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MENTAL MODELLING FOR GUITAR ACOUSTICS

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"The sciences do not try to explain, they hardly even try to interpret, they mainly make models."

John von Neumann

1. INTRODUCTION

In recent years, a number of very powerful tools have come into being to aid acoustic analysis, like for example laser interferometry and mathematical modelling using computer power. This data should be of use to modern instrument-makers, enabling them to direct their efforts more specifically and reduce research time for new improvements.

This seems to have happened in only a very limited way and often the pattern is rather that acousticians produce "pure research" and makers are generally guided by "tradition". The main reason for this may be that acousticians are not in a position to convert their data into physical shapes and sizes of material, while makers are often not able to penetrate the rather abstract nature of much of the raw data. As a result, makers are often left much like sea-farers of old, to navigate by following the known coast of "tradition" because it makes for a relatively safe and predictable journey.

Around the middle of 1985, when I was struggling with this situation, I became aware of one of the most important models of the modern world - Albert Einstein's tram. So the story goes, Einstein was on his way to work one day on the tram in Zurich and he asked himself what would happen to his perception of the world if the tram could accelerate to the speed of light. The culmination of this line of thought led to the theory of relativity. There are two very important conclusions to draw from this. Firstly, modelling is one of the most powerful ways we can liberate the power of our imaginations by converting abstractions into a form that we can manipulate in our heads. Secondly, the model does not need to be complicated in it's essentials to give very sophisticated results. In fact, some of the best modelling seems to result from asking questions with a rather child-like innocence : it is very easy for all of us to get lost in our sophistication. A degree of the cartoon-like of the humorous also lends itself to improving clarity and memory.

Scientists are very familiar with the process of modelling, while the humanities often place emphasis on the power of the word alone. The result is that even quite complicated science is often strewn with illustrations, while a book of literary criticism, for example, can run to hundreds of pages of uninterrupted text. I use the term "mental modelling" to distinguish it from physical modelling. Physical modelling is clearly a very direct way of getting at the nature of things, but it can be slow to set up experiments and there is significant room for error. "Mental modelling" on the other hand has no physical content : the model can be manipulated in the mind alone. Like an electronic spreadsheet, changes can be made almost instantly, and general patterns are made much more visible. I currently use around fifteen mental models, but more can be added as necessary.

This process of "mental modelling" provides a short-cut in assessing the most important aspects of guitar construction. It is possible to prioritise areas of potential change so that the most important constructional changes happen first. By narrowing down the areas, it is possible for a maker to maintain viable research, funded solely by the commercial income generated by selling instruments. Unlike the very precise and mathematical data from which the models derive, the models necessarily give information of a qualitative kind : they are by their nature generalisations. However, all forms of engineering ultimately rely on making real things and testing the physical reality. It is quite acceptable to use the model as a starting point for construction and then refine the physical guitar by a degree of trial and error.

The process of "improvement" is always fraught with difficulty, not least in terms of definition. In starting this line of research, I made two important assumptions. Firstly, is important for a guitar to achieve the maximum power, since it is generally a rather quiet instrument in comparison with orchestral instruments in general. Secondly, the final design should have a versatile and pleasing tone.

Energy is like a woodworm, burrowing invisibly through the fabric of the guitar. To build an instrument is simply to shape that energy in a systematic way. If the aim is to increase the audible power, there are only two options : either increase the available energy within the system, or alternatively, convert the available energy more efficiently into sound. In order to manipulate energy, it is essential to have a clear picture of what the energy is doing and where it is going. It can be very instructive to look at instrument design in terms of energy flow. The broad scheme is very simple, and needs little explanation. Fig 1. The five models that follow are examples of "mental modelling" and serve as attempts to visualise physical mechanisms along this path.

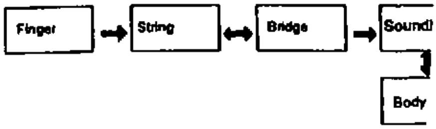


Fig 1. Energy path for a plucked string

2. THE LONGBOW.

This model illustrates how to maximise energy storage within a guitar.

