Part I. HISTORICAL REVIEW

Chapter 1

THE INTERACTION OF A SOUND WITH ITS REPETITION

1.1 Experiments in applied acoustics

In 1693 Christian Huygens, in a letter to mr. Ph. de la Hire, describes the following observation which he made at the castle at Chantilly de la Cour in France. Standing at the foot of a big stony staircase leading to the garden he noticed that the noisy sound coming from a fountain near the staircase was producing a certain pitch. He concluded that the pitch was caused by the periodic reflections of the sound of the fountain against the steps of the staircase (see fig. 1.1). We cite here the particular part of his letter:

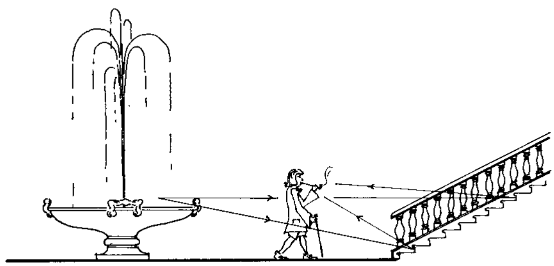


Fig. 1.1 The pitch due to the periodic reflections of the noise of the fountain against the steps of the staircase (Huygens).

Je veux ajouter ici au sujet de la réflexion du son une observation assez singulière, que j'ai fait autrefois étant à la belle maison de Chantilly de la Cour; où est la statue Equestre on descend avec un degré large de . . . . . marches dans le parterre où il y a une fontaine de celles qu'on appelle gerbe d'eau, qui fait un bruit continuel. Quand on est descendu en bas et qu'on se tient entre le degré et la fontaine, on entend du coté du degré une résonance qui a un certain ton de musique qui dure continuellement, tant que la gerbe jette de l'eau. On ne savait pas d'où venait ce son ou en découvrait des causes peu vraisemblables ce qui me donna envie d'en chercher une meilleure. Je trouvai bientôt qu'il procédait de la réflexion du bruit de la fontaine contre les pierres du degré. Car, comme tout son, ou plutôt bruit, réitéré à des intervalles égaux et très petits, fait un ton de musique et que la longueur d'un tuyau d'orgue détermine le ton qu'il a par sa longueur, parce que les battements de l'air arrivent également dans les petits intervalles de temps que ses ondoiements emploient à faire deux fois la longueur du tuyau à savoir quand il est fermé par le bout, ainsi je concevois que chaque bruit tant soit peu distingué que venait de la fontaine, étant réfléchi contre les marches du degré, devait arriver à l'oreille de chacune d'autant plus tard qu'elle soit plus éloignée, et celà par des différences de temps justement égales à celle que les ondoiements de l'air emploient à aller et venir autant qu'était la largeur d'une marche. Ayant mesuré cette largeur qui est de 17 pouces, je fis un rouleau de papier qui avait cette longueur, et je trouvai qu'il avait le même ton qu'on entendait au bas du degré. Je trouvai, comme j'ai dit, que la gerbe n'allant point l'on cessait d'entendre ce ton. Et ayant eu l'occasion d'aller à Chantilly pendant l'hiver, qu'il était tombé beaucoup de neige qui ôtait la forme aux marches, je remarquai qu'on entendait rien quoique la gerbe allât et fît du bruit à l'ordinaire.

From the physical point of view Huygens gives an adequate explanation of this pitch effect. Rightly, he points to the analogy between the system of the organ pipe and the system "fountain-staircase". Both produce a periodic signal. Assuming that each periodic signal produces a pitch corresponding to the inverse of the period, he solved the physical side of the problem.

However, the problem becomes interesting when the number of reflections is diminished and at last only one repetition follows a sound event. In that case no periodic signal is formed, but a pitch is still present. In literature, the observation of a pitch due to one repetition has quite often been reported. Minnaert (1941) describes how a steam locomotive, halting at the platform of a station and blowing off steam, produces a hissing sound in which a certain tone predominates (see fig. 1.2). This tone is discerned most easily when one approaches the locomotive; then one can perceive how the pitch gets lower and lower. Minnaert concludes that the effect may be compared with the "mirror-experiment of Fresnel" in which the pitches correspond to the coloured lines of interference.

