NUMERICAL MODELLING IN ACOUSTICS, DYNAMICS AND VIBROACOUSTICS

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1 INTRODUCTION

For many design problems in acoustics and dynamics a great deal can be achieved using relatively simple prediction methods based on well-established analytical, empirical or semi-empirical models and standards. Inevitably there are some problems that require the application of more sophisticated methods, either because of the unusual nature of the problem, or because of particularly demanding performance targets.

A wide range of software packages to predict complex problems using numerical modelling methods such as Finite Element Analysis, Boundary Element Analysis, Statistical Energy Analysis and ray acoustics are now readily available, and this paper illustrates the application of these methods to a range of engineering problems. The overall aim of the paper is to highlight how the choice of numerical method is dependent on the frequency range, physical domain and size of the system to be modelled, and how it is important to capture the physics of the problem whilst constraining the complexity of the model.

2 NUMERICAL MODELLING METHODS

The advent of CAD modelling for general engineering design, and the increasing power of desktop computers, means that detailed modelling of complex problems in acoustics and dynamics has never been more accessible. As a result, numerical modelling is now part of the mainstream design process, but the appropriate prediction method will vary with the physical problem and with different scales of frequency and size of structure. The case studies in the next section illustrate a few particular applications, but it is useful to first set out the general scope and limitations of the various methods.

2.1 Dynamics

The most widely used numerical modelling technique is the application of Finite Element Analysis (FE) to predict the dynamic response of a structure to excitations at low-mid frequencies. The definition of this frequency range depends on the size of the system, and the examples given below are for the design of machinery foundations in a yacht up to about 200Hz to control structure-borne noise, and the prediction of vibration transmission in a science building to protect sensitive equipment at frequencies up to 50Hz. Problems are generally aggravated if forcing frequencies coincide with natural frequencies of vibration, so predicting the modal frequencies is often the first step in assessing results from a model.

An FE model is generally produced by importing a simplified CAD model of the structure into the FE meshing software, which is then used to discretize the structure into a number of elements connected through discrete nodal points. Elements representing sections of beams, shells or solids are available, and the motion of each node provides up to six degrees of freedom in the model. The mechanical properties of each element are used to construct mass, stiffness and damping matrices representing the complete system. Models normally comprise many thousands of degrees of freedom, but large FE models with millions of degrees of freedom are not uncommon, and may require a significant amount of computer time and resource to solve.

The size and detail of the model is likely to depend on the stage through the design process. The starting point for initial design work may be to use a very simple model to estimate natural frequencies of vibration, or the local level of response for a single force input, so that a full model of the system is not generated until the later stages of design.

2.2 Acoustics

Acoustic FE modelling is now becoming much more widely used, partly driven by the requirements of the aerospace industry as illustrated by the aero engine intake example below. As for structural FE, the acoustic space is discretized into small elements, with element size typically being no larger than 1/8th of a wavelength. The convective effect of flow through the element is included in the governing equations, and infinite elements are available for the use in far-field sound radiation problems.

Because acoustics problems often require 3D models, computation times increase rapidly with frequency and with physical size of the problem. Whilst it is now relatively straightforward to model an aero-engine intake up to high frequencies in 3D, modelling a concert hall or an industrial workshop is still not possible, and this type of problem needs to be modelled using ray acoustics.

Another category of acoustic problem that can be successfully simulated using acoustic FE is the diffraction of sound around barriers, as illustrated again by the aero engine example, although for many problems it may be simpler to use the Boundary Element (BE) method in which only the 2D surface of the scattering body needs to be meshed.

2.3 Vibroacoustics

Considering next the issue of sound-structure interactions, sound radiation from vibrating surfaces may be predicted using either BE or acoustic FE methods, but where there is a fully coupled sound-structure interaction then a full multi-physics FE code is required.

