26-28 October 2009 • Edinburgh
EURONOISE 2009

Combining measurement and modelling in acoustic simulation

Andy Moorhouse[a]
Reader in Acoustics, University of Salford, UK

ABSTRACT

In the paper, a scheme for auralisation is presented based on two principles. The first is that any sound can be considered to be made up of a source component, which initially generates sound or vibration, combined with a passive filter function, which does not generate sound but shapes and colours that from the source. The second is that sounds from separate sources combine according to linear superposition. Together, these principles form the basis for an extremely flexible framework for producing auralisations in which the input data, representing the source and filter functions, may be derived from measurement or from modelling. Examples auralisations will be presented from domestic products and from building acoustics in which measured and modelled data has been successfully combined in different ways to produce a realistic result.

1. INTRODUCTION

Most acousticians have at some time been faced with the problem of 'explaining' what something will sound like. The inadequacy of using graphs and words to describe the personal experience of hearing a sound soon becomes obvious. The same problem does not arise when we want to communicate how something will look; in that case we simply find some way to sketch it. In a short space of time and with simple tools we can get across the essential visual features to virtually any audience. But in acoustics this is not so easy - the 'acoustic sketch pad' does not yet exist. Perhaps the nearest equivalent tool at our disposal is imitation, but it takes a brave consultant to imitate the sound of an industrial process to a public meeting! Consultants, designers, industrialists and environmental health professionals are now looking for more practical alternatives for simulating sounds of new designs and plans.

In this paper we will investigate some of the possibilities now becoming available for simulation of the sounds of not yet existing machines, buildings and environments. On the sound reproduction side there is much current research into methods of generating a 3D listening experience: surround sound, ambisonics and wave field synthesis, to head related transfer functions (HRTFs). However, the main focus of this paper is on the physical modelling side: how do we characterise machines, parts of machines, buildings and environments and how can the data be combined in the computer to produce a realistic auralisation? In particular, an approach termed Virtual Acoustic Prototypes will be described.

The need for auralisation tools is particularly important in industries where design targets are set in purely subjective terms. To take a real-life example, the sound quality of some automotive

[a] Email address. A.t.moorhouse@salford.ac.uk

components is judged by (acoustically) non-specialist test drivers, who give a score from 0 to 10 in terms of the component's acceptability or otherwise sound-wise. An average score below seven out of ten is likely to mean a lost sale. From the car assembler's point of view the logic of this approach is clear, but from the component designer's perspective, unless they have appropriate design tools, this situation is beyond their control. In other industries too, like domestic products, subjective judgments by customers are given a high priority. In such situations there is no substitute to the development of subjective design tools and, where sound is concerned, this will inevitably involve auralisation in some form.

A non-mathematical treatment is given in this paper, but various references are provided for a fuller treatment.

2. A FLEXIBLE SCHEME FOR ACOUSTIC SIMULATION

In this section, a scheme for auralisation is presented. No claim for originality of this scheme is made, but in subsequent sections some novel applications of the scheme will be presented. The scheme is based on two fundamental principles. First, the sound at a receiver location can be considered to be composed of a source contribution, appropriately filtered by the transmission path to the receiver. Second, sounds from separate sources combine according to linear superposition. Together, these principles form the basis for an extremely flexible framework, illustrated in Figure 1 which can be applied to many (although not quite all) situations.

Referring to Figure 1, each rectangular box symbolizes a digital data file. The 'resultant sound' is not a sound as such, but a wave file that can be reproduced over headphones, with loudspeakers, or in a variety of more or less sophisticated arrangements for generating 3D sound fields. These elements of the auralisation chain are referred to here collectively as 'sound reproduction'. However, the main focus of this paper is in the parts of the process up to and including the 'resultant sound' box. The term Virtual Acoustic Prototype (VAP) has previously been used to describe this part of the auralisation chain and we will retain the term here, although it will become clear that the application of the scheme is potentially far wider than just machine prototypes.

