2008 Helmholtz Medaille Address

A Life in Technical Acoustics

Frank Fahy

I should begin by explaining the origin of my family name, Fahy. All my grandparents were born in the West of Ireland and I am therefore a Celt by descent but an Englishman by birth and upbringing.

I retired in 1997 from University teaching and research to pursue other interests such as learning to play the piano, playing tennis, painting and growing vegetables. Consequently, I have only a very general appreciation of the developments in acoustics made during the past decade. I therefore intend to present a brief account of a small selection of my experiences in acoustical research together with mention of some of the more recent developments in areas of the subject on which I worked.

I began my professional life as an aeronautical engineer, designing and testing aeroelastic models of aircraft in high-speed wind tunnels. Much of my work was on Concorde. In 1963, I joined the newly established Institute of Sound and Vibration Research (ISVR) which was founded by Professor Elfyn Richards at Southampton University. My initial project concerned interior noise in Concorde, but I was not happy with the project, as I told Professor Richards. He generously responded by telling me to "go and do whatever research interests you" – which I gladly did.

I had become very interested in the new form of vibroacoustic modelling called 'Statistical Energy Analysis' (SEA). I was fortunate to be in the right place at the right time. In 1961, a new gas-cooled nuclear reactor in the West of England had suffered acoustical fatigue during the commissioning tests - fortunately before the fuel had been installed. The gas circulators generated sound pressure levels of over 180 dB in the CO2 gas at a pressure of 30 atmospheres. Figure 1 shows examples of the acoustic fatigue damage caused to the 9 mm thick walls of a steel cooling duct and to the stator blades of a gas circulator. The frequency of excitation was 1100 Hz. The failure occurred after 200 hours of testing.

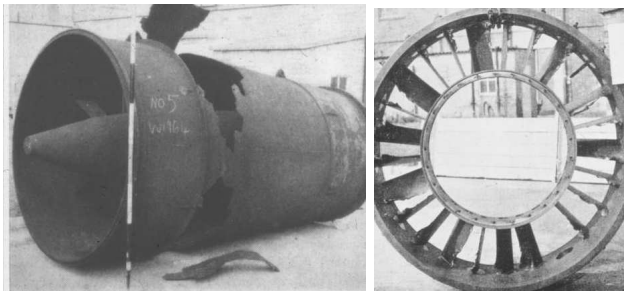

Figure 1: Examples of acoustic fatigue damage

The electrical power generating company (CEGB) visited the ISVR for advice on the prediction of such high frequency fatigue damage. At that time it was difficult enough to predict the acoustically induced response of individual panels of an aircraft tail at 100 Hz. How could we possible predict the response of such a large and complex structure at 1100 Hz? I suggested that we should try to use SEA, but the company hadn't even heard of it, let alone trust it. Thus began thirteen years of research sponsorship by the CEGB of the ISVR into vibroacoustic problems in gas-cooled nuclear reactors, led by myself. In order to test the efficacy of SEA, one of my first research students designed and tested a 1:5, vibroacoustically scaled model of a proposed reactor gas circuit which is shown in Figure 2.

Figure 2: 1:5 vibroacoustically scaled model of a proposed reactor gas circuit

The scaled metal thickness was about 1.5 mm. It was fitted with many strain gauges. A siren drove a dense fluorocarbon gas having a sound speed of 120 m/s. The wooden container leaked badly and I confess to increasing the size of the hole in the ozone layer. The siren speed was swept slowly through the important scaled frequency range and the strain responses were recorded. We had to solve the problems of converting from the theoretical SEA estimates of frequency- and space-averaged vibrational energy to single frequency, dynamic strain concentrations. We derived the statistics of the swept frequency response of the model structure, and made theoretical and experimental studies of dynamic strain concentration in a range of plate and curved shell structures. The project successfully demonstrated the practicability of using SEA to predict the vibroacoustic response of complex structures at high frequency. The reactor still operates safely today.