Because acoustic FE models become very large at high frequencies, especially where there are multiple acoustic spaces, then Statistical Energy Analysis (SEA) may be used. SEA predicts the flow of energy around a built up network of structural and fluid subsystems, an example of which is the LNG carrier described below. The energy storing subsystems comprise decks, bulkheads or acoustic spaces, coupling loss factors governing the flow of energy between subsystems, and damping loss factors control energy losses. The SEA model uses a ‘power balance equation’ to predict the steady state distribution of energy at each frequency for a given set of power inputs. This is then converted into vibration levels and sound pressure levels for each subsystem.

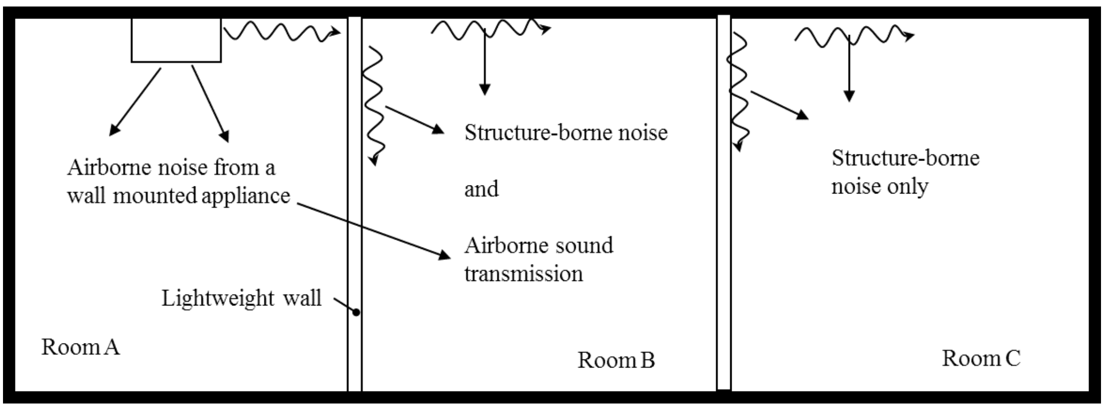


Figure 1: illustration of airborne and structure-borne noise transmission between rooms

As a generic example of a problem in vibroacoustics, figure 1 shows an illustration of three washrooms with a hand drier fixed to a wall in room A. As a source of noise and vibration the appliance will have a number of different mechanisms, including out-of-balance forces from the motor and rotor acting on the wall and causing noise from the casing, and aerodynamic noise produced by the airflow.

If the wall is reasonably massive then the sound field inside room A is likely to be dominated by airborne noise from the appliance, but if the wall is insufficiently rigid then it will act as a sounding board and increase the sound power radiated into room A at the rotational frequencies of the motor and fan. The noise distribution in room B will comprise a mix of airborne noise transmitted through the lightweight partition wall and structure-borne noise from the mechanical forcing. The noise in room C is likely to be completely dominated by the structure-borne energy.

To illustrate the capabilities of the various numerical methods outlined above, the following points might be considered when considering which methods to use in predicting the noise levels in each room:

- The complete system could be modelled using a fully coupled 3D structural-acoustic FE model. The mechanical excitation and airborne noise would be represented respectively by a force applied to the wall and a point acoustic source.
- A difficulty with that approach would be the potential size and complexity of the resulting model, which would depend on details such as:
  - The frequency range of interest and the size of the rooms
  - The physical complexity of the walls, especially for lightweight stud partitions.
- A limiting factor for the frequency range would be the FE representation of the 3D acoustic spaces. If the main interest is the noise in room C, then it is probably not necessary to model the interior of room B. The acoustic space in room A may or may not be needed depending on the relative balance of airborne and structure-borne power inputs from the appliance.
- The distribution of noise in room C generated by the vibrating walls could be calculated using a BE model. The internal sound fields in rooms A and B could also be calculated from BE, but this might neglect the airborne noise excitation of the partition wall.
- The system could also be modelled using SEA, but the accuracy would be affected by the relatively limited physical detail that can be included in an SEA subsystem which might affect:
  - The accuracy with which the mechanical power input from the appliance can be modelled, especially for the low frequency out-of-balance mechanism.
  - Some aspects of the transmission paths such as the coupling between the main walls and the partition walls, and the radiation efficiency of the latter.