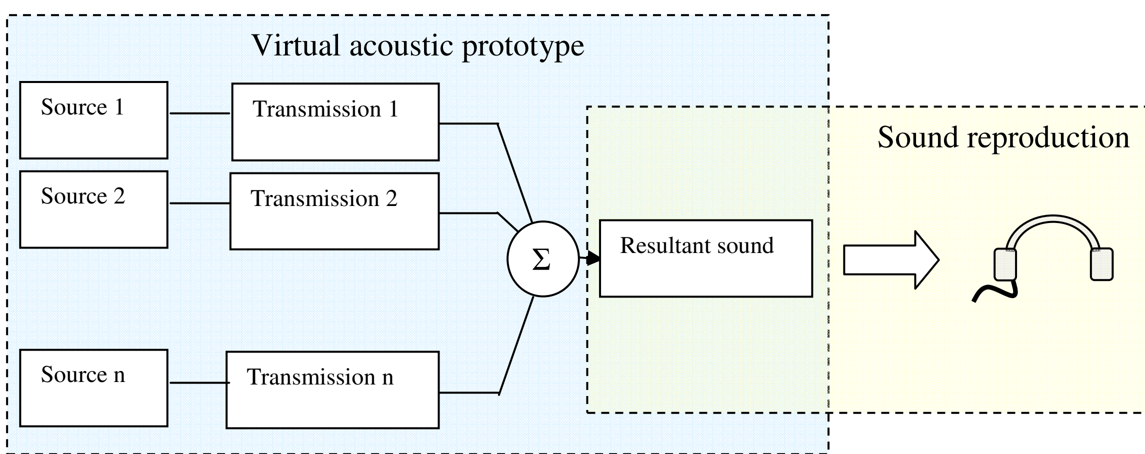

Figure 1: Scheme for auralisation of a Virtual Acoustic Prototype.

There are two sets of input data in a VAP, representing sources and transmission paths respectively. The source components, at the beginning of the chain, represent the active part of the process. Sound is always generated by fluctuating forces, whether in the air, within fluids, or within solid structures: the data file corresponding to each 'source' box is a representation of how these forces act on the transmission path. There are many ways in which such source mechanisms can be characterised, some examples of which will be presented later. The boxes representing the transmission path can be thought of as filter functions: they do not generate sound but modify and colour that created by the corresponding source. Physically they represent the frequency-dependent effects of diffraction, reflection, absorption and transmission as the sound travels between the source and the receiver. (Essentially the same scheme as above is also referred to as Noise Shaping Technology, NST [1]). The scheme can be interpreted in the time or frequency domain. In the time domain, the source data consists of time histories, and the transmission path data of impulse response functions. In the frequency domain the transmission data will be a frequency response function and the source data a narrow band Fourier spectrum. Examples of both time and frequency domain interpretations will be given in the following sections.

The main question addressed in this paper is how to find the data to fill these boxes, in other words how are sources and transmission paths to be characterised and represented as digital data files? It will be seen that 'source characterisation' is the key to answering this question. First, it should be appreciated that at current state of the art it is simply not possible to obtain all such data by numerical modelling. For acoustics and vibration sources, our ability to model source mechanisms 'from scratch', i.e. from first principles is not sufficiently advanced. It is beginning to become possible to predict the sound generated by some sound sources, for example fans, although this is likely to remain a highly specialised job for some time at least. Other mechanisms, like stick-slip friction are still not sufficiently understood for reliable models to have been developed. Numerical modelling of transmission paths is feasible for some simple cases, but in many other cases the only reliable approach is measurement. Therefore, at current state of the art, and for some years to come, most VAPs will need to be based at least in part on measured data.

In the following sections examples will be presented in which the either the source, or the transmission path, or both, are represented by measured data. It will be seen that the scheme in Figure 1 allows measured and modelled data to be combined and even interchanged. The VAP approach has been quite widely adopted in the automotive industry [2]. Other sectors potentially have as much to gain, but do not have the resources to follow the automotive example, such as construction, 'medium technology' industries like domestic and outdoor products, consultants and environmental health professionals.

3. VENTILATION SYSTEM EXAMPLE

The first example is of a ventilation system, built in to the door of a telecommunications base station. Figure 2 shows the outside of the cabinet, illustrating the ventilation openings at the top and bottom of the door. In the centre of Figure 2 is shown a cutaway of the inside, illustrating the two small axial fans, which act as noise sources, and the complicated ductwork path inside the door. This was one of five case studies investigated in the European-funded NABUCCO project [3, 4, 5].

A. Sub-structuring into active and passive parts

The first stage in the construction of a VAP is to separate out the (active) sources from the (passive) transmission paths. This involves drawing an imaginary surface all around the source and defining everything inside as belonging to the source and everything outside as the part of the transmission path [5]. To an extent, the position of the source-transmission interface is arbitrary, provided that all source mechanisms are on the inside. This emphasizes the difference between source *modelling* and source *characterization*. In modelling, we wish to understand and represent the detailed mechanisms of sound generation. However, to construct a VAP we do not need to know *how* the sound is generated, rather we need to quantify its net *effect* on the outside world (as represented by the transmission path). In other words we need to *characterize* rather than to model the source. For this purpose we can treat the source as a black box, with unknown internal mechanisms [6]. The problem then is to find a suitable quantity by which to characterise the source strength of the black box.

