THE MISSING FUNDAMENTAL

A PLACE THEORY OF FREQUENCY ANALYSIS IN HEARING

G. A. HOOGLAND

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PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE GENEESKUNDE AAN DE RIJKSUNIVERSITEIT TE UTRECHT, OP GEZAG VAN DE RECTOR-MAGNIFICUS DR. V. J. KONINGSBERGER, HOOGLERAAR IN DE FACULTEIT DER WIS- EN NATUURKUNDE, VOLGENS BESLUIT VAN DE SENAAT DER UNIVERSITEIT TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER GENEESKUNDE TE VERDEDIGEN OP DINSDAG 2 JUNI 1953, DES NAMIDDAGS TE 4 UUR

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GERRIT ANTHONIE HOOGLAND
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PROMOTOR: PROF. DR. A. A. J. VAN EGMOND

Aan de nagedachtenis van mijn vader.
Aan mijn moeder.
Aan mijn vrouw en kinderen.

Bij het verschijnen van dit proefschrift betuig ik U, Hoogleraren, Oudhoogleraren en Docenten van de Medische en Natuur-Philosophische Faculteiten van de Rijksuniversiteit te Utrecht, mijn dank voor het van U ontvangen onderwijs.

Hooggeleerde *van Egmond*, Hooggeachte Promotor, het is mij een groot voorrecht geweest enige jaren onder Uw leiding te mogen werken. De wijze waarop Gij steeds het verband legt tussen de kliniek en de theoretische onderdelen van de geneeskunde zijn voor mij bepalend geweest bij de keuze van mijn specialisme. Naast de zuiver practische opleiding, waarbij Uw grote ervaring ons als jonge assistenten steeds weer te hulp kwam, wist U onze belangstelling voor de wetenschappelijke problemen te wekken en te leiden. Bij de bewerking van dit proefschrift gaf U telkens blijk van grote belangstelling — nooit was het U te laat om een experiment mede te maken — en Uw critiek was steeds aanleiding de inzichten te verdiepen.

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Uw critisch beschouwen van medemens, ziektegeval, theoretisch probleem en eigen handelen zal ik steeds trachten voor ogen te houden.

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CONTENTS

The missing fundamental is a subjective tone heard when under certain conditions a complex of harmonic tones, with a constant frequency difference between the components, is presented to the ear. The pitch attributed to this complex is equal to that of a tone having a frequency equal to the "frequency difference" (fundamental). As such a frequency, though perfectly audible, is absent in the complex, it is called "the missing fundamental". (Stevens & Davis, Hearing, 1948)

CHAPTER I

INTRODUCTION

The frequency-analysis, the perception of pitch, of the organ of hearing has been the subject of profound investigations for more than a hundred years. Numerous theories have been given about this subject. Even today this problem has not been solved completely.

In the last decennia the mechanism of the cochlea has been observed and calculated. The results of both these approaches are in agreement: it appears that the cochlear duct, when stimulated by a pure tone, has a whiplike motion, increasing in amplitude from stapes footplate to a maximum, after which follows a sharp fall. There are several indications that the area of the organ of Corti which is stimulated by the quickly decreasing movement is responsible for the subsequent pitch perception.

This is strictly a place-theory: the centre of the area determines the pitch of the tone. Every other place on the organ of Corti, higher up or lower down the cochlea, when stimulated, would cause another pitch to be heard.

At this moment there are still other theories, which more or less state, that pitch is not so strictly correlated to a certain place in the organ of Corti, but that the frequency as such is introduced into the neural elements and is thus transmitted to the brain (Pulse- or Volley-theory) *Wever* (1949).

If a complex sound is considered as a whole and the resulting amplitude-envelope is observed, it may be possible, that, if all the components of this complex were very near to each other in frequency, only a small part of the cochlea would be stimulated. According to these theories, this stimulation would not be constant but would almost pulsate in the rhythm of the envelope of the complex, the cochlea lacking the necessary power of analysis. From this small stimulated area, the action potentials would be sent to the brain more or less in numbers per second, fluctuating with the mentioned rhythm and the observer would attribute two sensations to this kind of stimulation:

1. a high sharp sound, caused by the components;
2. a low pulsating sound, caused by the interference of the components;

this should be the replica of the envelope.

Consequently it is of interest to find some means to ascertain whether a strict place-theory or a pulse-theory, even in a mitigated form, is valid for the organ of hearing. Secondly the question should be answered, how far the conditions for mutual interference of neighbouring components in a small area of the organ of Corti really have been present in the experiments which gave rise to the "pulse"-theories, e.g. the residue-theory (*Schouten,* 1939, 1940).

The controversy between the theories can be exposed most clearly in the "case of the missing fundamental". The two points of view, place-theory as supported by *Fletcher* (1933) and pulse-theory (*Wever*), the here specially mentioned residue-theory of *Schouten,* can be confronted most sharply, as both authors published their experiments extensively on this same subject of the missing fundamental.

As the experiments were not conclusive it was attractive to try another approach in the same field, which has led to this thesis. First a historical survey will be given. Then the theories of *Fletcher* and *Schouten* will be discussed.

A new method of investigation is developed trying to carry the phenomena to the extreme. The results appear to point out, that a place-theory of frequency-analysis is the most probable solution for the organ of hearing.

CHAPTER II

HISTORICAL SURVEY

The subject of the missing fundamental belongs to the chapter of the combination tones. The first to write a treatise on the combination tones was *Tartini* (1714). He observed, when playing two tones together on a violin, a low tone, which appeared to be the difference tone between these two.

Seebeck (1841) using a siren with two disks with holes heard a low tone with an astonishing loudness beside the two tones generated by the siren. He could not explain the presence of this extra-tone by *Ohms* principle of frequency analysis. Later on *Helmholtz* (1863) explained the phenomena mentioned by assuming an alinear element in the sound conduction mechanism of the ear. Then distortion is responsible for all kinds of combination tones, as he pointed out in his famous book: "Die Lehre von den Tonempfindungen". *Stumpf* made an analysis of speech sounds and, based on the work of *Helmholtz*, explained the low pitch of vowels, which have not much energy in the low frequencies, by the distortion principle, which would introduce a strong low tone component.

