MUSICAL ACOUSTICS

BENJAMIN F. TILLSON*

PART III

This is the third of a series of articles on music theory, written especially for sound engineers.

The literature on sound and acoustics would lead one to believe that his hearing would experience the same nodal changes in sound intensity or amplitude as graphically represents the patterns of wave interferences. Each pattern represents a different phase, frequency, and amplitude relationship of its component waves.

In "Scientific Papers" I, p. 409 Lord Rayleigh describes two unison organ pipes mounted side by side, with ends close together, on a common wind-chest: and that if blown for a short time they sound, but when blown longer but less than a second the sound dies away to a small fraction of that due to either alone. This may not properly exhibit the interference of sound waves in the open because the pressure pulsations emitted from one pipe may be sucked into the adjacent pipe when out of phase. However, he observed that when the two pipes were out of tune they sound a common note which may be higher than that due to either alone.

When a vibrating tuning-fork is rotated before an ear four positions will be found that make it inaudible, but the sound will again be heard if something is interposed between the ear and one prong of the fork. A half-pint cream-bottle will resonate a fork tuned to "A" equals 440; and the silent position occurs when the plane of the prongs makes an angle of forty-five degrees to the axis of the bottle.

When both waves are of the same frequency, the amplitude "beats" between them have a common frequency, so no change of pitch takes place and the resultant sound is either louder or less loud. At the most such amplitude is doubled and the intensity quadrupled, or increased only 6 decibels, which is inconsiderable. It is well to remember that the energy and intensity of a tone vary directly with the square of its frequency and also with the square of its amplitude. However, the null position is observable in the tuning-fork experiment.

But if one makes a repeated striking of the same piano key, with the damper off, it seems impossible to obtain a null point or noticeable variation of sound intensity. Perhaps that is chance, or else the presence of overtones masks the interference results obtained with pure tones.

When one strikes the arpeggio of a chord (the notes of a chord in sequence), with dampers off, the resultant tone sounds the same as when the keys are struck simultaneously. This might lead one to believe that the ear analyzes complex sounds into their component frequencies, and that the brain synthesizes them again into a pattern dependent only on pitch and amplitude, but ignoring phase differences.

However, when graphs are plotted of mixed frequencies the respective phases of the components give entirely different patterns. This is illustrated by *Fig. 6*, where a fundamental and five of its overtones (with amplitudes varying inversely as their frequencies) are plotted for respective conditions of all starting in phase with maximum amplitudes, or all starting with zero amplitudes at the same instant. Different patterns are also shown for the chord of the Tonic and the Fifth, C and G. Since no difference of sound results, such analysis by the ear seems indicated.

How that analysis is accomplished is a matter for conjecture. Probably the canals and chambers of the external and internal ear, the bony amplifying mechanism (the maleus, incus, and stapes), the rods of Corti on the basilar membrane, and the membraneous diaphragms all have specific resonant frequencies, varying fidelities of response to impressed vibrations, and certain inertia and imperfect forces of restoration: and the nerve ends may also vary in sensitivity throughout the areas of the basilar membrane in the cochlea.

At least it has been shown that the ear does not give a linear response to the sound waves it receives. Just as the non-linear portion of the characteristic curve of a radio tube is used for the detection and transformation of the frequency of incoming signals, so the ear uses a combination of incoming sound frequencies to manufacture "subjective" tones whose frequencies are equal to either the sum or the difference of the incoming frequencies. The unequal response of the ear to different frequencies is shown in *Fig. 7*.

Each curve in *Fig. 7* shows the intensity of sound waves in decibels at various frequencies to impress the ear as having the same loudness level indicated for each curve at the pitch of 1,000 cycles per second. It will be noted

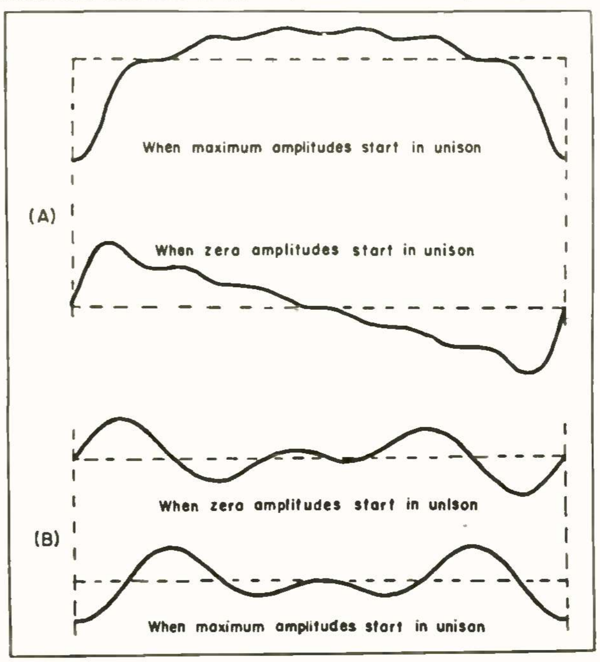


Fig. 6. Graphs of mixed frequencies when phase relations are changed.