3 CASE STUDIES

3.1 Machinery foundations in a yacht

For the luxury yacht industry, controlling the vibration and structure-borne noise from engines and gearboxes is an important issue since owners expect a very refined environment in the lounge and bedrooms just a short distance way. Problems can be difficult to rectify, so controlling noise and vibration at source by careful design of the machinery foundations is a sensible precaution, and structural FE modelling is ideal for this task.

Figure 2a shows a typical model of the machinery support structure. The power flow into the foundation is best represented by the point mobility at mounting points, and figure 2b illustrates how the resonant behaviour of a finite structure can cause large deviations from the behaviour of a nominally similar infinite structure. It is important that the frequencies generated at cruising speed do not coincide with resonances in the transmission path.

At low frequencies, where vibration may be an issue, the accuracy of the model will be dependent on the global stiffness of the main support beams, and so it is important to ensure that a sufficiently large section of the vessel is modelled. The aim is to understand the whole body modes of the vessel, such as bending and whipping, and it may be necessary to include the effect of water loading. A model of this sort will use large shell elements to represent the hull plating and bulkheads while beam elements can be used to represent frames and beams. Monolithic components such as engines can be represented using solid elements or lumped mass components. A model of this type will generally have less than 100,000 nodes and will be used at frequencies below 10 Hz.

At the higher frequencies important for structure-borne noise the local stiffness of the machinery mounts will control the mobility, and so this requires detailed local modelling, for which a much finer mesh of a local area is required, as illustrated in figure 2a. In this type of model all the structure is likely to be modelled with shell elements to give a high definition to the structural geometry. Due to the complexity of such a model, it is confined to a relatively small area of structure and is used to obtain the local stiffness and mobility of the structure up to several 100 Hz.

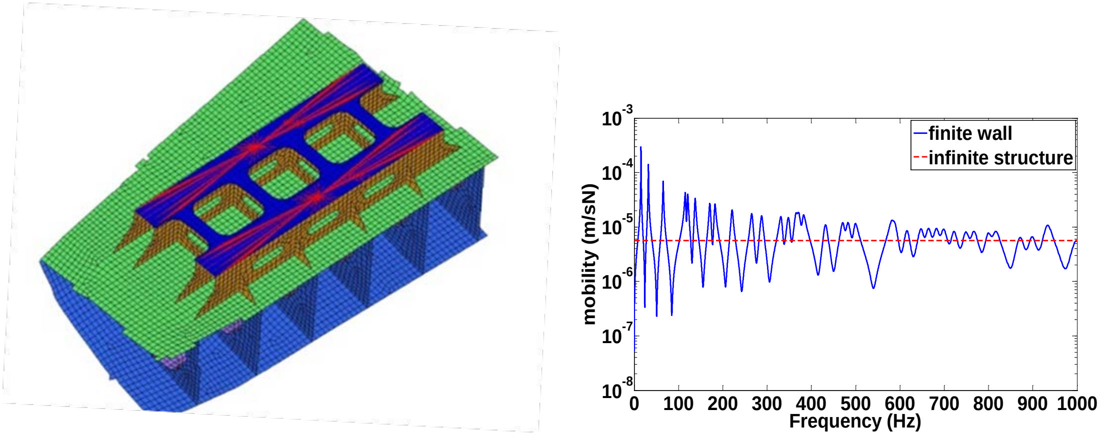


Figure 2 a) FE Mesh for the machinery foundations of a 50m yacht, b) mobility of a finite structure and a nominally similar infinite structure

3.2 Vibration transmission in a science building

For science and medical facilities using high resolution imaging equipment it is vital that the structure of the building is designed so that vibration levels are below a specified 'VC' curve. The model presented in figure 3 was used to predict the vibration response of NMR scanners in the basement, due to large backup generators installed on the roof of the building. Some background to the general issues involved in these types of predictions is given in [1], but for the specific example given here particular attention was paid to modelling the stiffness of the piled foundation, and modelling the vibration isolation of the machinery.

