# Pitch Related to Spectral Edges of Broadband Signals [and Discussion]

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# Pitch related to spectral edges of broadband signals

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## SUMMARY

A complex tone often evokes a pitch sensation associated with its extreme spectral components, besides the holistic pitch associated with its fundamental frequency. We studied the edge pitch created at the upper spectral edge of complexes with a low-pass spectrum by asking subjects to adjust the frequency of a sinusoidal comparison tone to the perceived pitch. Measurements were performed for different values of the fundamental frequency and of the upper frequency of the complex as well as for three different phase relations of the harmonic components. For a wide range of these parameters the subjects could adjust the comparison tone with a high accuracy, measured as the standard deviation of repeated adjustments, to a frequency close to the nominal edge frequency. The detailed dependence of the matching accuracy on temporal parameters of the harmonic complexes suggests that the perception of the edge pitch in harmonic signals is related to the temporal resolution of the hearing system. This resolution depends primarily on the time constants of basilar-membrane filters and on additional limitations due to neuronal processes.

## 1. INTRODUCTION

Broadband signals with a steep transition in the amplitude spectrum can produce pitch sensations related to the frequency of the spectral edge. These edge pitches have been mostly studied for band-limited noise signals (see, for example, Small & Daniloff (1967); Rakowski (1968); Fastl (1971, 1980); Klein & Hartmann (1981)). Fastl (1980), for instance, measured the pitch strength of low-pass noise as a function of the spectral slope at the cut-off frequency. For an edge frequency of 1 kHz, he found that the pitch strength decreases as the spectral slope was reduced below $-36$ dB per octave. Even for very steep filter slopes, however, the pitch strength associated with noise edges is much lower (more than a factor five) than the pitch strength of a pure sinusoid (Fastl & Stoll 1979).

It has been proposed that the noise edge pitch is due to lateral inhibition in the hearing system (v. Bekesy 1960, 1963; Small & Daniloff 1967). As in the case of optical 'Mach bands', the excitation caused by the stimulus is raised at the spectral edge. This relative maximum in excitation then leads to a pitch sensation.

In the present article, we study pitch effects created at spectral edges of harmonic complex sounds. The main difference between these stimuli and band-limited noise is found in the temporal waveform. Besides periodicity, the waveforms show high-frequency ripples in their fine structure which closely correspond to the spectral-edge frequency. These pure-tone-like parts of the waveform alternate with peaks, and their relative duration within each period depends on the harmonic number of the edge component. This relation is illustrated by the two signals in figure 1, which both have an edge frequency of 2 kHz. The left signal has a fundamental frequency of 100 Hz and the highest harmonic has order 20, whereas for the other signal, with a fundamental of 250 Hz, the order is only 8. Both complexes have a flat spectrum and the components are added in zero phase.

An alternative way to emphasize the spectro-temporal properties of complex tones is a short-time Fourier analysis. Figure 2*a*, *b* shows such an analysis for the two sounds from figure 1. The short-time spectra in both panels are calculated using a Hanning window of 10 ms duration. The time axis, running from front to back, covers approximately 25 ms. The temporal shift between adjacent spectra is 0.5 ms. Figure 2*a* shows the complex with 100 Hz fundamental and reveals two different spectral patterns alternating in time. One is a flat spectrum showing the spectral extent of the complex from 100 to 2000 Hz. This pattern results from those time points where the window is centred on a pulse of the temporal waveform. The other pattern (visible, for example, in the first spectrum) shows distinct maxima at the edge frequencies, slightly amplitude-modulated in time. This pattern results from window positions in between the peaks.

Such an alternating pattern is only seen if the window covers no more than one period of the sounds. In the left-hand panel, the total window length is exactly equal to one period. The effective window duration, however, is shorter due to the raised-cosine ramps of the Hanning window. In figure 2*b* the same calculation is performed for the complex with 250 Hz fundamental. In this case, the window length is 2.5 times the period of the time signal and therefore, the short-time spectra emphasize the individual harmon-

