Proceedings of the Institute of Acoustics

A PERSONAL VIEW OF MUSICAL ACOUSTICS.

Seventh R.W.B. Stephens Lecture

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1. INTRODUCTION

It is a great honour to be asked to give the R.W.B. Stephens Lecture, I am keenly aware of the eminence and achievements of those who have spoken before, but take heart in the great diversity of this lecture series. As David Weston said in 1988, "the first rule of the Series says that there aren't any rules". I plan to take advantage of this lack of rules and am not going to present a closely reasoned discourse on some aspect of my subject; instead I am going to range around in both topic and period with the aim of showing you why it is that I am so fascinated by the subject and feel that it requires, as well as deserves, more attention from all.

R.W.B. Stephens, or "Steve" as my contemporaries and I called him in the days when he supervised us, does not seem actually to have supervised any PhD Theses in musical acoustics, though he undoubtedly participated in many of those presented at Chelsea College, including that by John Carmichael, the only one mentioning the trombone (one of my favourite instruments) in its title. I must confess that I find this a little surprising since "Steve" is a truly remarkable person; he not only seems to be interested in *anything* to do with acoustics, however widely one defines the subject, but also exhibited in my time, as well as later, an almost annoying ability to pick for research topics which were going to be important later. Many are the times my friends, associates and I have reminded ourselves of ideas from "Steve" which we laughed at when we first heard them, only to discover later that he was right and we were wrong. Why he did not foresee the great explosion of work in musical acoustics in the 70s must remain a mystery.

Musical acoustics is undoubtedly the mother of all acoustics: not only did it come first but nearly all the other branches can be traced back to a musical root. The path may be long sometimes, but can usually be found; though I have to admit to some problems with underwater acoustics. For thousands of years, people have asked questions about music. Some want to know how it is that we perceive sound: how is it that a particular sound can attract our attention over others? Others want to know why it is that some sequences of sounds arouse extremely strong emotional reactions whilst others are seemingly of no interest. Many, of a more practical bent perhaps, want to know how the sound reaches us from the source; they become interested in the way that differently shaped rooms, spaces and enclosures can affect not only the perception of the sound by the listener, but even the way that the sound is produced in the first place. They explore the way that our brains make use of the information arriving at our ears and build up a picture of the surrounding world. Others are fascinated by the mathematics which underlies music; they become almost obsessed with a desire to explore charted and uncharted regions of number theory with the intention of, perhaps, explaining the musical scale. The very large body of important work that has been done on the perception of beats clearly has as its root the problem of the musical scale - how much has been learnt about the operation of the brain from this age old problem! Still others want to find out how those incredibly complicated devices known as musical instruments work: how they evolved into their present forms; what physical processes govern their operation, what physiological factors appear in the process of sound production, what psychological aspects of the performer and listener are important. I shall mention later how tremendous advances in mechanics have resulted from musical instrument investigations. I belong to this last group, but do not want to confine my essay to its work today.

Musical acoustics is therefore a blend of many disciplines: physics, mathematics, psychology, physiology, engineering, electronics, signal processing, various crafts, architecture, *etc. etc.* These aspects are not separate, they interact at many levels and this interaction is both a strength and a weakness of musical acoustics. It is a strength because the interaction has to be pursued to high orders to be valuable, and this task is a stimulus, a challenge, an excellent training and highly rewarding to an enthusiastic and dedicated scientist; a weakness because it is not at all easy for one person to cope to the extent required with all aspects of the work; a regrettably large amount of published work is disappointingly superficial. It is also apparent that it is particularly difficult for administrators to cope with the wide diversity of musical acoustics, and many of them have proved to be very unsympathetic to the needs of potential researchers.

2. BEGINNINGS

It is commonly held that Pythagoras (b. 570 BC) started musical acoustics by his investigations into the vibrations of strings and the relationships between the parameters of the string and musical intervals. Musical instruments were, of course, known before him, but this idea is so widespread that it seemed worth while spending a little time looking into it. I have not been able to lay my hands on his original paper, but did discover a report (Farrington) of an account by Boethius (6th AD) referring to the original work.

