TIMBRAL STRUCTURES FOR COMPUTER MUSIC

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1. Background

The American Standards Association defines timbre as "that attribute of auditory sensation in terms of which a listener can judge two sounds similarly presented and having the same loudness and pitch are dissimilar." Such a definition seems designed to cause confusion. Two points are clear: first, timbre should be described in perceptual, rather than acoustic, terms. Second, timbre is a multidimensional "bushel basket" attribute that can only be understood if it is broken down into a number of other attributes.

The ASA definition was obviously an attempt to describe a concept which would account for the identification of different musical instruments, but it was a rather crude idea to suppose that it is a single attribute that makes this possible. A little reflection on your own musical experience ought to convince you of the unreality of this classification. Sometimes, such as when a solo instrument is playing, it is easy to identify. At other times, when an entire ensemble is playing together, identification of some instruments can be very difficult. Certain tones on different instruments sound almost identical, and it is only when other tones are played that the correct instrument comes into focus. Of course, these properties are often taken into account by composers, who will orchestrate a passage so as to make the instrumental structure clear; this is an aspect of compositional technique. Solo stringed instruments can sound very different from a string section.

Finally, the ASA definition begs the question of how we would map out timbral structures if we did not have an intuitive basis formed by our acquaintance with musical instruments.
There are, indeed, several other intuitive concepts that could be used as a basis for timbral structures. The classification of vocal sounds by vowels, with diphthongs creating transitions from one to another, is one. Another would be by analogy with electronic music synthesizers or other electronic-acoustic instruments. But similar objections could be raised to these as to the ASA definition.

I propose the following as a working definition of timbre as it relates to the structure of music (as opposed to other audio phenomena—an important distinction that is not always taken into account in psychoacoustical research): timbre is the structure of frequency components other than perceived fundamental frequencies. The fundamental frequencies of a musical passage constitute its pitch structure, which is very important according to any understanding of practically any music. The definition I have proposed is not at all arbitrary, but is an attempt to account for this term in the manner in which it already seems to be employed by many musicians, particularly those working in the electronic medium where they have become sensitive to overtones through the use of filters and additive synthesis. We all recognize that the overtones of a fundamental frequency are not usually heard as separate tones but as part of the "color" of the fundamental tone. Whether or not this is true depends, of course, on the specific overtones present, and also to some extent on the musical context itself. When overtones are heard separately, then I would argue that they become part of the pitch structure of the music.

The situation becomes more complex when non-harmonic partials are used, because they have the property that there is no perceived fundamental frequency. Traditional music theory, however, is remarkably deficient concerning sounds like this, as it is also deficient concerning any percussive
myself included, feel that the future of computer music ought not to lie in its ability to duplicate the sounds of musical instruments or of natural phenomena, regardless of how important it may be to know and to understand how to do these things. The real problem, of course, is that, facing such uncharted territory, we really don't understand where to begin.

It is not really relevant to try to establish a notational scheme for timbre at this point. The most general notation would be to use specifications analogous to Fourier analysis, showing an amplitude envelope for each harmonic partial over the course of the duration of each tone. An easier proposal would be to duplicate the process employed in the synthesis — for example, to specify an input signal consisting of a certain series of partials together with filter settings, including variations. Since there is a one-to-one correlation between the synthesis specifications and the sounds produced, there is no inherent problem in using this method, except for the fact that the same sounds might be produced through several different processes.

The remainder of this paper will be concerned with explaining some of the ways that timbral structures for computer music might be created, and why.*

* In the live presentation of this paper, this was followed by the playing of taped examples of some of the sounds discussed and a performance of a section from the author's composition Improvisation on the Overtone Series.
tones in general, which have been used in music far longer than the inharmonic sounds that have been exploited fully only since we have had electronic music. In fact, traditional music theory is often deficient concerning rhythmic structure in general, which is also remarkable in view of the fact that the rather well-developed theories of pitch structure depend upon unstated and not always correct assumption about perception of fundamental frequencies. I am arguing here that it is pointless to analyze the pitch structure of a passage if that structure is not perceptible in some easily-verifiable and relevant manner.