In 1933 *Fletcher* published an article on the perception of complex tones. The instrument, producing this sound, was an optic siren, consisting of a number of glass disks (10), mounted on one axis, driven by a motor. A sinusoidal curve, drawn on a large scale in polar coordinates had been photographed; the reproduction on the glass disk showed a camwheel-like structure, the teeth having the sinus-form in polar coordinates with a high degree of accuracy. Each disk was illuminated at one side with a lamp; on the other side a photoelectric cell collected the light which passed through the teeth. If the disk was rotated with a constant speed, the fluctuations of the voltage across the photoelectric cell were purely sinusoidal. The signal was then amplified.

To prevent slight phase-inconstancies caused by an excentric mounting of the disk, a narrow electric filter was used in the amplifier, which maintained the constancy of the phase and reduced the harmonic content so that a pure tone resulted.

The number of teeth on a disk and its speed determined the frequency of the tone thus generated. With an arrangement of ten disks, the instrument allowed the production of a fundamental and nine of its harmonics, each of which could be adjusted in intensity.

Fletcher demonstrated that if the fundamental (number 1) was left out, the rest (no. 2, 3, 4, 5, 6, 7, 8, 9), if produced together, gave the fundamental with a great loudness. If the loudness of each harmonic, taken separately, was adjusted to be equal to that of the fundamental, the complex in total would give a loudness, equal to the sum of the individual loudnesses. Loudness is an additive phenomenon, provided that the components are not too near to each other (5 %). A complex consisting of no. 1, 3, 5, 7, 9 gave the octave of the fundamental, so would a complex with no. 2, 4, 6, 8, 10. These two complexes sounded together gave the fundamental again.

The pitch of the complex is determined by the frequency difference; its loudness is the sum of the individual contributing loudnesses of the components. "The peculiar phenomena of loudness are no doubt principally due to the ear acting as an analyzer separating the components having different frequencies in such a way that they produce stimulations on different sets of nerves."

Schouten too made use of an optical apparatus (optic siren) for the production of sound of any prescribed wave form. The principle of this arrangement is as follows:

one period of the desired wave form is drawn in polar coordinates on stiff paper and cut out as a diaphragm. A homogeneous beam of light is sent through this diaphragm and scanned by a rotating disk with slits and finally transformed into sound by means of a photoelectric cell, amplifier and loudspeaker.

By changing the wave form in the diaphragm it is possible to suppress a fundamental or any combination of harmonics in a complex sound.

Schouten developed a theory — residue-theory — in which he suggests that in a complex of harmonics, without a fundamental, this same fundamental is still heard because of interference of the high components, causing a pulsation in the rhythm of the fundamental. The perception of this "missing fundamental" should take place in the area of the organ of Corti stimulated by the mutually interfering high tones.

"In a periodic sound the higher harmonics cannot be perceived separately as pure tones but are perceived collectively as *one* component of sharp tone quality: the *residue*. The pitch of the residue is equal to that of the fundamental tone."

According to *Schouten* the missing fundamental does not beat with a pure tone of approximately the same frequency.

CHAPTER III

PROBLEM

The contradictory conceptions of *Fletcher* and *Schouten* concerning the missing fundamental deserve a closer inspection. *Fletcher's* theory was fundamentally a place-theory whereas *Schouten* gave a dual meaning to the function of the sensory cells in the organ of hearing i.e.:

1. there is a place-theory;
2. each sensory cell-fibre-cortex-unit is able to respond to every stimulating *rhythm* and attribute a special pitch to it.

If *Schouten's* residue theory is right then a complex of high tones tuned to a constant difference of frequency and phase would always cause a fundamental to be heard at whatever level the complex should be presented. The perception of the said fundamental should take place in the same area where the complex stimulated the organ of Corti. The perception of the fundamental should then be ascribed to an insufficient analysis of the high tones by the organ of hearing.

The mentioned experiments of *Fletcher* and *Schouten* are in some respects different from ours. Both investigators used a harmonic overtone structure from which the fundamental has been removed afterwards. The overtones are always multiples of the fundamental.

In our experimental arrangement the components need not be multiples of the difference tone, because all components are individually generated. As it is of interest to avoid mutual masking of difference tone and complex we chose a complex in the 3000 cps-band whereas the difference tone was in the range between 60 and 150 cps.

As an exception we once used a difference tone of 500 cps.

This combination of a very high tone complex with a low frequency of the difference tone cannot be accomplished by the method of *Schouten*. We think this a very valuable point in establishing the true background of the "case of the missing fundamental".

It is the purpose of this work to ascertain whether *Fletcher's* or *Schouten's* view is valid.

CHAPTER IV

METHOD

If one wants to solve this problem one has to avoid the possible errors inherent to the method. One of the chief errors would be the introduction of the difference tone in the high tone complex by a slightly alinear element in the apparatus, so that the complex already contained a difference tone when presented to the test subject. To avoid this difficulty a combination of independent frequency generator-loudspeaker-units was used here.

With a sound level meter and filter combination [1]) which allowed the measurements of intensities as low as 8 db above 2×10^{-4} dyne/cm^2 it was checked that the fundamental was absent in the high tone complex as presented to the test ear at a level of 95 db re 2×10^{-4} dyne/cm^2 of the components.

Figure 1 shows the arrangement. The independent frequency generators — number I—V — feed 5 separate loudspeakers, which are framed together with 2 spare loudspeakers in a rosette-like stand so giving a slightly conical sound field.

The frequency difference meter can be connected to a pair of generators (in fig. 1 connected to II and III) allowing a direct reading of the frequency difference in cycles per second. To check this reading and to ascertain the phase constancy the frequency difference meter is coupled to an oscilloscope

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[1]) This highly sensitive instrument was a grant from the Foundation of Pure Scientific Research (Stichting voor Zuiver Wetenschappelijk Onderzoek) in the Netherlands.

whose time-base is fed by a standard frequency generator. The latter feeds also a loudspeaker for the "best beat method" (explained later on).