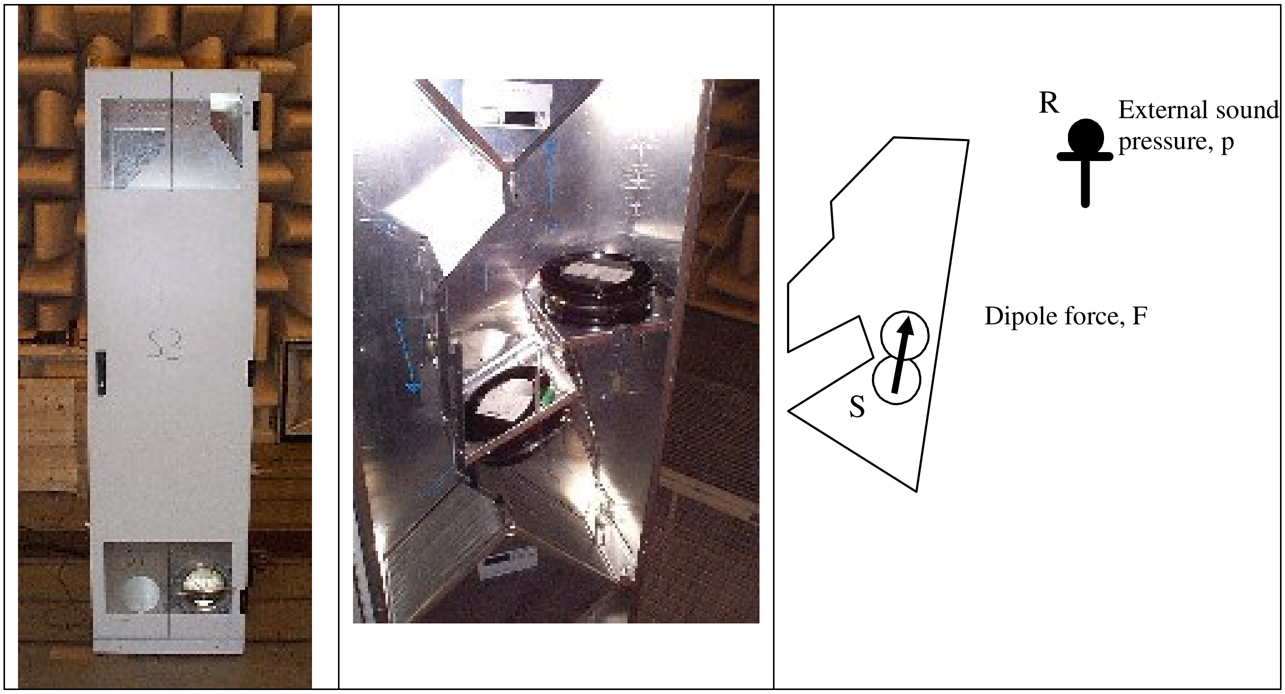

Figure 2: Left: telecommunications base station. Centre: fans and ducting located inside the door. Right: schematic representation of the source and transmission path.

Sound power is the most often used parameter for characterisation of sound sources, but is not suitable in this confined location because it is affected by the presence of reflecting surfaces within an acoustic wavelength. In other words, if we put the same fan in a different duct the sound power delivered will change due to the different acoustic impedance of the duct (the source strength may also vary due to different flow conditions but that is a separate issue). In order to get round this problem, a novel source description was developed [7, 8] where the fan was represented as a single equivalent dipole at its centre, oriented in the direction of flow (see Figure 2). The dipole strength can be back-calculated from the sound power, as measured in free field conditions, using slightly modified standard measurements (see [7] for further details).

Whilst the dipole strength is a less familiar parameter than sound power, it has the over-riding advantage that it is independent of the impedance of the duct. This is a key feature in the design of VAPs: the parameters used to characterise the source must be independent of the transmission path and vice versa which then allows sources and transmission paths to be interchanged.

Having defined the source and characterised it by the dipole force, the characterisation of the transmission path is clear: it is the quantity that links the source strength at S to the sound pressure at the receiver location, R. In other words the path is characterised by the transfer function giving the receiver sound pressure per unit dipole force, or $H = p / f$. The effects of both the ductwork and the free field path from the ventilation openings to the receiver are all bound up in this transfer function. The measurement of this transfer function requires some thought. Direct measurement would require a known force to be input at S whilst the resulting sound pressure at R was measured. This is not a practical approach. However, it can be measured by a reciprocal technique where a calibrated volume velocity source is placed at R and an intensity probe at S [9, 10]. The required transfer function is then given by the ratio of particle velocity, *v*, at S to volume velocity, *q*, at R, or $H = v / q = p / f$.