*Consulting Engineer, Montclair, N. J.

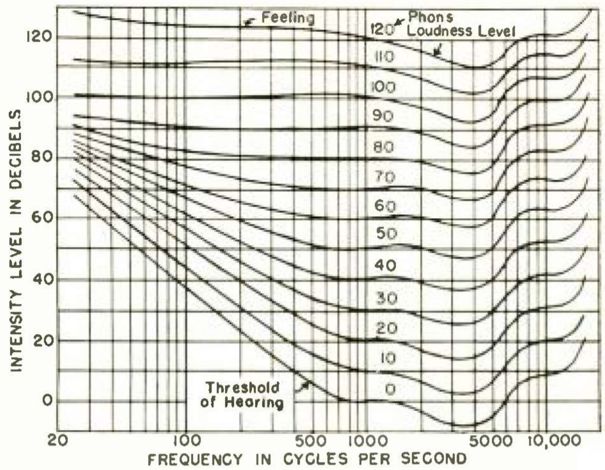


Fig. 7. Intensity of sound waves at various frequencies (Fletcher).

that below 700 cycles or above 7,000 cycles the intensity of the tones must be greater, and that it is particularly so with the bass notes to give a loudness of 60 db. The decibels of loudness levels are called Phons.

The required increase of intensity of the frequencies above 7,000 cycles does not vary greatly with the various degrees of loudness; but such increase does vary greatly in the frequencies below 700 cycles per second, and a higher fidelity is favored by great loudness. Therefore, any controlled reduction of amplified volume causes a greater loss in bass response and warrants a "boosted bass" in phonograph records and radio amplifiers, but it also makes automatic volume control likely to produce an unbalance between bass and treble tones.

Within certain limits all of our sense organs conform to the Weber-Fechner Law in psycho-physics: that equal increments of sensation are associated with equal increments of the logarithm of the number which represents the comparative ratios of the stimuli (therefore, the relationship between increase of stimulus and resulting increase of sensation).

If one listens to music from a point 100 feet away and approaches to 10 feet, since the intensity of sound varies inversely as the square of the distance, it will be 100 times or 20 db greater. Also, all tones below 700 cycles frequency will sound disproportionately louder and a 100-cycle tone will have a loudness level a further 20 db above a higher-pitched tone. Thus the bass tones are lost as we get farther away or as the volume of a loudspeaker is reduced.

Overloading

When the ear is overloaded it acts as does an overloaded electron-tube amplifier by departing from a straight-line magnification of impressed frequencies and acting as a modulator which originates harmonic frequencies. This takes place when the intensity of the impressed tone exceeds 40 decibels above its threshold of hearing value; and higher harmonics result from increased overloading.

Another result of overloading is the impression in the brain of a shift in pitch, which is particularly noticeable for tones of 100 to 200 cycles per second. At 60 db, the tone seems two per cent lower in frequency, at 76 db three per cent lower, and at 93 db eleven per cent lower (as determined by S. S. Stevens at Harvard). Dr. Harvey Fletcher noted that a 222-cycle tone at 100 db sounded the same pitch as a 200-cycle tone at 40 db; and that a 421-cycle tone at 100 db was the octave above the 222-cycle tone and sounded the same in pitch as a 400-cycle tone at 40 db. Since the intensities produced by orchestras may be as high as 100 db it is evident that the crescendos produce dissonances.

Furthermore, if a pure tone receives a cyclical variation of its intensity its frequency is increased and decreased by the frequency of the intensity change; and the fundamental has only one-half intensity and each side-band one-quarter. A different modulation occurs where there is a cyclical variation of the frequency of a pure tone. This produces the musician's vibrato, which is best when varying six to seven times per second.

Visual Perception

An equivalent illusion occurs with visual perception where the speed of a rotating body appears to increase as the illumination is decreased, and vice versa. This indicates that there is a timing function associated with the mechanism of transmission of nerve impulses to the brain. About twenty years ago the writer proposed an electrostatic bio-chemical hypothesis to explain the transmission of nerve impulses as due to the charging and discharging of electrical condensers in the nerve system.