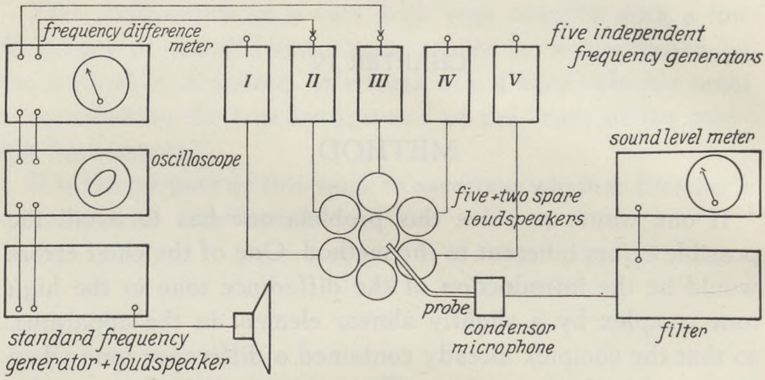


Figure 1.
Arrangement. Description in text.
See appendix.

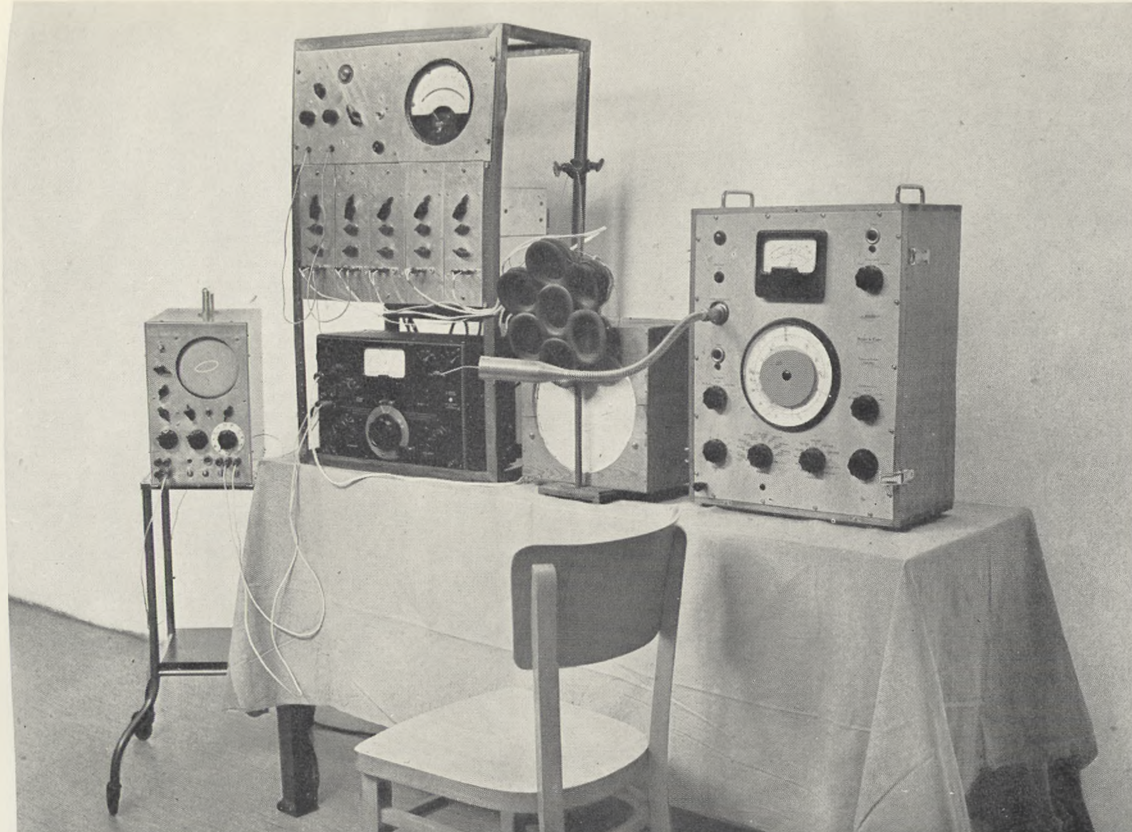
The test subject was placed with the ear to be tested about 30 cm from the rosette. A condensor microphone with probe was put near the external meatus to measure the sound level, which entered the ear, by means of a sound level meter and filter system.

The frequency characteristic of the probe (fig. 2) was taken into account in the following measurements. All figures imply a correction for use of this probe.

The maximum output of the speakers near 3000 cps amounted to about 95 db each at a distance of 30 cm from the rosette.

Tuning of the frequency generators.

To explain the tuning of the apparatus an example is given: I is tuned to 3000 cps in comparison to the standard generator. Output 65 db re 2×10^{-4} dyne/cm^2 at 30 cm distance.



Experimental arrangement.

From left to right:

1. Oscillograph.
2. Frequency difference meter (top).
   5 frequency generators (middle).
   Standard frequency generator (bottom).
3. Rosette of loudspeakers.
   Behind rosette loudspeaker of the standard frequency generator.
   In front of rosette condensor microphone with probe.
4. Frequency analyser (sound level meter with filter combination).

Then II is tuned to 3100 cps and equal output. The difference of 100 cps is read on the frequency difference meter connected with I and II and controlled by the oscilloscope.

I is disconnected and III is tuned 100 cps higher than II (3200 cps) and so on.

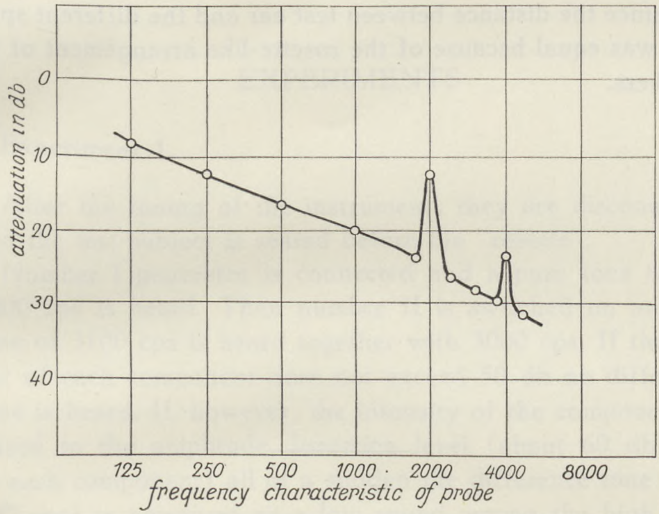


Figure 2.

