MATERIALS FOR MUSICAL INSTRUMENTS

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ABSTRACT: The relation between musical instruments and the materials from which they are made is discussed. In most cases the particular material used was originally dictated by availability or by technological necessity – only wood was suitable for the bodies of stringed instruments, only tin-lead alloys could be made into organ pipes, only bronze could be cast into bells – but this fact then determined the way in which these instruments evolved. Today the choice of materials is almost limitless, but often nothing better than the traditional materials has been found. The technological and, where appropriate, the acoustical basis for this situation is discussed.

1. INTRODUCTION

Those of you who play musical instruments will probably be convinced, if you have thought about it, that the materials from which they are made have an important effect upon their tone and general response. The top plates of violins and cellos, for example, are always made from sitka spruce and the backs from curly maple, and the special varnish used was one of the secrets of Stradivarius. Clarinets are made from African blackwood, recorders from apple or pear wood, and flutes from silver or, if you can afford it, gold. Trumpets and trombones are made from brass, plated with silver. Bells are made from bronze, and organ pipes from a tin-lead alloy.

In a spirit of inquiry, it makes sense to ask how well founded these traditions are. Why not a bassoon made from plastic, a flute of glass, or a violin of fibre-reinforced epoxy resin? Why not bells of aluminium and trumpets of stainless steel? Would it make any difference to the sound? In this short article I shall examine these questions in the light of both tradition and acoustics, and try to come to some appropriate conclusions.

2. STRINGED INSTRUMENTS

Vibrating strings are too thin to radiate any appreciable amount of acoustic energy, and it is therefore essential that they be coupled to some sort of radiating structure – a taut diaphragm in the case of a banjo, a flat soundboard in a harpsichord or piano, and a vented box in a violin or guitar. Since any structure like this will have its own mechanical resonances, and these depend both on shape and material, it is an inescapable conclusion that such details will affect the sound and response of the instrument. The important material parameters are the speed of vibrational waves, which is proportional to $(E/\rho)^{1/2}$ where E is the Young's modulus of elasticity of the material and r its density, the mechanical impedance which is proportional to $(E\rho)^{1/2}$, and the mechanical damping contributed by losses within the material itself. In wood, the Young's modulus is very different along the grain and across the grain, the ratio being as high as 20:1 for spruce and as low as 3:1 for some other woods, which means that, even if average properties are matched by some other material, the frequencies of the vibrational modes will be quite different. Because of this anisotropy, the wood in violin and guitar tops always has its grain running along the length of the instrument, and something similar is built into pianos and harpsichords.

The effect of these body modes is clearly heard in the sound of a violin or cello – they are what makes one instrument different from another and one note different from another – and they show up clearly in the spectrum, as can be seen if a cellist bows a steady low note and we examine the sound with a spectrum analyser. For a featureless resonator the bowed-string spectrum should decline at a steady 6dB/octave, but a real cello body will introduce peaks and valleys of as much as 20dB. The internal damping of the wood has a rather different effect, since it becomes most important at high frequencies, and again differs considerably from one timber to another, and even from one tree to another of the same timber. If the high-frequency damping losses are very low, then the sound will be bright and clear, while if they are larger the sound will be smooth and mellow.

Can these properties of wood be duplicated by any other material? The answer is that perhaps they can. The elastic anisotropy can be introduced by using fibre-reinforced material, which has, indeed, a structure quite like that of wood. The density can be matched fairly well, and adjustments made by small changes in the plate thickness. Internal damping can similarly be controlled by adjustments in composition. All these things have been done with moderate success as a sort of scientific tour de force, but while suitable timber can be procured it is difficult to match its suitability and appearance for making traditional stringed instruments.

Of course the strings of the instrument are important too, but we return to consider these later.

3. ORGAN PIPES

Pipe organs have a history going back 2000 years, and organ pipes have changed little for more than a millennium. Why is the traditional material a lead-tin alloy similar to pewter, and why is it still used? How does it effect the sound quality?

To answer these questions we need to examine how organ pipes are made, since this is still the same today as it was 1000 years ago. Pipes of many different lengths and diameters have to be made for each pipe rank, and the first step is to produce the metal sheet. This is done by melting suitable metal in a wooden box with an exit slit at the foot of one side. The box is then slid along a flat stone table covered with cloth and this casts a uniform metal sheet 1 to 2mm in thickness, perhaps 500mm wide, and 5 to 10 m long. This sheet is rolled up and used to make the pipes. We can see immediately that the choice of suitable metals is very limited. In the middle ages all that were available were lead, tin, copper, zinc, precious metals such as silver and gold, and a little iron. Copper-tin alloys produced hard bronze for armour, copper-zinc produced brass for ornaments, and tin-zinc or tin-lead produced low-melting pewter alloys. Silver and gold were too expensive to use commonly, and iron was too difficult to work. Of these, then, only the pewter alloys were suitable for low-temperature casting, and the lead-tin eutectic at about 62% tin with melting point 183°C was ideal. It was strong enough to form self-supporting pipes, provided they were not too large – impurities in the metals helped with this – and soft enough that the pipes could be easily fabricated and adjusted. The only option that was reasonably available to the organ builder was to vary the composition slightly.