B. Assembling the VAP

Having obtained the data to characterise the source and transmission path the completed VAP can be assembled by inputting the data into the scheme shown in Figure 1. The result is a narrow band power spectrum of the sound pressure at the receiver. The simulated spectrum showed extremely good agreement with that directly measured [3, 7, 8]. Since the result is in the frequency domain it is necessary to transform to the time domain in order to auralise the result. At this point we realize that there is insufficient information to achieve the inverse Fourier transformation required. This is because a Fourier spectrum is, in general, complex whereas in this case, as in many other practical cases, the phase data has not been retained and only magnitude data is available. It turns out that, for steady state sounds, there is a relatively straightforward solution to this problem in that the phase can simply be assumed to be random. A random phase spectrum was therefore generated, added to the magnitude spectrum and the resulting complex Fourier spectrum transformed to give a time series which could be auralised. Examples will be played at the conference.

4. RAIN NOISE SIMULATOR

The second example of a VAP is of a rain noise simulator developed at the University of Salford [11] in response to requests from architects wanting to avoid the 'miserable' sound of rain on the roof of new barracks. Again, this gives an example of a design target couched in purely subjective terms which, as mentioned before, is not easily met without some sort of auralisation tool.

Whereas in the previous case both source and transmission path data were measured, in this case modeled data is used for the source. The source was taken as the force exerted by raindrops falling on a skylight. The corresponding transmission path therefore consisted of everything between the point, or points of impact to the receiver position in the room below. Unlike the previous example it is more convenient in this case to work in the time domain.

A. Force pulse of a raindrop

The forces exerted by a falling raindrop have been described in a mathematical model by Petersson [12], see also [13]. It turns out that the bottom of the drop becomes flattened during freefall due to the effects of wind resistance so that raindrops are not spherical, as might be thought, but are more closely described by a round-topped cylinder (see Figure 3). When the drop hits a hard surface it first deforms elastically and then quickly bursts, sending water jetting out sideways. During this 'flow' phase the mass of the drop changes rapidly which results in a change of momentum and a corresponding force on the surface. This force can be calculated using Newton's second law in its original form (force equals rate of change of momentum). The result is a force pulse with a shape as shown in Figure 3. Both the height and the length of the pulse depend on the drop diameter and velocity, larger drops causing longer and stronger pulses than small ones.

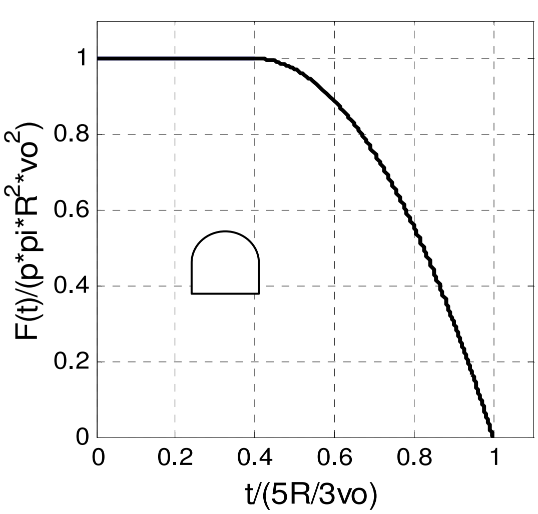

Figure 3: Force pulse due to raindrop on a hard surface

Also, it turns out that rain drops fall with terminal velocity, so the impact velocity also depends on drop size. Thus, the force pulse for any raindrop can be calculated knowing only its diameter.

B. Transmission path

The transmission from point of impact to the receiver position is affected by the structural properties of the skylight and the acoustic reverberation of the room. All these effects are included in a single measured impulse response function. Note that as a general rule this impulse response function must be compatible with the source properties, which in this case are described by the force pulse. Thus, the required impulse response function is the sound pressure at the receiver caused by a unit impulse at the excitation position on the skylight. In fact the units of this function are the same as in the previous example, the difference being that in this case the force is applied to a solid structure whereas in the previous case the dipole force was considered to act directly on the air. The function was measured by tapping the skylight (gently!) at the excitation position with a force hammer and measuring the resulting sound pressure in the room below as illustrated in Figure 4. In practice, the measurement was repeated at several impact positions on the skylight since it was suspected (correctly as it turns out) that each would produce a different sounding drop at the receiver.