Tones containing non-harmonic partials can usually be divided into two categories: sounds which are heard as a kind of "cluster" or "blur", in which each of the discrete components makes some unique contribution to the overall tone; and sounds which create the impression of a complex, possibly changing, chord, similar to a chord that could be formed using only harmonic partials. Because of auditory effects like masking, it may not be possible to perceive the difference between such a sound and a "chromatic" chord. Describing the "pitch" of such tones is an exercise in futility, although it might not be unreasonable to describe them in terms of such characteristics as "density", "height", "spacing" between components, and so forth.*

The definition I have proposed for timbre implies that it is a property of tones containing harmonic partials only.

Computer music composers, unlike composers working in any other medium of sound production, do not have to accept the limitations of either the simple synthesis methods that have been used in the past or of the so-called perceptual "models" of musical instruments or whatever. Instead, they should strive for creativity in timbral structures, and to do things that illustrate both the power and the uniqueness of the computer medium. Many people,

* If you are interested in timbral structures involving inharmonic components, I commend to you the article "Operations on Waveforms" from "Three Lectures to Scientists" by J.K. Randall in Perspectives of New Music, Vol. 5, No. 2 (Spring-Summer 1967). This article is curiously mis-titled, because of the fact that the operations he is describing are not on waveforms at all but on sets of partials.
2. Theory

The harmonic partials of a fundamental frequency create an overtone series above the fundamental, and the overtone series has had a long history, influencing both musical theory and practice, since the beginnings of music. One of the earliest uses of the overtone series was for the construction of musical scales and harmony out of what we now call "pure" intervals, which are expressed as simple ratios between two tones or as successive overtones above a fundamental. A fifth, for example, is created by two tones whose frequencies are in a 3:2 ratio. Thus it is formed between the second and third partials, of course, but also between partials 10 and 15, or 8 and 12. "Major seconds" exist both between partials 9 and 10 and 10 and 11, but these are horribly out of tune if adjusted so that the lower frequencies involved are identical. These deliberations suggest that one use of the overtone series is the exploitation of these intervallic relationships between overtones to create pitch structures or to relate to the pitch structure of a passage.

When the harmonic partials of a tone are sounded together, there is no beating, whereas if the slightest intonation deviation is allowed beating will be created. When the equal-tempered scale was constructed, partly in order to do away with discrepancies such as the difference between the 9:10 and 10:11 major seconds, beating was introduced between any two tones
of the scale except between octaves. Beating seems to be a desirable characteristic; sounds that have beating among their components are said to have "warmth". Whether we view beating in positive or negative terms, it is important to understand that it is an inevitable by-product of any musical context that involves more than one tone, and it becomes a significant property of the music. It is important for computer music composers to understand beating, and it is also important for them to realize that it can be controlled by the use of minor intonation discrepancies that are scarcely perceptible except in terms of the beating produced.

While discussing the subject of timbre in general, it is important to remember that we are much more accustomed to timbres that have some sort of variation than those that don't. Only two musical instruments produce non-varying timbres: one is the organ, which is capable of producing a wide variety of different timbres, but rather deficient in its characteristics of envelope and variation. The other is the electronic music synthesizer, which is capable of a limited range of timbral variation, but not always exploited in that way. Computer music composers have sometimes created dull imitations of these instruments.
When I wrote my composition entitled *Improvisation on the Overtone Series*, I had been experimenting with these concepts for some time and was able to employ many of them in the structure of the piece. The piece is based entirely on the use of harmonic partials. I made two important assumptions pertaining to the work: (1) Overtones would be audible as separate tones, yet still contribute to the "color" of the fundamental frequency, which would be perceptible over a longer duration. (2) The order in which the overtones occur is determined by the "harmony" of the passage in which the tone occurs. This is possible because overtones are different pitches formed at pure intervals above the fundamental.