So does the alloy composition – or even the choice of metal, since with modern techniques we can now use any metal we choose – affect the tone of the pipe? Most organ builders believe the answer to this question is "Yes", but most acousticians disagree. Certainly the walls of the pipe do vibrate a little, particularly during the onset transient of the sound, though they are so stiff relative to the air column that their vibration level is around 40dB below the air motion. They may therefore influence the relative levels of harmonics in the sound by 1dB or so, and may contribute inharmonic partials at a very low level during the onset transient. But is this influenced by the pipe material? The answer is certainly that the main variable that could influence these wall effects is not the pipe material but the wall thickness.

Most organs do, of course, also have wooden pipes, particularly for flute stops, and these do sound different from metal pipes. Is this the effect of wall material? Once again, the answer is "No". What is different about a wooden pipe, apart from scaling variables such as pipe diameter, is the geometry of the mouth – not particularly because the pipe is square in section, but rather because the wooden walls are typically about 20mm thick, compared with 1 to 2mm for metal pipes. If, however, large bass pipes were made from thin plywood, then we would indeed be able to hear the vibrations of the pipe walls, but no organ builder would contemplate this!

4. WOODWIND INSTRUMENTS

The conclusions reached above for organ pipes apply also to woodwind instruments, though their history is very different. Most woodwinds were initially made from hollow "found" objects with little modification. Examples are the panpipes made from lengths of bamboo with one end open and the other sealed by a septum in the plant stem, the gemshorn, made for a goat's horn, and then various flutes made from bamboo or cane with added finger holes, such as the Japanese shakuhachi and the flutes of South America.

As the instruments were refined, the obvious choice of material was wood, since it could be easily drilled and turned on a simple lathe. In this case, again, the initial requirement was for workability – a fine smooth grain that would take a polished finish and resist the damaging influence of condensation from the player's breath which was liable to cause cracking. Fruit woods such as apple and pear were good for this purpose, and later rainforest timbers such as ebony or blackwood from Africa. Appearance is also important, though many instruments are actually stained and oiled or varnished – bassoons made of white maple and stained red or brown are a typical example.

The only properties of the wood that are of acoustic significance in woodwinds are the smoothness and porosity of the bore and the sharpness with which the edges of the tone holes can be cut. The thickness of the walls is, of course, also important, but only from a geometrical viewpoint. The importance of surface finish arises from its relation to viscous losses from the vibrating air column and, since the viscous boundary layer is typically only about 0.1mm in thickness, structure down to this level is relevant. Thermal conductivity in the wall material is only of borderline significance, because almost any solid has a conductivity that is high compared with that of air, but if anything it argues for walls with low conductivity.

In all cases the bore of the instrument is rather small, rarely exceeding 20mm except in the case of bassoons, and the walls, if the instrument is made of wood, are at least 5mm thick so that the tube is quite rigid. Wall vibrations, even at the level encountered in organ pipes, scarcely come into consideration. Good quality plastic is clearly a possible substitute for wood in this case, and has the advantage of durability, though lacking the good appearance of wood. The often poor reputation of instruments made from plastic rather than wood arises from the fact that they are usually cheap student instruments from large makers, though some plastic-bodied clarinets of excellent quality are made. An exception occurs in the case of bassoons, which are never inexpensive. All top-quality bassoons have the upper half of their bore lined with plastic or with metal to overcome the ravages of breath condensation, and at least one top quality maker also produces expensive bassoons made entirely from plastic material.

When we come to flutes, the situation is different, perhaps because of their relationship to flue organ pipes. Until the middle nineteenth century, flutes were made of wood like other instruments, with a few exceptions made from ivory. About 150 years ago, however, the German silversmith and flute player Theobald Boehm completely redesigned the flute. His initial modification involved making the tone holes much larger and using a system of coupled padded keys to close them. This flute, like its predecessors, had a cylindrical head joint and tapering main bore. Boehm's second modification to the flute gave it a tapered head joint and a cylindrical body, with tone holes nearly as wide as the body diameter and closed by padded keys. Boehm's original flutes were still of wood, but he soon changed the material to thin-walled silver tubing, with the tone holes and embouchure hole built up to mimic the thickness of the original wood. This design is still used today with very little alteration.