It appears that Pythagoras, haunted by the problem of giving a mathematical explanation of the fixed intervals in the musical scale, happened, 'by the Grace of God', to pass a blacksmith's shop, and found his attention gripped by the more or less musical chime rung out by the hammers on the anvil. It was an opportunity to investigate the problem under new conditions which he could not resist. In he went and observed long. Then he had the idea that the different notes might be proportioned to the strength of the men. 'Would they change their hammers round?' It was plain that his first idea was wrong, for the chime was unaltered. The explanation must lie in the hammers themselves, not in the men.

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There were five hammers in action. 'Might he weigh them?' Ah, miracle of miracles, the weights of four of them were in a proportion of 12:9:8:6. The fifth, the weight of which bore no significant numerical relation to the rest, was spoiling the perfection of the chime. It was rejected and Pythagoras listened again. Yes, the heaviest hammer, which was twice the weight of the lightest, gave him the octave lower. The doctrine of the arithmetic and harmonic mean (12:9:6 and 12:8:6) revealed to him the ratios which gave the intervals of the fourth and the fifth sounded by the other two hammers. Surely it was the will of God that he had passed that blacksmith's shop. He hurried home to continue his experiments, one might say, under laboratory conditions.

The story goes on to relate how he tried strings and found that the note was inversely proportional to the length. He went on to try the tension and the thickness and satisfied himself of the truth of his findings.

Although very appealing; that story cannot be true. The weights of hammers do not relate to the natural frequencies in the way described, nor could Pythagoras have satisfied himself when he explored the relationship between the note and the tension and thickness of the string because the relationships are not linear (or reciprocal); remember Pythagoras used pebbles to count, we are in the days before irrational and incommensurable numbers had been found, so the square root law for the tension and thickness would surely have puzzled Pythagoras very much. Thus we find that although this may be an account of an experiment in classical Greece (at a time when it is commonly supposed that only 'thought' experiments were done), the details of the experiment are not at all satisfactory and one begins to suspect that the results may have been adjusted to fit the theory.

Notwithstanding that criticism of Pythagoras' experimental technique, it certain that we owe the basis of the theory of musical scales to him. He found that it was possible to construct a complete scale using the frequency ratios 2:1 and 3:2 only.

Moving on quickly, we come to another figure in the work on musical scales: Aristoxenus, the greatest musicologist of antiquity according to Sarton. Aristoxenus deserves much credit as the first to raise the eternal question: 'are the cogitations of theorists as important as the observations of musicians themselves?'. Would that that question were inscribed over the desk of every worker in musical acoustics today! Finally, for the moment, I want to mention Claudius Ptolemy who not only created a great catalogue of musical scales, but also suggested a fundamental principle in tuning lore: 'the best tuning is that for which ear and ratio are in agreement'. Another principle which deserves the widest publicity. However, for Ptolemy, the correct tuning ratio had to be superparticular, so to my mind, he rules himself out of court. Nevertheless, even today I find his catalogue to be of great use: papers are still being written on the development of new systems of tuning, and from time to time I am asked to referee them. The first thing I do is to check Ptolemy's catalogue to see if the 'new' scale is in it. Somewhat over half the time I find that it is, so my task as a referee is made much easier.

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3. EARLY SPEECH WORK

It is convenient for me to leave scales but stay in this period of history for a few moments and talk briefly about two Romans, one famous in the field of Architectural Acoustics and the other in physics. Both have written (admittedly incidentally, but I am free to talk widely in the R.W.B. Stephens Lecture) on the acoustics of speech which they (rightly?) considered to be part of music, since the singing voice is the supreme instrument. These may well be the first reports in the enormous literature of the speech community.