These days, we have sophisticated hybrid SEA vibroacoustic software. The next figure illustrates a range of practical problems to which it is now routinely applied.

Although SEA has proved very useful in estimating the time-average vibrational and acoustical energies of complex systems exposed to broadband excitation, a long-

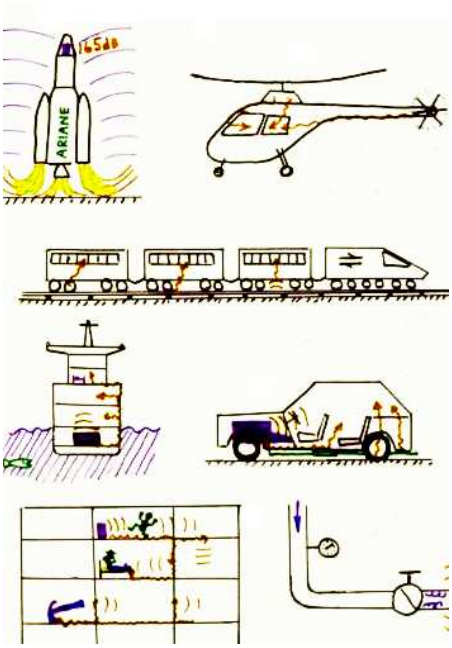

Figure 3: A range of practical problems to which SEA is now routinely applied.

standing historical shortcoming of SEA was the lack of a reliable means for estimating the variance and probability distributions of the responses of ensembles of similar complex structures, such as cars leaving a production line. The problem is illustrated by the results of our acoustic excitation tests on an ensemble of vital structures, seen in Figure 4: these are very precisely fabricated.

Figure 4: Ensemble of vital structures

First we had to face the challenging task of emptying them (Figure 5).

Then we measured the acoustically induced vibration response at the same point on each. The next figure (6) shows the repeatability of response of one sample and the scatter of responses of 41 samples.

I can assure readers that this was not alcohol induced scatter. It demonstrates that very small differences of detail of even simple structures can influence high frequency response. This problem has only recently yielded to theoretical prediction by other researchers.

In the early 70s, in parallel with my nuclear reactor projects, I became fascinated by the possibility of measuring sound intensity in a simple way. Figure 7 shows

Figure 5: Challenging task

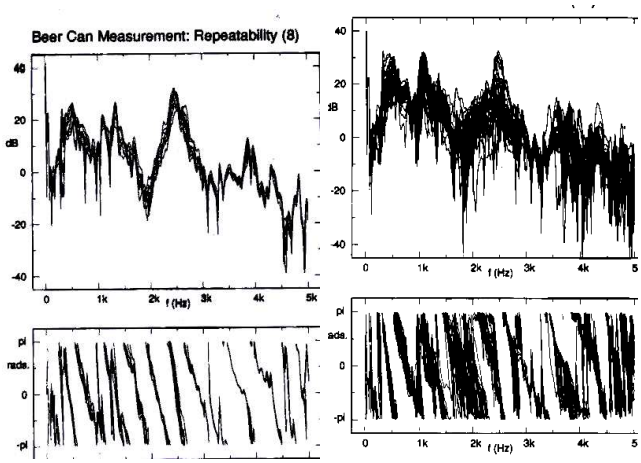

Figure 6: Illustration of the repeatability of response (left) and the scatter of responses of 41 samples (right)

the ISVR analogue sound intensity meter constructed in 1976 and an earlier version of me.