If we ask whether a modern Boehm-pattern silver flute sounds different from an early eighteenth century wooden flute or from an Irish folk instrument, then the answer is certainly "Yes", but the reason does not lie with the change from wood to silver, but principally with the change from small finger holes to large tone holes closed by pads. This modification raises the efficiency in the upper part of the spectrum and gives the instruments a much brighter and more open sound. The change from a tapered to a cylindrical bore has a smaller effect, and indeed orchestral piccolo players generally prefer wooden instruments with the old tapered bore, while band players use cylindrical metal piccolos. Another minor effect of the change from wood to metal relates to the smoothness of the bore and the sharpness of the edges of the tone holes, both of which have a small but strictly geometrical effect on the sound.

Silver (actually sterling silver, which contains about 7.5% of copper and is much harder than the pure metal) was Boehm's material of choice for the flute, again by reason of the ease with which it can be worked and also its fine appearance. From there it is possible to go in one of two directions: either to the use of gold (usually a 12 to 18 carat alloy with 30 to 50% of added copper, silver or nickel) or even platinum, or to the use of cheap metals that are later plated. Both courses have been followed, but at opposite ends of the price spectrum. Gold flutes are superior to flutes made of silver in two ways: firstly the gold is nearly free from tarnish, which gives the flute a better appearance, and secondly a gold flute is always made by a top craftsman in a flute company and is therefore an example of its best instruments. "If gold is good, then platinum should be better," and some fine flutes now have the tubing made from this metal, though the keys are usually of white gold. There is even a well-known solo flute piece called Density 21.5 written by Edgar Varese for the platinum flute! Most of the superiority is, however, illusory, and there is more difference between silver flutes by different makers than between a gold and a silver flute by the same craftsman. There is no way in which the properties of the metal itself can influence the sound, except indirectly through the psychology of the player!

Flutes made of cheap alloys, generally cupro-nickel, and then plated with silver, on the other hand, are generally mass-produced for student use. Their tone again can be excellent and their mechanism reliable, but they lack the refinement that comes from hand-work on the delicate edges of the embouchure hole, and the silver plating is sometimes not very durable.

The family of saxophones, developed by Adolphe Sax in Brussels in the middle nineteenth century, also belongs to the woodwind family, though they are always made from metal, usually brass. Again the choice of material was dictated by manufacturing requirements because of the large flaring bore, but the typical sound of a saxophone can also be heard in the Hungarian tarogato, which has a similar bore shape but is straight and made from wood. It is this wide conical bore and the geometry of the mouthpiece and reed that are responsible for the tone quality.

5. BRASS INSTRUMENTS

In this category we include all forms of lip-blown instruments, from the didjeridu of the Australian aboriginal people and the conch shell of Egypt, through the trumpets of the Roman legions to the refined trumpets and trombones of today. Setting aside the didjeridu and the conch shell, which are essentially "found" instruments, the choice of construction materials was limited by the nature of the instruments themselves. Wood was generally out of the question because of the complicated geometry of the instruments, but there were a few exceptions among the conical lip-blown instruments with finger holes, such as the cornett and the serpent. Cornetts were generally made of wood, and serpents either of wood or of varnished papier-maché covered with leather. Trumpets and trombones (originally sackbuts), however, were always made of metal. The tin-lead alloys were too soft for this purpose, and bronze too hard, so the copper-zinc alloy brass was the material of choice, and remains so. Brass can be easily formed into tubes and these, even now, are bent to final shape by filling them with water and freezing it to ice, to prevent tube collapse during the forming operation. Brass sheet or wider tube can also be formed into sections for the flaring horn by spinning it against a former in a lathe. In all cases the sound of the instrument is determined by the detailed profile of the bore and the exact proportions of the mouthpiece cup.

Once again, the stiffness of the walls of the instrument is so great that they can contribute little or nothing to the sound production. The exception is perhaps the flaring bell of instruments such as French horns but, once again, the effect is controlled not by material but by wall thickness. Only if one goes so far as to make the flaring horn of the instrument from some sort of rubber-like material can one measure any significant acoustic effects.

6. BELLS, GONGS AND CYMBALS

When we come to discuss instruments that are impulsively excited and act to radiate their own sound – idiophones in the terminology of musicologists – we find a situation in which construction materials can have a significant influence on sound quality. In Western cultures, the most notable of such instruments is the bell, as found in churches and in carillons and, in some countries such as the United States, in handbell choirs.