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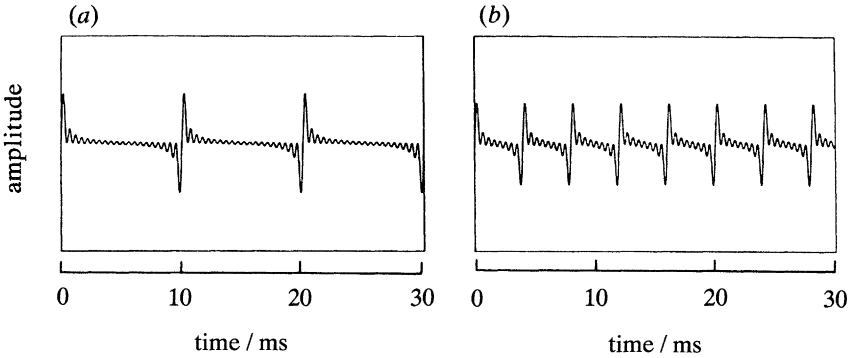

Figure 1. Time functions of two harmonic complexes with an upper-edge frequency of 2 kHz: (*a*) shows a complex with 100 Hz fundamental frequency, consisting of 20 harmonics, (*b*) shows a complex with 250 Hz fundamental and 8 harmonics. All components in the complexes have the same amplitude and zero starting phase.

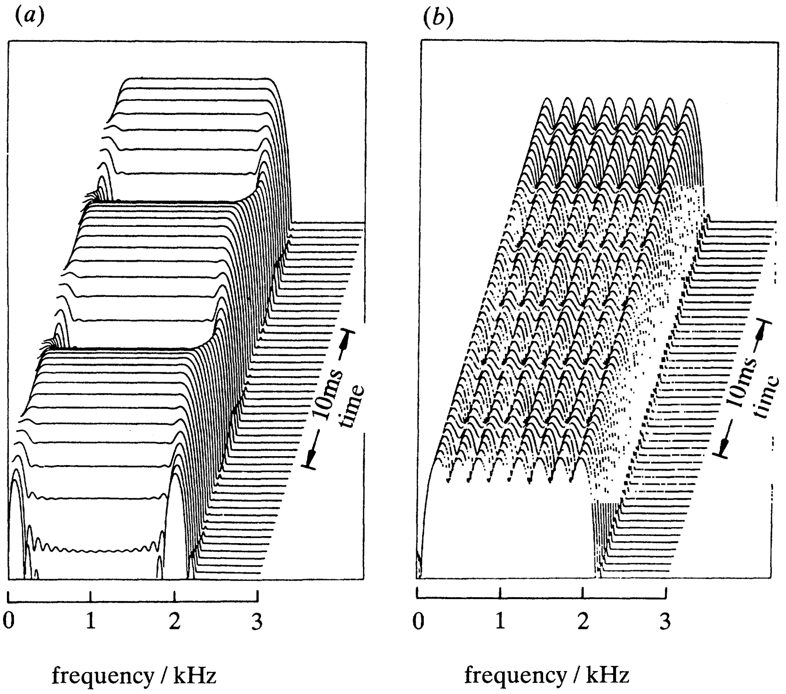

Figure 2. Short-time spectra of the two sounds from figure 1. The spectra are calculated using a Hanning window of 10 ms duration.

ics of the complex. In other words, the creation of a spectral peak at the edge frequency as shown in the left-hand panel of figure 2 will depend on the effective time constants of the analysing system.

Edge-pitch effects of harmonic complexes have been mentioned previously in the framework of complex sound perception by several authors (Martens 1981, Mehrgardt 1982; Patterson 1987; Kohlrausch 1988; Moore & Glasberg 1989). Martens mentioned that for low-pass complexes with a flat spectrum up to 4 kHz, a faint high-frequency tone was perceived, if $F_0$ did not exceed 100 Hz. He compares this effect with the 'tonal quality of low-pass noise' (Martens 1981, p. 235). Moore and Glasberg, on the other hand, remarked that band-limited harmonic complexes create a clear, sine-tone-like pitch, which is perceptually quite different from the pitch created by noise bands. They also provided individual frequency matches to a complex tone with a fundamental frequency of 50 Hz and an upper edge at 1000 Hz. The comparison tone was adjusted on average by the three subjects to frequencies 15 to 75 Hz above the nominal edge. For a complex with $F_0$ equal to 100 Hz and an upper edge at 2 kHz, the average matched frequency was 2.054 kHz.

