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Echolocation: Measurement of Pitch versus Distance for Sounds Reflected from a Flat Surface

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When sound containing many frequencies is reflected from a flat surface, an observer in the field of both the incident and reflected sounds hears a broad tone with an associated pitch that varies inversely with distance from the surface. Measurements made in three experiments have led to an explanation of the phenomenon. First, reference tones were sounded and positions located where their pitches matched those of a sound field produced with thermal noise. Again with thermal noise as a source, the field was carefully analyzed with a sound spectrograph. With an array of discrete frequencies used as the source in the third experiment, the regular array of standing waves thus produced gave rise not only to a pitch change at the barrier, but also to similar pitch changes at points in front of it. The pitch that is heard is a subjective tone produced by the ear from the sound pattern in front of the reflector. This pattern is caused by interference between the incident and reflected sounds. Although the phenomenon can be produced with a very narrow band of frequencies, it cannot be produced with a single pure tone. It is most easily noticed with frequencies ranging from 200 to 2000 cps and does not depend on frequencies above 10 000 cps.

INTRODUCTION

As an observer approaches a flat, sound-reflecting surface in the presence of certain sounds, a pitch sensation can be noticed that seems to be superimposed on the sound. The pitch of this sensation is found to rise as the observer approaches the reflector. This pitch-change phenomenon is used by some blind people in locating objects in their path. Different explanations of the cause of this phenomenon have been offered.

In 1944, a series of experiments performed at Cornell University by Supa, Cotzin, and Dallenbach[1] showed that blind men use reflected sound to locate objects. In later experiments,[2] subjects listened through earphones to sounds being sent from a moving speaker, reflected from a wall, and picked up through a microphone moving on the same carriage with the speaker. When the test sound was thermal noise, the subjects were able to detect the barrier quite well. They reported the main clue to the presence of the wall to be a change in the "pitch" of the thermal noise—a "sort of a siren effect," the pitch continuing to rise as the carriage drew nearer to the wall. Using pure tones as the test sound, they were unable to detect the wall, except when they used a 10 000-cps tone. These experimenters attributed the pitch change to the Doppler effect and concluded that high-frequency sounds of approximately 10 000 cps and above were necessary to produce it.

Twersky[3] also reports hearing a variation of pitch with distance from a barrier. He offers a theoretical explanation based on a change in pitch due to an increase in intensity of the sound as the distance to the wall decreases.

The variation of pitch due to a change in intensity, and to some extent the Doppler effect, deals with variations 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 tones 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[4] and the observer. This shift should be constant as long as the carriage moves toward the wall at a constant speed. The subjects, however, reported that the pitch rose continuously up

[1] M. Supa, M. Cotzin, and K. M. Dallenbach, "'Facial Vision': The Perception of Obstacles by the Blind," Am. J. Psychol. **57**, 133–183 (1944).

[2] M. Cotzin and K. M. Dallenbach, "'Facial Vision': The Role of Pitch and Loudness in the Perception of Obstacles by the Blind," Am. J. Psychol. **63**, 485–515 (1950).

[3] V. Twersky, "On the Physical Basis for the Perception of Obstacles by the Blind," Am. J. Psychol. **64**, 404–415 (1951).

[4] The source in this case is really the "image" of the moving speaker on the opposite side of the reflecting panel.

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.

I. PRELIMINARY OBSERVATIONS

Some general, qualitative observations gave some insight into the properties of the phenomenon and a feeling for the importance of the different variables. It was found that a satisfactory source to produce an easily noticeable pitch change could be almost any sound that is fairly continuous and has many random pitches. Thermal noise from an amplifier works well. The more the source approaches white noise, the more easily the pitch change is heard. A fairly large, flat, reflecting surface is all that is needed to provide sufficient sound reflection to make the phenomenon detectable. The observer can be either a person or a microphone. A large body is not necessary at the observation point. Indeed, even a small probe microphone will pick up the change readily.

The pitch change can be heard either with the observer moving along a line between a fixed source and a fixed reflector, or with the source moving between a fixed observer and a fixed reflector, or with observer and source moving together with respect to the reflector. For most of the work reported here, the first situation was the one used. To simplify the discussion in this report, let D represent the distance from source to reflector, and d the distance from observer to reflector.

