibration environment for the equipment shelf was specified as a PSD spectrum. Main structural data of the aircraft fuselage, bulkheads and equipment shelf were known. A regular boundary layer excited SEA model with ca 15 subsystems of the front of the aircraft was used to estimate the airborne sound pressure levels in the radar compartment.

The challenging SEA modelling was for the radar unit. The concept design decision needed a sufficiently accurate estimate of the relation between acoustical power input to the unit and the mechanical input via the mounting points. If the acoustic excitation input power was much smaller than the mechanical, then the entire unit will use resilient mounts, which was the favoured concept. The accuracy for the relative contributions did not have to be better than about 10 dB.

A major issue was the complex electronic unit with a large number of circuit boards, bulkheads etc. and details were not yet fixed. Detailed modelling was not possible and would also delay the project. Both power inputs acted on the outer reinforced walls of the unit. The walls were well coupled, and a much simplified SEA model was used consisting of one aluminium plate, coupled to two beam subsystems, representing integrated stiffeners, see Figure 9.

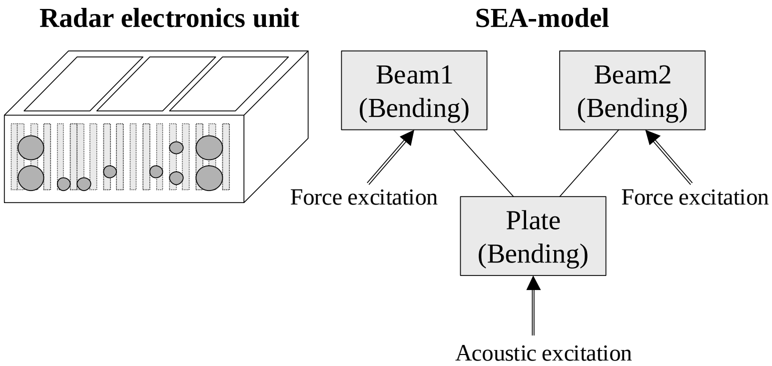

Figure 9. Example of a simple SEA model for estimation of relative excitation contributions for an airborne radar unit.

Acoustic excitation was applied to the plate and mechanical excitation to both beam subsystems. An older unit was also used to validate this modelling approach experimentally. Although extremely simplified, this model was sufficient to predict that the airborne excitation would be too large to be neglected. Individual, internal vibration isolation of components was necessary for reaching specified performance, although a more complex and expensive concept.

4.2 "Quick-SEA" –Examples

This example illustrates the use of SEA to analyse the impact of a proposed reduction of the wall thickness from 20 mm to 10 mm for cylindrical pulp storage tanks used in paper mills. This would save material and reduce manufacturing cost and weight. The possible impact on noise radiation was realized very late. Change in noise radiation had to be estimated very quickly and necessary noise control measures proposed before the final go-ahead to production.

Pump vibrations transmitted by the connecting pipe was the excitation of the tank. The structure borne sound power into the tank was estimated to drop a little due to a larger impedance mismatch at the pipe attachment with a thinner cylinder. The simple SEA-model shown in Figure 10 was used to estimate the differences in vibration level as well as the radiated noise for excitation with a unit power spectrum as shown in Figure 11 since the actual excitation spectrum was unknown. The analysis took only a few hours, including a short analysis report and a go-ahead recommendation after comparison with the present radiated noise spectrum. The SEA-modelling and calculation time was only a small fraction of that.

The increase of the vibration level for the tank is relatively easy to predict. However, the prediction of the difference in radiation efficiency between the two cylinders is not especially simple, and hard to manage in e.g. an Excel spreadsheet.