Frequency characteristic of the probe.

After this tuning the high tone complex is controlled by the ear whether there are no beats present. Beats would point to a shift in phase or frequency which has to be corrected before the actual experiments begin.

The apparatus we used showed an extremely low drift and could be adjusted precisely. For practical reasons the number of units has to be restricted. Five, and with much care, six units can be so worked together that the phases do not change appreciably. With more units the guarantee of relative phase constancy of all the components becomes questionable.

Control of phase constancy was made from the output of the generators by means of the frequency difference meter and oscilloscope and not from the actual sound delivered by the speakers. However, the phase differences between the speakers may be assumed to be equal, since the speakers were selected with care as to uniformity in frequency characteristics and since the distance between test ear and the different speakers was equal because of the rosette-like arrangement of the speakers.

CHAPTER V

EXPERIMENTS

Experiment 1.

After the tuning of the instruments they are disconnected and the test subject is seated before the "rosette".

Number I generator is connected and a pure tone of e.g. 3000 cps is heard. Then number II is switched on and the tone of 3100 cps is heard together with 3000 cps. If the output of each component does not exceed 50 db no difference tone is heard. If, however, the intensity of the components is raised to the amplitude distortion level (about 60 db level of each component) all of a sudden the difference tone (here 100 cps) is perceived as a low sound among the high components. Since the difference tone is formed in the ear and is not actually present in the room its loudness can not be measured directly. But the loudness of this difference tone (fundamental) can be compared with the loudness of a pure tone from the standard frequency generator. This may be done by two methods:

1. comparing alternately standard sound source and difference tone;
2. best-beats between these two.

Since no significant differences in results were found in these two procedures the latter one, judgment of beats, was used generally, being the more convenient method.

The value of the best-beat-method was recently discussed by *Warren, Egan* and *Klumpp* (1951). Mistakes in loudness judgments are to be expected only if the harmonic under examination is near threshold, and if it is influenced by neighbouring frequencies.

As the difference tone in our experiments was mostly well above threshold and there were no other frequencies in its vicinity, the second harmonic being well outside critical bandwidth, no difficulties may be expected for the loudness judgments.

So when the difference tone was distinctly heard a pure tone from the standard unit, tuned some cycles higher or lower, was presented to the test ear simultaneously, the output being adjusted until the beats were best heard. At this moment the loudness of the standard tone was measured by the sound level meter — it then being equal to the loudness of the difference tone. The band pass filter of the sound level meter excluded entirely the high tone complex.

Conclusion.

We conclude from this experiment with 2 units that a difference tone is perceived only if distortion level has been reached. The loudness of the difference tone is measured by an indirect method. These results agree very well with those given by *von Békésy* (1934) and *Newman* c.s. (1937).

The distortion of the sound conducting system, consisting of middle ear and cochlea, has been the subject of various investigations. The most important examinations have been done by *von Békésy* (1934) whose results have been confirmed and completed by *Newman* c.s. (1937) and *Stuhlman* (1937). The distortion of a pure tone as a function of its intensity is given in fig. 3, by demonstrating quantitatively the presence of the harmonics as measured with the method of best beats.

Whether the distortion takes place in the middle ear, in the suspension of the stapes footplate or in the cochlea itself is beyond the scope of this paper, as it is of no importance to the object of our investigation i.e. the presence of the difference tone.

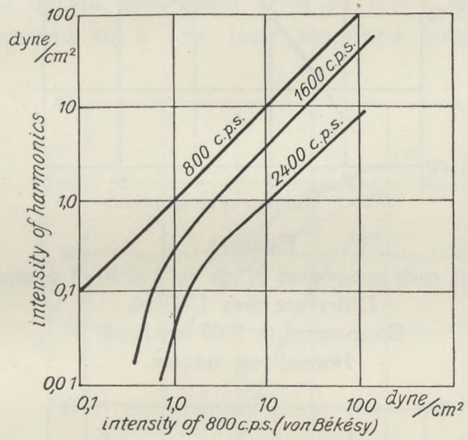


Figure 3.

Distortion of the ear.

In the next experiment the 3rd unit is brought into action, its output being adjusted to the same level (e.g. 65 db) as of the units I and II.

Comparing the loudness of the fundamental from three units to that of two — intensity of the components being the same — it appears that a normal addition has taken place i.e. the loudness of the fundamental of three units is two times that of two units. With four units — intensity and phase properly adjusted — the fundamental is found to be three times louder than in the case of two units, and so on.

We have already mentioned that for practical reasons the number of units has to be restricted to five. In addition there

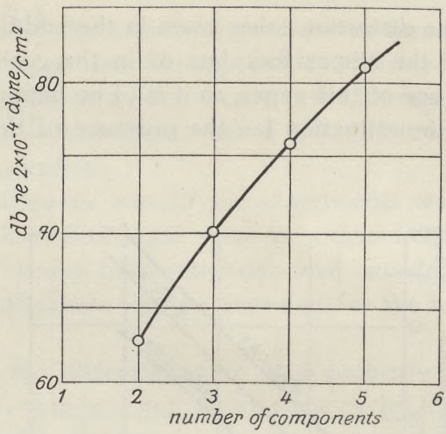


Figure 4.

Level of each component 97 db re 2×10^{-4} dyne/cm^2.

Difference tone 100 cps.

Components in 3000 cps-band.

Normal test subject.

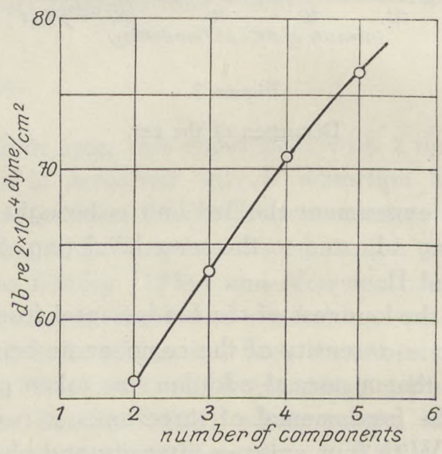


Figure 5.