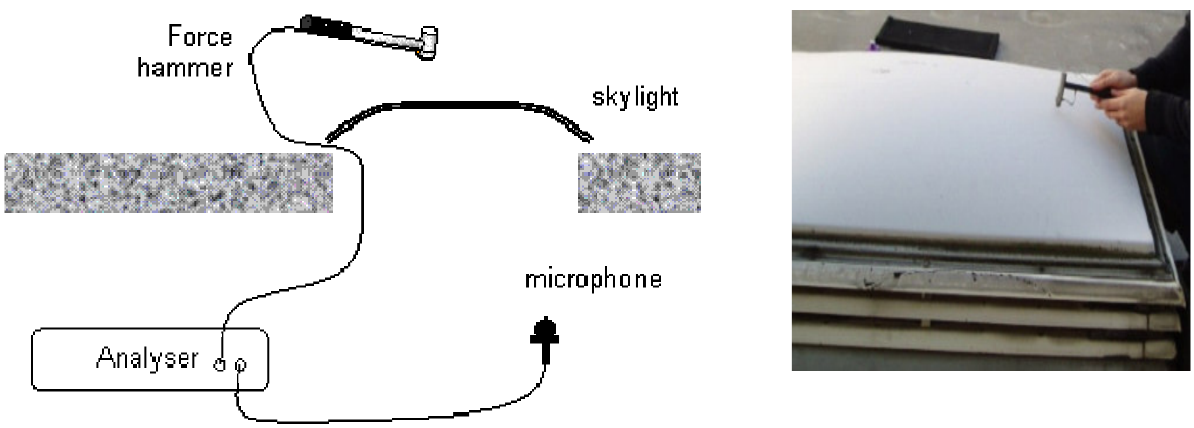

Figure 4: Measurement setup to obtain the impulse response function of the skylight and room. Left: schematic. Right: the skylight under test.

The impulse response function measurement was the most labour intensive part of the construction of the simulator since it was required to access the outside of the skylight. Furthermore, specialist equipment was needed in the form of the force hammer. However, it has since been shown that the impulse response function could be measured reciprocally using an omnidirectional loudspeaker source at the listening location, together with a lightweight accelerometer on the skylight at the point of impact.

C. Auralisation for a single raindrop

Having obtained the force pulse and the impulse response function of the transmission path, the sound pressure at the receiver could be calculated by convolution of the two waveforms. It was then a relatively easy step to auralise the resulting waveform in headphones. In this way the sound of a single simulated raindrop on the skylight could be heard with no real rain being involved at any stage [11].

In order to validate the approach, the whole process was repeated using a plastic tray in place of the skylight in the controlled conditions of a semi-anechoic chamber. A 'control' sound was then produced by dropping calibrated water droplets of different diameters onto the tray form a fixed height of 1 or 2 meters. The simulated waveforms showed remarkable similarity to those of the real drops [11]. Moreover, the auralised sounds were practically indistinguishable, which of course can be considered the true test of the concept since the aim was to produce a realistic sounding simulation.

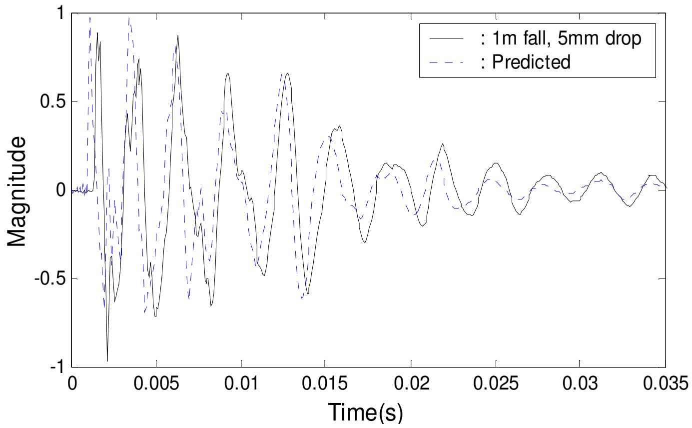

Figure 5: Pressure pulse from the simulated and real drops

D. The sound of rainfall

To reproduce the sound of actual rainfall it was simply necessary to generate the sound of many drops with randomized diameter, arrival time and impact position and to add the resulting pulses by superposition. At this stage it became clear that in order to produce a realistic sound it was important to use accurate drop size distribution data from actual rain fall. Fortunately such data is available for a wide range of different rainfall types [11]. Thus, the simulator can reproduce the sound of any type of rainfall on the skylight of our building in Salford, including some rainfall types, like monsoon rain, which have never been experienced in that part of the world!