One of the first significant features noticed in the phenomenon was a definite relationship between the pitch and the variable distance d. The pitch is low and the change is slow for large values of d. As the observer moves between $d=1$ m and $d=0$, the change is quite rapid and easily heard. Upon recording and carefully listening to the pitch change, it became further apparent that as the distance was doubled the pitch would vary through one octave.

Some interesting results were obtained by introducing a bandpass filter between the microphone at d and the listener in another room. The microphone was swung like a pendulum in front of the reflector so that d varied between about 5 and 35 cm. Bands one octave wide were allowed to pass. The variation was not detectable with bands below the 150- to 300-cps range. It became progressively easier to detect as higher bands were passed. For all bands between the 200- to 400- and the 1200- to 2400-cps ranges, the pitch change was easily noticed. The effect became less and less noticeable as higher bands were passed, until finally it could only be faintly heard as the microphone swung closer to the reflector. The apparent pitch of the sound swept through the same frequency range with each swing of the microphone, regardless of which band was passing. This varying pitch seemed to superimpose itself on whichever part of the total noise came through the filter.

II. EXPERIMENTAL WORK

A. Experiment 1: Preliminary Measurement of d vs f

This preliminary experiment was set up in a small anechoic chamber to determine whether a certain pitch always occurred at a particular distance, and to get some idea of what relationship might exist between them.

The source of sound was thermal noise from a tape recorder, amplified and sent out through a small speaker system held by the observer. A pure tone of variable frequency was sounded at the same time from an oscillator through a 7-in. speaker. This provided a comparison tone. A reinforced, unpainted plywood board 85×150 cm was suspended vertically and used as a reflector. The sound field was observed directly by an observer holding the speaker just in front of him.

The comparison tone was sounded at a particular pitch. The observer held the speaker emitting the thermal noise. While listening to both the comparison tone and the thermal noise, he moved along a line perpendicular to the reflecting surface. The distances d and D were thus varied simultaneously and were

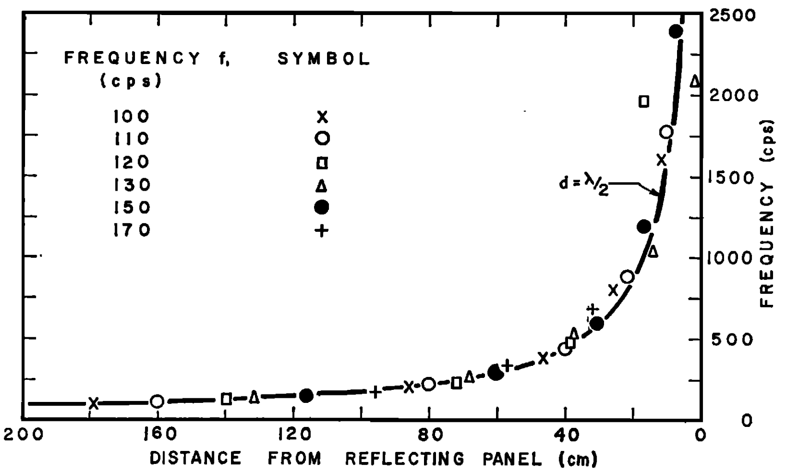

FIG. 1. Variation of distance from reflecting panel with frequencies of comparison tones and their octaves.

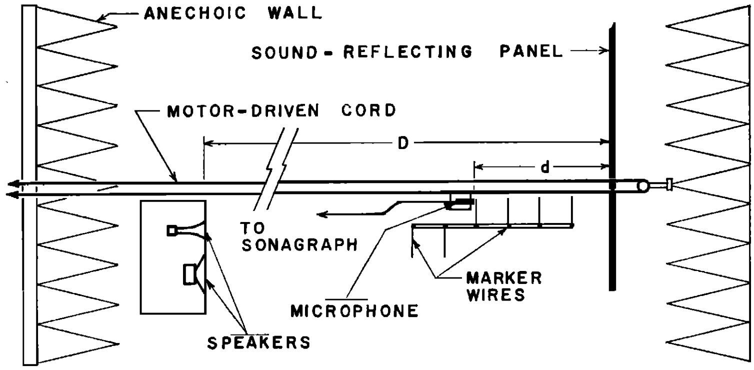

FIG. 2. Arrangement of apparatus for Experiments 2 and 3.

approximately the same. He moved up and back, listening to the pitch change in the thermal noise until its apparent pitch matched that of the comparison tone. The frequency and the value of d were recorded. The observer again moved up and back until the value of d for each octave of the comparison tone was found. A different comparison tone was then sounded and the same procedure was repeated for this tone.