Vitruvius is very well known for being aware of, and understanding, several concepts of wave theory and applying them to room acoustics. However, he is less well known for his opinions on speech: he reports that it is 'well known' that people from Northern countries have deeper voices than those from the South. The reason lies in the very structure of the universe: if we draw the circle of the horizon, bisect it with a diameter running north and south and then draw an oblique line up from the southern end of the diameter to the Pole Star, it is clear 'that the world has a triangular shape like the sambucca' (a Greek stringed instrument). If we imagine the longest string of this world instrument to be a vertical dropped from the Pole Star to the diameter we have drawn and the rest of the parallel strings to grow progressively shorter towards the south, we can understand by analogy why the human voice becomes deeper as we go North.

I have to admit that I find Vitruvius' argument somewhat difficult to follow; even if we grant that the world is an enormous musical instrument (a fascinating idea in itself), why should human vocal chords follow its structure so closely, and what happens to the traveller from, say, Egypt to Sweden during his journey?

Lucretius is famous in physics as one of the chief progenitors of atomic theory. I have used some of his writings myself during arguments with the Science and Engineering Research Council: it was put to me that the acoustical research programme I was submitting was not necessary because 'the basis of the work had been done before by Rayleigh' (how often have we acousticians heard that!). I responded with a short paper showing that much of the work being done in CERN had been anticipated by Lucretius and wasn't it time they ran down their enormous contribution to that organisation and spared some money to those of us doing new physics. I regret to report that they do not seem to have taken my advice.

Lucretius on speech and hearing: 'all forms of sound and vocal utterance become audible when they have slipped into the ear and provoked sensation by the impact of their own bodies. The fact that voices and other sounds can impinge on the senses is itself a proof of their corporeal nature. Besides, the voice often scrapes the throat and a shout roughens the windpipe on its outward path. What happens is that, when atoms of voice in greater numbers than usual have begun to squeeze out through the narrow outlet, the doorway of the overcrowded mouth gets scraped. Undoubtedly, if voices and words have this power of causing pain, they must consist of corporeal particles. [....]. There is a marked difference in the shape of the atoms that enter our ears when a low-toned trumpet booms its *basso profundo* and the hoarse-throated roar re-echoes from savage crags, and when the swan's plaintive dirge floats up in doleful melody from the winding glens of Helicon.'

Back to scales; jumping a few centuries and leaving aside Robert Smith whose paper received from Augustus de Morgan one of the most damning reviews I have ever read: he described it as 'vilely written and obscure'; I must mention, albeit very briefly, Helmholtz whose contributions to psychoacoustics are immense and firmly based on music. He greatly developed the ideas of consonance and even anticipated some of the versions of the critical band which abound in the modern literature. I feel that there can be no doubt that psychoacoustics as a discipline arose as a result of musical questioning.

Figure 1, Hermann von Helmholtz

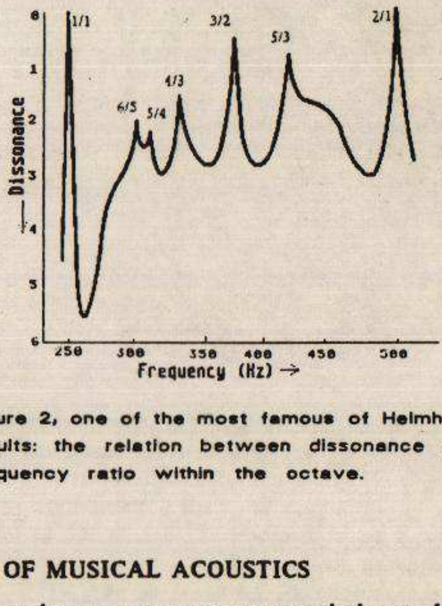

Figure 2, one of the most famous of Helmholtz's results: the relation between dissonance and frequency ratio within the octave.

4. AN ILLUSTRATION OF MUSICAL ACOUSTICS

After that large temporal jump, I want to take up a more conventional theme. I hope that you will allow me to illustrate the demands of musical acoustics by the example I use in lectures to school children. Precisely because the level is low, I feel that the complexities and pleasures of the subject make their presence felt in an even more dramatic way. I make some asides today which I would not make to school children.

