Acoustics. — *The perception of subjective tones.* By J. F. SCHOUTEN.

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It is a well-known fact that the ear sometimes perceives tones which do not correspond with any of the Fourier-components of the objective sound. Of these "subjective" tones the difference tones and the summation tones are the best perceptible. When a pure tone of increasing intensity is presented to the ear, the tone quality gradually changes from a pure one into a harsh or rough one. This change of quality is generally ascribed to a generation of higher harmonics in the ear, which is most probably due to non-linear distorsion in either the middle or the inner ear.

The existence of these subjective [1]) harmonics was demonstrated independently by FLETCHER [2]) and by VON BÉKÉSY [3]) with the aid of the method of beats. If a tone of say 200 cycles of high intensity is sounded together with an "exploring" tone of 406 cycles of low intensity, the ear perceives 6 beats per second. These beats are interpreted as an interference between the objective tone of 406 cycles and the subjective tone of 400 cycles (the second harmonic) which is generated within the ear.

At a certain intensity of the exploring tone the beats are reported to be most pronounced. This intensity is taken as the intensity of the subjective second harmonic. In the same way the best beat obtained with an exploring tone of 606 cycles gives the intensity of the subjective third harmonic, etc. FLETCHER and VON BÉKÉSY give data of 8 and 5 harmonics resp., obtained by means of this method.

A peculiarity of their results is that the percentaged intensity of the harmonics is almost constant over a wide range of intensities of the fundamental tone. Practically all known non-linear mechanisms, however, produce harmonics, the percentaged intensity of which is strongly dependent upon the intensity of the fundamental tone.

CHAPIN and FIRESTONE [4]) and TRIMMER and FIRESTONE [5]) investigated the influence of the phase of an objective harmonic on the tone quality,

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[1]) We shall, throughout this paper, use the term "objective" when referring to the actual sound pressure and the term "subjective" when referring to the sound heard by the ear.

[2]) H. FLETCHER, J. Acoust. Soc. Am., **1**, 311—343 (1929).

[3]) G. VON BÉKÉSY, Ann. Phys., **20**, 809—827 (1934).

[4]) E. K. CHAPIN and F. A. FIRESTONE, J. Acoust. Soc. Am., **5**, 173—180 (1933).

[5]) J. D. TRIMMER and F. A. FIRESTONE, J. Acoust. Soc. Am., **9**, 24—29 (1937).

when added to the fundamental tone. The fundamental tone and its next five harmonics were generated by means of 6 electrostatic inductor alternators. In this way it was possible to add a certain harmonic of known intensity and phase to the fundamental tone.

If the second harmonic is generated in the ear, one might expect that, by addition of an appropriate amount of second harmonic to the objective sound, the tone quality as well as the intensity of the sound perceived would become dependent upon the phase of this objective second harmonic. In one phase (phase A) the objective and the subjective harmonic would just counterbalance, in the opposite phase (phase C) the two would reinforce one another.

This phase effect was found, according to expectation, at an intensity level of 104 db and about 10 % second harmonic. In phase A the addition of the objective harmonic produced a sound perception of smoother tone quality and of less intensity than that produced by the objectively pure tone. In phase C the tone obtained a rough or dissonant element and became of greater loudness.

The same authors [5]) severely criticize the use of the method of beats as a quantitative method of measuring the subjective harmonics, especially so because the presentation of the exploring tone might change the amount of harmonics generated in the ear and might give rise to disturbing overtones and combination tones. Below we shall describe a phenomenon which seems to justify this criticism.

Optical arrangement for the production of synthetic sound.

We constructed an optical apparatus for the production of sound of any prescribed waveform. One period of the desired waveform (in this case the fundamental tone) is drawn in polar coordinates on stiff paper in such a way that one period corresponds with forty degrees.

The paper enclosed between the drawn waveform and the circle passing through the largest negative value of the waveform is then cut out. The paper, which can be shoved into a holder H_1 (Figs. 1 and 2), is illuminated homogeneously by a point source of light P. A revolving wheel W containing 9 narrow slits S is placed immediately behind a holder H_1 and is driven by motor M.

By means of a lens L an image of the light source P is formed in the photo-electric cell C. The light transmitted by the slit wheel, which is linearly proportional to the prescribed waveform, is finally transformed into sound by means of the photo-electric cell C, an amplifier and a loudspeaker. A cathode ray oscillograph O permits to visualize the waveform actually obtained. The fundamental frequency is 200 cycles.