Figure 1 shows the variation of the values of d thus found with the frequencies of comparison tones and their octaves. On the same graph, a curve is plotted showing the locus of points corresponding to a distance of one-half wavelength from the reflecting panel.

It was found that only one pitch could be heard for each value of d no matter which way the approach to that point was made. It is quite evident from the close agreement between the experimental points and the theoretical curve that there is a direct relationship between the value of d and f: namely,

$$f=c/2d, \tag{1}$$

where c is the speed of sound in air. This experiment has one definite weakness. The results depend upon human judgment and mental comparison of tones.

B. Experiment 2: Measurement of d vs f with Thermal Noise

This experiment is designed to determine more carefully and accurately the relationship between the apparent pitch and the distance from the wall to the observer. It was performed in a large anechoic chamber.[5] Only one-dimensional situations are considered. The source and observer lie always on a line perpendicular to the face of the reflector.

The sound for this experiment was thermal noise from a preamplifier and power-amplifier combination with the input terminals open. The gain control on both amplifiers was turned up high to produce as much of the random noise as possible. This sound was sent into the anechoic chamber through a 7-in. speaker and a tweeter. Both the speaker and the tweeter were placed and held at a distance $D=560$ cm from the panel (see Fig. 2).

The sound was reflected from a large unpainted board made from several pieces of $\frac{5}{8}$-in. plywood. The entire panel measured 246 cm on each side and was reinforced along the edges and in the back. This panel was suspended near one end of the anechoic chamber.

The sound was received through a small microphone suspended from a nylon cord so that it faced the panel and was about 60 cm above the lower edge. The cord was driven by a variable-speed electric motor making the microphone move with constant speed along a line toward the panel. The position of the microphone was recorded by placing small wires in its path in such a way that the moving microphone would strike a wire every 20 cm. An audible click would be produced as the microphone knocked the wire out of the way. The click of the wire against the face of the microphone was recorded along with all the other sounds present. These recorded clicks established the position of the microphone with a possible error not larger than ± 2 cm. They did not disturb the sound field by any appreciable amount.

The signal from the microphone was amplified and fed into the input of a sound spectrograph. This instrument displays the frequency spectrum as a function of time on a chart called a Sonagram. The intensity of the sound is indicated by the darkness of the trace. A single pure tone would appear as a line on the chart, and a pulsating tone would appear as a series of dashes. Using the narrowest analysis possible, a single-frequency tone produces a line 45 cps wide on the Sonagram. In this experiment, the microphone moved at constant velocity so that the time axis of the Sonagram was made to correspond to the distance d through which the microphone moved. By adjusting the speed of the driving motor, it was possible to show just 1 m of distance on each Sonagram. These charts when placed end to end give a "picture" of the sound field in front of the reflecting panel, showing what frequencies were heard at any point. Three series of these Sonagrams are shown in Fig. 3. The top series pertains to Experiment 2 and the lower two to Experiment 3. The differences in the horizontal scales are due to small changes in the

[5] For a complete description of this chamber, see H. Fletcher, E. D. Blackham, and R. Stratton, "Quality of Piano Tones," J. Acoust. Soc. Am. 34, 749 (1962).