There are thus some hints in the literature that edge pitches of periodic sounds have sources other than or additional to edge effects of noise bands. The present article investigates how accurately the pitch at the upper spectral edge of harmonic complexes can be matched with a sinusoidal comparison tone. This quantitative measure is then used to determine the existence region of the edge pitch as well as the accuracy of the matches for a wide range of the following parameters: fundamental and upper-edge frequency of the complex, order of the highest component and phase values of the individual components of the complex.

## 2. METHOD

The test sounds consisted of equal-amplitude sinusoids with a common fundamental frequency $F_0$. All components below the upper-edge frequency were present in the complex. The stimuli had a duration of 500 ms and were shaped with 20 ms raised-cosine ramps. They were presented diotically to the subjects via headphones (TDH 49) at an average sound pressure level of 65 dB. Sounds were generated digitally and converted by either a 12-bit or a 16-bit D/A converter at a sampling rate of 10 kHz.

Sinusoidal comparison tones had the same duration (500 ms) and alternated with the test sounds with a 500 ms silent interval in between. The frequency of the comparison tone was adjusted by the subjects with an unmarked ten-turn potentiometer, which controlled the frequency of an oscillator (Philips P5190). The potentiometer received a random offset at the beginning of each new measurement in order to avoid systematic errors. There was no temporal limit for the matching procedure, but a typical match took about 30 s. The finally adjusted frequency was taken as the data point for further evaluation.

Three subjects, among whom were the two authors, participated in the experiments and performed ten matches for each test complex. Within one experimental session, typically seven different complexes were matched five times. In successive matches, different complexes were presented. From the ten matches, the mean and unbiased standard deviation were calculated. Evident mismatches (e.g. octave confusions) were omitted.

## 3. RESULTS

In a pilot experiment the distribution of the matched frequencies for one typical complex and a larger number of matches was examined. The test stimulus was a complex with $F_0 = 100$ Hz, an upper-edge frequency of 2 kHz and zero phases of the components (cf. figure 1*a*). In figure 3, the distribution of matched frequencies is shown separately for the three subjects. All subjects were able to adjust the frequency of the comparison tone within a narrow frequency range of approximately 50 Hz width. The standard deviation is very similar for the three listeners and lies between 11.2 and 12.7 Hz. This corresponds to a relative accuracy of about 0.6%. The means of the matches show a greater variation and lie between 2019 and 2072 Hz. It turned out in the measurements that the shift between nominal and average matched edge frequency depended very much on the individual listener, while the accuracy (spread) of the matches was more similar. On the basis of this initial observation we decided to use the standard deviation of repeated matches as an indication of how clearly the edge pitch could be perceived by the subjects. The data points in the following figures are calculated by averaging the individual spreads of the three observers.

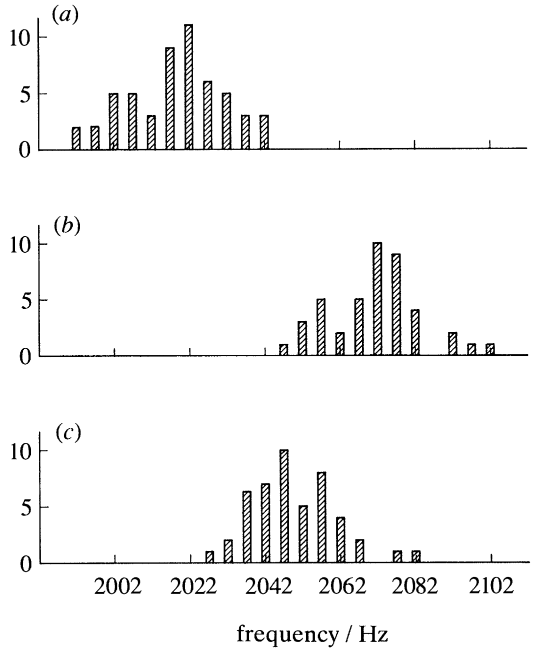

Figure 3. Distribution of matched frequencies for the signal in figure 1*a* with a nominal edge at 2 kHz. The abscissa denotes the frequency of the matches, the ordinate gives the number of matches within a bin of 5 Hz. Individual results for three listeners: (*a*) A.K., $n=54$, $\bar{x}=2019.1$ (12.7) Hz; (*b*) A.H., $n=43$, $\bar{x}=2071.6$ (11.9) Hz; (*c*) N.V., $n=46$, $\bar{x}=2049.3$ (11.2) Hz; $n$ is total number of matches for this sound.