I start with a simple minded approach to the violin and the stretched string and show a slide illustrating the ways that an ideal string mounted between two fixed supports and stretched with a given tension can vibrate. The diagrams show that the two ends of the string do not move at all, and that the rest of the string moves in certain shapes called modes. Each mode can exist on its own or the string can have a more complicated motion made up of number of modes added together in differing amounts and with different time relations. It is remarkable how scientists of the 17th and 18th laboured unsuccessfully on this point. Mathematicians of the eminence of d'Alembert and Euler were defeated by the problem of the slope discontinuities exhibited by the stretched string. Would so much effort have been expended had it not been for the musical interest?

The frequency of the string (what we would call the fundamental frequency) was, apparently, not given in a complete form until Mersenne, who found the constant in the equation relating frequency to length, tension and mass per unit length by counting the vibrations of a brass string 138 feet long and 1/48" in diameter. I have already mentioned that the basic behaviour of the variables was *supposed* to be known to Pythagoras about 2200 years before. This experiment must hold the record for being the longest delayed in physics.

Figure 3, Marin Mersenne

The most important thing to note about the modes is that their frequencies of vibration are related by a very simple rule: if we call the frequency of the simplest mode of vibration 'one', then the others have frequencies 2, 3, 4, etc. The reciprocals of this sequence of numbers are called 'harmonics', the modes are said to form a harmonic series, and each member of that series is often called a harmonic. The rule comes about because we have to fit a whole number of loops into the length of the string and if the velocity of waves along the string is constant, the harmonic series follows at once. Given this series of harmonics, the string can adopt any periodic shape. This well known result is inextricably linked to the great work of Fourier and I am going to allow myself the liberty of talking about him for a moment or two.

5. AN ASIDE

I decided to look up the famous paper by Fourier which is the basis of so much musical acoustics; this is published in an excellent biography by Grattan-Guiness. Reading it, I discovered many interesting things:

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Jean Baptiste Joseph Fourier was the nineteenth (and not the last!) child of his parents both of whom died before he was nine. He had a very difficult childhood and failed to get into a military school at the age of 13 despite the support of the mathematician Legendre; instead he went to the Benedictine Abbey of St. Benoît-sur-Loire, where he later taught, and wrote a paper on the theory of equations at the age of 19. This paper was not published because the French Revolution supervened. He showed considerable ability in politics and was a member of the Comité de Surveillance which enforced government decrees in his region (Auxerre). He became an outspoken critic of the corruption rife amongst officials of the revolution and was sentenced to be guillotined. He went in person to Robespierre in Paris to plead his case, but was unsuccessful; on his return to Auxerre, he was arrested, released, arrested again and was finally released only when Robespierre himself was executed on the 28 July 1794. Later, he was arrested by the post-Robespierre régime who accused him of being an abettor of Robespierre, thus he was arrested by both sides in the revolutionary disputes. Who thinks that academics today have a hard life!

Figure 4, Joseph Fourier

Fourier submitted the first version of his famous work on the diffusion of heat to the Institut de France in Paris on 21 December 1807; this version caused great controversy among the examiners, mainly because of the surprising nature of some of its mathematical results. He submitted extra material in 1808 and 1809 to meet criticisms and eventually yet another version in 1811 for a prize which the Institut had inaugurated on the problem of heat diffusion; this version won the prize but was still not published! Eventually, Fourier had to write his famous book (1822) to have his ideas published.

The paper contains material on the vibrating string problem which shows that he was able to make useful advances over the work of d'Alembert and Euler on the problem of the discontinuities which arise when the vibrating string has a corner. Mathematicians had laboured for nearly two centuries over the problem of the vibrating string - in particular over whether the normal modes could co-exist. The general technique of analysing a periodic motion into a series of trigonometric functions which can coexist is clearly Fourier's, and we all owe a great debt to his genius and persistence.