The time interval for charging would depend upon the intensity of the stimulus, and the frequency of charge-discharge cycle would also vary with such intensity. Therefore, an image would move a shorter distance (for a given velocity) upon the retina between successive periodic stimulations of the optic nerve endings when receiving a high illumination intensity than it would with dim illumination. Similarly with the stimuli of sound, the more rapid nerve transmission of high intensities gives a brain sense of a greater interval between each cycle, and therefore a lower pitch of tone.

In the construction of a nerve there is a central "axis cylinder" of about nine per cent of the nerve fibre, encased by a sheath of fatty myelin. The mineralized plasma of the central core makes of it an electrical conductor, while the fatty sheath is an insulator. Such is the manner of an electrical condenser.

Twenty years ago it was dicovered that no graduated impulses are carried by a nerve fibre, and that sensations were observed in steps or quanta and that a certain quantum represents the threshold of perception. If the transmission of nerve impulses were by direct electric current any stimulus would produce a proportionate effect by gradual change. This is not so.

We find that there is a threshold of hearing and that the loudness heard is directly related to the number of nerve fibres excited and the rate at which these excitations occur, since each fibre always carries its maximum impulse. When all nerve fibres have been excited at their maximum frequency no further loudness is possible as sound.

After a nervous impulse has passed through a nerve there is a refractory phase during which time the ionized nerve plasma and tissue is reconstructed and the nerve is unable to respond or conduct. Then there follows a relative-refractory phase during which the excitability, the conductivity, and the speed of propagation gradually return to normal, and upon doing so an inertia effect is exhibited by passing the normal to a supernormal state when the nerve is more sensitive, more highly conductive, and permits a greater speed of propagation, and so conducts quanta less than the threshold values. Then the supernormal state returns to normalcy.

The time interval of the refractory state is one millisecond, and for the relative-refractory state is three milliseconds. Therefore, the maximum number of nervous impulses that a single nerve fibre can send to the brain is 1,000 per second; and those periodic excitations greater than 300 per second will not be transmitted as normal impulses since

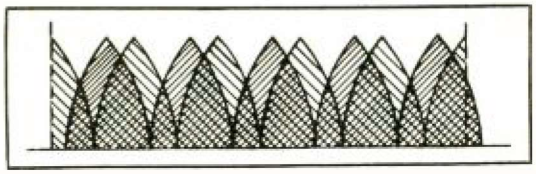


Fig. 8. Analogy of reflected light effects to acoustic reflections. See text.

each succeeding excitation would then lie in the relative-refractory phase. But Adrian determined a longer relative-refractory period for the nerve endings so as to respond to no more than 150 impulses per second. Regardless of the quantitative values the possibility is present for a subjective inter-modulation distortion which must be given consideration.

Consequently a pure tone of 3,000 cycles per second probably sends impulses to the brain at as few as 20 per second, and the rate of discharge cannot exceed this. Nerve stimulation in the inner ear occurs four times in each frequency cycle: at wave crests and troughs, and at change across the static position. The louder the exciting impulse the greater the area of basilar membrane stimulated and the greater the number of nerve endings and fibres excited. Intermodulation of the basilar membrane produces additional frequencies.

When two or more tones are impressed upon the ear they produce beat tones whose frequencies are the sums or differences of both the fundamental tones and their harmonics. These are called Subjective Tones, or Combination Tones.

A continual application of intense sound vibrations will ultimately destroy the cilia (hair cells) and possibly the auditory nerves, as could be expected from continuous ionization or electrolysis of the plasma without normal biogenetical reconstruction or supply.

A complex tone, consisting of a fundamental and its harmonics, also varies in its pitch as its intensity (loudness) is increased; but it varies less than a simple pure tone. But it retains the pitch of the fundamental even though the latter, and even some of the lower harmonics, are filtered out. That is because the difference between each pair of successive harmonics is the same as the frequency of the fundamental. Therefore loudspeakers too small to resonate to the low frequencies give the illusion of bass tones.

A complex tone of 200 cycles with five harmonics was found to increase in pitch by only 4 cycles (two per cent) when its loudness level was lowered from 100 db to 40 db; whereas a pure tone of 200 cycles increased about 20 cycles (ten per cent) in pitch for the same change in loudness levels.