The guitar is simpler than a violin in that the initial energy available is easy to calculate, and is stored in exactly the same way as a longbow. A string and a spring balance one another. The string is displaced to on side, then released. Just like the bow, you get one single "packet" of energy before you have to repeat the process. A fairly strong man can pull with a force of around 350 Newtons. If the distance of pull is around 0.6 m, the maximum muscular energy available energy would be around 0.6 x 350 = 210 joules, and in a perfect world all of this energy would be converted by the bow. In practice, things do not work out so well, as can be seen from one of the simplest forms of bow : the English longbow. The string is quite long, and when the bow is at rest, the tension is minimal. The energy stored in such a system can be represented by the a graph Fig 2. The energy stored in this drawn bow is around *half* of the available energy. It is possible to increase the power of a bow in two ways. Firstly, you could make the spring harder. The disadvantage here is that it quite rapidly it falls beyond the strength of a human being to pull against it. In terms of bow design this gave rise to the cross-bow, which was tensioned using a mechanical winch or lever. Guitar players would generally prefer not to use winches or hammers to displace guitar strings, so this option is somewhat limited!

There is a better option: you can pre-stress the system. In Ancient Greece, the bows were shorter and reverse curved in their relaxed state. As a result, it was necessary to flex the "palintonos" a considerable amount in order to fit the string, and such a bow was much more efficient in storing energy Fig 3. This was not an option in Northern Europe, because the palintonos used a wood/bone laminate to prevent breakage whereas in the damp British climate, the only glues available would have de-laminated very rapidly.

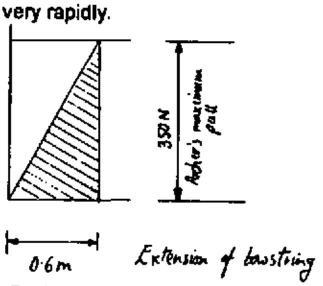


Fig 2. Energy stored in longbow
ABC = 105 joules

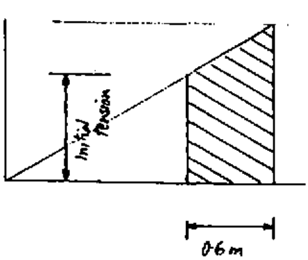


Fig 3. Energy stored in "palintonos"
ABCD = 170 joules

Conclusions:

2.1 The energy available for a single plucked note is very limited. Any increase in volume can only be achieved by better design.

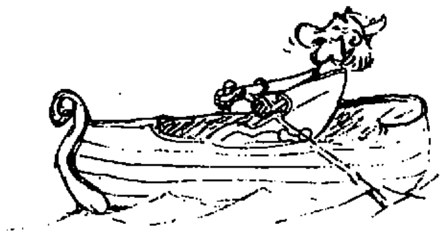
2.2 Harder springs (soundboards) and tougher strings offer very limited improvements.

2.3 Pre-stressing works by improving the nature of the spring. This offers many opportunities to the luthier, since both the top and the strings of a guitar are pre-stressed.

2.4 The palintonos was more efficient because of better technology in the form of better materials. Soundboard design could follow the same route by incorporating materials other than timber. This offers a number of interesting possibilities, such as incorporating metals or advanced composites into the soundboard.

3. THE PADDLE.

This model examines the relationship between soundboard area and acoustic energy output.



Having created a system to hold as much energy as possible, it is tempting to disperse it "efficiently". Various attempts in this direction have been made, the principle being to increase the live area of the soundboard. You need only look at an oarsman in a boat to realise how misleading this idea can be. Rowers do not make their boats go faster by using bigger paddles. If the area of the paddle becomes too great, the tail will wag the dog, and the rower will be catapulted from the boat! You row faster by increasing the rate of stroke : in other words, you drive a small area harder.