Measurements of the intensity level of the fundamental tone and of the higher harmonics were carried out by means of an electrostatically calibrated condenser microphone and a wave analyzer. If a pure sine is cut out, the amount of higher harmonics introduced by faults in the optical system and by non-linearity in the electrical and the acoustical system is measured to be limited to 1 %.

For studying the phase effect use was made of a second holder H_2

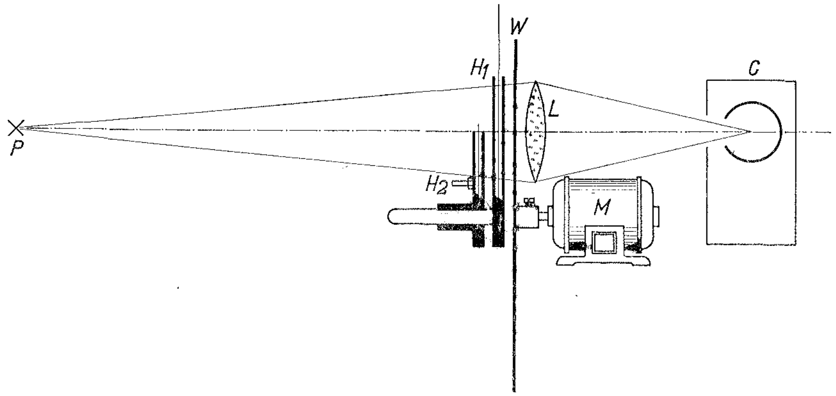

Fig. 2. *Sketch of the apparatus used for obtaining synthetic sound.* The holders H_1 and H_2, holding the desired waveform, are illuminated homogeneously by the point source of light P. The light transmitted by the slits of the rotating wheel W is concentrated by means of lens L into the photoelectric cell C.

which could be turned round the axis of symmetry. In this way a harmonic of continuously varying phase could be added to the fundamental tone.

At an intensity level of 105 db and an objective second harmonic of 4—8 %, a very marked phase effect upon the tone quality is heard. At this level the second harmonic can even be heard separately to vanish (phase A) or to reappear. If the phase is adjusted in such a way that the second harmonic is no longer perceptible and the objective second harmonic is then removed, the subjective harmonic can actually be heard to be present in the objectively pure sound. After a few seconds this subjective harmonic seems to blend with the fundamental tone and cannot be heard separately again until after comparison with the sound of phase A.

At higher intensity levels the phase effect on the tone quality still exists, although the second harmonic is no longer separately perceptible. The tone acquires a strongly increasing rough quality.

The phase effect on the intensity confirmed the findings of previous investigators [4, 5]).

That indeed in phase A the effect of the objective second harmonic consists in suppressing the subjective harmonic generated in the ear, can be beautifully demonstrated by combining the phase method with the method of beats.

For this purpose a tone of 406 cycles was produced by a second loudspeaker. It should be expected that in phase C, where the subjective harmonic is reinforced, strong beats occur, whereas in phase A, where the subjective second harmonic is suppressed, the beats should vanish. A strong

phase effect for beats was indeed found, which confirmed the above hypothesis.

A disturbing effect, however, was noticed. Although at phase A the beats of the second harmonic practically vanish, other beats, which probably can be best described as beats of the fundamental tone, remain audible. These beats have the same frequency as those of the second harmonic. The only explanation presenting itself seems to be that these beats are due to the fundamental tone of 200 cycles and the difference tone of the fundamental and the exploring tone of 206 cycles. This effect confirms the criticism of TRIMMER and FIRESTONE [5]) in sofar that one should be very cautious before interpreting beats heard between the tones 200 and 406 as being due to the second harmonic and the exploring tone alone. As neither FLETCHER nor VON BÉKÉSY explicitly mention that the beats heard were beats of the second harmonic and not of any other tone, the possibility remains that this effect affected their measurements, which give values so greatly differing from those obtained by other methods.