Within this framework, I designed two basic kinds of computer "instruments", one of which is again divided into two types. The first "brings out" the partials one-at-a-time by means of an amplitude-control function. The shape of this function shows an increase over the first 3/16ths of the duration of a cycle, a sustain for the next 3/16th of the cycle, and a decrease for the rest of the cycle. By the "cycle" I mean the duration over which all of the partials enter and leave the tone in this fashion. Each tone in the piece usually goes through a few cycles over the course of its complete duration.

The second kind of instrument attacks each partial (i.e., a sine tone) separately and sustains it for 3/8ths of the duration of a cycle; but after this duration, the tone dies out completely, so that there is never the impression of a "floating background" as with the first instrument. In this case the impression of the fundamental does not emerge until a few tones have sounded. Each of these instruments normally employs 16 partials, stretching from the fundamental up over a range of five octaves. In the last part of the piece, there is a section where only partials 8 through 16
are used, on an instrument that is otherwise identical to the first type described above. The fundamental emerges clearly, but the timbre is nasal in character.

Before describing some of the compositional ideas used in the piece, let me explain the manner in which the overtone cycle relates to the "harmony" of the music. All "harmonies" (and I use this term in quotation marks) in the piece are derived from 3-note and 4-note collections. Sometimes more complex chords are formed by combining these, but in that case the overtone cycle used is also "doubled". The overtone pattern I selected was chosen by placing overtones that create the "harmony" in question at the beginning of the cycle, so that they are heard as a separate "chord" but still blend in with the fundamental as part of the timbre of the sound. Following these tones, which always occur in a descending order, the other overtones occur in a manner that tends to be dispersed over the entire five-octave range of the first sixteen partials.

For example, two of the harmonies used in the piece are the major and minor triads, 047 and 037.* The fact that triads are used as simultaneous sounds in this piece in no way implies that it is based on triads in any tonal sense! The overtone cycle for the major triad, labelled 047, is very simple, for the "chord of nature" includes the first six partials as well as their octave duplications. The cycle chosen was 16, 12, 10, 8, 6, 5, 4, 3, 7, 9, 11, 13, 14, 2, 1, followed by those left out in ascending order. The minor triad, 037, on the other hand, is rather difficult to form. The one that is least out of tune includes partials 15, 12, and 10 and their duplications in the

(*) The "037" and "047" notation is based on the intervallic structure of the chord in normal form. See my article "Some Combinational Properties of Pitch Structures" in Perspectives of New Music, Vol. 4, No. 1 (1966).
lower octaves. The cycle chosen for this series was 15, 12, 10, 6, 5, 3, followed by 2, 9, 1, 11, 4, 13, 7, 16, 8, and 14. These patterns are shown in Table 1. In Table 1, the vertical line drawn after the first six partials of 037, 034, and 014, and after the tenth partial of 047, shows where the set of overtones forming the harmony in question stops.

Table 1: **Overtone Patterns for 014-group**

<table>
<thead>
<tr>
<th>Trichord</th>
<th>Order of Partialss</th>
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<tbody>
<tr>
<td>037</td>
<td>15 12 10 6 5 3</td>
</tr>
<tr>
<td>047</td>
<td>16 12 10 8 6 5 4 3 2 1</td>
</tr>
<tr>
<td>034</td>
<td>15 14 12 7 6 3 16 9 5 11 1</td>
</tr>
<tr>
<td>014</td>
<td>14 12 11 7 6 3 1 15 8 5 16 9 13 4 10 2</td>
</tr>
</tbody>
</table>

The major and minor triads usually occur in the piece in conjunction with their cycle-of-fifths equivalents, 034 and 014. Overtone patterns corresponding to these structures are also shown in Table 1. The intervals closest to 034 are formed by partials 15, 14, and 12, and therefore the series relating to this trichord begins with these partials. Similarly, the set 014 is formed by partials 14, 12, and 11, and the series for this trichord begins with these partials.