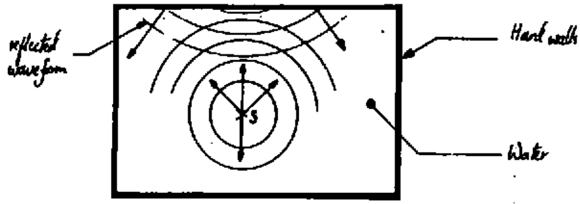
Conclusions

3.1 In a guitar the live soundboard has very little to do with the overall size or shape. For best results, it is necessary to physically define and confine the live soundboard.

3.2 The guitar and the violin define their paddle size in rather different ways, but in the case of the guitar, there is a particularly effective strategy, called "the swimming pool".

4. THE SWIMMING POOL.

This model illustrates how the vibration in a guitar top can be kept localised by defining a "live soundboard area".



Many of us, as children, will have thrown pebbles into the water and watched the ripples spread. In still conditions, the ripples will spread almost perfectly until they hit a boundary. In the case of a swimming pool, the boundary is very "hard"- the discontinuity is very abrupt. In such a situation, the energy of the wave will reflect back into the pool and not be lost to the surroundings. This effect is analogous to the propagation of sound waves in a guitar soundboard. It is very easy to build a "swimming pool" into a classical guitar, and there are significant gains, particularly in terms of sustain. It is interesting to note that this strategy is apparently also now used in the manufacture of some loudspeakers. The edge of the cone is reinforced by a heavy metal rim, and the efficiency improves accordingly. There are doubtless other applications as well.

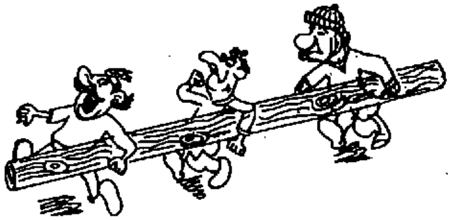
Conclusions

4.1 Many sound radiating areas suffer energy drain round the edges.

4.2 By giving the area a "hard" edge, energy will be reflected back into the system, resulting in greater efficiency.

5. THE BATTERING RAM.

This model illustrates the relationship between inertia and energy flow within a guitar.



Inertia is a difficult thing to model, because it is essentially a rather negative quality - resistance to change. However it is absolutely critical to our perception of the sound of a guitar, and a luthier must find a way to visualise the consequences. Instead of trying to picture resistance or absence, inertia can be visualised in terms of energy flow. Energy will flow along the easiest route, as you will find out if you stand in the way of the battering ram. However if the opposing force is sufficiently large, like a huge boulder, those carrying the ram will get more than they bargained for. The stone will have the greatest reluctance to move and like the edges of the swimming pool, push the energy back where it came from. Many of the qualities of sound that we appreciate from a plucked string are the direct consequence of how happily the string energy can flow into the top during the first moments. This we know as the "attack". It is vital that this initial energy is easily converted to sound. A responsive instrument fills out every note with a rich blend of overtones, like sunlight sparkling on the sea. In much the same intuitive way that we react to such natural phenomena, we perceive this as a very pleasing characteristic in guitars. By contrast, a high inertia instrument will be called "dull" or "dead". A better description might be "sleepy", since the problem is caused by delayed response time. Not only does the sluggishness affect the treble response, it also has a significant part to play in shaping the note envelope. It is no accident that much of the quality in the best microphones lies in the thinness of the diaphragm - in other words the crucial quality is the ease of movement (or lack of resistance to change).

Conclusions.

5.1 High inertia soundboards must be avoided.

5.2 Low inertia systems allow faster response, better response to overtones and better dynamic range.

5.3 It is possible to build lower mass soundboards. The situation is analogous in many ways to aircraft design, where engineers continually try to develop materials with better strength : weight ratios and many of these materials are commercially available. Also, by better understanding the forces acting on their structures, engineers can maximise the performance of these materials. While options are limited for makers working in wood alone, very good results can be achieved by incorporation high-modulus materials.