In figure 3 values are represented of the percentage second harmonic and the intensity level of the fundamental tone at which the phase effect

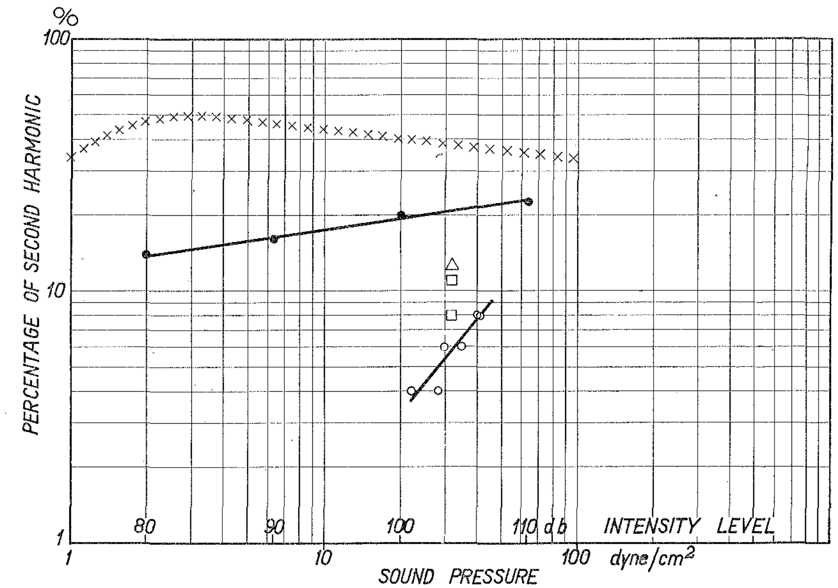

Fig. 3. *The percentaged intensity of the second harmonic generated in the ear as a function of the intensity level.*

● ● ● ● FLETCHER — best beat method
× × × × VON BÉKÉSY — best beat method
△ △ △ △ CHAPIN and FIRESTONE — phase method: minimum loudness
□ □ □ □ TRIMMER and FIRESTONE — phase method: minimum loudness and minimum roughness
○ ○ ○ ○ Our measurements — phase method: minimum roughness and minimum beats

on tone quality and beats was best pronounced. These values may give a fair impression of the intensity of the subjective second harmonic. For comparison the values obtained by other observers are also given.

Subjective tones and the perception of pitch.

Some sounds exhibit the peculiarity that the fundamental tone is missing or of very low intensity compared to the higher harmonics. As an example we reproduce (Figs. 4 and 5) photographs of the sound spectra obtained from strips of sound film on which the lowest *g* of the violin and the vowel "a" in "father" are recorded [6]).

The pitch ascribed to these tones, however, is that of the missing fundamental. Similar results were obtained by FLETCHER [8]) with sounds from which the lower harmonics were artificially removed.

The customary and attractive hypothesis [8]) to account for this effect is to assume that the fundamental tone, although not present in the objective sound, is generated as a subjective tone in the ear. Because of the non-linear distorsion in the ear this fundamental tone would occur as the difference tone of all adjoining harmonics and would thus be of great strength.

It should be stated that the tacit assumption underlying this hypothesis is that the perception of pitch is determined by the lowest harmonic actually present in the ear.

There is one objection which might be raised beforehand against this hypothesis, namely that even at lowest intensities no one was yet reported to judge the pitch of these tones an octave higher. Subjective tones, however, do not become noticeable until above a certain intensity level.

In order to study this effect, we used the waveform *A* reproduced in figure 6. This waveform can be described as a periodic impulse of finite width (one twentieth of the fundamental period). A periodic true impulse contains all harmonics in equal strength. The periodic impulse of finite width contains the lower harmonics in gradually decreasing strength. The tone quality is very sharp.

By using the procedure described in the above paragraph, the fundamental tone could be exactly cancelled. The intensity of the fundamental in the actual sound field was ½ % of the second harmonic. The waveform is represented in fig. 6, *B*.

After that the same setting was made but now subjectively. It was found that these adjustments are very critical and therefore easy to make. For

[6]) It can be shown [7]) that the diffraction pattern of variable-width sound film provides a visual Fourier-analysis of the registered sound. This rule only holds true on the horizontal axis of symmetry of the spectrum. The intensity of the lines, is proportional to the square of the amplitudes of the harmonics.

[7]) J. F. SCHOUTEN, Nature, **141**, 914 (1938).

[8]) H. FLETCHER, Phys. Rev., **23**, 427—437 (1924).

very slight alterations of the phase or the amplitude of the periodic impulse the fundamental could be heard separately in the sound again.