Level of each component 74 db re 2×10^{-4} dyne/cm^2.

Difference tone 68 cps.

Components in 3000 cps-band.

Normal test subject.

can be said that the loudness gain by changing over from 5 to 6 units is too small to be of further importance.

Conclusion.

Increase of the number of components gives an increase of the loudness of the difference tone by simple addition. It is possible to obtain best-beats with as many as five or six units, compared to a low tone standard frequency sound source.

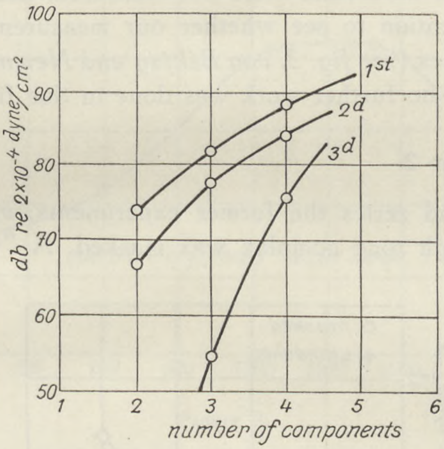


Figure 6.

Level of each component 92 db re 2×10^{-4} dyne/cm^2.
Difference tone 110 cps.
Components in 3000 cps-band.
The measurements of the second and third difference tones are given too.
Normal test subject.

The same experiments with normal test subjects were repeated for several difference tones and intensities as shown in the figures 4 and 5. [1])

As the difference tone appears to be a distortion phenome-

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[1]) Each point is an average of four measurements. Mean error about 2 db.

non, it is of interest to measure the loudness of the multiples of that difference tone too. In fig. 6, the results are given of such a measurement. It should be noted, that a second harmonic is clearly heard if two components at a level of 92 db are presented. The third harmonic could not be heard. However with three components, the third harmonic was just distinguishable and was judged to have a loudness equal to a 330 cps tone of an intensity of 54 db re 2×10^{-4} dyne/cm^2.

The higher harmonics were not measured, because it only was our intention to see whether our measurements agreed with older ones (*see fig. 3, von Békésy* and *Newman*). As this was the case no further work was done in this field.

Experiment 2.

In a second series the former experiments were repeated while the high tone complex was masked. A "white noise"

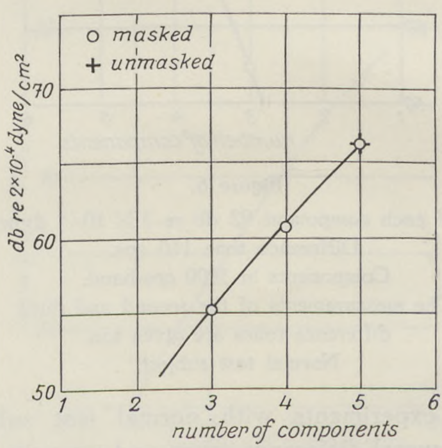

Figure 7.

Components in 3000 cps-band.
Difference tone 80 cps.
Level of components 79 db re 2×10^{-4} dyne/cm^2.
Noise level overall 85 db.

source was led through a high pass filter so that low tones (under 1000 cps) were attenuated. The high tone complex could be masked sufficiently by this "filtered white noise" while the low difference tone was heard as if no masking were present (fig. 7 and 8).

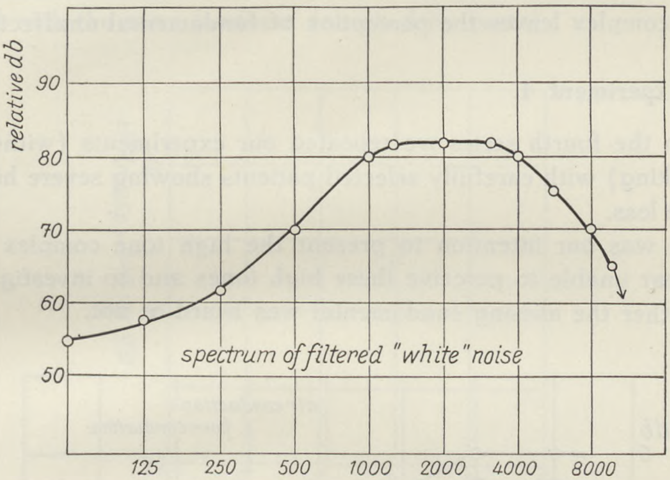

Figure 8.

Measured with a frequency-analyser, bandwidth 20 db/octave.

Conclusion.

While the area of the high tone complex in the organ of Corti was "disturbed" by the white noise masking, the perception of the low difference tone took place quite regularly.

Experiment 3.

Apart from these experiments with masking we noticed in our first series of experiments a fatiguing effect of the high tone complex if the time of exposure was considerably extended. (Artificial loudness dip) cf. *J. D. Hood,* 1950.

After having been exposed to a loud complex for 10 minutes, the fundamental is still heard with its initial loudness, whereas the loudness of the complex is considerably decreased even so far that it almost submerges in the volume of the fundamental.

We conclude that extenuation of the stimulated area of the complex leaves the perception of fundamental unaffected.

Experiment 4.

In the fourth series we repeated our experiments (without masking) with carefully selected patients showing severe high tone loss.

It was our intention to present the high tone complex to an ear unable to perceive these high tones and to investigate whether the missing fundamental was heard or not.

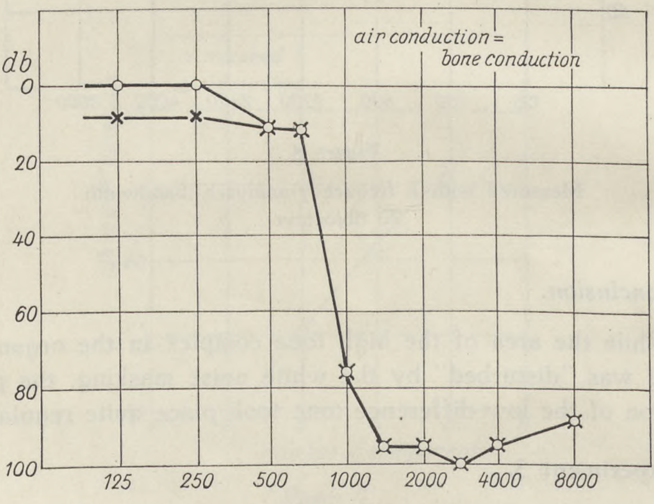

Figure 9.