The rain noise simulator is a relatively unusual example of the use of measured transmission data, combined with modelled source data. It is still under development. As well as building up a data base for various types of roof construction we are investigating application of the technique to simulation of the sound of rainfall on vehicle windscreens and in dishwashers. Furthermore, we are looking at the possibility of measuring the impulse response function data from a standard transmission loss test setup.

5. TRAFFIC NOISE SIMULATOR

In the previous example, measured transmission path data was combined with modelled source data. In this example we combine measured source data with modelled transmission path data. The example is a simple simulator for vehicle pass-by noise. Other more advanced simulators are available (see for example [14]) but the traffic noise simulator is presented here in order to illustrate the flexibility and simplicity of the scheme presented in Figure 1 and as an example of the sort of scheme that can be developed relatively simply.

The sources considered were tyres, engine (in various gears) and exhaust. Vehicle speed was included by taking measurements at various speeds and by playing back the sounds at modified sample rates. The sources were characterised using recordings with a single microphone at a fixed distance from each source. Engine noise was recorded at the side of the stationary vehicle, and exhaust noise with a single microphone close to the exhaust pipe. Tyre noise was recorded with a microphone at a fixed position at the side of the coasting vehicle (engine off). The recordings were then adjusted in level so as to be consistent with a single point at 5 meters to the side of the vehicle. Effectively then, each source was characterised by the sound pressure it causes at 5 meters to the side of the vehicle under free-field conditions. The assumption of point sources is implicit.

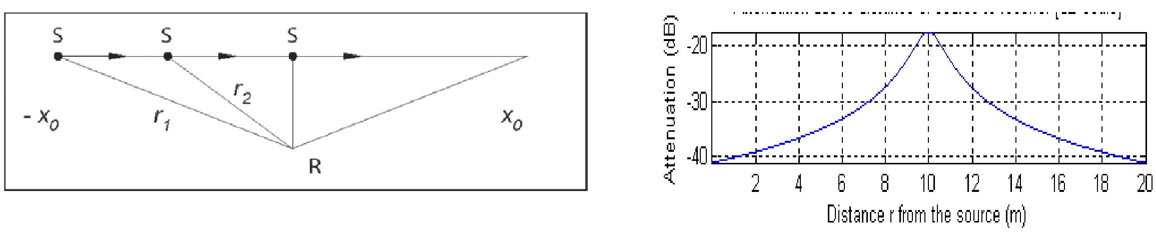

Figure 6: Calculation of distance attenuation for a vehicle pass-by.

The main transmission path effect is distance attenuation which can be calculated based on simple geometry as shown in Figure 6. It was also possible to include the Doppler effect by playing back the recording, made at a constant speed, with a variable sample rate. The effect of engine load, for example caused by a gradient, can be approximated by adjusting the level of engine and exhaust noise while keeping tire noise constant. The result is a realistic sounding vehicle pass-by which can be combined with other vehicles to give a realistic impression of traffic. The flexibility of the scheme allows one to alter the number of vehicles, their speed and engine load.

6. MORE COMPLEX EXAMPLES

Other VAPs have been developed using the above general approach, including a refrigerator [5], a washing machine [15, 16, 17], an air handling unit, a chiller [4], a tumble dryer [18] and several lawnmowers. Considerably more sophistication is required in some of these cases than for those described above to account properly for all significant mechanisms, particularly fluid-borne, and structure-borne sound. In some cases it is necessary to extend the scheme given in Figure 1 in order to account for coupling between the source and the transmission path.

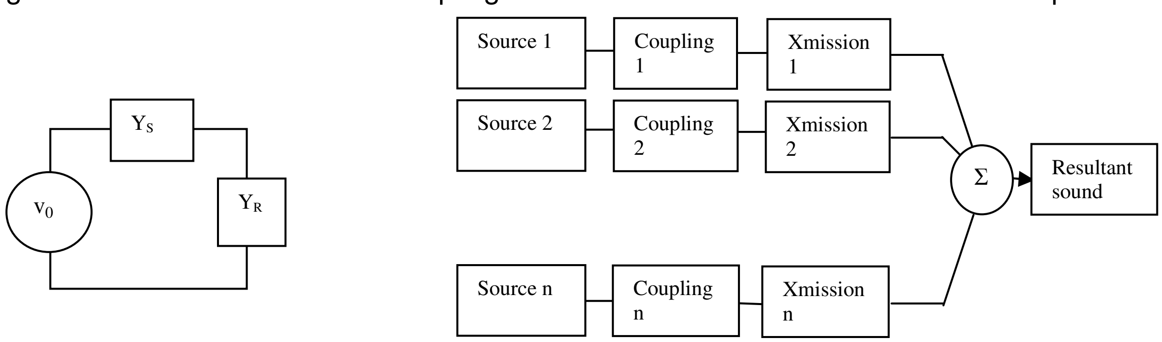

Figure 7: Electrical analogy for fluid and structure-borne sound sources, and right, scheme modified to include coupling.