Western church bells and their relatives are all tuned to nearly a common pattern that is dictated by their general shape. As many as six of the lowest vibrational modes of the bell are tuned, initially in the design and finally by turning material off the inside of the bell on a vertical lathe, so that their frequencies are in harmonic relationship – that is, they are integer multiples of a common fundamental. The one exception to this simple rule is the third mode or tierce, which is tuned to a minor third (6:5) in this progression. It is this mode that gives western church bells their characteristic sound, and a bell designed to have a major third for this mode (which requires a peculiar bulgy shape) sounds entirely different. Eastern European and Asian bells, which all have shapes quite different from those of Western bells, have very different sounds.

Bells have always been made by casting metal, and again this limited the options available to medieval bell-founders. Since bells have metal clappers, the tin-lead alloys were too soft, and the options were essentially brass (copper-zinc) or bronze (copper-tin). Bronze was found to be harder and to give better sound and has been used nearly universally. The casting technology was also well advanced, since it was essentially the same as used for casting cannon!

Since the shape of the bell is fixed by the tuning requirements, its size for a given frequency is determined by the velocity of sound, which is proportional to $(E/\rho)^{1/2}$ as discussed before. If the sound velocity is low, then the bell will be relatively small, which means that it will not be as loud but will sustain its tone longer, although this latter statement depends upon the balance between internal losses in the material and radiation losses. Both are actually of comparable importance in bronze.

If bells are made from cast iron, which has the benefit of being a good deal cheaper than bronze, then, because the sound velocity in cast iron is about 30% greater than in bronze, the bell must be made larger by the same amount for a given pitch. The situation is even more extreme in aluminium, where the sound velocity is 50% greater than in bronze. These larger bells can produce a louder sound, if appropriately struck, but radiate their sound away more rapidly. Aluminium is favoured, however, for large handbells.

Gongs and cymbals differ from bells in that their walls are thinner, so that their sound often exhibits nonlinear effects. Some of them are cast and some either spun or beaten from an initial flat plate. Bronze and brass are both suitable for this purpose, and work harden to give strong structures that will resist the impact of the hammer or stick used to excite the instrument. Hardness, workability and low internal losses are the main requirements for such gong and cymbal materials, though internal losses are generally less important since losses to the air tend to dominate.

7. OTHER PERCUSSION INSTRUMENTS

The variety of percussion instruments used in various parts of the world is very large. Apart from the bells, gongs and cymbals discussed above, we can recognise other "tuned idiophones" such as marimbas and xylophones, untuned idiophones such as Aboriginal music sticks and log drums, and then the whole family of "membranophones" which we ordinarily call drums.

In the tuned instruments the vibrating element is usually a wooden or metal bar, sometimes shaped in thickness to tune its second mode to a harmonic of the fundamental. Apart from necessary mechanical hardness and durability, the main acoustic features desired are high density, so that considerably vibrational energy can be stored, and low internal losses, so that the sound rings for a relatively long time. Many metals are suitable for the metal instruments, and the low damping of metals at high frequencies gives a bright tone. Instruments with wooden bars, on the other hand, have a mellow tone and shorter ring time because of the greater internal losses of wood, particularly at high frequencies. Fine-grained rainforest hardwoods are ideal for such instruments, and are actually nearly the same woods sought for woodwinds. Wood anisotropy is not important in these instruments, for the bars bend only across their narrow dimension, so that synthetic materials could be used, provided they have adequate hardness and density and that their internal damping has a frequency dependence similar to that of wood.

The membranes of drums were traditionally made from animal skins, for want of any alternative, and these suffered from uneven thickness, only modest strength, and sensitivity to both temperature and humidity. Synthetic polymers overcome these problems and are used nearly universally in modern instruments. The damping of a drumhead is almost entirely caused by viscous losses to the air and by sound radiation, so that the requirements on the membrane are almost purely mechanical.

8. ACOUSTIC LOSSES IN MATERIALS

Since minimising internal losses is important in all idiophones, and the frequency dependence of internal losses influences the response of the bodies of stringed instruments, it is interesting to see how these losses arise. There are essentially just two processes involved – atomic or molecular rearrangement, and thermal conductivity – and their relative importance varies from material to material.

In natural materials such as wood, and also in plastics, the thermal conductivity is low and the material is rather soft. Thermal conductivity losses can therefore be ignored compared with losses from molecular rearrangement. In wood, some of this rearrangement may be associated with water absorbed within the structure, but the dominant mechanism is the rearrangement of weak inter-molecular bonds. Some of these rearrangements are slow, leading to gradual distortion of the material, but those that vary over only intermolecular distances may have relaxation times of the order of a millisecond, leading to loss peaks within the high audio range. It is these losses, generally characteristic of the material but perhaps even varying from specimen to specimen, that are important in choosing materials for stringed instruments and percussion idiophones. The instruments tend to be a little "temperamental" because the magnitude and frequency of the internal loss peaks depend upon both temperature and absorbed atmospheric moisture.