The greatest change in pitch occurs at frequencies variously given by different observers in the range of 100 to 200 cycles frequency of pure tones. Taking as the base 40 db above the threshold of hearing H. Fletcher found a drop in pitch of 8 per cent for a 200-cycle tone at 100 db, and W. B. Snow found a drop of 21 per cent at 120 db, but the maximum per cent of drop in loudness occurred for 100 cycle tones and was 10 per cent for 100 db, 6 per cent for 80 db, and 2 per cent for 60 db. If the frequency of pure tones at 120 db increased from 200 to 400 cycles (pitch rating at 40 db) the actual tones heard increased from 158 cycles (21 per cent less than 200) to 368 cycles (only 8 per cent less than 400 cycles), or a change of 1.21 octaves at 120 db instead of the one octave change which would be heard at 40 db.

This illustrates the danger of dissonance from reproducing at high sound levels.

We, therefore, learn that an auditor's idea of the pitch of a tone depends upon three physical characteristics of sound waves: their frequency, overtone structure, and intensity.

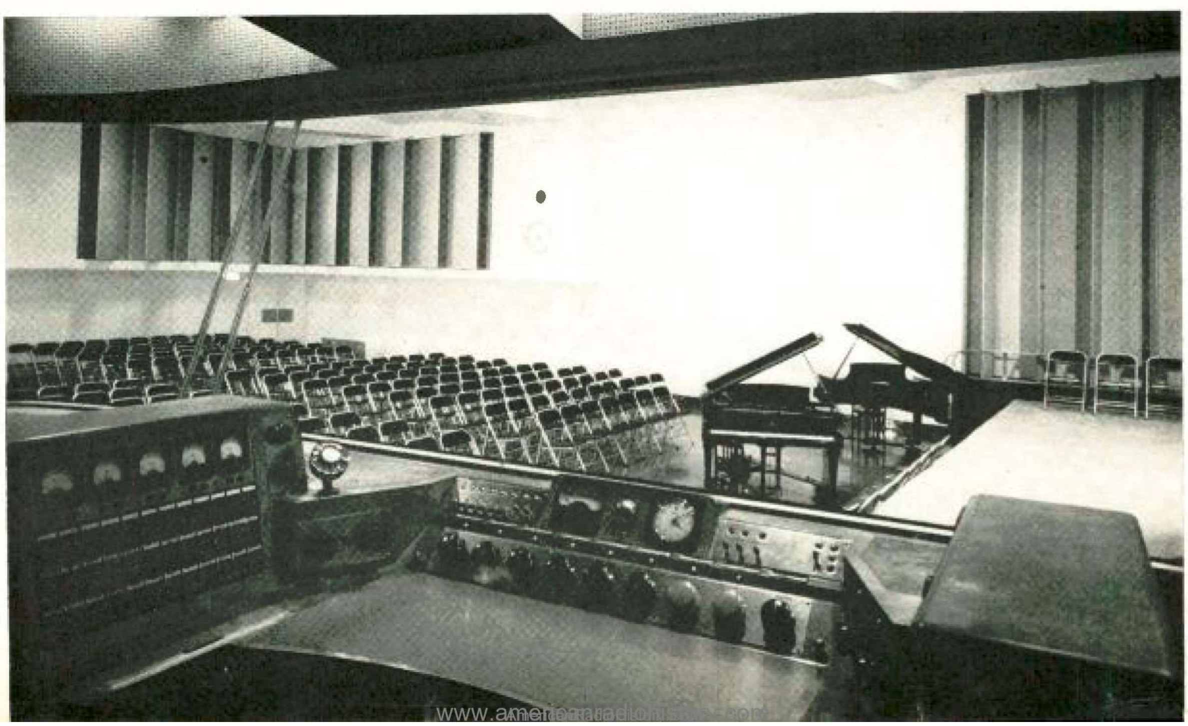
Timbre

The "timbre" or color of a complex tone has already been mentioned as dependent upon the specific partials and their relative intensities. But since the auditory pitch depends upon variable intensities at different frequencies an increase in the loudness of a complex tone produces different percentages of pitch changes of the various partials, thereby further changing the timbre.

Furthermore, Messrs. Chapin, Trimmer, and Firestone reported in 1934 and 1937 to the Acoustical Society of America that a change in phase relation of two harmonic tones of low frequency and high sensation level produces a perceptible change in both loudness and tone quality (timbre). This is contrary to the conclusions already expressed by this writer: that tone structure and not wave form is responsible for the character of the sound heard.