A completely different aspect of aircraft design leads to the final model of this paper.

6. "RELAXED STABILITY".

This model demonstrates how a degree of irregularity within the structure of a guitar can improve tonal characteristics.

Stability is generally considered desirable, and contains all sorts of positive connotations. Early aircraft were built to be stable and would quite happily turn into gliders if the power failed. The advantages are clear. However, at a certain point in the evolution of aircraft, fly-by -wire became a possibility : in other words the plane could be flown using computer control. Fly-by-wire opened up the possibility of creating unstable planes. At first sight, this may not seem hugely desirable and it may well have been difficult to get the pilots to fly in them. "Hey, Fred, we'd like you to take this wonderfully unstable plane up for a test flight...." To overcome such psychological hurdles, these planes exhibit the virtue of "relaxed stability". In fact, what they are doing is taking advantage of chaos, which is another word to send shivers down the spines of those who love order and predictability. Conventional wisdom tells us that chaos is definitely not good. Now, it is probably true that random is not good, but chaos is *different* and can offer tremendous advantages. A "typical" plane has large, flat wings and as a result is forced to move in long, slow curves. Relaxed stability offers manoeuvrability utterly impossible with a conventional design. The latest fighter aircraft force us to rethink our image of aerodynamics.

Guitars and violins were designed as perfectly symmetrical, Pythagorean creations. This was absolutely implicit in the world view of the craftsmen who made them : deep in their internal construction, instruments echoed the glory of creation. (It is not possible here to discuss fully the relationship between the renaissance interpretation of Pythagoras and instrument design. As well as the references below, the concept is discussed in my series of articles entitled "Quadrivium", shortly to be published). It rapidly became clear that not only was a Pythagorean instrument not achievable, it was also not desirable : totally symmetrical instruments, especially bowed instruments, would exhibit such excessive peaks and troughs in their frequency response that they would be very unpleasant to use. As a result, instruments moved ever further from such a rigid interpretation towards a situation of (to coin a phrase) "relaxed acoustics". It takes 10 seconds and a small piece of blue-tak to bring the Renaissance concept crashing down. Just place the blue-tak on a guitar string near the bridge but not on an obviously nodal point. The perfect harmony of the string is lost in an incoherent jumble of overtones. However, a great deal of good guitar design uses this property. The paradox within "relaxed acoustics" is that by allowing a guitar to freely form many frequencies, you also make it less likely to prefer only a few. It is probable that "rigid acoustics" will tend to package frequencies into narrowly focused bands of high energy, while "relaxed acoustics" will give a wider frequency spread which may also be to some extent self-limiting. This is particularly true with phenomena like turbulence in fluids, where vortices can absorb considerable energy by using the energy to propagate smaller and smaller "sub-vortices". There are doubtless many lines of research still to pursue in terms of instrument response and also noise control. It would be possible to shape the frequency response of instruments (or machinery) using either "rigid acoustics" or "relaxed acoustics". The former might lead to a small number of relatively intense peaks in output, while the latter might favour a wider spread of frequencies with lesser intensity.

Conclusions

1. Chaos is not necessarily bad, and can be exploited to advantage.

2. In guitars, the possible benefits include better balance and suppression of wolf notes.

3. The main constructional tools available to the maker seeking "relaxed acoustics" are irregular distribution of mass, irregular distribution of stiffness, and asymmetry of design.

7. CONCLUSIONS

"Mental modelling" provides a quick yet sophisticated way of directing research. As long as the model used is appropriate to the situation, the conclusions reached will be valid. Modelling is also a way of interpreting concepts and making them much more accessible to ordinary mortals. The proof of the pudding, as they say, lies in the eating : the process of modelling has enabled me over the last 10 years, to produce two series of high-performance concert guitars using composite reinforcement and very sophisticated energy control.

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