Contrary to expectation the objective and the subjective settings practically coincided, which means that no subjective fundamental of

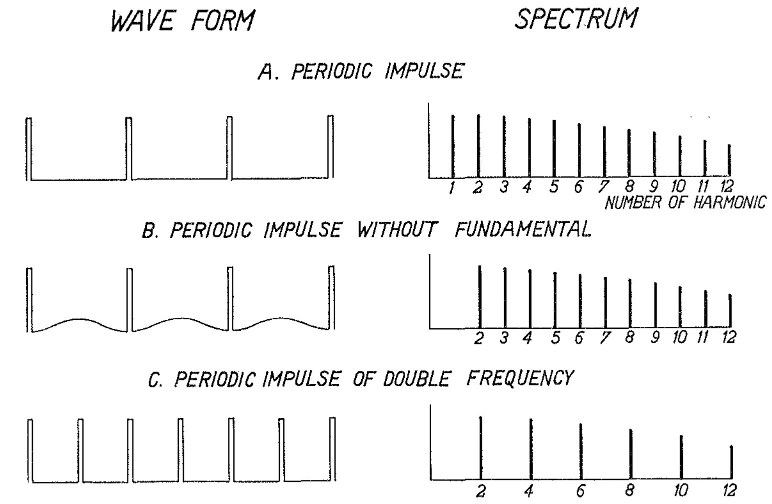

Fig. 6. *Various periodic impulses and their Fourier spectra.*
Waveform *A*: periodic impulse of finite width. Frequency 200 cycles. The spectrum contains all harmonics in gradually increasing intensity.
Waveform *B*: same as *A*. The fundamental tone is suppressed.
Waveform *C*: periodic impulse of double frequency (400 cycles).

appreciable intensity is formed in the ear. The amount of the subjective fundamental for pressure amplitudes of the same order as those used in the experiments with a pure tone is certainly less than 3 %.

We shall, however, leave this part of the matter aside for the present and turn to another surprising phenomenon. No matter whether the fundamental is generated in the ear or not, the subjective fundamental can be made to vanish completely. This can be corroborated by means of the method of beats. If an additional tone of 206 periods is presented to the ear, 6 beats per second are distinctly heard at random settings. These beats, however, disappear completely at the setting obtained above. We are, therefore, justified in concluding that indeed no fundamental tone is present in the ear at that setting.

The pitch ascribed to this tone (waveform B), however, is the same as the pitch of the periodic impulse with fundamental tone (waveform A) and is an octave lower than the pitch of a periodic impulse of frequency 400 (waveform C).

It is not without interest to analyse the sound impressions obtained from the three waveforms somewhat further. By concentrating the attention (the difficulty of which has been so adequately formulated by

HELMHOLTZ [9])) on the fundamental, the second and the third harmonic, each of these can be heard separately in waveform *A*. We might say that, as to the actual perception, this sound consists of four entities: a sharp tone of pitch 200 and the pure tones of pitch 200, 400 and 600. The relative prominence of these four entities is so strongly dependent upon the concentration of the attention that it is scarcely an exaggeration to say that one can hear at will a tune built on these four tones.

In the sound with waveform *B* there are three separate entities. The second and third harmonic are still separately recognizable, the rest is a sharp tone of the *same* pitch and almost the same timbre as that of waveform *A*.

The sound impression obtained from waveform *C* was that of a sharp tone of double frequency; we did not succeed in hearing any of the harmonics separately.

Sometimes the difference between waveform *A* and *B* is heard as a jump of an octave, but it should be explicitly stated that this only occurs when the attention is concentrated on the lowest harmonic perceptible in the sound. The sharp tone itself does not change in pitch.

Historically we may distinguish between three stages. In the first stage it was thought that the perception of pitch was determined by the lowest harmonic present in the objective sound. It was then found that tones which either naturally or artificially miss the fundamental tone and even some of the lower harmonics still have a pitch equal to that of the fundamental tone.

In the second stage it was assumed that the fundamental tone, although not present in the objective sound, is generated in the ear as a subjective tone. It is now found that tones which miss the fundamental, even as a subjective tone, still may have the pitch of the fundamental tone.

Therefore the perception of pitch is not determined by the lowest harmonic present in the ear, although the ear is sometimes capable of ascertaining whether the fundamental tone is (subjectively) present in the sound or not.

One might ask now whether there is any sense in this behaviour of the ear. There is scarcely any sense in it, if we look at the Fourier spectrum. Why should the pitch of a pure tone be the tone itself and that of a sharp tone be the frequency difference of its harmonics? There is very much sense in it, if we look at the oscillogram, because, as in figure 6 *B*, although the fundamental tone is missing, the oscillogram is still periodic with the frequency of the fundamental tone.

There must be some way in which the ear, when perceiving pitch, is able to become aware of this fundamental period of the oscillogram.

Eindhoven, 29th November 1938.

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[9]) H. v. HELMHOLTZ, Lehre von den Tonempfindungen.