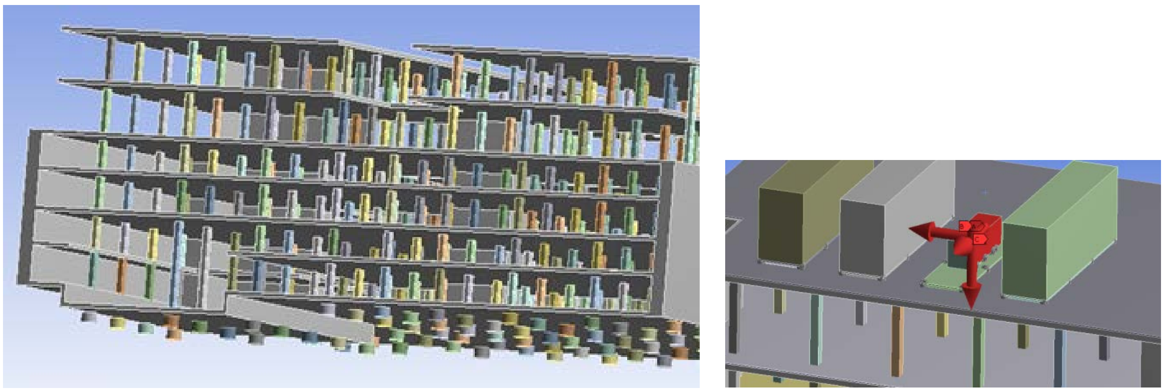


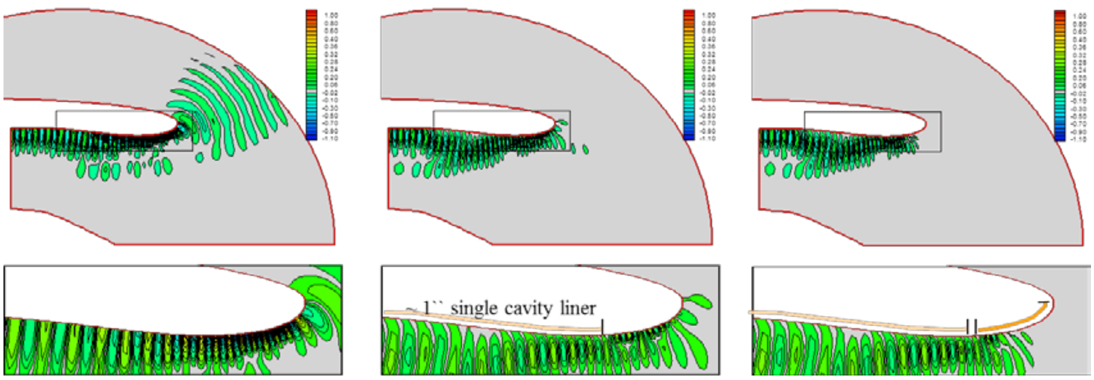
Figure 3 a) model of a building to predict vibration transmission from backup generators on the roof to sensitive locations in the basement, b) local model of the gensets

3.3 Duct acoustics for aero engines

Over the past three decades noise levels from aircraft have been dramatically reduced, and part of that progress has been provided by improvements in the design of acoustic liners for the intake. Figure 4 provides an example of the attenuation provided by acoustic liners in the barrel and on the lip of an intake [2].

The plots illustrate how an acoustic FE model can predict the diffraction of sound at a barrier, in this case the lip of the intake. The effect of high speed flow around the lip of the intake on the wavelength of sound is also apparent, and this affects the efficiency of the acoustic liners in that area.

These modelling methods may be used to predict the performance of many other types of duct silencers, as described in reference [3].



Hard walled Barrel Lip+Barrel

Figure 4 propagation of noise through an aero engine intake with acoustic liners in the duct and on the lip of the intake [2]

3.4 Boundary element modelling

FE modelling can, in principal, be used to predict many problems in acoustics, but is relatively inefficient for modelling large acoustic spaces. For structure-borne noise problems it is often better to use FE to predict the transmission of vibrational energy through the structure, then use BE to predict the resulting sound radiation.