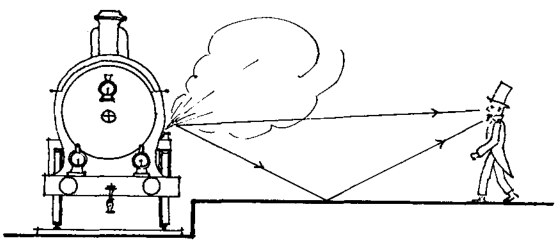
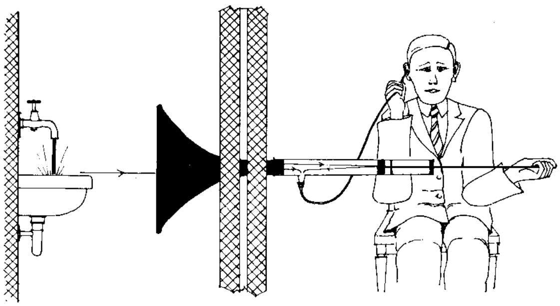


Fig. 1.2 The pitch due to the interference of the hissing sound from the locomotive with the reflection from the platform (Minnaert).

Keen observers like Baumgarten (1876), Pfaundler (1877) and Hermann (1912) heard identical effects in the murmer of waterfalls, flood-control dams and in the rustle of the wind in the leaves of a tree; in all the cases (reflecting) walls were in the neighbourhood of the "noise"-source. Hermann (1912), investigating both the Reflection Tone and the Interruption Tone being the low pitch due to the periodic interruption of a high pure tone, looked for an explanation of both pitch effects based on time separation. In fig. 1.3 one of his experimental set-ups has been outlined.

Fig. 1.3 The pitch due to the interaction of the noise from the running water with its reflection against the cork at the end of the tube (Hermann).



In 1944, a series of experiments performed at Cornell university by Supa, Cotzin and Dallenbach showed that blind men use reflected sound to locate objects. It appeared that an observer approaching a flat, sound-reflecting surface in the presence of certain sounds, perceives a "broad tone" with an associated pitch which seems to be superimposed on the sound. The pitch varies inversely with distance from the surface. In 1950 (Cotzin and Dallenbach) the experiments were repeated in a more detailed manner: subjects listened with earphones to the sounds from a moving loudspeaker, reflected from a wall, and picked up by a microphone moving on the same carriage with the loudspeaker. When the sound was thermal noise, the pitch was quite clear and a sort of siren effect was noticed as the carriage drew nearer to the wall and back again.

When the test sound consisted of pure tones instead of thermal noise, no pitch effect was perceived, except for a pure tone of 10000 Hz. The authors attributed the pitch change to the Doppler effect evoked at frequencies of about 10000 Hz.

Analogous experiments were performed by Twersky (1951). His explanation of the pitch variation with distance is based on a change in pitch due to an increase in intensity of the sound as the distance to the wall decreases.

Bassett and Eastmond (1964) criticized the explanation given by Cotzin and Dallenbach and also that given by Twersky. "The variation of pitch due to a change in intensity, and to some extent the Doppler effect, deals with variation of a single frequency tone. Thermal noise has no specific pitch, but rather it is made up of many random pitches. Thus, it should be easier to hear changes in the pure tone than in the thermal noise. The reports of Cotzin and Dallenbach's subjects show that this is not the case. Further, the Doppler shift depends on the relative velocity of the source and the observer. This shift should be constant as long as the carriage moves towards the wall at a constant speed. The subjects, however, reported that the pitch rose continuously up to the wall. A more thorough examination of this pitch change effect will show that neither the Doppler shift nor changes in intensity are the main cause of the phenomenon".