6. RETURN

Returning to the school level story: the real snag about those ideas mentioned above when we want to talk about musical instruments like the violin is that they are not true! Violin strings are not ideal strings. An ideal string has no stiffness and vibrates between rigid supports with small amplitudes. The result then was that the vibrations form a harmonic series. What is this restriction to small amplitudes? - is this its first mention? It is, and it is not mentioned at all in many of the books, but if the motion of the string is not restricted to very small amplitudes, inconvenient things happen. First, if the amplitude is not small, it is obvious that the tension in the string must change; it will be greater when the string is at the extremes of its movement than when it is at the middle of its motion and is just a straight line. Second, if the amplitude is not small, the velocity of the waves along the string depends upon the angle any part of the string makes with the undisturbed position. So the frequencies of the modes change with the amplitude.

In real life, the string is stiff, not like the ideal string which is perfectly limp if you remove the tension. String players are well aware of this, and find it difficult to keep a new string uncurled when taken out of its packet. This stiffness has the effect of changing the allowed frequencies of vibration from harmonic to inharmonic, the higher the frequency, the modes become sharper and sharper. The mathematics of this problem were solved by Lord Rayleigh. In addition, the properties of a real string change along its length and to do a better analysis, one must allow for that as well.

A string on its own is not very loud, so it is put on a box. The ends of the string then move a little, so that the sound waves can appear on the box and thence drive the air so that we can hear.

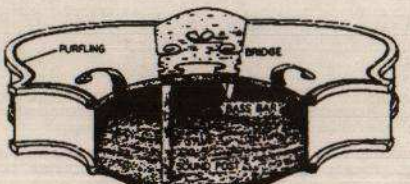

Figure 5, section through the body of a violin

This is obviously a very complicated structure - far from the simple rigid ends which support the ideal string. When it vibrates, different parts are going to move with different amplitudes and phases.

THE 1990 R.W.B. STEPHENS LECTURE: MUSICAL ACOUSTICS

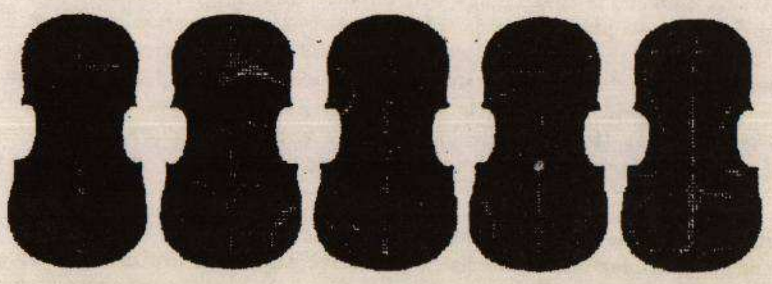

Figure 6, Chladni patterns on a brass plate shaped to imitate a violin. The mode frequencies are 260, 340, 436, 620 and 780 Hz from left to right.

The lines join those parts of the plates which are not moving. The figure is of a brass plate, but frequently nowadays drawings are calculated from a mathematical model of a piece of wood with the shape and properties of a violin plate made of spruce. This is an example of how progress with complicated problems is often made today. We build a model in a computer which we can study and change under much greater control than trying to work with the real thing. Of course, one has to keep comparing with the real thing to stop major errors creeping in; but when the model has been built and its behaviour explored, more has been learnt than from making measurements on the real thing when it is not known what measurements to make.

I interpose a point here if the audience is mature enough and discuss briefly the traps one can fall into if one's model is inadequate in some way. I feel that this is a very important maxim in scientific research as a whole: be *sure* of your model. For example, work on the acoustics of brass instruments was confused for many years by the fact that the playing frequencies of a good instrument are very nearly harmonic and can be predicted quite closely by measuring the length of the instrument and treating it as an open-open pipe. In fact, making the playing frequencies harmonic requires a great deal of work by the maker in shaping the tube and flaring the bell to make the natural modes of the system harmonic and it is a 'disastrous coincidence' (as I have written elsewhere) that the final result can be explained so nearly by a wrong model.