Figure 5 shows an example in which low frequency noise from a music venue was anticipated to be a problem in residential apartments above. A complex transmission path was modelled, and vibration levels in the walls, windows, ceiling and floor of the apartment were predicted. The BE calculation produced a map of the standing waves that occured at key frequencies, enabling the maximum and mean levels in the rooms to be estimated.

Whilst the BE calculation does not explicitly calculate the modal frequencies of the room, at frequencies where a mode exists the levels will be damping controlled, and so it was necessary to introduce an impedance boundary condition at the walls so that the damping and reverberation time of the room was accurately modelled.

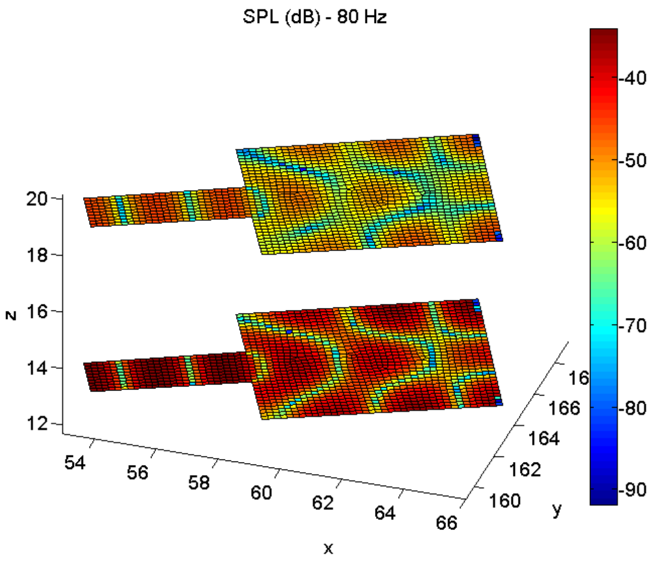


Figure 5 Boundary element prediction of standing waves in apartments at 80 Hz

3.5 Transmission loss of lightweight cabin walls

A recent Innovate UK study into the use of composite materials for the cabin walls of cruise ships highlighted how the 40% weight reduction compared with standard constructions could provide significant fuel savings, but that the acoustic insulation properties of such materials are not ideal so that meeting industry requirements for acoustic performance is difficult [4]. The study investigated different modelling techniques for the transmission loss of double leaf partitions tested in a reverberation chamber suite and in a real cabin configuration.

Modelling transmission loss is a complex problem because results are affected by factors such as the characteristics of the incident sound field and relatively small details of the test installations, so that correctly modelling all of the test parameters requires considerable care. The method developed in the study was to simulate as accurately as possible the cabin-to-cabin acoustic test represented in figure 5a), by predicting the sound field at a number of measurement locations in the source and receiver cabins as shown in figure 5b).

Figure 6 shows results for a double leaf wall with a 20mm airgap. There is reasonable agreement between predictions from the 2D and 3D FE models, compared with experimental data and with simple mass law predictions double walls [Treviso]. In particular, the experimental data show a mass-air-mass resonance at 200Hz and a coincidence dip at 1250 Hz which are also seen in the predictions. Discrepancies at low frequency may be due to the following:

- Only the partition between the two cabins is modelled, whereas in the test all of the cabin walls, ceiling and floor are actually responding to the sound field. Contribution through these paths are not accounted for, and the boundary conditions at the edge of the test wall are not accurately modelled;
- The FE model is limited to the main living space, whereas the actual cabin is bigger and includes a small corridor and a bathroom, which certainly contribute to the global acoustic behaviour of the cabins;
- The effect of the bed and bedhead is not modelled; the absorption in the entire room is modelled by specifying an equivalent impedance value at each cabin wall.