Fluid-borne noise was a significant contributor from the compressor of the refrigerator and the pump of the washing machine and boiler. Standards exist for the characterisation of positive displacement pumps as fluid borne sound sources, which is significant since it has been mentioned above that source characterisation is the key to a successful VAP. Fortunately, a plane wave assumption is often valid so that a pair of pressure transducers can be used to decompose the outgoing and reflected wave at a position in the pipe close to the source. The source can then be characterised in terms of the outgoing wave. It is also necessary in general to obtain the impedance of the source which is made difficult by the fact that the pump must be in an operating state when the measurement is made. It is clear that specialist knowledge and equipment are required to handle the fluid-borne case. Nevertheless, in the Nabucco project it proved possible to obtain good quality predictions and auralisations of the fluid-borne component of sound in the case of a refrigerator and a washing machine pump.

Regarding structure-borne sound, source characterisation remains an unsolved problem except in simple cases. The theory has been well established for many years but there are difficulties in accounting for all the detailed mechanisms of coupling that occur when two structures are rigidly connected together. This makes it difficult to obtain a data set for the source which is truly independent of the support structure (which forms part of the transmission path) and vice versa. This can be illustrated by the example of Transfer Path Analysis (TPA), which is now widely used as a diagnostic technique in the automotive field. Using TPA it is possible to calculate the contribution to the sound pressure, for example at a driver's ear position, from a structure-borne sound path. The approach follows a similar logic to that shown in Figure 1, but does not account for the coupling step shown in the extended scheme of Figure 7. This means that the data sets from a TPA analysis, whilst they may provide an accurate auralisation for a single vehicle, cannot be transferred to another vehicle. It may seem that, without this possibility, the measurement effort would not be worthwhile. Nevertheless, the fact remains that TPA is considered by industry to be a valuable technique. This illustrates that even without the full functionality of a VAP, there is considerable value in the process of breaking down the sound output into contributions from the various sources and transmission paths.

In the Nabucco project it proved possible to auralise the structure-borne sound contribution from a washing machine motor and a refrigerator compressor from source data obtained on separate test rigs. Subsequent work on lawnmowers has achieved similar results. Figure 8 compares the simulated and measured sound power spectrum from a washing machine with a motor operating at spin speed. Both airborne and structure-borne sound is included. It cannot be claimed that the auralised sound is exactly like the true sound, and without care quite large errors can occur. Nevertheless, in all cases the auralisation was sufficiently realistic to provide a useful representation for design purposes. In any case, we might argue that the primary role of a VAP should be to give an accurate impression of the *change* in the sound due to some modification, which was found to be reliable.

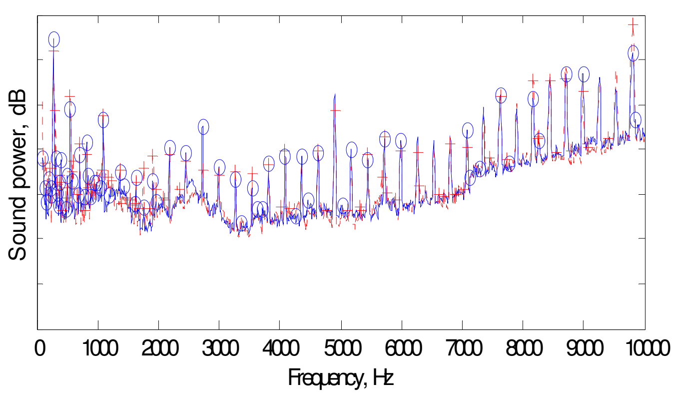

Figure 8: Simulated and measured sound pressure spectrum from a washing machine motor.

7. CONCLUDING REMARKS

Several examples of Virtual Acoustic Prototypes (VAPs) have been presented from which it was possible to produce realistic auralisations in a wide variety of situations ranging from machinery and domestic products to rainfall and traffic noise. It has been demonstrated how measured and modeled data can be combined, within the framework of a simple scheme, to produce a realistic and representative sound.