That diversion on the behaviour of the box was necessary to allow me to explain the next thing which goes wrong with the simple picture of the stretched string. When it is mounted on a box, the ends of the string move in a way dictated by the properties of the box. If, at a certain frequency, the bridge moves in the same direction as the string the string seem a little longer and the frequency of that mode of vibration will go down. If the bridge moves in the opposite direction the frequency of the mode will go up. When a violin string is plucked or driven by the bow, it vibrates at several frequencies at once, so, depending on the properties of the support, some frequencies may be sharpened and some may be flattened. We cannot say which because we do not know enough about the violin or the string to answer that question. What we can definitely say, though, is that things will be very different for another note. They will also be different if we play louder or softer because the properties of the string change; this, of course, has dramatic implications for the psychoacoustics of the sound. The properties of the material comprising the box affect the response and sound of the instrument greatly and much subtle, and elegant, work has been done, particularly in the last two decades (for example by McIntyre and Woodhouse), on establishing the real and complex parts of the frequency- dependent elastic moduli of orthotropic materials.

We then consider the way that the bow interacts with the string. The bow/string interaction is non-linear, the bow hairs and stick support wave motions of their own, the bow hairs tend to introduce rotational modes into the string, the player varies the force of contact and bowing speed continuously. The radiation of sound from the whole system made up of these varying linear and non-linear factors and vibrating with a complicated nodal structure has to be analysed. Of course the wavelengths involved are just in the awkward range: neither large nor small, the player is in the near field and the listener is (usually) in the far field. The player reacts psychologically not only to the sound he is producing, but also to his perception of the reaction of the room and the listener. The spectra are not continuous in frequency and are time varying, even 'simple' power measurements are very demanding (e.g. Meyer and Angster). Nevertheless, some very significant progress has been made in the physical measurement of the sound radiated by complex bodies (for example, by Weinreich and Arnold), and we have yet another example where a musical acoustics need has driven the art of acoustics forward.

7. INTERLUDE

Francis Bacon is not widely known as a musical acoustician, but there is a passage in *New Atlantis* which is so striking that I have reproduced it as a figure in this paper. I have been to some trouble to ensure that the quotation is accurate because I found that many different versions exist. Just look at how much of modern acoustics is in that short passage; he even foretells the skills of British Rail in transforming the sounds of spoken language!

8. BRASS INSTRUMENT WORK IN SURREY

Many of you will be expecting at least a little about our work on brass instruments and I cannot disappoint you. I had a programme of work at the University of Surrey which, from the first, was planned to integrate many of the factors mentioned above.

The work was largely carried out by an excellent team of research students, Richard Pratt, Steve Elliott, Pete Watkinson, John Goodwin, Anne Deane (née Duffield) and Andy Watson, to name them in chronological order; by Research Officers Richard Bacon, Richard Shepherd and, briefly, Bernard Smith; by a Post-Doctoral Fellow, Robert Edwards; and by colleagues Peter Simpson and Mike Jones. I must give my very special thanks to the continuing interest and support of Dr Richard Smith, formally of Boosey & Hawkes but now of Richard Smith Musical Instruments Ltd.

New Atlantis

A Worke unfinished.

Written by the Right Honourable, Francis

Lord Verulam, Vifcount St. Alban.

Wee have alfo Sound-Houfes *wher wee practife and demonstrate all* Sounds, *and their* Generation. *Wee have* Harmonies *which you have not, of* Quarter-Sounds, *and lesser* Slides *of* Sounds. *Diverfe* Instruments *of* Musick *likewife to you unknowne, some* sweeter *then any you have; Together with* Bells *and* Rings *that are dainty and fweet. Wee reprefent* Small Sounds *as* Great *and* Deepe; *Likewife* Great Sounds, Extenuate *and* Sharpe; *Wee make diverfe* Tremblings *and* Warblings *of* Sounds, *which in their* Originall *are* Entire. *Wee reprefent and imitate all* Articulate Sounds *and* Letters, *and the* Voices *and* Notes *of* Beafts *and* Birds. *Wee have certaine* Helps, *which fett to the* Eare *doe further the* Hearing *greatly. Wee have alfo diverfe* Strange *and* Artificiall Eccho's, Reflecting *the* Voice *many times, and as it were* Toffing *it: And some that give back the* Voice Lowder *then it came, fome* Shriller, *and fome* Deeper; *Yea fome rendring the* Voice, Differing *in the* Letters *or* Articulate Sound, *from that they receyve. Wee have alfo meanes to convey* Sounds *in* Trunks *and* Pipes, *in ftrange* Lines, *and* Distances.