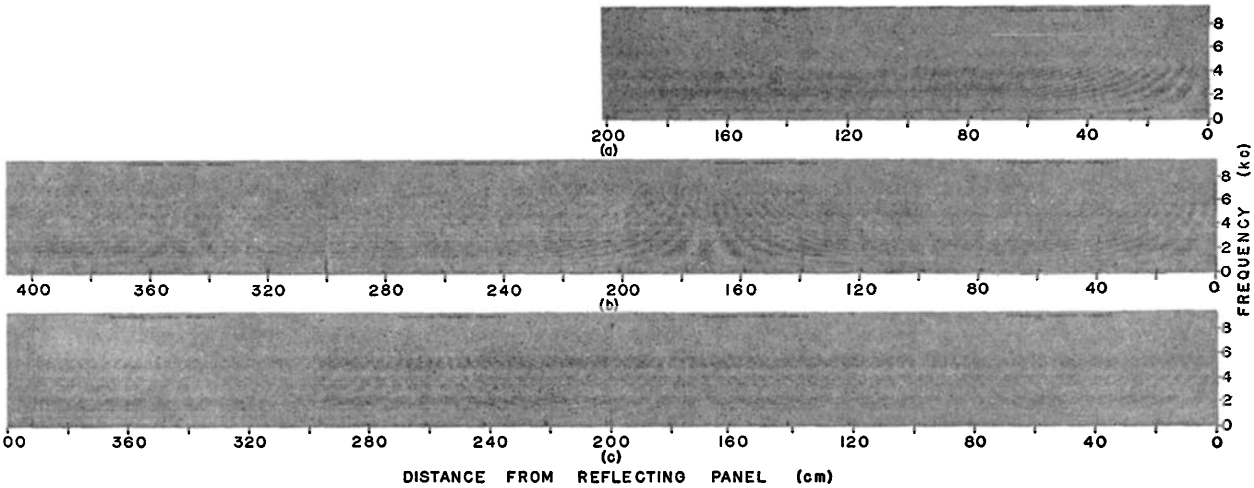

FIG. 3. Picture of three series of Sonagrams, showing sound field between source and reflecting panel.

speed of the driving motor. The top series has been enlarged and reproduced in Fig. 4 for a more detailed study.

The sounds present are shown to range from 100 or 200 to 6000 cps. Along the lower edge of the Sonagram, every 20 cm are the "blips" made by the microphone striking the marker wires. These were used as a scale to determine d. The four wide horizontal bars most easily seen on the left end of Fig. 4 show the characteristic output of the speaker used and of the thermal noise itself, but are unimportant to the phenomenon being discussed.

The important feature of this Sonagram is the family of curved lines most clearly visible near the right end of the trace. These get broader, farther apart, and curve upward as the distance decreases. At any d, there is a certain number of these lines visible. They seem to be evenly spaced frequencywise. This means that, at any particular distance, one would hear a series of somewhat broad tones, each separated by a certain frequency from its neighbor.

This series of tones, when presented to the ear, will produce a subjective difference tone[6] within the ear, whose pitch corresponds to the frequency spacing of the tones heard. The frequency spacing between the lines gets larger as d gets smaller, causing an increase in the pitch of this difference tone.

To determine accurately the relationship between d and f, the Sonagram was analyzed as follows: Lines were drawn along each curve tracing out as nearly as possible its center from its beginning to the 200-cm mark. At points 10 cm apart, the frequencies of the lines were recorded and the average frequency difference found, using the method of differences. These average values are compared in Table I with the theoretical frequencies determined from Eq. (1). The speed of sound was taken as 3.48×10^4 cm/sec, corresponding to the room temperature of 28°C.

From Table I, it can be seen that the theoretical and observed frequencies compared favorably for all values of d except the smaller ones. There are several reasons why the percent difference might be higher for these smaller values: (1) there are fewer lines available for averaging in this region; (2) the lines themselves are much wider there, making it more difficult to find their centers; (3) when d is small, a very small variation in d causes a large variation in f.

The evenly spaced tones observed on the Sonagram are created through interference between the incident and reflected sound waves. At the panel, there is pres-

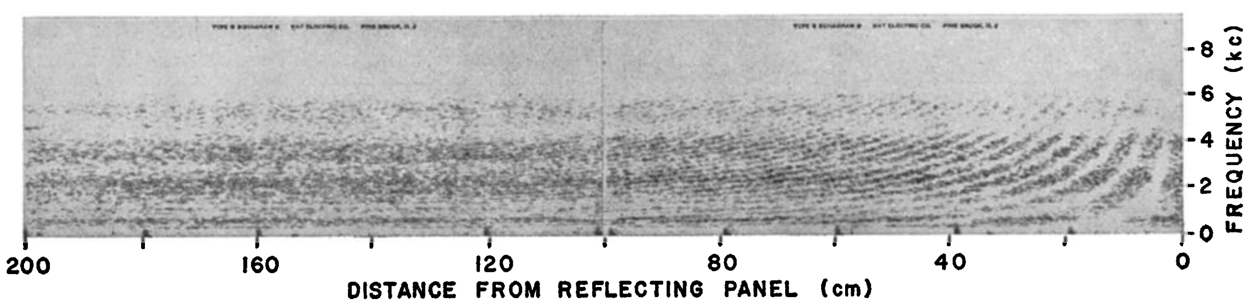

FIG. 4. Sonagrams showing thermal noise near a reflecting panel.