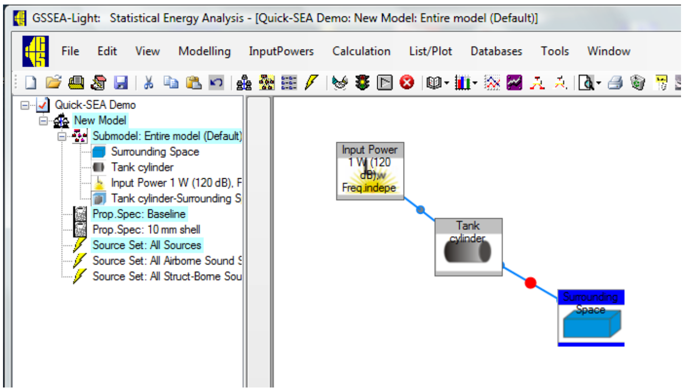

Figure 8. "Quick-SEA" model for a pulp tank

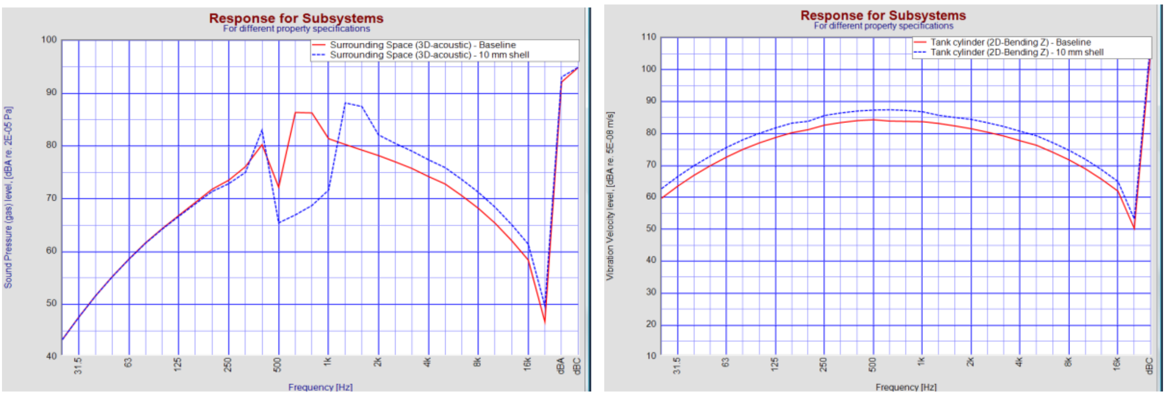

Figure 11. Analysis of the impact of reducing wall thickness from 20 mm to 10 mm for a pulp tank. Vibration levels will increase slightly but radiated sound below 300 Hz remains the same. It is reduced between 500-1000 Hz and increased above 1000 Hz for the thinner wall tank.

Another "Quick-SEA" example is the analysis of the STL of a wrapped inlet duct for a gas turbine. The simple SEA model is shown in Figure 12a and the two response contributions, the perfect double wall (non-resonant connector) and the two resonant sheets coupled via the cavity and a number of point bridges are shown in Figure 12b. Resonant transmission dominates above ca 2 kHz and the design of and number of bridges/m^2 becomes critical. The bridges are modelled as beams with longitudinal waves, and the power transmitted per bridge is determined by the mechanical impedance matching of this beam to the two plates. Design of the bridges is therefore not straightforward.

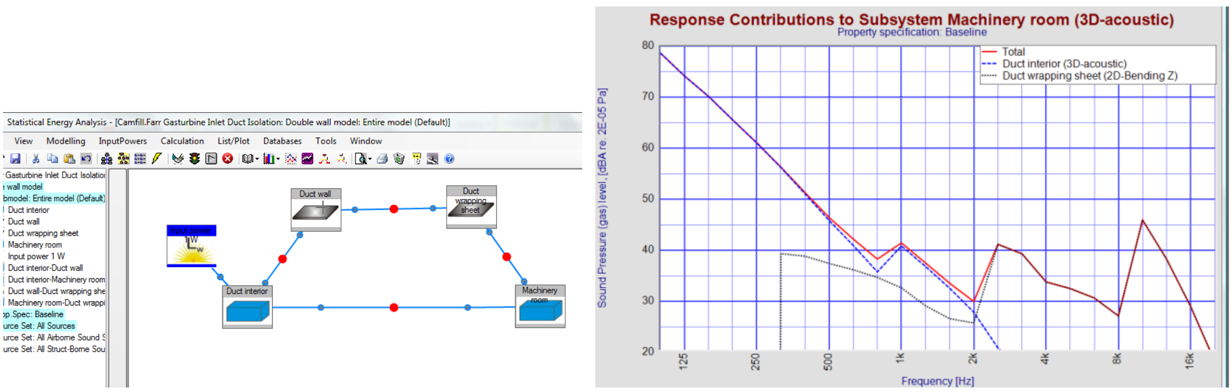

Figure 12. a) The SEA model used for determination of the sound power level transmitted by the duct; b) the sound power contributions via the non-resonant and resonant paths respectively.

These are two examples of various design support situations that have to be addressed fast by an acoustic consultant. Special programs are available that can be used for determination of STL for various partitions, typical building acoustic designs etc. General purpose SEA software may however be more practical to use also for modelling these rather simple systems since the models can easily be expanded to include more comprehensive data for sources, damping, connected structures etc. It is a more rational approach, especially for a good vibro-acoustic specialist.

4.3 Large SEA model example

A model of a very large luxury yacht may exemplify the use of GSSEA-Light for more extensive modelling. This model was developed during the main beta-testing phase together with a customer. The general model data is given in the following table:

Number of components	≈ 200
Number of subsystems	≈ 250
Number of connectors	≈ 400
Number of coupling paths	≈ 1000
Number of input power sources	≈ 20
Bandwidth of the SEA matrix equation	≈ 40

Figure 13 shows a part of the SEA model network. The model was developed from 2D drawings of the general arrangement and the steel hull. Principal information about the accommodation linings, deck coverings etc was also used. The source data (propulsion, engines, HVAC etc) was obtained from suppliers and the shipbuilder. Stiffened plates were used for the steel hull and proper fluid loading has been added where appropriate. Critical interior spaces onboard have been included in the model. A couple of property specifications for the model have also been used in order to estimate the effect of different measures.