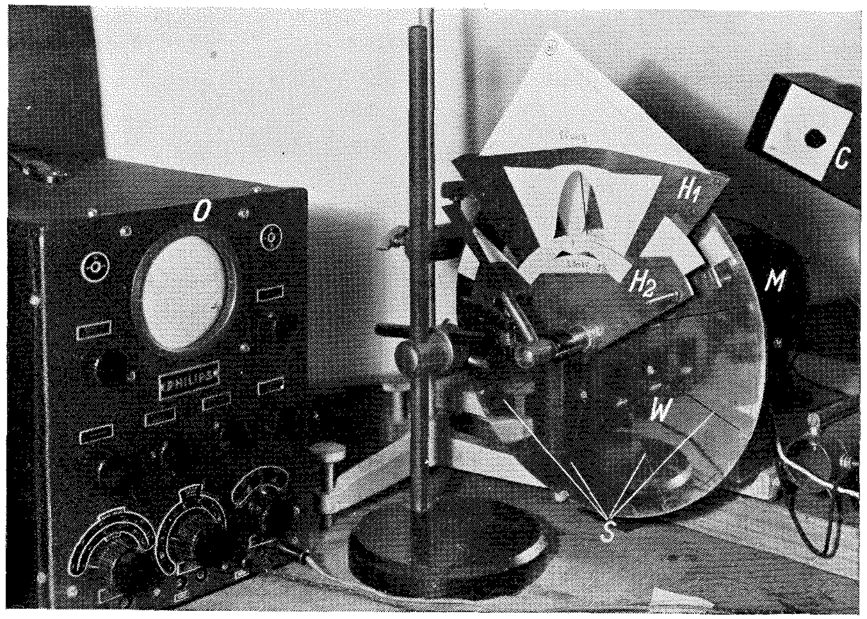

Fig. 1.

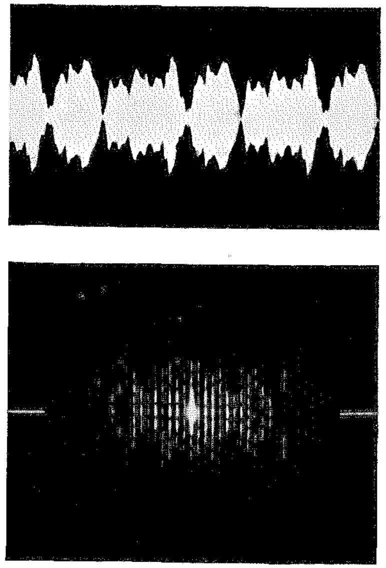

Fig. 4.

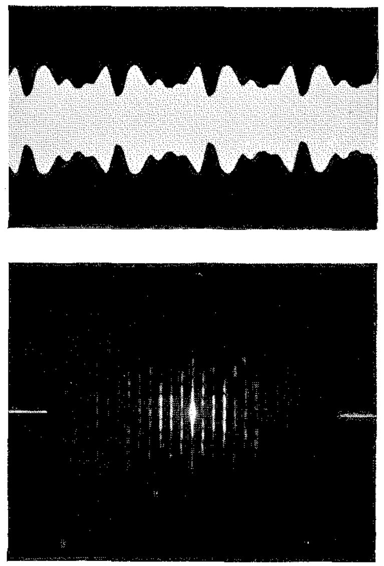

Fig. 5.

LEGENDS TO FIGURES:

Fig. 1. *Photograph of the apparatus used for obtaining sound of any prescribed waveform.* The fundamental tone is cut out in the paper held by holder H_1, whereas the second harmonic is cut out in the paper held by holder H_2. The papers are illuminated homogeneously. The light transmitted by the slits S of the rotating wheel W driven by motor M is proportional to the desired waveform. The light is concentrated into the photo-electric cell C. The cathode ray oscillograph O serves to visualize the waveform actually obtained.

Fig. 4. *Above*: tenfold enlargement of a strip of sound film on which the lowest *g* of the violin is recorded (193 cycles).
Below: photograph of the pattern obtained from this strip by diffraction of light. The intensity of the lines on the horizontal axis of symmetry provides a visual Fourier analysis of the sound recorded on the film. Note the very low intensity of the fundamental tone.

Fig. 5. *Above*: tenfold enlargement of a strip of sound film on which the vowel "a" in "father" is recorded (290 cycles).
Below: photograph of the diffraction pattern obtained from this strip. Note the very low intensity of the fundamental tone.