Figure 7

A passage written in 1627 by Francis Bacon which foretells with uncanny accuracy future happenings in musical acoustics, sound engineering and telecommunications. The above text has been transcribed from the copy of the first edition held in the British Museum Library. I am very grateful to Henry Rozenburg of the University of Surrey Library for going to the British Museum and writing out the passage for me.

Without his help and encouragement, the work would certainly not got as far as it did.

8.1 Frequency Domain
We worked mainly on the trombone - an instrument I play of usefully simple construction. Initially we measured the input impedance of the trombone, there was clearly a need for an absolute measurement of this quantity, and we decided to remember that impedance is a quantity which is defined as the ratio of two others (pressure and volume velocity) and therefore was better measured using both. We measured the particle velocity of the oscillating air with a hot wire anemometer, and it is interesting to note that measuring the particle velocity directly is again being done; this time by the group in Edinburgh who are using laser photon correlation spectroscopy for the task. The impedance was measured using a computer controlled apparatus: we were the first in my department to use an on-line computer in this way.

Measurement resolution raises a problem worth mentioning: for musical purposes it was necessary to have very high resolution (an error of 1 Hz in the location of the second peak in the curve of impedance against frequency is an error of 30 cents). But the experiment would take a long time to run with small steps. The frequency of a peak depends on the velocity of sound, and to obtain the required level of accuracy, the temperature of the air within the instrument has to remain constant to within less than a quarter of a degree. I am not aware of much work, apart from that by John Goodwin, on the effects of temperature distributions within the body of the instrument; this is worrying in view of the practical implications of such neglect.

Energy losses caused by the properties of the inner wall surface and by vibration of the walls of the tube were studied by Pete Watkinson, who contributed a useful new technique to the measurement of the attenuation coefficient relevant to propagation in tubes. He also applied finite element analysis to the complicated structure of a trombone bell and showed others how this technique can be used in musical acoustics. In addition, he worked out how the air column is coupled to the vibrating bell walls which is of great practical importance. After working out the coupling between the internal air column and the vibrating bell of the instrument, one could in principle go on to work out the radiation to the outside world from the bell walls. This has yet to be done and would advance understanding of sound radiation from complex structures. Near field wall radiation affects the sound heard by the player, particularly if he is a trombone or tuba player, has an effect on his perception of the quality of sound radiated by the instrument, and so will affect his playing.

The radiation from the instrument walls is much less than the radiation from the end of the air column, but few people have studied the latter in detail. The very detailed analyses of the wavefronts necessary for a complete description of the near-field and its effects on the perception by the player and on the terminating conditions of the standing waves inside the instrument just do not exist and are a good topic for future work.

THE 1990 R.W.B. STEPHENS LECTURE: MUSICAL ACOUSTICS

8.2 Time domain

More recently, Anne Deane and Andy Watson worked with impulses. By exciting an instrument at the input with an acoustic pulse, reflections are generated from acoustic impedance mismatches along the instrument. Structural faults in an instrument can easily be detected and located by the impulse technique and so accurate comparisons between instruments can be made to check for consistency in manufacturing output. This aspect of the work has proved to be very valuable to makers and we were of direct assistance to two before our programme was terminated.

There is rather too much sloppiness of definition in many papers on impulse work, and many apparent disagreements have been created needlessly. In our paper, Andy and I go over some of the basic points. If we remove the characteristics of the input pulse by a deconvolution procedure the result is clarified by giving the response of the instrument to a delta function of pressure. Once an accurate determination of the impulse response has been obtained, one can tackle the inverse problem of determining the bore of the instrument at all points along its axis. We developed various algorithms and here are the results for a trombone and an alphorn.