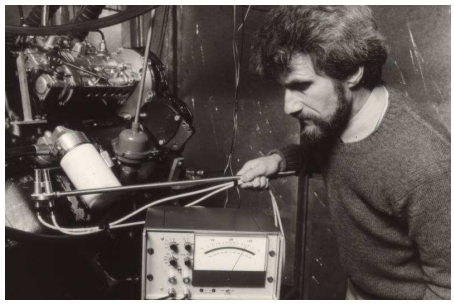

Figure 7: ISVR analogue sound intensity meter constructed in 1976

A little later, it became evident that sound intensity could be measured with no more than an FFT analyser and two well-matched microphones. We felt that the 'philosopher's stone' of acoustics had been discovered. Little did we appreciate the complexity of intensity fields. In the early 1980s, I was invited to convene an ISO working group on the standardisation of sound power determination by means of sound intensity measurement. I accepted, and boldly predicted that the job would be finished in five years - it actually took ten! Because the technology was so new, each working group meeting was like a research seminar, with members actually researching the problem between meetings. Dr. Gerhard Hübner

was a vital member of the group, bringing many new research results to the table and making us all think very hard.

The major advantage of measurement of the vector quantity sound intensity over the scalar quantity sound pressure is that, in principle, the integral of its surface normal over any surface that encloses a steady source of sound energy is equal to the sound power of the source, irrespective of any steady sources operating outside the enclosing surface. The practical reality is somewhat more complex (hence the ten years!). But it is an invaluable tool in applications such as the determination of the sound power of a machine, or part of a machine, in a noisy, reverberant factory. Figure 8 shows a Norwegian Elab engineer using a sound intensity sweep to determine the sound power of a gearbox on a North Sea gas platform.

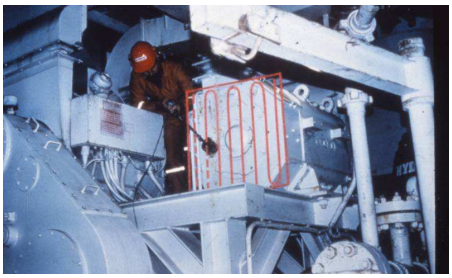

Figure 8: A Norwegian Elab engineer using a sound intensity sweep to determine the sound power of a gearbox on a North Sea gas platform.

Another of the great advantages of sound intensity over earlier pressure-based measurement methods is that it can be used to determine the spatial distributions of sound energy radiation from distributed sources and sound energy transmission through partitions, and can be used to detect leaks and flanking transmission, which is invaluable in building acoustics. During the past decade, Dr. de Bree and his colleagues in the Netherlands have developed a new type of sensor for the measurement of acoustic particle velocity which, in combination with a conventional pressure sensor, forms the very compact 'Microflown', which may be used to measure sound intensity and specific acoustic impedance.

In the late 1980s, my student Phil Joseph and I also developed a method of measuring sound intensity in low speed turbulent airflow in a duct. The next figure (9) shows the so-called Zeppelin probe in a wind tunnel.

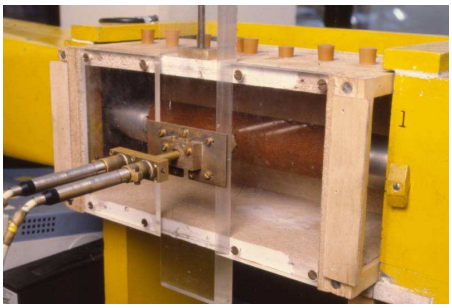

Figure 9: Zeppelin probe in a wind tunnel

The signals from each of the two microphones within the windscreen probe were conditioned by a signal from an upstream turbulence tube, based upon the work by Wolfgang Neise. The system worked rather well. Sadly, the research grant was cut and the project was discontinued. This remains a difficult problem which has not yet been completely solved.

In the late 1980s, I became very interested in the development and exploitation of measurement techniques based upon the principle of vibroacoustic reciprocity. The theoretical foundations had been laid by Helmholtz and Rayleigh in the 19thC and were elaborated in the 20th C by Lothar Cremer, Manfred Heckl and Leonid Lyamshev, among others. Although the technique had been very successfully developed at TNO in Delft in the Netherlands, principally for application to marine vessels, I knew that few industrial engineers were aware of the principles of vibroacoustic reciprocity. And those few who were aware were very sceptical about its validity and reliability. Some of the readers will have seen my 1995 paper in Acustica in celebration of Manfred Heckl's 65th birthday, but many will not; so I take the liberty of illustrating some of the applications with which we engaged during the 1990s.