Audiogram. Patient v. d. B., male, age 54.
o right ear.
x left ear.

The audiogram of Patient B shows an abrupt fall at 1000 cps, whereas the perception in the low tone range (100 cps) is normal.

Patient B did not hear any component when presented separately or in combination, but he heard the difference tone appear at the same level as a normal test subject would do, and with the same loudness (checked by beats).

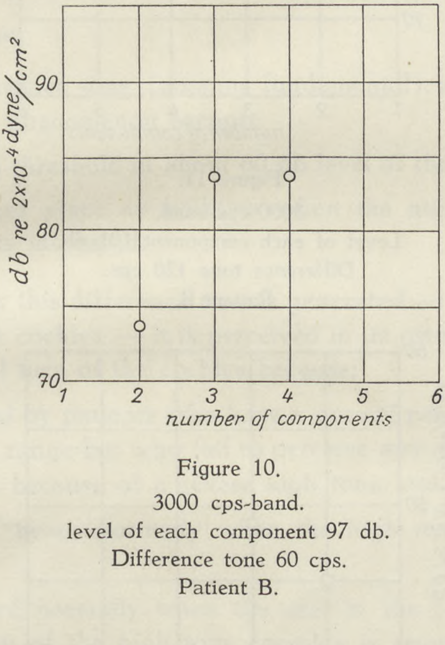

Figure 10.
3000 cps-band.
level of each component 97 db.
Difference tone 60 cps.
Patient B.

This was examined for several difference tones (60, 120, 500 cps), (fig. 10, 11 and 12).

In two other patients with abrupt high tone loss — though not so abrupt as in case B — we obtained analogous results.

Owing to the difficulties of loudness judgment it was not possible to obtain actual data in these cases. Only the first appearence of the fundamental was observed for 2, 3, 4 and 5 components.

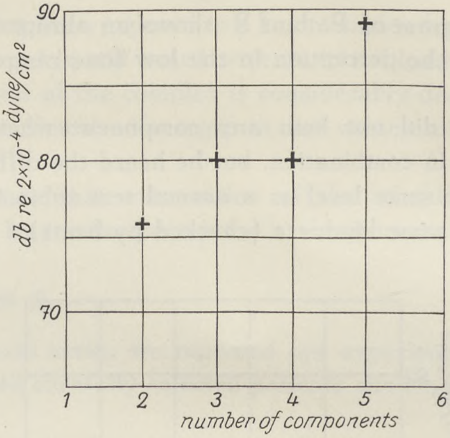

Figure 11.
3000 cps-band.
Level of each component 101 db.
Difference tone 120 cps.
Patient B.

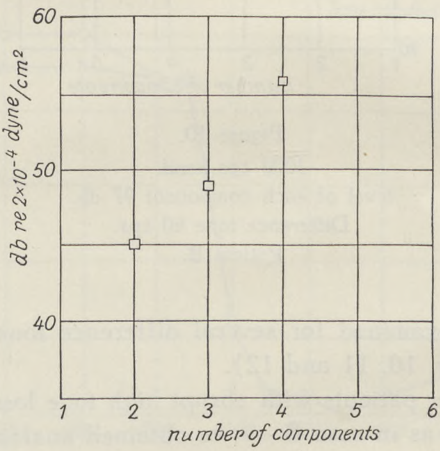

Figure 12.
3000 cps-band.
Level of each component 77 db.
Difference tone 500 cps.
Patient B.

Sometimes it was necessary to shift the component band from 3000 cps up to 4000, 5000 or 6000 cps, owing to the type of hearing loss of the patient. As to its first appearance, the fundamental was always heard by these patients in the same way as by normal test subjects.

From these experiments we conclude that the perception of the missing fundamental has nothing to do with the perception of the high tone complex.

Conclusion.

The difference tone (missing fundamental) appears to be a distortion phenomenon because

a. there is a threshold at about 60 db level of the components;

b. there takes place an addition when the number of components is increased.

Wherever this difference tone is generated — in the middle ear or in the cochlea — it is perceived in its own proper place in the apical turn of the cochlea because:

a. it is heard by patients who have a normal perception in the low tone range but who fail to perceive any stimuli beyond 2000 cps because of a severe high tone loss;

b. it is still heard normally when the high tone complex is masked;

c. it is heard normally when the area in the cochlea of the perception of the high tone complex is severely fatigued;

d. it will beat with a pure tone tuned some cycles higher or lower.

CHAPTER VI

DISCUSSION

With the results of our experiments in mind we may now return to *Schouten's* residue theory.

We have to assume that an alinear element in the apparatus of *Schouten* is responsible for his results. The difference tone, which should not have been present in the objective sound complex, must have been there. If *Schouten* failed to find it in the sound presented to the listeners ear, this failure may be explained by the procedure of the measurement by a filter system which does not respond properly to a tone of which the phase changes continually.

The phase changes too quickly for the response of the filter but slow enough for the ear to produce the difference tone, which gets a hissing character due to the phase changes.

The same inconstancy of phase may be held responsible for the failure to produce beats between the missing fundamental and a standard tone a few cycles higher or lower.

The procedure of *Schouten*, where a disk from which slits have been cut out rotates in front of a diaphragm with the form of a sine wave in polar coordinates, is liable to introduce inconstancy of the phase of the difference tone, especially in the higher components.

As *Fletcher* considered it necessary to insert an electric filter after each disk-photoelectric cell-unit to suppress phase-inconstancy and overtones, it seems that an optic siren always introduces these undesirable secondary phenomena.

As a matter of fact one of the most difficult parts in the tuning of our instrument was to keep a constant phase relation between the components of the high tone complex. But the smallest inconstancy of phase was noticed immediately on the oscilloscope. This control is not possible in *Schouten's* arrangement.

We therefore suggest that *Schouten* did not take the necessary precautions in the production of the tone complex; his results leading to the "residue-theory" are likewise questionable.