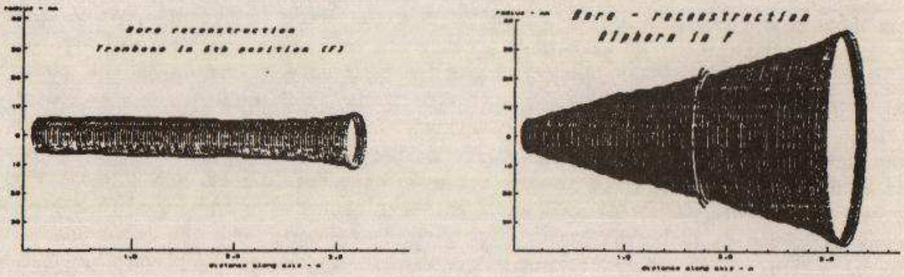

Figure 8, comparison of bore reconstructions of trombone and alphorn in same pitch

8.3 Interaction between player and instrument

In brass instruments the interaction between player and instrument is very strong. Helmholtz has been the foundation of most approaches and a note is considered to be produced by the action of a variable valve controlled by the mouthpiece pressure which adjusts the flow rate of the air passing into the instrument from a reservoir. Assumptions usually made are that the pressure in the reservoir is much higher than that in the instrument and remains constant during the flow cycle. Thus the flow would always be into the instrument and would consist of a fairly large steady flow with a small alternating component. No one, apparently, actually made measurements of the pressures and flows in the mouth of a player and mouthpiece until Steve Elliott's work. It turned out that the assumptions of constant and high mouth pressure were not met, the mouthpiece pressure exceeded the mouth pressure and the flow reversed every cycle. Steve was able to develop a theory of the interaction which could explain many of the abilities of players, for example, it is fairly easy to make a downward glissando on a fixed instrument, and I feel that had it been possible to continue this work, a really important contribution would have been made to our understanding of sound generation in wind instruments.

8.4 Attitudes of players

We surveyed in two ways: in the first Bob Edwards asked a large population of trombone players what they thought about their instruments. However, we were not able to correlate the results with the frequency domain measurements we were doing at the time. Secondly, he interviewed selected players in depth and analysed the interviews to discover how the players used language to describe instruments and the sounds they produce. The words used by players were rather informal and it was not easy to describe the results of this sort of work succinctly. However, a useful advance was made by analysing the statistics of the words used by players and building up a matrix of meanings which could be handled by multi-dimensional scaling.

Lack of space prevents me from describing some of the further work done in this area, notably by Peter Simpson. Briefly, we showed that the complexities of the problems were far greater than many had anticipated. It became obvious that the percepts of timbre or of instrument quality are extremely complex and involve some sort of pattern matching algorithm together with an expectation in the player's or listener's consciousness of the qualities desired. This implies a marked degree of familiarity with the task and it is remarkable that there are so few reports describing the seemingly simple task of instrument identification under various experimental conditions. I have mentioned this at conferences several times, yet a watch over the major journals still fails to reveal any significant papers. We concluded that very much more psychoacoustical work needed to be done to cope with the reconciliation to a strongly structured pattern of knowledge performed routinely by players and listeners.

We proposed that an elaborate control structure governed the playing of instruments; this agreed with results from workers in other fields, but we could not fully test the structure before funds were exhausted.

9. CONCLUSIONS

It is not easy to draw conclusions from a discursive paper like the above. I hope that I have fulfilled my intention of showing you that not only is musical acoustics the oldest branch of acoustics, it is also one of the most stimulating and challenging. It stretches both ideas and people to their limits and brings together so many aspects of both science and art that it must surely be one of the high points of human endeavour.

10 SOME LITERATURE FROM THE UNIVERSITY OF SURREY GROUP

The presentation of this paper affords me an excellent opportunity to show my gratitude to my students and colleagues who worked so successfully on many aspects of musical acoustics. Here is a collection of some titles by group members.

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