One of the simplest examples is illustrated by Figure 10. This shows the transfer functions between an omnidirectional point acoustic source and an omni-directional pressure microphone measured directly, and by exchange of the positions of source and receiver. The phase agreement was similarly good.

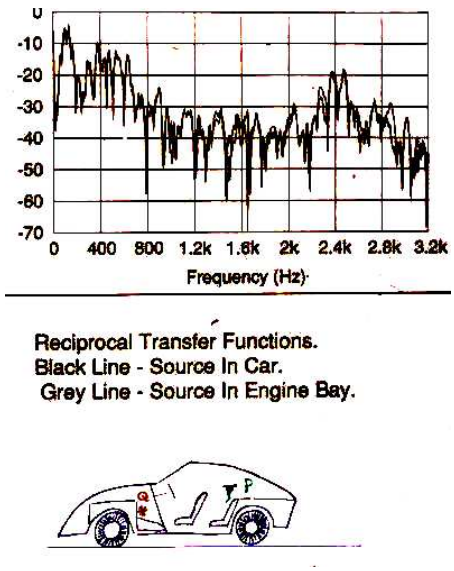

Figure 10: Transfer functions between an omnidirectional point acoustic source and an omni-directional pressure microphone measured directly.

To the surprise of many engineers who were not familiar with the principle, these two transfer functions are the same, even in such a complicated, non-uniform, dissipative system. In the case shown, it is far easier, cheaper and quicker to place a source at the position of the driver's head and to measure the sound pressure at positions very close to the engine block, than to try to simulate surface

vibration of the block by means of moving a small loudspeaker around the engine. This method is widely used today.

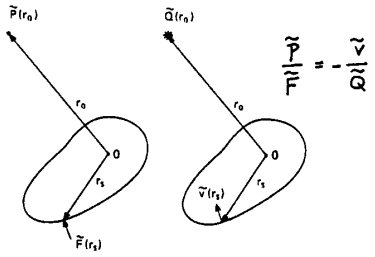

Figure 11: The vibroacoustic reciprocity principle.

Another form of the vibroacoustic reciprocity principle is illustrated by Figure 11. In 1959, Lyamshev showed that the transfer function between a mechanical force applied to a structure and the sound pressure in the radiation field (however complicated) is the same as that between the volume velocity of an omni-directional sound source placed at the microphone position and the resulting vibration velocity at the position of the original force and in the same direction (with zero external constraint). Figure 12 shows the experimental arrangements for the direct and reciprocal measurements made by Gyorg Pankoke, a German masters student of ISVR, of the generation of sound in a Mercedes car by a vibrational force acting on the gearbox support point.

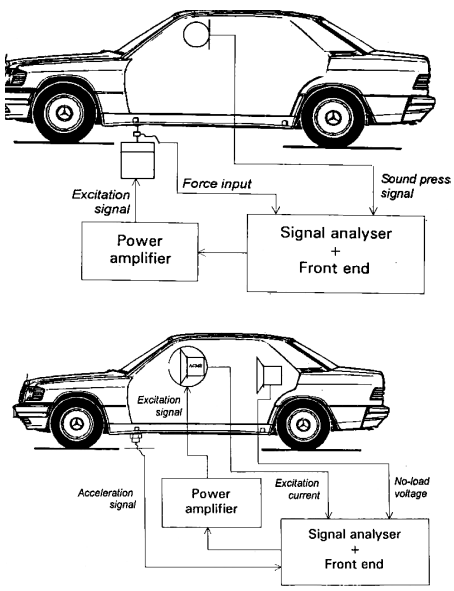

Figure 12: Experimental arrangements for the direct and reciprocal measurement of the generation of sound in a Mercedes car.

Figure 13 shows the results of the direct and reciprocal measurements. Gyorg placed two loudspeaker sources inside a rigid sphere, with the sound radiating from holes on either side, so that the diffractive effects of the head were approximately simulated and left and right ear responses could be distinguished (See 'left ear' in the legend).

