Investigating the Acoustic Properties of Materials with Tuning Forks.

Z. Laughlin, F. Naumann, and M. A. Miodownik

Abstract—**Sounds and their cultural resonances are built upon material relationships that produce specific acoustic effects and connotations. The aesthetic qualities and scientific properties of sounds and our perception of them, is key to our understanding of the world around us, and the relationships we build with materials.**

To test the comparative acoustic properties of different materials we made a set of tuning forks of identical shape from varying materials. The three principle factors that influence the production of sound by a tuning fork are the shape, the density and the elastic modulus of the material from which the fork is made. The qualities of the sound produced by a tuning fork are experienced as a note of a specific pitch (frequency), with a particular brightness (a combinatory factor of duration and amplitude). Ashby and Johnson plotted the theoretical relationship between the acoustic pitch and the acoustic brightness of a wide range of materials in their multidimensional scaling (MDS) map of acoustic properties [1]. We used the tuning forks to investigate the effects of materiality on sound, with exact frequency produced by each fork measured and the shift in pitch attributed to the change in materials. The tuning forks were also played and assessed by musicians whose perceptions of pitch and brightness were judged against those of the MDS.

In terms of the frequencies produced by the tuning forks, we found broad agreement with the theoretical predictions, apart from a few anomalies. We also found that judgements of pitch made by musicians were also in agreement with the frequency measurements. The greatest surprise was that the pitch of disparate materials could be very similar, whilst the brightness of the note varies dramatically, due to variations in materials coefficient of loss.

Index Terms—**materials, acoustics, tuning forks.**

I. INTRODUCTION

FROM a purely physical perspective, two principle factors influence the sound of a tuning fork: the shape of the fork, and the material from which the fork is made. These factors affect both the pitch of the note, and its quality. The pitch of a tuning fork can be expressed through a simple equation:

$$f \propto \frac{1}{l^2}\sqrt{\frac{AE}{\rho}}, \quad (1)$$

where f is the frequency of the fork, A is the cross-sectional area of the tuning fork, l is the length of the forks tines, E is the elastic modulus of the material, and ρ is the density of the material [3]. As equation 1 demonstrates, an increase in the length, l, of the fork tines increases the amount of a material that needs to oscillate in order to produce the sound wave.

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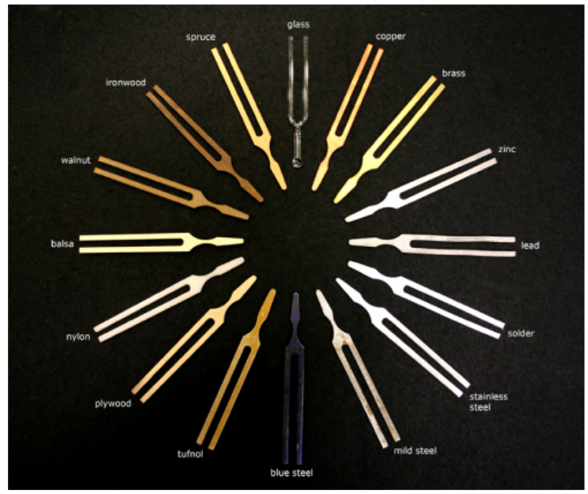

Fig. 1. The set of tuning forks, identical in size and shape, from the following materials; mild steel, stainless steel, zinc, copper, brass, solder, lead, nylon, acrylic, glass, spruce, walnut, obeche, ironwood, bass, plywood and balsa.

As a result, the tines move more slowly, with each oscillation compressing the air over a greater period of time, generating waves of lower frequency. This lower frequency is heard as a tone of a lower pitch, or in other words, a deeper note is produced. Therefore, a standard set of tuning forks produce a scale of notes by offering a range of sizes, where the shorter forks produce the higher frequency notes and the longer forks make the lower frequency notes. In order to fine tune the tone of an individual fork to the desired note, material is removed from either the ends of the tines in order to shorten them by a tiny amount, or from the base of the forks to fractionally lengthen them.

Equation 1 also shows that changing the density or elastic modulus of the tuning fork material, will also change the pitch of the note produced. This is the origin of the characteristic sound of a material.

Acoustic brightness is another acoustic property of materials which defines how much a material damps vibrations. Bright materials, like brass, emit sounds for a long time, while the reverse is true of dull materials, like foams, which absorb sound strongly. The property is typically quantified experimentally by measuring a material's coefficient of loss, which is a measure of how strongly vibrations are absorbed by a material.