Besides, *Schouten* (1940, 3) notes that the analysing power of the cochlea is not sufficient to separate stimulation of the 10th—20th harmonics of a 200 cps tone. However, these harmonics (2000, 2200, ... 3800, 4000 cps) are outside one another's critical bandwith, which according to *Fletcher* (1938) is less then 5 % in this region of the basilar membrane. So there is no reason why these high harmonics should not be distinguished separately.

In some of our experiments we chose the difference tone so low that the high tone components were crowded in *one* critical bandwith. This did not at all interfere with the formation of the missing fundamental if the output only reached the distortion level.

On the other hand our experiments are in strict concordance with the conception of *Fletcher*. As we pointed out before we tackled the problem from another angle, building up a complex tone with separate components whereas *Fletcher* used a harmonic overtone structure from which the fundamental and lower harmonics were removed.

While *Fletcher* did not go beyond the 10th harmonic, it was possible with our apparatus to build a high tone complex consisting of (e.g. the 30th—35th harmonic, thus eliminating possible sources of error introduced by vicinity of the area of the fundamental and the area of the components.

CHAPTER VII

CONCLUSION

We may now reconsider our results and see what they imply.

1. The missing fundamental (difference tone) is originated in the ear as a distortion phenomenon. This was proved by the fact that the difference tone was only heard when distortion level was reached by the components and that a loudness addition of the fundamental took place when the number of components was increased.

2. The perception of the difference tone takes place on its own proper area in the organ of Corti (apical turn) and not in the region of the high tone complex, as was proposed by *Schouten*. This followed from the experiments with beats, masking and fatigue of the high tone complex and patients with high tone loss.

The perception of the high tones has nothing to do with the perception of the missing fundamental. We may look upon the high tone complex solely as the carrier of the difference tone, the latter being revealed by the alinear system of the ear. That is the only relation existing between the difference tone and the components.

It is concluded that the difference tone and the high tone components are perceived according to a strict place theory.

SUMMARY

The phenomenon of the missing fundamental (difference tone) was investigated by a new procedure. By means of five separate frequency generator-loudspeaker-units, mutually tuned to a constant frequency difference, a high tone complex was generated.

With proper adjustment of the instrument — chapter IV — it is possible to hear a difference tone (missing fundamental).

The following results were found:

a. The loudness of the difference tone — as measured by the method of best beats — increases with the number of high tone components.

b. The difference tone is originated in the ear as a distortion phenomenon.

c. The difference tone is heard unaltered if the area of the organ of Corti, in which the perception of the high tone complex takes place, is fatigued, masked or absent.

These experiments suggest a strict place theory of frequency analysis in the organ of Corti and corroborate the findings of *Fletcher, von Békésy* and others. *Schouten's* residue theory seems to be improbable.

SAMENVATTING

Het verschijnsel van de „missing fundamental" (verschiltoon) werd onderzocht met een nieuwe methode. Door vijf afzonderlijke frequentie-generator-luidspreker-toestellen, onderling afgestemd op een constant frequentie-verschil, werd een hoge tonen-complex opgewekt.

Wanneer het instrument goed is afgestemd — (hoofdstuk IV) — is het mogelijk een verschiltoon te horen.

De volgende resultaten werden verkregen:

a. De luidheid van de verschiltoon — gemeten met de methode van de „optimale zweving" — neemt toe met het aantal van de hoge toon-componenten.

b. De verschiltoon ontstaat in het oor als een distorsie-verschijnsel.

c. De verschiltoon wordt onveranderd gehoord, indien het gebied in het orgaan van Corti, waar de perceptie van het hoge toon-complex plaats vindt, vermoeid, gemaskeerd of uitgevallen is.

Deze proefnemingen wijzen op een strenge plaats-theorie voor frequentie-analyse in het orgaan van Corti en bevestigen de uitkomsten van *Fletcher, von Békésy* en anderen.

De residu-theorie van *Schouten* lijkt onwaarschijnlijk.

RÉSUMÉ

Le phénomène du son fondamental absent (son différentiel) a été examiné selon une nouvelle méthode. Au moyen de cinq unités de générateur de frequences-hautparleurs différentes, accordés avec une différence constante de fréquence, un complexe de sons aigus était crée.

Après avoir ajusté l'appareil (chapitre IV), il était possible que l'ouïe saisisse un son différentiel.

Les résultats suivants étaient obtenus:

a. L'intensité du son différentiel — mesurée par la méthode des battements optimaux — s'accroît avec le nombre des composants aigus.

b. Le son différentiel est excité comme phénomène de distorsion dans l'oreille.

c. Le son différentiel est percu inaltéré si la zone de l'organe de Corti affectée par les sons aigus, est fatiguée, assourdie ou absente.

Cette expérimentation démontre une théorie d'analyse des fréquences comme vibration localisée dans l'organe de Corti et confirme les résultats de *Fletcher, von Békésy* et d'autres. La théorie de résidu d'après *Schouten* paraît invraisemblable.

ZUSAMMENFASSUNG

Das Fenomen der „missing fundamental" (Differenz-ton) wurde untersucht mit einer neuen Methode. Mittels fünf verschiedenen Frequenz-Generator-Lautsprecher-Einheiten, abgestimmt auf fünf verschiedene Frequenzen mit konstanten Differenzen, wurde ein Hochtonkomplex erzielt.

Durch genaue Reglung des Instrumentes (Kapittel IV) ist es möglich ein Differenzton hörbar zu machen.

In dieser weise wurden untenstehende Resultate gefunden:

a. Die Lautheit des Differenztones — gemessen mit der Methode der optimalen Schwebungen — nimmt zu mit der Anzahl der Komponenten.

b. Der Differenzton entsteht im Ohre als Verzerrungs-Erscheinung.

c. Der Differenzton wird unveränderlich gehört wenn derjenige Teil des Cortischen Organes, wo die höhen Töne perzipiert werden, ermüdet, maskiert wird oder gar nicht funktionniert.

Die Versuche unterstützen eine exakte Lokalisationstheorie der auflösung der Frequenz im Cortischen Organe, und sind in Übereinstimmung mit den Befunden *Fletcher's, von Békésy's* und Anderen. Die Residü-theorie *Schouten's* erscheint als unwahrscheinlich.