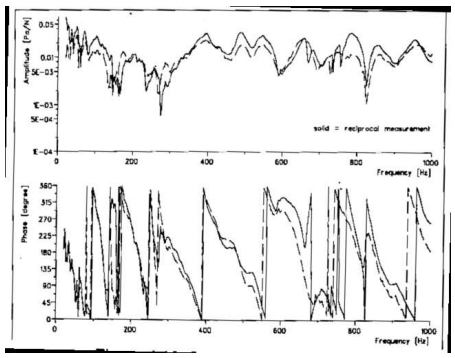

Figure 13: Comparison of direct and reciprocal measurements (- - - left ear)

Reciprocal velocity measurements can be made in three directions using a triaxial accelerometer. It is obvious that this much simpler and quicker than trying to apply controlled vibration forces in three directions. Even moment excitations can be treated by using rotational accelerometers. One of the problems of applying the vibroacoustic reciprocity technique to sound radiation and transmission by complex structures is that the structural vibration field is often very non-uniform, as illustrated by Figure 14 which shows the vibration at various points on an acoustically excited, stiffened, circular cylindrical shell.

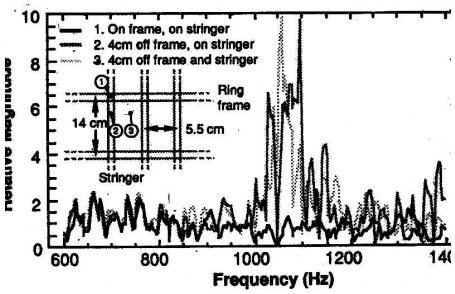

Figure 14: Vibration at various points on an acoustically excited, stiffened, circular cylindrical shell

This raises the question of how to choose appropriate target points on the structure. One solution is to measure the volume velocity of a target areas (patches) of the structure, instead of the point velocity. This is valid provided that the extent of each patch is far smaller than an acoustic wavelength. In a project initiated by Renault trucks, and continued with the support of Daimler-Benz, which was aimed at determining sources of cabin noise at frequencies below 400 Hz, we developed a surface volume acceleration transducer (VAS) based upon an array of pressure difference microphones, as seen in the next two figures (15 and 16).

Comparison between spatially integrated laser velocimeter measurements at 100 points on a vibrating panel made by Daimler and a single VAS measurement gave acceptable agreement, as shown in the Figure 17. Vibroacoustic reciprocity testing is now widespread and routine in the automobile industry, especially for diagnostic purposes.

The final example is taken from the aircraft industry.

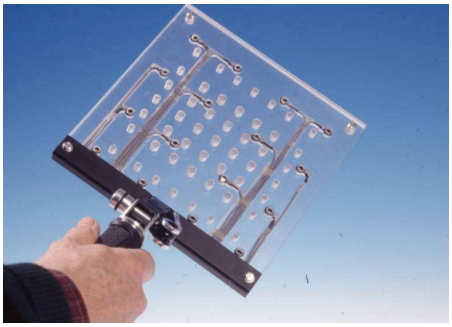

Figure 15: Surface volume acceleration transducer (VAS)

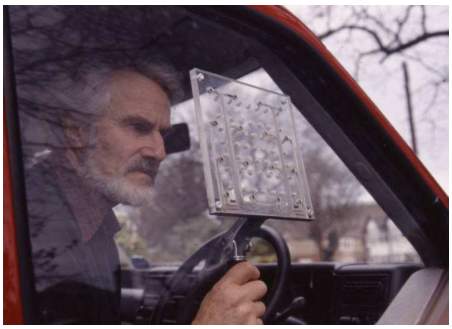

Figure 16: VAS in action

Propellers generate strong tonal sound pressures on the cabin wall. It is common to simulate this by means of rings of loudspeaker units placed around a fuselage test section, and driven by signals that are tailored to simulate the propeller field. My PhD student, James Mason, designed a model fuselage rig to demonstrate the application of an extended form of Lyamshev reciprocity to this problem. A special form of capacitative transducer was developed to measure the volume velocities of skin patches and the transfer functions between these and an omni-directional sound source placed in the cabin. The rig is shown in Figures 18 to 20.