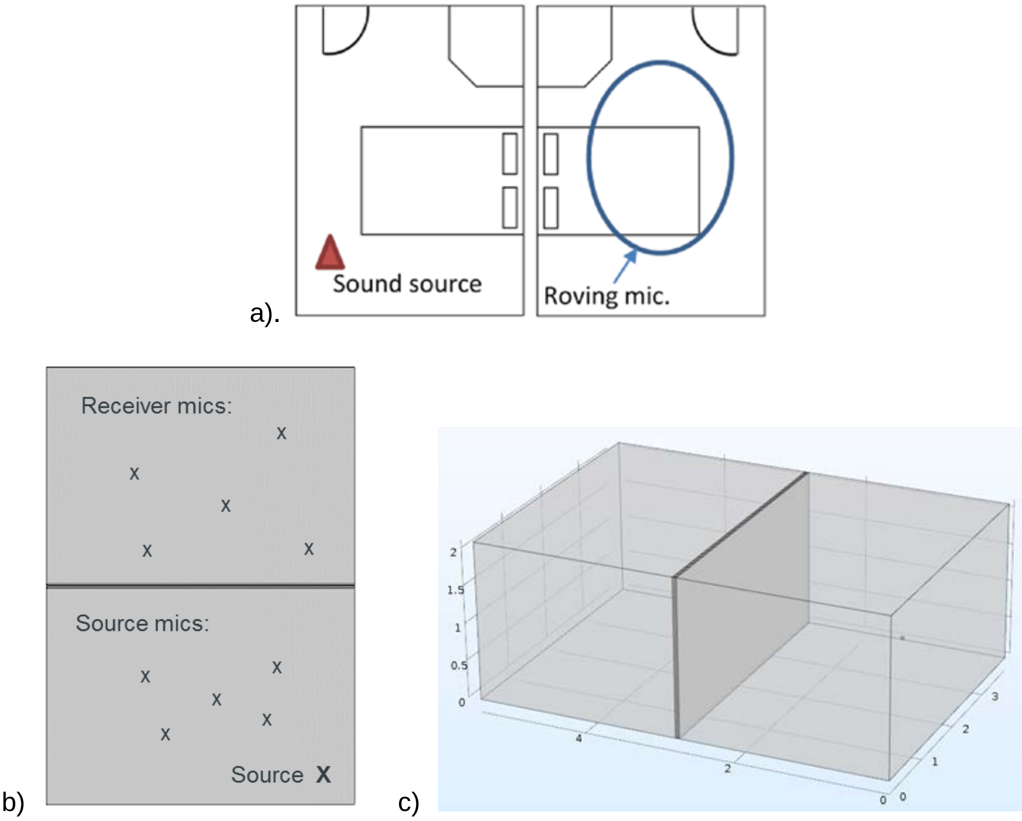


Figure 5 a) test configuration for a cabin to cabin sound transmission test b) 2D simulation of the test c) 3D FE model of the test [4]