Ashby and Johnson have combined acoustic pitch and acoustic brightness into a materials selections tool for acoustic properties by plotting the theoretical relationship between the acoustic pitch and the acoustic brightness of a wide range of materials in their multidimensional scaling (MDS) map of acoustic properties [1]. The map shows the distribution of different types of materials in relation to their acoustic properties: materials close together on the map are predicted to behave similarly acoustically even if their are from a different family material such as metals, ceramics, natural materials and polymers. It is interesting to note that according to this MDS, the pitch of steel is within the range of pitches attributed to balsa wood, differentiated simply by the difference in acoustic brightness. With this in mind, the MDS offers a range of interesting material relationships that warrant closer examination in the form of rendering the material actual in the form of a tuning fork. This interesting approach has never been experimentally examined, neither from a physical perspective nor from a experiential perspective of human acoustic perception. To carry out such an analysis has been the aim of the investigation reported in this paper. To this end we created a set of tuning forks that keep form constant and employ materiality as the variable, enabling the exploration of the effect of different materials on acoustic pitch and acoustic brightness. Our aim was to establish, firstly whether our experimentally measured MDS diagram matches that predicted by Ashby and Johnson; and secondly to investigate whether musicians perception of the quality and pitch of the sound of the tuning forks matched classifications predicted by theory and measured by experiment.

II. Materials and Methods

A. Manufacture

Two John Walker 440Hz steel tuning forks, of equal dimensions but different surface treatments, were purchased: one fork had a passivated iron oxide coating produced by the bluing process, whilst the other was gold plated. We then commissioned the making of other tuning forks of the same dimensions from the following materials; uncoated mild steel, stainless steel, zinc, copper, brass, solder, lead, nylon, acrylic, glass (with cylindrical tines), spruce, walnut, obeche, ironwood, bass, plywood and balsa, see figure 1.

B. Playing and Recording: Quantitative Methods

In order to obtain consistent repeatable data the following experimental set up was created. A wooden vice was secured to a laboratory bench top and used to hold the tuning fork tightly in place. No resonant bodies were used to amplify the signal [2], [4], instead a microphone that rested upon a foam base was mounted 1 cm from tines, in a stand at 90° to the face of the fork. The output of the microphone was connected directly to the sound card of a computer. Each fork was played by pinching the tines together with forefinger and thumb then releasing them simultaneously (we checked whether the style of pinching or the initial amplitude of the pinch affected the recorded pitch or dampening coefficient and found that it had no effect except where the amplitude was so small that signal to noise ratio became large).

MATLAB, the interactive environment for algorithm development, data visualization, data analysis, and numeric computation [5], was used to digitally record and analyse the data. The standard MATLAB function, 'wavrecord' was used to interface the acoustic signal and a combination of MATLAB and custom tools were used for signal processing, further analysis of the input, to generate amplitude versus time plots, and to generate power spectra. Each fork recorded a number of times to gain four noise free data sets using a sample rate of 11,025 Hz. Figure 2 shows an example of the data obtained, a plot of the amplitude of the wave function versus time. Note that the amplitude decays over time from the moment that the tuning fork is initially excited, denoted as $t = 0$. The resonant frequency of each tuning fork was measured by extracting the peak to peak time interval of the wave function. To measure the coefficient of loss we assumed that the equation of motion of the tuning fork tines was given by:

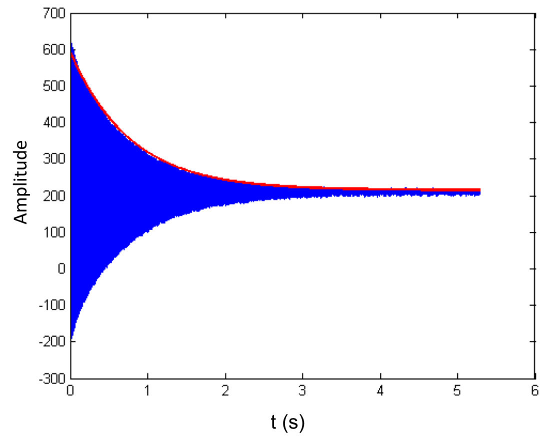

Fig. 2. A plot of amplitude versus time for the gold plated steel tuning fork. The red line indicates an exponential fit to the maximum amplitude.