It was automated to rotate in steps and to measure the transfer functions at each step. These transfer functions may be multiplied by a theoretical sound pressure field to investigate the effect of variation of propeller and cabin wall structural and acoustic parameters on sound trans-

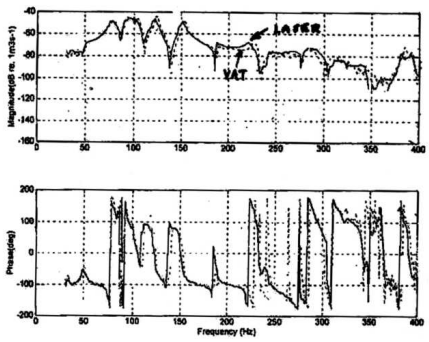

Figure 17: Comparison between spatially-integrated multi-point laser measurement and single VAT measurement on vibrating panel

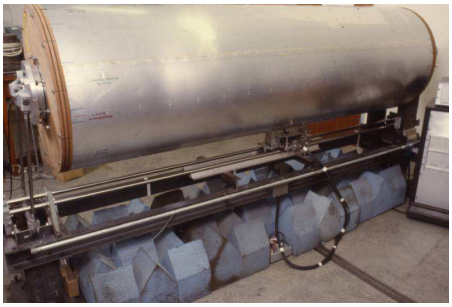

Figure 18: Model fuselage rig

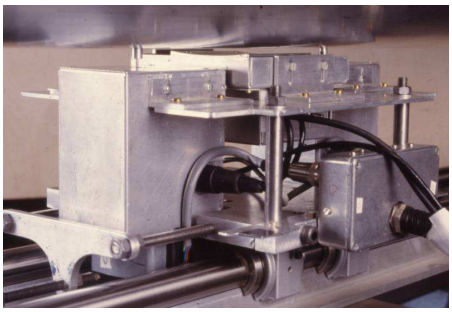

Figure 19: Model fuselage rig

mission. In effect, each patch of the fuselage is calibrated as a transmitter of the average external sound pressure on the patch. These tests may be made on a standard aircraft in any acoustic environment and need no special test rig. The transfer functions required for investigations of the effects of varying localised areas of wall trim may be limited to the vicinity of those areas. Even forward flight can be easily simulated with the aid of a theoretical propeller field model. This technique is clearly cheaper than the construction of special test rigs and test structures. An example of a comparison of direct and reciprocal transfer functions measured on a fully trimmed Dash-8 aircraft, for which a full-size volume velocity transducer was constructed, are shown in the final figure (21).

Model tests were made in the ISVR to investigate the effects of variation of the distribution of wall trim on interior noise. Mason's PhD thesis was examined by Manfred Heckl. Today, skin volume velocities could be measured by the use of the VAS or laser-based scanning systems. I am disappointed that this technique has found no favour with the aircraft industry.

Now it gives me great pleasure to acknowledge with grati-

Figure 20: Model fuselage rig

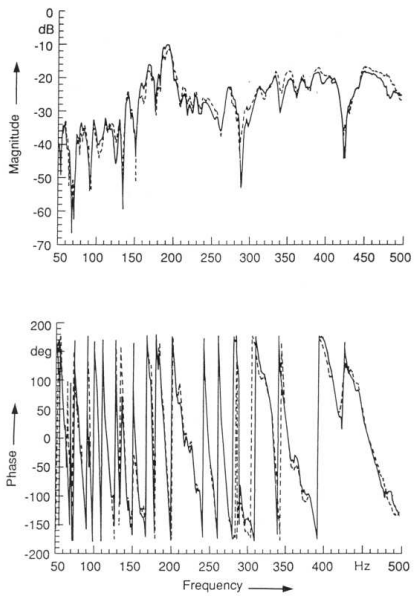

Figure 21: Comparison of direct and reciprocal transfer functions measured on a fully trimmed Dash-8 aircraft.