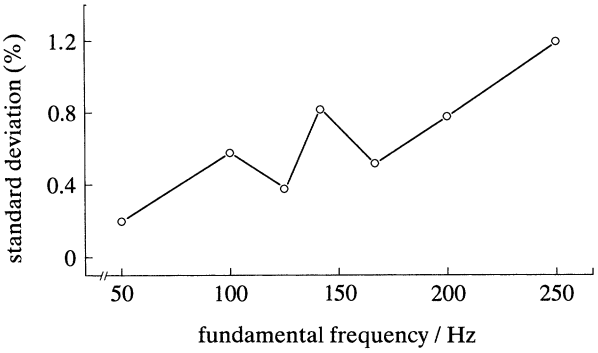

Figure 4. Standard deviation in percent of the edge frequency for complexes with a constant upper-edge frequency of 2 kHz and different fundamental frequencies. Averages of the three listeners.

In the first experiment, a set of test sounds was used having a constant upper-edge frequency of 2 kHz but different values of the fundamental frequency. The fundamental frequency varied between 50 and 250 Hz. Therefore, the order of the highest component decreased from 40 to 8 and the duration of a period decreased from 20 ms to 4 ms. In figure 4, the standard deviation of the matches (as a percentage of the edge frequency) is plotted as a function of the fundamental frequency. For all values of $F_0$, the subjects could clearly hear a pitch related to the edge frequency. The accuracy of the matches, however, decreases with increasing fundamental frequency. The average accuracy for $F_0 = 50$ Hz is about 0.2% and the value at 250 Hz fundamental is about 1.2%. In a purely spectral (or place) view, this increase could be a consequence of the decreasing density of spectral components for higher values of $F_0$. This, however, contradicts the observation with low-pass-filtered noise signals which have the highest spectral density. Typical accuracies for edge pitches of such signals are in the order of several percent (Fastl 1971; Klein & Hartmann 1981). In a temporal view, one has to consider that the increase in $F_0$ leads to a decrease in the period of the waveform. Therefore, if the waveform is analysed with a fixed temporal window, more envelope peaks fall into one window and the high-frequency ripple becomes less prominent.

In the following experiment, the influence of the fundamental frequency was studied for a wider range of edge frequencies. Complexes of three fundamental frequencies were used, namely 50 Hz, 100 Hz, and 200 Hz. The upper-edge frequency was increased in steps of 200 Hz from 600 Hz (800 Hz for 200 Hz fundamental) to 2000 Hz. The results in figure 5 are again plotted as averages over the three observers. The data for 50 Hz are represented by circles, the 100 Hz data by squares and the 200 Hz data by triangles. At all edge frequencies, the 50 Hz complex leads to the lowest standard deviation. The values for these complexes decrease towards higher edge frequencies from about 0.4% to 0.2%. The order of the highest harmonic varies between 12 and 40 and we can thus assume that the edge component is in all cases not resolved.

This is obviously not the case for the two other fundamental frequencies. Thus, for these two data sets the edge frequencies cover a transition region from well resolved (at the left-hand side) to less or not resolved harmonics (at the right-hand side). The accuracy of the match always remains less than for the 50 Hz complex and at frequencies above 1 kHz, the difference is a factor of two or more. The fact that the 50 Hz complex with a period of 20 ms gives rise to a much clearer edge pitch than complexes with a higher fundamental and thus a shorter period, supports the finding from the previous experiment.

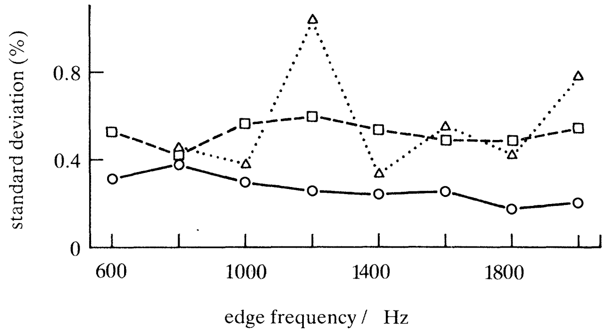

Figure 5. Standard deviation in percent of the edge frequency for complexes with a fundamental frequency of 50 Hz (circles), 100 Hz (squares) and 200 Hz (triangles).