Many other harmonies occur in **Improvisation on the Overtone Series**. Another group of trichords and the overtone patterns corresponding to them is shown in Table 2. These are all derived from the set 013 and its equivalents under M1, M11, M7, and M5 (Identity, Inversion, Cycle-of-Fifths Equivalence, and Inversion of Cycle-of-Fifths Equivalence). In the case of 035, the partials creating the trichord are 7, 8, and 6, and their octave duplications, 14, 16, and 12. In this cycle these partials occur in two different locations, the first at the beginning and the second half way
through. The other patterns all have the partials relating to the set at the beginning, as with the 014-group. These examples illustrate that every harmony constructed in this manner has not only a different pattern corresponding to it, but also that different considerations must be taken into account in order to create the overtone pattern. In each case, all partials are stated over the course of a cycle, so that the only variable is the order. The sounds created are very different from one another.

Table 2: Overtone Patterns for 013-group

<table>
<thead>
<tr>
<th>Trichord</th>
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<tbody>
<tr>
<td>035</td>
<td>7 8 6 13 3 10 15 4 14 16 12</td>
</tr>
<tr>
<td>013</td>
<td>11 12 13 6 16 5 9 2 7 10 4 14 8 15 1 3</td>
</tr>
<tr>
<td>025</td>
<td>9 10 12 5 6 13 2 15 8 11 16 7 4 14 1 3</td>
</tr>
<tr>
<td>023</td>
<td>10 11 12 6 5 16 7 8 15 4 9 2 13 1 14 3</td>
</tr>
</tbody>
</table>
4. Compositional Applications

Finally, I would like to discuss some of the compositional possibilities that can be explored using the timbral structures I have outlined above. These methods allow musical passages to be created involving properties like the following: (Each of these is used in Improvisation on the Overtone Series.)

(1) A single tone contains other tones used in the same context, as overtones above the fundamental. This property is partly a result of the basic assumption that relates the overtone pattern to the harmony of the passage, but the transpositional level of the structure contained in the overtones is often different from that contained in the pitches of the passage. This property is possible only if the overtone pattern contains one of the octave partials. For example, the trichord 034 occurring on a C would include the notes B, B-flat, and G, so that containment would be impossible; but the trichord 035 occurring on a C would introduce the notes G, B-flat, and C, so that the other tones in the context would be included if this were the highest note only. This property is most obvious in a passage such as the ending of Improvisation on the Overtone Series, where the final tone is the lowest note of a major triad.

(2) Some passages, such as section 2 of Improvisation on the Overtone Series, exploit the contrast between tempered pitches and partials of other (lower) tones in the same octave. When I have been discussing the relationship between tones occurring as fundamental frequencies and tones occurring as overtones, usually there is a difference of three or four octaves. In general, the pitches used in the piece are quite low. This allows the overtones to occur in octave areas where pitches usually occur in music, so that the listener will be more sensitive to the timbres. Of course, when the contrast between pitches and overtones is highlighted, intonation deviations between pure and tempered intervals is one of the most obvious features of the resulting music.
(3) All frequencies present in a given musical passage are in the same octave area, although the fundamental frequencies of which these may be possibly overtones are in a different and much wider area. This technique is analogous to feeding music through a graphic equalizer and filtering out everything except a certain octave band, but using additive synthesis such as in the two instruments used in Improvisation is really more precise and different from any kind of filtering.

(4) The registers in which partials occur, when frequencies are restricted to one or more octave bands, unfold in a manner that parallels or relates to the unfoldment of pitches or other characteristics of the music. There is a long passage in Improvisation (section 5) which does precisely this, and at its conclusion the entry of partials in other octaves is a very dramatic moment in the piece.

(5) This final characteristic is something that occurs only with instruments of the second type mentioned above, in which each of the partials of a tone are attacked separately and given a separate envelope. Sometimes, either at the beginning of a tone when not all of the partials have yet had time to make their entrance, or if the durations of the partials with separate envelopes are not long enough, the perception of the fundamental is not present, and the overtones are heard as separate pitches. It is very interesting to hear the fundamental enter and leave a tone in a passage like this, and it certainly makes you aware of the existence of separate structures in the music for the pitch successions and the overtone successions that you hear in the foreground.