[6] Harvey Fletcher, *Speech and Hearing in Communication* (D. Van Nostrand Co., Inc., New York, 1958), pp. 160, 233.

sure doubling, or a pressure antinode, for all frequencies. Pressure antinodes exist for any particular frequency at all points between the source and the panel where d is an integral multiple of a half-wavelength. Conversely, any given distance d_1 is an integral multiple of half-wavelengths for a series of frequencies nf_1. These frequencies exhibit complete constructive interference and will be clearly heard at that point, giving rise to the subjective difference tone of frequency f_1. Frequencies near this series exhibit partial constructive interference and are heard also, but with a lower intensity. The result of this arrangement is a rather broad tone in agreement with the observed phenomenon.

C. Experiment 3: Variations Produced by Combinations of Pure Tones

This third experiment was set up to study the effect of using a combination of pure tones as a source instead of thermal or white noise.

The sound for this experiment was produced by a tone generator, or sound synthesizer.[7] This instrument consists of 100 oscillators that can be set to give any frequency between 50 and 10 000 cps. The intensity of each oscillator can be varied independently over a wide range. For this particular experiment, they were set to give tones of nearly equal intensity of frequencies 200, 300, 400, etc., up to 8000 cps for the first part of the experiment and frequencies 200, 400, 600, etc., up to 8000 cps for the second part. All the other apparatus was the same as that described in Experiment 2.

The same procedure was followed here as in the preceding experiment, except for a doubling of the distance through which the frequency spectrum was studied. The following qualitative observations were made at the onset of the experiment: (1) The pitch change was not as easily detected. The tone generator produced quite an uncomfortable "droning" noise, making it harder to hear the more-subtle changing tone. The droning noise was a very loud difference tone produced by the combination of evenly spaced pure tones from the source. As could be expected, its frequency was the same as the separation frequency f' of the oscillators. The pitch change could still be heard, however, and sounded much like it did with the thermal noise. (2) At certain distances from the board, another change of pitch, exactly like the one near $d=0$, could be heard. As the observer approached one of these points, the pitch would rise just as though there were a wall there. As he passed through the region, the pitch would reach a maximum and then fall off smoothly on the other side as though he were walking away from a wall. Several of these were observed in the space between the panel and the speakers. Because each of these regions gave the impression of a wall where there was no wall, they were called "false walls."

Parts (b) and (c) of Fig. 3 show the Sonagrams for this experiment. The location of the false walls is easily seen. The sound pattern on either side of each false wall is seen to be the same as that near $d=0$, just as the sound heard by the observer in each area is the same. Another significant feature of these Sonagrams is the spacing between successive false walls. On Sonagram (b) where the frequency separation f' of the tones was 100 cps, the spacing is just twice that of Sonagram (c) where $f'=200$ cps. One should expect from this to see a simple relationship between these two factors.

TABLE I. Comparison of theoretical with observed frequency as a function of distance from reflecting panel.

Distance d (cm)	Observed frequency spacing f (cps)	Theoretical frequency f (cps)	Numerical difference (cps)	Percent difference %
10	1900	1740	160	11.4
20	960	870	90	9.8
30	600	580	20	3.4
40	440	435	5	1.1
50	360	348	12	3.4
60	296	290	6	2.0
70	252	248	4	1.6
80	220	218	2	0.9
90	196	193	3	1.5
100	175	174	1	0.6
110	158	158	0	0.0
120	145	145	0	0.0
130	133	134	1	0.7
140	125	124	1	0.8
150	116	116	0	0.0
160	109	108.8	0.2	0.2
170	104.6	102.3	2.3	2.1
180	97.3	96.8	0.5	0.5
190	91.9	91.6	0.3	0.3
200	86.0	87.1	1.1	1.3

The simplest way to interpret these patterns is to build them up from single tones. Suppose that a single pure tone of $f=1000$ cps were sounding; a standing-wave pattern would be set up whose Sonagram would resemble Fig. 5(a). Each of the horizontal bars indicates a pressure antinode in a standing-wave pattern. The observer would hear a pulsating tone as he moved through the sound field. Adding another tone [Fig. 5(b)] does not alter the first one at all. There are simply two sets of bars on the Sonagram. No pitch-change effect would be heard. With superposition of several tones as in Fig. 5(c), a pattern begins to appear on the Sonagram. The typical Sonagram drawn in Fig. 5(d) has a frequency separation of 500 cps. The pattern is quite easily seen.