For a comparison with the above-mentioned results from Moore & Glasberg (1989), we should also mention the average shift for the 50 Hz complex with an edge frequency of 1000 Hz. The average matched frequency for the three observers lies 17 to 35 Hz above 1000 Hz. This result is well within the range found by Moore & Glasberg.

As mentioned previously, one important difference between edge pitches of complex tones and of low-pass noises lies in the accuracy of matches to the pitch. If, on the other hand, the edge pitch has a quality very similar to a pure sinusoid – especially at low fundamental frequencies – one might expect the accuracy of matches to come very close to that of pure tones. Unfortunately, literature data for pure-tone matches show a great variety, depending on the specific procedure and subject's training. For the method of adjustment and highly trained subjects, an accuracy of 0.02% to 0.08% has been reportd (Nordmark 1968; Rakowski 1971).

To have a reliable comparison with the complex-tone matches, we performed matches to pure tones and to low-pass noises with the same apparatus and subjects as used in the complex-tone measurements. The sinusoidal stimuli were generated digitally and D/A converted at a rate of 20 kHz. The noise stimuli were generated by an analogue noise generator followed by a digitally adjustable low-pass filter with a spectral slope of 180 dB per octave. These measurements were performed for (edge) frequencies between 1000 and 4000 Hz. In the lower octave, matches were obtained every 200 Hz. In the higher octave, matches were obtained every 400 Hz.

Figure 6 shows the results of these two measurements. Open symbols indicate matches to pure tones and the results must be referred to the left-hand scale. Noise matches are represented by the filled symbols and are referred to the right-hand axis, which has a scale factor of 10. The spread of the pure-tone matches is around 0.1% at 1 kHz, increases slightly above 2 kHz and reaches a value of 0.25% at the highest tested frequency of 4 kHz. Such an increase of the relative accuracy has been reported previously for frequency difference limens (Moore 1974).

As expected from literature data, the noise matches

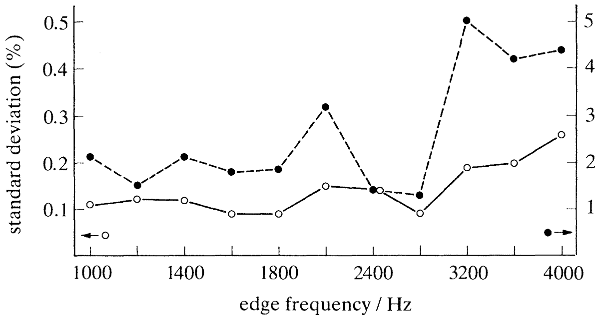

Figure 6. Standard deviation of the matches to sinusoids (open symbols) and to low-pass-filtered noise bands (filled symbols) as a function of the (edge) frequency. The left-hand ordinate has to be used for the pure-tone data and the right-hand ordinate has to be used for the noise data.

are an order of magnitude less accurate. In the low-frequency region, the average accuracy is around 2% and this value increases to 5% at the highest frequency tested. A possible restriction for the noise data could lie in the limited slope at the spectral transition. Although comparable measurements with digitally generated frozen noise (additive synthesis) yielded some improvement over the running-noise conditions, standard deviations were still much larger than those obtained with tone complexes.

If we compare these accuracies with the results from the complex-tone matches, we can conclude that the matches to the 50 Hz complexes are less than a factor of two worse in terms of accuracy than the pure-tone matches. Also, the standard deviations observed for higher fundamental frequencies are still significantly lower than typical values for noise edges. This can be taken as an indication that temporal properties of the complex sounds play an important role in the perception of the edge tones.