To strengthen their criticism Bassett and Eastmond carried out the following experiment. They used an experimental set-up very similar to that of Cotzin and Dallenbach. In an anechoic room a loudspeaker, producing white noise, was placed opposite to a flat reflector. A microphone could be moved to and fro between the loudspeaker and the reflector. The signal from the microphone was analysed by a sound spectrograph. At a certain microphone position a pattern was present which was due to the interference between incident and reflected waves, causing a cancellation of certain frequencies and an augmentation of others. The frequency interval between the maxima of this pattern appeared to correspond to the reciprocal value of the delay time between the incident and the reflected wave. The perceived pitch also corresponded to this value. From that correspondence Bassett and Eastmond concluded that the subjective tone is generated in the ear as a difference tone (see Fletcher, 1924) corresponding to the frequency spacing between the frequencies thus augmented by the interference. Further, they experienced that the tone does not depend on frequencies greater than 10000 Hz and that it is most easily noticed for almost any sound that is fairly continuous and has many random pitches, in particular in the region from 200 to 2000 Hz.

Bassett and Eastmond experienced the pitch effect under more or less ideal test circumstances because disturbing reflections were absent. However, also under less ideal circumstances, namely under the presence of many disturbing reflections, for example in a music hall, a pitch and timbre (coloration) may be perceivable due to a strong early reflection. Kuhl (1965) drawing on his experience with recording studios, writes: "In kleinen Räumen, z.B. in Sprecherstudios, ist der Pegelunterschied zwischen den direkten Schall und den ersten Reflexionen so klein, dass starke Interferenzen, also Schwankungen der Frequenzkurve des Uebertragungsmasses auftreten, die subjektiv zu einer unerwünschten Klangfärbung führen".

Moreover, he points out that it makes a great difference whether the listener is present in the studio or listens to the sound from a microphone positioned in that studio. In the second case effects like coloration, lack of definition, excess of reverberation, manifest themselves stronger than in the first case because of the missing of directional hearing.

Somerville, Gilford, Spring and Negus (1966) note that a shrill tonal quality has become associated with modern concert halls having efficient direction of sound to the audience. In search of an explanation they performed experiments in an anechoic room in which two loudspeakers were located about 3.4 m apart in one line with the listener. These were fed with the same programme. "These experiments showed a marked deterioration in the quality of orchestral music, particularly the string quality, and the deterioration was of the same type as has been noticed in some concert halls with reflectors. Speech became coloured with both low-frequency and high-frequency distortions. Violin tones also showed distortion and the bowing noise became coloured and therefore more noticeable. Some subjects thought that vibrato made these effects worse but an equal number did not. It was also noticed that random noise from the loudspeakers became very coloured and a warble tone developed a thumping sound in some conditions of loudspeaker phase. There seems to be no doubt that all these distortions can be explained as comb-filter effects due to interference between the sounds from the loudspeakers".

Klimenko (1966) dealt with this problem because sometimes the production of a single-channel recording from a stereophonic recording has given an unpleasant sensation like that in the monaural perception of speech subjected to interference distortions. Speech assumes an unnatural, strident character.

Experiments on the critical relative level of the repetition with respect to the original sound for a coloration to be perceivable, were carried out by Somerville et al (1966), Klimenko (1966), and Atal, Schroeder and Kuttruff (1962). The work of the latter authors is of great theoretical importance; we will refer to it in chapter 7.

1.2 Experiments in psychoacoustics

In this section we will give a short review of the experiments carried out in the past on pitch effects which are identical with the phenomenon in study. The authors listed here were especially interested in the mechanism of perception of pitch.

Thurlow and Small (1955) reported on experiments performed to determine the pitch behaviour of sequences of band-pass filtered pulses. In particular, we refer to their experiment with two identical sequences delayed with respect to each other (see fig. 1.4). Shifting a sequence of band-pass filtered pulses (a, b, ...) continuously in time with respect to a second identical sequence (α, β, ...) a "sweep pitch" was perceived that, at any given instant, appeared to be related to the time interval $a-\alpha$ or $\alpha-b$, depending on which was shorter.