tude the inspiration for many aspects of my research and teaching that I derived from the work of German colleagues. In the early years of my work, I eagerly studied the papers on sound radiation and wave propagation by Manfred Heckl. Körperschall by Cremer and Heckl was my vibroacoustic bible. At that time I also began to teach a Masters course in Building Acoustics and learnt much about room acoustic statistics from the papers of Manfred Schröder. Heinrich Kuttruff's book on 'Room Acoustics', and the comprehensive book 'Bauakustik' by Dr. Fasold, were invaluable sources of guidance. Later, I used the Modulation Transfer Function of Manfred Schröder in experimental studies of SEA subsystem coupling. The publications of Dr. Mechel on duct acoustics and absorbers were most helpful in our studies of sound intensity distributions in ducts. In the late 1960s he, together with Drs. Odin and Kurze, derived expressions for the relations between spatial gradients of phase and squared pressure and the active and reactive components of sound intensity which paved the way for the subsequent developments of instruments for the measurement of sound intensity. The few works of Drs. Schirmer and Kraak that I could obtain were also of great assistance. The VDI DIN standards on pipe noise developed by Müller BBM have been most useful in my attempts to model pipe noise sound radiation.

I must recount an invaluable piece of advice given to me by Manfred Heckl. After he had presented a talk at the ISVR, which I chaired, I made the suggestion that good experiments were fundamental to acoustical research. He chided me by retorting 'But there is nothing better than a good theory': I conceded the point.

This brings me to the final subject of my address. At Euronoise 98 in München, I presented a paper on my view of the relationship between vibroacoustic theory and experiment. I made the point that the construction of a valid, efficient and economical theoretical model of a system requires (i) the appropriate choice of influential parameters; (ii) a proper appreciation of the relative orders of magnitude of their influences on the target responses of the modelled system; (iii) the need to tailor the complexity of the model to the precision required of its predictions. These decisions depend crucially upon a thorough understanding of the physical origins of the parametric sensitivity of the behaviour of the type of system modelled. In some cases, the relative influences of different elements of a system on the target response can be established by rather simple ad hoc experiments. To give a very simple example; if the noise in a car is not significantly influenced by loading the roof with a heavy rubber mat, don't trouble to include roof vibration in your radiation model.

In the recent past, it has been common practice in some industries to separate the offices of those members of staff developing theoretical, computational models of systems from those who design and perform the experimental test programmes. This schism is all the more regrettable in these days when engineering students spend more and more time in the imaginary world of computational simulation and less and less time in the real world of laboratories and test sites. This is partly due to financial pressures to reduce expense on equipment and technicians; but also, in the UK at least, due to the reluctance of students to study in the laboratory. As one student said to me a few years ago " I don't like lab work. Labs are so messy and the results often seem to be wrong". I didn't ask him how he defined 'wrong', but I did remind him that when he sits in front of his PC, he is in control; but when he is in the lab, nature is in control.

In the days before computational simulation became practicable, we used to say of the printed page that "black and white is right". Nowadays, I believe that some industrial managers are disproportionately impressed by multi-coloured computer outputs. Perhaps they believe that "red, yellow, green and blue is true": and they are not the only culprits! It is therefore very important that both engineers and their managers should be fully aware of the continuing need to validate theoretical models by comparison with experimental data. Indeed the real and imaginary worlds can be combined very effectively to understand a complex world; but the need for all concerned to appreciate the strengths and weaknesses of both components is still of vital importance to a satisfactory outcome.

I would like to conclude by acknowledging the inspiration and motivation that I have received over many years from my academic colleagues and my research students, without which I would not be in a position to be able to express my gratitude to DEGA for the great honour done me and for the pleasure of receiving such a prestigious award.

*Apology

I apologise for the poor quality of some figures. This has been caused by a combination of old originals, scanning and compressing files.