To test further the temporal aspects of the edge pitch, in the last experiment we varied the phase values in the complex. A strong phase effect, with an otherwise constant spectrum, indicates the role of temporal effects. The complexes in this measurement had a fundamental frequency of 100 Hz and an upper edge between 600 and 2000 Hz, which was increased in steps of 200 Hz. The choice of phase values was inspired by earlier results from masking experiments, from which conclusions about the internal excitation of the complexes were drawn (Smith *et al.* 1986; Kohlrausch 1988). Besides a zero-phase complex, two complexes with a positive or a negative Schroeder phase were used. The formula for the Schroeder-phase values for a flat-spectrum complex is as follows (Schroeder 1970):

$$\phi_n = \pm \pi * n(n-1)/N. \qquad (1)$$

In this formula, $n$ indicates the order of the individual harmonic and $N$ gives the total number of harmonics in the complex. The resulting temporal waveform for both signs of equation (1) has a relatively flat envelope. However, after transformation in the hearing periphery, the waveform of the '+complex' is transformed into a very peaked waveform which can be even more peaked than the internal waveform of the sine-phase complex (Kohlrausch 1988). One can therefore expect that for this complex the edge pitch is as clearly audible as for the zero-phase complex. The '−complex', on the other hand, has a very flat envelope even after cochlear filtering. Therefore, its edge pitch should be less pronounced.

In Figure 7, we present the results for these three complexes. The different symbols represent the three phase relations of the masker: circles indicate zero phase, open triangles the positive Schroeder phase and filled triangles the negative Schroeder phase. As expected from the results of masking experiments, the positive Schroeder phase leads to results very similar to the zero-phase complex. This similarity is not only observed for the accuracy, but holds also for the subject-dependent shift between nominal and matched frequency (Kohlrausch & Houtsma 1991).

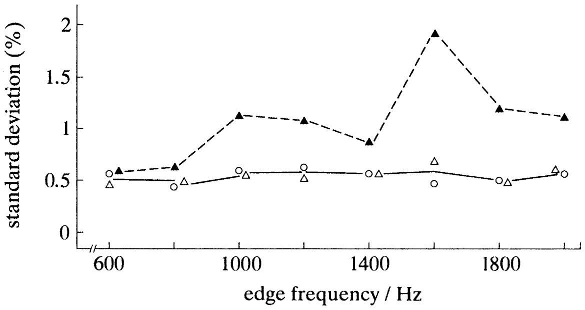

Figure 7. Standard deviation of the matches to complexes with a fundamental frequency of 100 Hz and various upper-edge frequencies. The three symbols indicate different phase choices for the components. Circles: zero phase; open triangles: positive Schroeder phase; filled triangles: negative Schroeder phase. Averages of the three listeners.

Comparing the three curves at different frequencies, the increasing influence of phase effects at higher frequencies becomes obvious. Here, the filled symbols are about a factor two above the open symbols. At the left-most data point, however, the two sets of curves approach each other. The data point at the lowest edge frequency corresponds to an order of six for the edge component. Components of such a low order are generally assumed to be well resolved in the hearing system (Plomp 1976). This means that the interaction between harmonics is minimal and therefore the relative phase between adjacent components should not influence the internal representation (Goldstein 1967).

In summary, the following results were obtained in the pitch-matching experiments: The pitch related to the upper spectral edge in harmonic complex tones can be matched quite well with a sinusoidal comparison tone. The standard deviation calculated from repeated matches appears to be very similar for the three subjects, whereas the average matched frequency differs significantly between subjects (figure 3). For a fixed edge frequency, complexes with a lower value for $F_0$ and thus a higher harmonic order of the edge component create a clearer edge pitch (figures 4 and 5). Matches to complex-tone edges are much more accurate than matches to noise edges. On the other hand, matches to a pure tone are only a factor two more accurate than matches to a complex with $F_0$ equal to 50 Hz (figure 6). The accuracy of the matches depends on the phases of the masker components. This phase effect only disappears, if the edge component has a low harmonic number of 6 or 8 (figure 7).