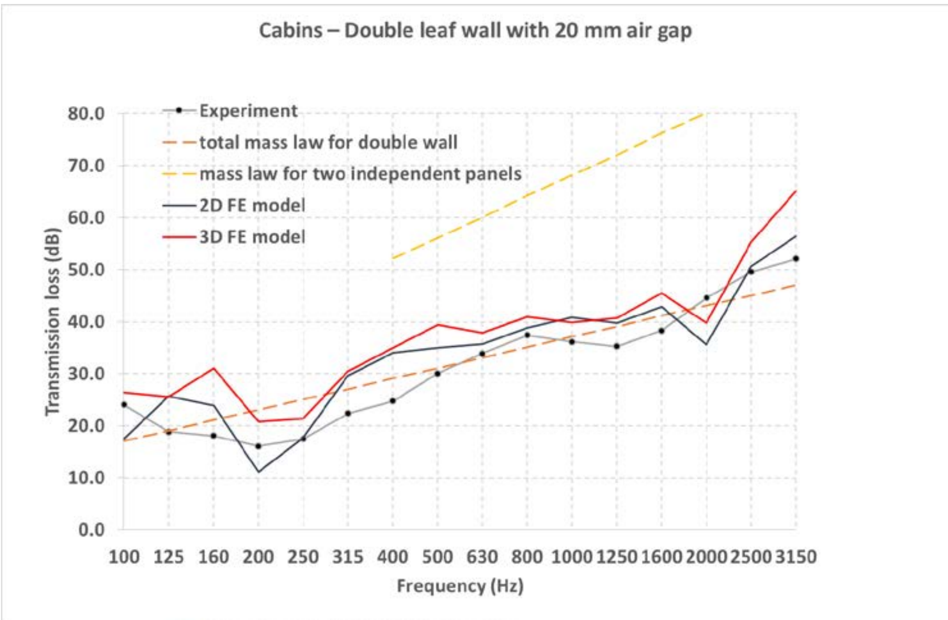


Figure 6 Predicted and measured transmission loss for a double leaf cabin wall. [4]

3.6 SEA model of structure-borne noise in an LNG carrier

The International Maritime Organisation specifies noise limits for workers on ships in engine rooms, communal spaces and cabins. Although cabins are usually well separated from machinery spaces, structure-borne noise is always an issue, but FE modelling at the frequencies needed for noise exposure calculations is not possible. The options available for predictions are either empirical models, which generally rely on measured attenuation rates with vertical or fore-aft distance, and Statistical Energy Analysis.

SEA is a high frequency method, requiring subsystems to be large on the wavelength scale so that there are sufficiently many modes in each frequency band of interest for their statistical behaviour to be well represented. This means that accuracy may be reduced for discrete frequency components, especially at low frequencies. The fact that there are only a couple of commercial codes is an indication that the method is still viewed with some caution, perhaps partly because of the 'statistical' label, but, providing suitable care is taken in building the model, valid and useful predictions can be made.

Figure 7 shows a section through an SEA model representing the accommodation and machinery rooms of a tanker, showing the typical size and number of the structural and acoustic subsystems and the distribution of power inputs. Such a model may take weeks to build, but solves in minutes to give the distribution of vibration and noise up to high frequencies. In addition the software may be used to provide information on transmission paths and source contribution analysis which makes it easy to devise suitable means of noise control.

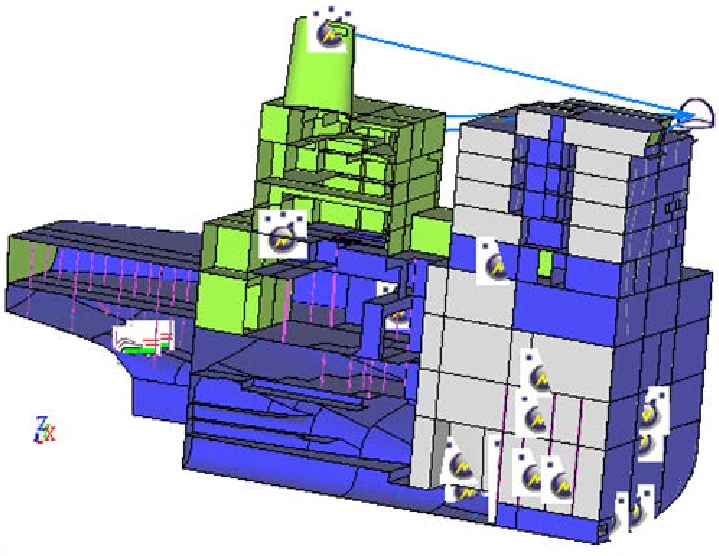


Figure 7 SEA model of an LNG carrier, used to predict structure-borne noise transmission from power inputs in machinery rooms to noise levels in accommodation areas

4 CONCLUSIONS

The limited range of examples presented here can only illustrate the diverse range of application of numerical prediction methods in acoustics, dynamics and vibroacoustics. The choice of numerical method is dependent on the frequency range, physical domain and size of the system to be modelled, as well as cost in terms of computational time, software charges and modelling hours for the engineer.

Whilst the wider use of numerical prediction methods is encouraged, it is vital that any model correctly captures the physics of the problem, and that results are carefully validated.

5 REFERENCES

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