Metals can also suffer slow creep and atomic rearrangement, generally described in terms of the movement of dislocations, particularly if they have low melting point, as in the case of tin and lead. Quite small quantities of other metals added to form an alloy can, however, pin these dislocations and harden the metal. Pure metals are therefore very little used in any application requiring mechanical strength and stability. Among the harder alloys used for musical instruments, the main cause of internal loss is by thermal conductivity, the heat flowing between parts of the metal that are compressed and those that are stretched during a cycle of the vibration. The frequency at which these losses are large generally depends upon the dimensions of the vibrating element. This frequency is low for large metal objects such as bells, but may range up to several kilohertz in the case of thin metal wires.

9. STRINGS AND WIRES

We return now to consider the other essential component of a stringed instrument – the strings. In early times these were made from biological sources such as the tendons or twisted gut of animals, but now these materials have been largely superseded by the use of synthetic plastics, such as nylon, or by metals.

In a bowed-string instrument there is a steady source of energy in the moving bow, and the main requirement placed upon the strings are that they support adequate tension stress σ to give an appropriate vibrational frequency $(\sigma/\rho)^{1/2}/2L$, where ρ is the density of the string material and L the string length. Strings of gut, or later of twisted nylon, were generally adequate for this purpose, though over the past century or so the lower-pitched strings have been overwound with metal to give extra mass, and the highest pitched strings replaced with metal to give added brilliance. Indeed, twisted strings, whether of gut or of nylon, tend to have large internal losses at high frequencies because of dry friction between the separate strands.

In plucked or hammered string instruments, internal losses in the strings are of great importance, because the string must store all the mechanical energy from the exciting impulse. This argues for the use of monofilament nylon strings or of solid metal strings to reduce internal frictional losses. The metal gives lower damping at high frequencies, and higher initial energy storage because of its greater material density. A change in string material from gut or nylon to metal, as happens in the transition from a classical to a popular guitar, changes the character of the instrument by increasing the energy content at high frequencies, and may be resisted for aesthetic reasons because the sound becomes too bright or even "hard" in addition to being louder.

The harpsichord and the piano, however, were both developed after metal wires became available, so that their natural sound is based upon metal, although the plucking and hammering mechanism is non-metallic. Only in the clavichord is the exciting tangent of metal, but the sound is in any case very gentle. While piano stringing is universally of steel, though the lower strings are overwrapped with copper or brass for added mass without excessive stiffness, harpsichord stringing is traditionally with iron or steel in the treble and solid brass in the bass. This is in part because the shorter-than-proportional length of these strings requires reduced tension, and the added density of brass counteracts this to some extent, thereby reducing inharmonicity due to string stiffness. There are also more subtle effects because of the different thermal loss frequency of the brass strings. The piano avoids excessive brightness, while introducing a change in sound quality from mellow to bright with increasingly vigorous playing, through the use of graded felt in its hammers

10. CONCLUSION

Throughout history there has been a close connection between musical instruments and the materials from which they are made. Some of this connection is aesthetic – what could be more repulsive than a harpsichord covered in Laminex or a violin made from painted tin-plate? – but much of it has shaped the whole evolution of the instrument concerned. Bells are a prime example, since they could hardly have been developed without knowledge of the casting of bronze, a craft also of importance for the making of cannon. Woodwind instruments required initially the existence of natural hollow plant stems, and then the availability of dimensionally stable but easily worked wood. Pipe organs depended upon the discovery and ready availability of the stable, soft and low-melting alloys of tin and lead, hardened with a little antimony. Brass instrument development relied upon readily rolled and bent brass and upon the techniques of soldering tube and spinning horns.

Over the years a great mystique has grown up around the use of some of these materials. Some of the mystique is supported by modern acoustics – there are indeed good and poor timbers for stringed instruments, and even good and poor trees; there are appropriate and inappropriate metals for casting bells and gongs, and no superior modern substitutes have been found for many traditional materials such as tin-lead alloys for organ pipes and brass tubing for trumpets. But some of the mystique is unfounded, or at least wrongly founded – gold is excellent for making flutes, but not because it produces a superior sound; cocus wood is excellent for oboes and maple for bassoons, but the reasons are mechanical rather than acoustic.

But progress in understanding thrives on controversy, and our knowledge of what is important and what is possible continues to expand.

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