## 4. DISCUSSION

In this section, we will try to relate the experimental observations to known properties of the hearing system. First of all, the results indicate a large and possibly fundamental difference between the upper edge pitch of harmonic complex sounds and of low-pass-filtered noise. While the noise edge pitch can be matched with an accuracy of several percent, the complex-tone edge pitch, at least for low fundamental frequencies and a high order of the highest harmonic, can be matched with an accuracy well below one percent. This accuracy is similar to values obtained in tone-on-tone matching (see Letowski 1982) and it supports the subjective impression of a pure-tone-like pitch percept, which is superimposed on the virtual pitch related to the fundamental frequency of the complex. As was already mentioned in connection with the time-function plot of figure 1, the broadband waveform contains the edge frequency in the fine structure. It remains to be checked whether this sinusoidal waveform will be present after cochlear filtering.

Because such an analysis has been performed previously by Duifhuis (1970) in the context of a related experiment, we will first recall some of his findings. Duifhuis investigated the percept of periodic pulse sequences with fundamental frequencies 25, 50 and 100 Hz. The spectrum of such a sequence is a series of cosines with constant amplitude and zero starting phase. The task of the subjects was to vary the amplitude of a certain harmonic until the harmonic was just audible as a pure tone, characterized by a given pitch. This paradigm can be performed for every harmonic by increasing its amplitude. What is particularly relevant in the context of the present discussion is the observation that for high-order harmonics (above an order of 16), also a decrease in the amplitude leads to a pitch percept. The decrease in the amplitude is equivalent to the addition of a cosine in antiphase with an amplitude lower than the amplitude of the individual components in the complex. Thus, the waveform of a pulse sequence with a suppressed harmonic is very similar to the waveform of a low-pass pulse sequence with its cutoff at the suppressed harmonic. Close inspection shows that the amplitude of the high-frequency ripple in a low-pass complex is half the amplitude of the ripple in a complex with a completely suppressed harmonic, given that the individual harmonics have the same amplitude in both signals.

Duifhuis explained his finding on the basis of waveforms resulting from a band-pass filter tuned to the suppressed harmonic. For a sufficiently high quality factor of the filter (Duifhuis proposes a value of about 10, a value in the range of recent auditory-filter estimates according to Moore & Glasberg (1983)) the suppressed harmonic is seen within each period of the filtered waveform as a pure tone. He further assumes that an appropriate detector which is only active during that part of the period showing this tone-like property could respond to this sinusoidal waveform.

For the explanation of our result we can follow this reasoning very closely, as did Moore & Glasberg (1989) in their analysis of the edge tone. That is, for high harmonic numbers of the edge component and zero phases of all components, the fine structure of the edge tone will be preserved in each period of the signal resulting from the inner-ear filter tuned to the edge frequency. The higher the harmonic number, the greater the part within each period showing this pure-tone-like fine-structure. The increasing accuracy of the matches for increasing harmonic number of the highest component (figure 4) indicates that this temporal information is indeed used by the subjects.

The observation of a phase effect further supports this explanation. Randomizing of the phase values reduces the peak factor of the broadband signal, and also of the filtered waveforms. In such a stimulus, there are no longer time sections within a period where high excitation in the edge-frequency region is contrasted with low excitation in lower spectral regions. Thus, the temporal fine-structure cue is no longer available. The increase in the standard deviation for the negative Schroeder phase for higher harmonic numbers (figure 7) supports this view, but the results do also indicate that additional, probably purely spectral cues, still allow for a pitch percept for this complex.

While Duifhuis (1970) and Moore & Glasberg (1989) only considered the consequences of band-pass filtering, we have some indications that basilar-membrane properties are not the only critical parameters for the perception of the edge pitch. This can be demonstrated by measuring edge pitches for complexes always having the same order of the highest component, e.g. 10 or 14. Following the above arguments, one would expect the same accuracy of matches for all fundamental frequencies, since the relative bandwidth of the basilar-membrane filters is, as a first approximation, independent of frequency above 500 Hz. The accuracy of the pitch matches, however, decreases significantly for fundamental frequencies above about 250 to 300 Hz, where the edge frequencies are in the region 3 to 4 kHz (Kohlrausch & Houtsma 1991).

One can think of two possible causes of this effect. On the one hand, the edge pitch seems to disappear for edge frequencies of 3 kHz and higher, i.e. the breakdown occurred at a lower $F_0$ with the edge at harmonic order 14 than with the edge at harmonic order 10. Consequently, the absolute frequency of the breakdown appears to remain fairly constant, which could be due to a decrease in neural phase locking. In the auditory nerve such a decrease begins around 1 kHz (e.g. Rose *et al.* 1967), and can be modelled by a half-wave rectifier and a subsequent low-pass filter with cutoff frequency 1 kHz following each auditory filter. A loss in phase locking should make it more difficult for a subsequent detector to recognize the edge tone in the complex pattern resulting from cochlear filtering.