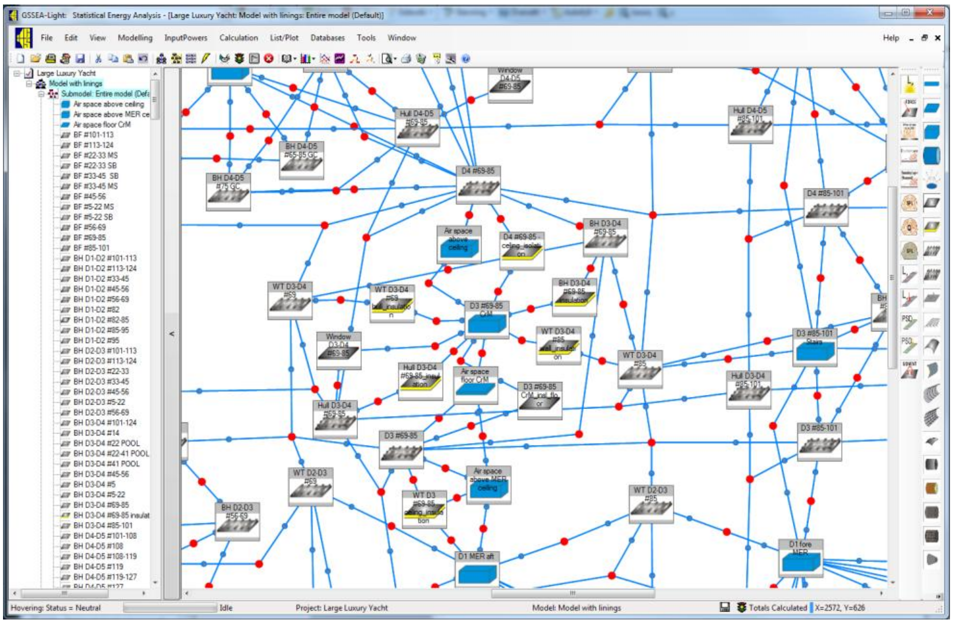

Figure 13. Part of the model network for the large yacht model, showing a lined mess space close to a machinery room.

GSSEA-Light can optimize the numbering of the subsystems in order to minimize the bandwidth of the linear equation system (Equation 2), in this case from a bandwidth of ca 250 to ca 40. This reduces computation times for larger models. The complete computation and storage of computed data to the database takes less than 2 minutes with a good (multi-processor of 2010) stationary computer. Most of the time is thus invested in model creation and the selection, analysis and plotting of the results also takes a fair amount of time, see one example in Figure 14.

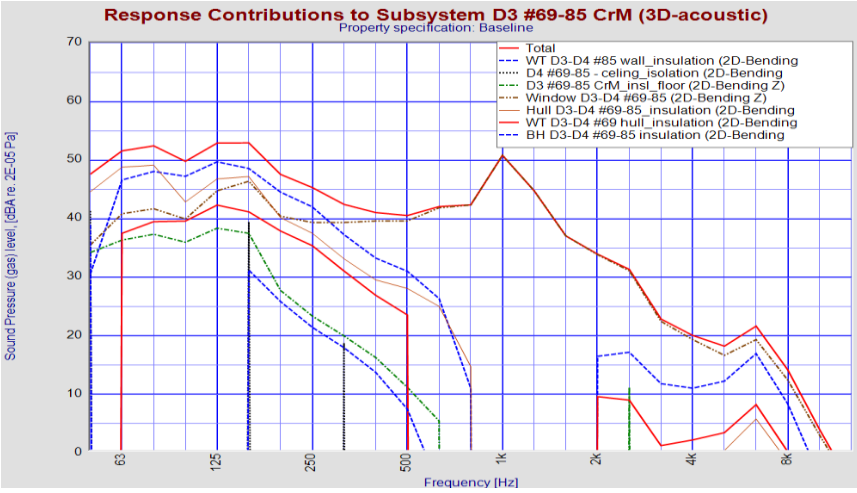

Figure 14. Path contribution analysis for the response in the crew mess.

Conclusions

A SEA program package that has sufficient component, connector and input power source types is sufficient for most applications. The trend today for commercial software to include advanced 3D-modeling and CAD-model import capabilities is not necessary for good, rapid results of the analysis. More “light-weight” programs, like the one shown here are sufficient for the needs of most acoustic consultants, universities and small and medium size companies and will have substantially lower licensing and support cost.

The fundamental idea behind the SEA method is to neglect details that are insignificant for the response levels of the object to be analysed and it is ideal for “what-if” studies during early concept or system design phases, when those details are not worked out anyway. The network modelling concept works as well as a 3D modelling interface and will be as fast to use in those circumstances. It maybe demands somewhat more vibro-acoustic and SEA knowledge from the user, who is free to design the model as he finds most suitable.

The network model will never be taken for more than what a SEA model actually represents. It is a highly abstract model of different modal groups and the energy flow between those when subjected to defined input powers. This is easily understood when one tries to construct the real life object, starting from such an abstract SEA model.

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