H. Fletcher has determined that about

CBS-New York studio 21 viewed through the control room window. A CBS 2A studio control console is in the foreground. Rotatable wooden panels enable the reverberation characteristics of the studio to be altered.



one-twentieth second is the minimum time for which a frequency must be sustained for the ear to recognize a tone of definite pitch. At a shorter time it hears only a transient sound. Thereby we are relieved of much of the transient distortions in acoustical and mechanical systems if they are masked by higher intensities of musical sounds. Many consonants used in speech are transients of very brief duration, especially the "stop consonants", and their decay is very rapid. They add to difficulty in understanding certain words in telephone conversations. Longer transitory periods result from musical instruments or apparatus because of the greater inertia of the vibrating elements.

The sound of music out-of-doors should be different from that heard in concert halls or chambers, even though the latter are free from reverberation or echo, because there is always some sound reflected from bounding surfaces. The combination of original and reflected tones will affect the amplitude and phase relationship of tone patterns. *Figure 8* gives a simple example of equivalent effects illustrated by light and shadows. A single light bulb located in front of a mirror produces two sources of illumination which cast two shadows of the tops of uniformly spaced, repeated sections of a steam radiator. The combination of two shadows gave the darkest and most prominent shadows with a cyclical variation of amplitudes and lower maximum amplitudes.

Difference Tones

The Difference Tones were first discovered by A. Sorge in 1740 and were independently discovered by G. Tartini in 1754, and were named after the latter. H. von Helmholtz developed in 1863 a theory for their formation in the middle ear from the non-linear response of the ear-drum and its bony linkage, because of the damping of the forces of restitution; and he predicted the difference tones and later confirmed that by experiments.

Combinational tones may be formed between the overtones of two complex tones as well as between their fundamentals, and in some cases even between the combinational tones themselves. When formed between the fundamentals they are called of the "first order". The summation tones are much more difficult to perceive than the difference tones.

The richness of harmonies, their color, and their emotional appeal largely result from the transient dissonances of the subjective tones which they evoke. This has been the unconscious gift of the genius of composers rather than an analytical knowledge of combinational tones on their part. *Figure 9* depicts by music notation, as the black quarter-notes, the combination tones of the first order from simple musical intervals shown by half-notes.

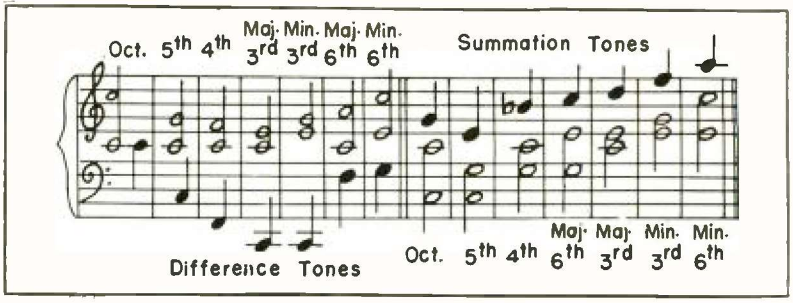


Fig. 9. Combination tones of the first order from simple musical intervals.

Figure 10 shows in music notation the first six measures of the music "My Country 'Tis of Thee", and beneath them the additional subjective first order difference tones with which the ear of the listener enriches it. This makes it evident that the hearing of music and its appreciation is a far more complicated matter than listening to simple tunes. And it points out the need for the reproduction of music to be at the highest fidelity.

If we represent the number of score notes in a harmony by *"n"* then the number of additional resultant difference tones will equal *n* times ($n-1$) divided by two. Therefore, four-part harmony may add six subjective difference tones, and eight-part harmony might add twenty-eight, all of the first order. Larger symphonic harmonies would greatly increase these numbers, and when played loudly the difference tones between the higher partials would greatly multiply such subjective tones.

Much has been printed to decry the need for sound reproduction systems which give a faithful undistorted delivery of the high frequencies of musical tones. And listener reaction has been quoted in support of that viewpoint without evidence that the demonstrations did not suffer from intermodulation distortions, confusion of reflected tones, or proper balance of sound intensities to free the ears from the distortions of overloading.

The author's personal experience about thirteen years ago was quite to the contrary. During an auditorium demonstration of audio perspective by a system with an upper limit of 15,000 cycles per second, the quality of the music suffered greatly. It lost tone color and liveness. The snare drum lost its tingle.

Because of the limitations of the grade of telephone lines between studios and transmitters, and because of the low musical quality of phonograph records, and of phono and radio amplifiers and loudspeakers, it is doubtful whether the public has the opportunity to hear musical fidelity any better today than the 8,000 cycle limit. So there is no chance for ear training to appreciate

[*Continued on page 44*]

Fig. 10. Music notation of a familiar composition and the subjective tones added by the listener's ear.