From the viewpoint of temporal resolution, on the other hand, one has to consider the decreasing duration of a period for increasing $F_0$. A fundamental frequency of 300 Hz has a period of 3.3 ms and such a duration agrees with the estimates of the minimal integration time of the hearing system (e.g. Green 1973). Following this consideration, the period of the complex would become so short that the envelope modulation, which is clearly present at the level of the basilar membrane, would no longer be represented in higher stages of the hearing pathway.

A similar argument is based on the effects of adaptation and forward masking, as they are seen for instance in non-simultaneous physiological masking experiments (Harris & Dallos 1979). If we apply the arguments presented in Kohlrausch *et al.* (1992), each amplitude peak in a waveform suppresses immediately following signal parts of lower amplitude. Because this temporal effect is thought to be a consequence of neural adaption, its duration should be independent of frequency. Such a temporal suppression will not be critical for the perception of the edge pitch, as long as the period of the stimulus is sufficiently long. However, for shorter periods, the suppression will affect the fine-structure information relevant for the pitch percept. Such an explanation makes it reasonable that an $F_0$ value of 50 Hz leads to much smaller standard deviations than $F_0$ values of 100 or 200 Hz (cf. figure 5).

In summary, all the data presented in this article are in line with previously published experimental data and models about how non-stationary acoustic signals are represented in the hearing pathway. On the other hand, it seems quite difficult to deduce precise quantitative predictions from the data about, for example, the ringing time of the peripheral filters or the frequency dependence of phase locking. This is due to the fact that a global measure such as pitch perception accuracy depends on many more stages of the hearing pathway than peripheral ones. What we definitely can say is that, from all we know, the information necessary for a pitch percept is retained in the peripheral stages of the hearing system.

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### *Discussion*

E. F. Evans (*Department of Communication and Neuroscience, University of Keele, U.K.*). Has Professor Houtsma investigated the effects of stimulus level?

From experiments looking at cochlear nerve fibre temporal discharge patterns to stimuli as those producing the 'rabbit ear' spectra, major differences are found in response at low stimulus levels (between 20 dB of threshold) and high levels (about 50 dB above threshold), such that the psychophysical effects that you are detecting should be those corresponding to the physiological responses obtained at the higher stimulus levels. In the physiological case, the systematic differences with level tend to disappear under two conditions: (i) increasing the fundamental from 40 to 125 Hz; (ii) randomizing the phase, both very much in line with Professor Houtsma's psychophysical findings.

Another prediction from the physiological data is that the pitch of the upper edge of the band of harmonics should be expected to increase with stimulus level from within the band at low levels to slightly outside at high level.

All these results can be modelled by a linear filter followed by an automatic gain control of about 10 ms time constant in a simple cochlear nerve model (Evans 1980, 1987, 1988).

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A. J. M. HOUTSMA. Yes, we did collect some pitch matching data to complex tones of 20 harmonics and fundamentals around 50 Hz, i.e. upper edge frequencies between 920 and 1080 Hz. Partials were in sine phase, and complexes were at 10, 20, 40 and 60 dB above hearing threshold. Matches were performed by the authors, using sinusoidal comparison tones of constant intensity for all complex-tone levels.

The first preliminary finding was that the standard deviation of the matches was not greatly affected by complex-tone intensity, even close to threshold. This may appear surprising since Horst *et al.* (1985) showed that the FFT of period histograms of 8th-nerve-fibre responses to similar complex tones has 'rabbit ears' only at relatively high stimulus intensities.

A second and rather robust finding was that means of matches (see pitch shift shown in figure 3) increased systematically with stimulus intensity, from 35 Hz within the band at 10 dB SL to about 50 Hz outside the band at 60 dB SL, at a rate of about 1.5 Hz $\text{dB}^{-1}$. This finding appears entirely consistent with the prediction from physiological data you mentioned.

*Reference*

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