Many acousticians will recognize the possibilities offered by auralisation to be far more than gimmicks. Auralisation can play a crucial role in bridging what can be a serious communication gap between professional acousticians and non-specialists. To the specialists, graphs and numbers can be translated into an imagined experience which has some reality, but to non-specialists written information is far removed from the experience of hearing sounds and many consultants will have been faced with a client for whom the leap of faith was simply too great. Hearing is believing! Some of the larger consultancies have for some time recognized the important role for auralisation in their business and have been developing their own facilities for sound reproduction. However, as illustrated above, there will always be a need for reliable data to represent the physical mechanisms of sound generation and transmission and in particular there will be a need for robust methods of source characterisation.

ACKNOWLEDGMENTS

Some of the work presented here was carried out the in EU funded project ‘Nabucco’ no GRD1-1999-10785. Several people contributed to the examples given here: Goran Pavic; Leon Gavric, Michel Darpas, Jean Tourret, Per-Olof Berglund, Mats Abom, Anders Nilssen, Leping Feng, Roland Sottek, Holger Kaempfer, Timo Avikainen, Krystof Kryniski, Marco Clara, Georg Eimer, Walter Angelis, Barry Gibbs, Gary Seiffert, Richard Cookson, Mark Hambly, Patrick Froment, Andy Elliott, Markus Bauer, Zbigniew Koziel.

REFERENCES

1. Goran Pavic. Noise Sources and Virtual Noise Synthesis. Proc. Internoise 2008, Shanghai, China, 2008.
2. H. Van der Auweraer Virtual noise reproduction based on vibro-acoustic modeling. Proc Novem, 2009, Oxford, UK.
3. Moorhouse A, Berglund P-O, Fournier F, Avikainen T, 2003, Fan characterisation techniques, Proc Fan Noise 2003, Senlis, France.
4. Pavic G, Gavric L, Tourret J, Sottek R, 2003 Synthesis of noise from a fan type source placed in a complex installation. Proc Fannoise 2003, Senlis, France.
5. Moorhouse A T, Virtual Acoustic Prototypes: listening to machines that don’t exist. Acoustics Australia 33(3) 97-105, December 2005.
6. Cremer, L, The second annual fairey lecture: The treatment of fans as black boxes. Journal of Sound and Vibration, Volume 16, Issue 1, 8 May 1971, Pages 1-8, IN1-IN2, 9-15
7. Per-Olof Berglund. Investigation of acoustic source characterisation and installation effects for small axial fans. Licentiate thesis. KTH, Dept. of Vehicle Engineering. Stockholm.
8. Per-Olof Berglund, Leping Feng, Mats Abom. An application of Noise Synthesis Technology (NST) to a system with an axial fan. Proc. Forum Acusticum. Seville, 2002.
9. Fahy FJ 1995, The vibro-acoustic reciprocity principle and applications to noise control. ACUSTICA 81 (6): 544-558.
10. L M Lyamshev, Theory of sound radiation by thin elastic plates and shells. Soviet Physica Acoustics 5(4), 431, 1960.
11. Moorhouse A T. Virtual acoustic prototype techniques applied to the simulation of noise from rainfall on skylights. Proc ICA, Madrid, 2007.
12. Petersson, B. A. T. The Liquid Drop Impact as a Source of Sound and Vibration. Building Acoustics. 2 (4) 1995, 585-623.
13. C. Guigou-Carter, M. Villot, C. Horlaville. Study of simulated rainfall noise on roofs and glazings. Proc Forum Acusticum, Sevilla 2002.
14. E. Bongini, S. Molla, P.E. Gautier, D. Habault, P.O. Mattéi, and F. Poisson. Synthesis of Noise of Operating Vehicles: Development within SILENCE of a Tool with Listening Features. Chapter in Noise and Vibration Mitigation for Rail Transportation Systems. Springer Berlin / Heidelberg. 2008
15. A.T. Moorhouse, R.D. Cookson, G. Seiffert, Measurement of operating forces of an electric motor, Proceedings of NOISE-CON, 2004, Baltimore, USA, July 2004.
16. A T MOORHOUSE, G SEIFFERT. Characterisation of an airborne sound source for use in a virtual acoustic prototype. Journal of Sound and Vibration, 296, 334-352 (2006).
17. A T MOORHOUSE. Simplified calculation of structure-borne sound from an active machine component on a supporting substructure. Journal of Sound and Vibration, 302, 67-87, 2007.
18. T Evans, R Cookson, A Moorhouse. Characterisation of small centrifugal fans for use in virtual acoustic prototypes. Proc IOA Futures in Acoustics Southampton 2006, ISBN 1 90165675 6.