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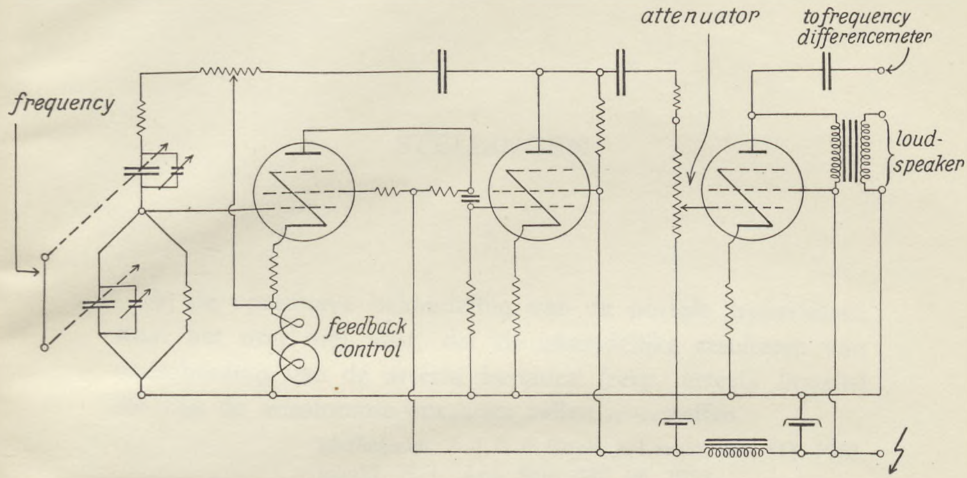
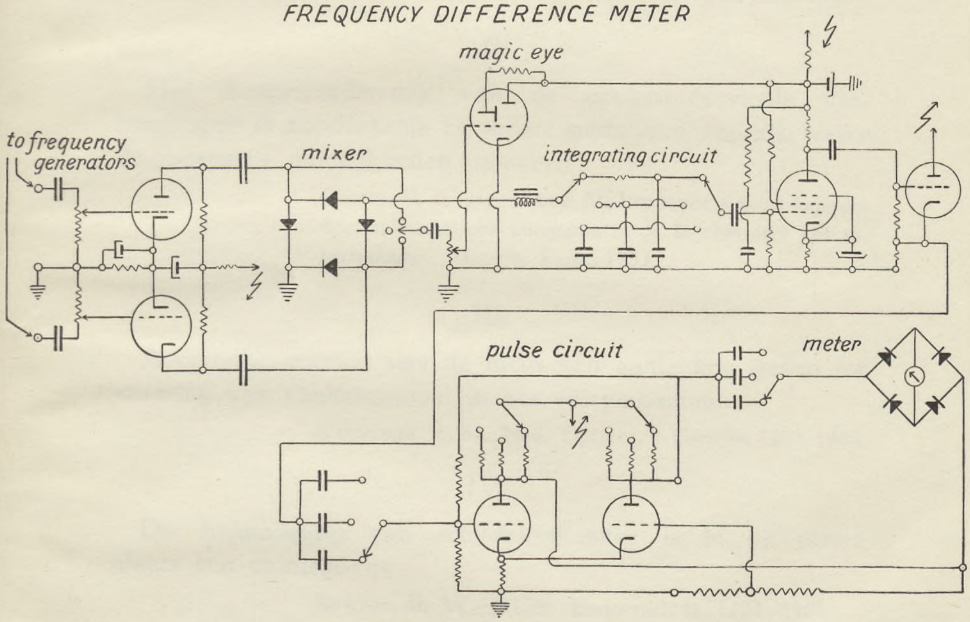
APPENDIX

FREQUENCY GENERATOR



FREQUENCY DIFFERENCE METER



The frequency generators and frequency difference meter were built in the laboratory of the University Clinic of Otorhinolaryngology at Utrecht.

STELLINGEN

I.

Bij de operatieve behandeling van de portale hypertensie staat het nog niet vast, dat de uiteindelijke resultaten van onderbinding van de arteria hepatica (resp. arteria lienalis) die van de anastomose-operaties zullen overtreffen.

McFadzean, A. J. S. & Cook, J., Lancet, **264**, 615, 1953.
Jahnke, E. J., Ann. Surg. **137**, 98, 1953.
Rienhoff, W. F., Bull. J. Hopkins Hosp., **88**, 368, 1951.

II.

Het röntgenonderzoek van de occipito-cervicale verhoudingen is noodzakelijk bij iedere medullaire stoornis, welke diagnostische moeilijkheden oplevert.

Garcin, R. & Oeconomos, D., Les aspects neurologiques des malformations congénitales de la charnière craniorachidienne, Masson, Paris, 1953.

III.

Aseptische necrose van de incus kan aanleiding geven tot vorming van cholesteatoom in het epitympanum.

Versteegh, R. M., Ned. Tijdschr. v. Gen. **96**, 1258, 1952.

IV.

De behandeling van schildklierkanker is in de eerste plaats een chirurgische.

Rawson, R. W., J. Clin. Endocrin., **11**, 1128, 1951.
id. Surg. Gyn. & Obs., **96**, 118, 1953.

V.

Bij hardnekkige facialis-spasmen is decompressie van de nervus facialis te overwegen.

Woltman, H. W. et al., Proc. Mayo Clin., 26, 236, 1951.

VI.

Men gebruike voor de behandeling van chronische erythematodes atebrine, indien de goud- en bismuth-therapie faalt.

Page, F., Lancet, Oct. 27, 1951.

VII.

Bij de fenestratie-operatie heeft toediening van A.C.T.H. geen invloed op het open blijven van de fistel.

VIII.

Bij de prophylaxis en therapie van retrolentale fibroplasie is de regeling van zuurstoftoediening aan praematuur geboren kinderen zeer belangrijk.

IX.

Onder pathologische omstandigheden kan groeiend mesenchym een dedifferentiatie van epitheel veroorzaken.

X.

Het verdient aanbeveling dat aan de opleiding tot keel-, neus- en oorarts een jaar algemeen chirurgische opleiding voorafgaat.

G. A. HOOGLAND.