$$m\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + kx = 0, \quad (2)$$

where m is the mass of the tuning fork tine, x is the displacement, t is time, γ is a hydrodynamic damping coefficient, and k is an internal (material) damping coefficient [2], [4]. Solving this equation assuming symmetric and real roots gives:

$$x = C_o e^{-bt}, \quad (3)$$

where C_o, b are constants. If b is positive, the equation describes an exponential decay of the wave amplitude, and b can be used as a measure of the coefficient of loss (related, though not through an explicit expression, to the Q factor [4]). The red line on figure 2 shows an exponential curve fitted to the data and shows good agreement with the basic analysis of equations 2 and 3, and is typical of our results. The sampling rate was shown not to affect the measured value of b (data not shown), nor was it dependent on the initial amplitude of the oscillation (data not shown), C_o, thus giving further credence to the notion that b is a measure of an intrinsic materials property.

C. Playing and Experiencing: Qualitative Methods

Ten participants were invited to interrogate the tuning forks individually and their reflection of the encounter recorded.

(The backgrounds of these individuals were either musical or performance related, all had good knowledge and experience of the playing of musical instruments). In every encounter the tuning forks were laid out as a set, side by side. Initially, the forks were appraised visually and their status as tuning forks recognised. The person was then invited to play each of the forks and asked to describe the experience. The playing of a tuning fork was characterised by the firm holding of the fork at the base, the striking of the tines against a hard surface and then the free oscillations of the tines. Once the tines are oscillating, the vibrations this produces could be both heard and felt by the hand grasping the fork. In order to hear more clearly the sound produced by the fork, players sometimes held the fork up to their ear or, after the instance of striking, placed the base of the fork handle onto a wood surface that then acts as a sounding board, amplifying the sound produced. In the case of quiet forks, an alternative method of playing was used: firstly the base of the fork is held firmly in one hand and brought it close to the ear, then the participant placed their thumb and forefinger in opposition at the end of the tines, pinched the tines together and then sharply released the pinch, effectively flicking the tines and provoking them to vibrate. The participants were free to play as few or as many of the forks as they wished, in any order they preferred.

III. Results

A. Quantitative

Figure 3 shows some of the results of the quantitative analysis. It is a plot of acoustic brightness (b) versus acoustic pitch (f). It shows there is a range of two orders of magnitude between the brightest metals (gold plated steel) and the dullest woods (bass). But despite this, some of the woods have a pitch that is higher than the metals, for instance walnut is higher than brass and copper. Some of the metals such zinc and lead, and lead-tin solder were so dull that we could not record an reproducible accurate signal from them and so are at present excluded from the plot. Similarly, nylon is not present either. The glass tuning fork was not produced in the exactly the same geometry as the others (it has cylindrical tines) and so is at present excluded from the plot. We expect to rectify these omissions in the near future, as well as adding further materials.

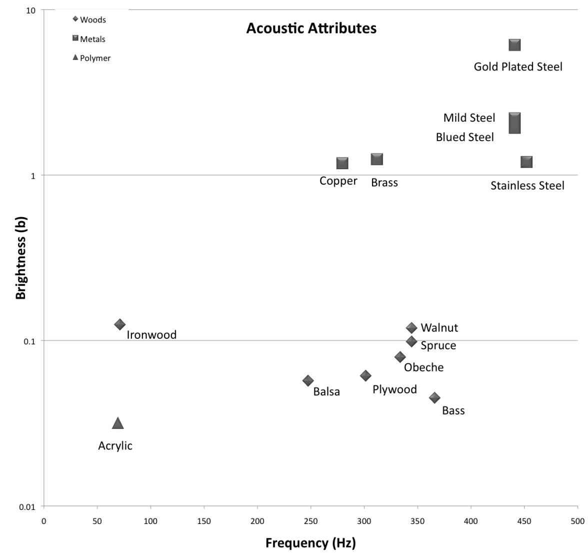

Fig. 3. A plot of acoustic brightness versus acoustic pitch measured for a range of tuning forks of identical shape made from different materials.