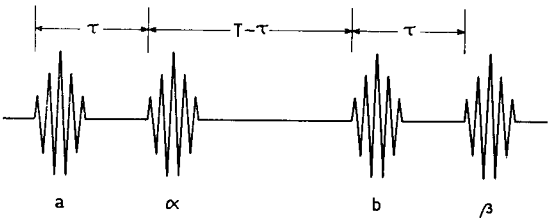


Fig. 1.4 The "sweeppitch"-effect: a periodic sequence of band-pass filtered pulse pairs evokes an additional pitch corresponding to the shortest time interval (τ) (Thurlow, Small).

In search of the mode of origin of this sweep pitch, the authors added low-pass masking noise with cut-off frequency lying above the sweep-pitch frequency. The sweep pitch was not masked out and thus could apparently not arise from low frequencies produced in the physical system of the ear.

Later, Thurlow (1958) found that when altering the polarity of one of the sequences of pulses a pitch jump upwards or downwards was perceived. The antiphasic condition, thus, has two pitches, one a little higher, the other a little lower than for the cophasic condition.

Experiments by Nordmark (1963) and Flanagan (1962) would seem to favour a time analysing system. Flanagan determined the time difference between a rarefaction pulse at the left (or right) ear and a condensation pulse at the right (or left) ear to produce a central sound image. Nordmark showed that the time compensation required to offset the pitch shift due to the reversal of polarity as reported by Thurlow (1958) could be compared with the compensation required to offset the lateralization shift in Flanagan's experiment. The similarity between the pitch and lateralization phenomena supported the hypothesis that the sweep pitch is related to the time pattern of neural firings in the auditory nerve.

An extensive series of experiments dealing with pitch matchings has been reported by Small and McClellan. They used different kinds of signals: a periodic sequence of pulse pairs (Small and McClellan, 1962) (Small and McClellan, 1963a), a random sequence of pulse pairs (Mc Clellan and Small, 1963b), a periodic sequence of pairs of different (uncorrelated) noise bursts and a periodic sequence of pairs of identical (correlated) noise bursts (McClellan and Small, 1965a) (McClellan and Small, 1965b) (McClellan and Small, 1966), and single pulse pairs (McClellan and Small, 1967). Because the original sound and the repetition always had the same polarity, they could not decide whether spectral cues or timing cues are responsible for the perception of pitch. One thing, however, appeared to be evident, namely that time separation between successive sound events (two uncorrelated noise bursts) alone is insufficient for the evocation of pitch. Obviously the successive sound events must be highly correlated. Further, they concluded that for the test signals listed above the amount of information available per unit time is not particularly important to pitch perception, because the distributions of pitch matchings appeared to be about the same for the different test signals.

The pitch character of the phenomenon was confirmed once more by Kylstra (1964) who reported that a periodic sequence of pulse pairs with changing interval between the two pulses of a pulse pair can produce a melody. The statement of Jenkins (1961) in which he said that what Thurlow and Small (1955) reported as a sweep pitch was, in reality, a timbre or quality change, is debatable. The failure of Jenkins to perceive pitch must probably be ascribed to the fact that he used a signal which was far from optimal to evoke pitch; this will be explained in section 4.5.

Some years ago the pitch effect evoked by signals of the form as described by Baumgarten (1876), Pfaundler (1877), Hermann (1912) and Minnaert (1941) was reported again by Fourcin (1965). He noticed that the monaural presentation of wideband noise together with the same noise delayed (delay time τ) gave rise to a pitch sensation corresponding to $1/\tau$. The delay was obtained by the use of a shift register. However, when the delayed noise was added with negative sign, the pitch appeared to have the value $7/8\tau$. The experiments of chapter 3 were carried out in such a manner as to provide a deeper insight into this phenomenon.