B. Experiential

The blued steel fork was clearly heard by all the participants when the vibrating fork was lifted to their ear and made an equally loud sound when placed on a sounding board. Many participants felt that the note was sustained for a fairly long time and regarded it as bright and strong with the vibrations readily felt in the hand of all participants. The sound produced by the mild steel tuning fork was found by the majority of participants to be identical to that of the original blued steel fork, with no perceivable shift in the tone produced. The frequency produced by the gold plated steel fork was reported as practically identical in pitch to the blued and mild steel forks, but one participant was particular in his efforts to describe differences in the tonal qualities of the sound, feeling it to be brighter. The stainless steel tuning fork was experienced as producing a note of a slightly higher pitch and less duration. Many participants required multiple playing of the stainless steel for to confirm their opinion of its standing in relation to the other steel forks.

In contrast to all of the steel forks, the lead tuning fork made no audible sound when played but slow vibrations were felt in the hand by participants. The tines of the fork were readily plastically deformed when struck, no matter how much care was taken to play the fork delicately. The zinc tuning fork also made no audible sound and the tines were observed to plastically deform when struck by a participant. Minimal vibrations of extremely short duration were felt in the hand and commented upon by a minority of participants (After prolonged playing, the base of one of the fork tines displays signs of metal fatigue). This was also the case for the lead-tin solder fork.

Participants reported that the tuning fork made from copper emitted a tone of low pitch, quite volume, and short duration. The vibrations produced were felt in the hand of the participants, though the intensity of the sensation was deemed less than that of the blued steel fork. In order to hear the sound produced by the fork, the participants found that they must hold it close to their ear and take care not to touch the tines against any surrounding hair for this distorted and dampened the already short lived sound. In contrast the brass tuning fork was perceived to give a loud bright tone of a pitch higher than copper but lower than the blued steel fork. The note was clearly audible when held some distance form the ear and made a clear and sustained sound. The duration of the note produced was agreed by all participants to be longer than any other of the forks and the vibrations continue to be felt even after they are no longer detectible audibly.

The glass tuning fork was approached for playing with some hesitation and trepidation. Participants feared that the force needed to induce the oscillation of the tines would cause the fork to shatter. With this in mind, participants tentatively tapped the tines against a hard surface to induce vibrations with what they judge to be the minimum of required force. On holding the tuning fork up to their ear all participants clearly heard a quiet but bright and high pitched tone being produced and felt the vibrations of the fork in their hand. The note sustained for a reasonable period of time and was deemed to be higher in pitch than any other of the forks.

When played, the spruce tuning fork produced no audible sound, but rather a singular note of no duration was produced when the fork is played by pinching. At this instant a note can be heard and the vibrations produced felt in the hand of the visitor. When played in this fashion, the sound produced was deemed by participants to be higher in pitch than the brass fork. The other tuning forks made from wood also produced audible notes when played using the pinch technique. The range of notes produced was regarded as surprising by all participants and not inconsiderable, with obeche, walnut and bass all producing tones higher than spruce, closer to the blued steel, whilst plywood, balsa and iron wood all produced notes lower than spruce with both balsa and plywood emitting tones perceived as similar to the copper fork.

On playing, the nylon tuning fork was felt to produce no sound when struck in the conventional manner but when played by the visitor using the pinch technique, a few participants reported that it produced a very low note of no duration. Those that felt able to judge the quality of the sound produced reported that they found the nylon fork produced the lowest note of all the tuning forks. Difficulties in perceiving any sound produced by the fork was also experienced when participants played the acrylic fork. On occasions when a tone was perceived it was regarded as fractionally higher than the tone of the nylon fork but identical in its dull thudding quality.

IV. Discussion

We have reported preliminary work to measure quantitative acoustic properties of materials and compare these to those experienced by music practitioners. From a quantitative view it is interesting to note that gold plating appears to have such a pronounced effect of the brightness of the steel tuning fork while not affecting its frequency. The copper tuning fork appears to have a similar acoustic brightness to brass and stainless steel, despite sounding very dull to the human ear. In contrast, the human and hand is able to differentiate between the different steels quite accurately, and also can appreciate the acoustic properties of the duller metals better than our current measurement set-up. The other interesting point to note is the extremely wide range of frequencies in the wood class of materials, which stretches from the low frequencies characterised by polymers all the way up to the high frequencies of brass alloys.

Acknowledgment

The authors wish to thank master craftsman Rex Garrod for his considerable skills and expertise when making the tuning forks.

The authors also grateful for the support of King's College London, Goldsmith's College London, The National Endowment for Science, Technology and the Arts (NESTA), Engineering and Physical Sciences Research Council (EPSRC), London Centre for Arts and Cultural Enterprise (LCACE), The Calouste Gulbenkian Foundation and The Leverhulme Foundation.

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