Since there is always a pressure antinode at the reflecting panel, all frequencies have a bar at $d=0$. The distance to the center of the next bar is different for each frequency, each one corresponding to one-half wavelength for that tone. A line joining the centers of each of these bars would be a hyperbola. This is shown by the dotted line in Fig. 5(d). Some distance out from the panel, another point can be located where the bars again line up vertically. At each multiple of this same distance, the bars also line up. Calling this distance d' and calling the frequency of separation of the tones

[7] See Ref. 5, p. 750.

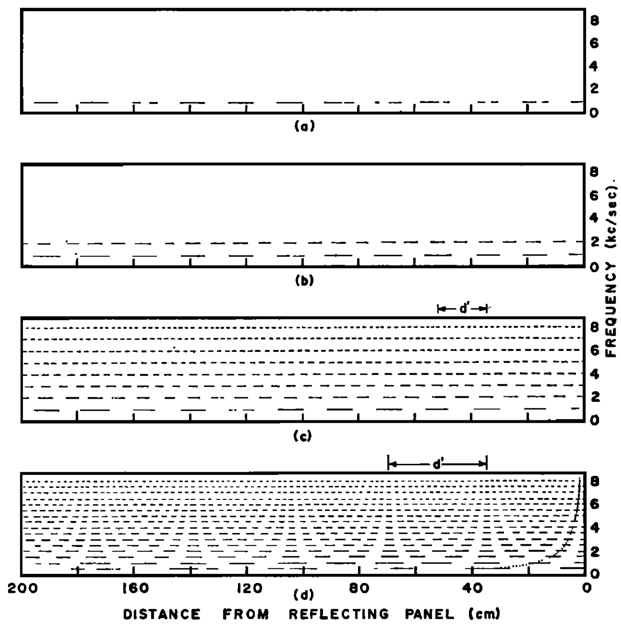

FIG. 5. Typical Sonagrams of simple combinations of pure tones, showing standing-wave patterns.

present f', it can easily be seen that

$$d' = \lambda'/2, \tag{2}$$

where

$$\lambda' = c/f'. \tag{3}$$

On either side of a point where the bars line up, a symmetrical distribution of antinodes can be seen, the pattern being the same as that at $d=0$.

If more frequencies are added until $f'=200$ cps, one has just what is shown in the actual Sonagram of Fig. 3(c). Here, the same pattern exists, but d' is increased to 87 cm. With the regions of symmetry this far apart, the pitch change can be detected audibly, giving rise to the false-wall effect. The irregularity of the pattern on Fig. 3(c) at about 4000 cps is due to two of the oscillators whose frequency shifted almost 100 cps.

For the Sonagrams of Fig. 3(b), the frequency separation f' was 100 cps. It is interesting to note that, although there was no 100-cps oscillator sounding and no 100-cps line present on the Sonagram, a very distinct 100-cps tone could be heard. This, of course, would be the difference tone produced in the ear by all the other tones. Again, on these Sonagrams, the same pattern can be seen. The configuration at $d=0$ remains the same and d' is greater (174 cm, corresponding to $\lambda'/2$ for $f'=100$ cps).

Each curved line is the result of the spacing of successive antinodes of the complete standing-wave pattern. If many frequencies are added so that f' goes to zero as in the case of white noise, Eqs. (2) and (3) show that λ' and d' become infinite and there are no false walls. Only the one pattern at the panel itself remains.

All of the observed phenomena can be explained through the interference of incident and reflected waves. The distance between false walls is inversely proportional to the frequency of separation f' of the tones from the source,

$$d' = c/2f'. \tag{4}$$

To eliminate the false walls, a white noise should be used instead of a combination of pure tones. These false walls would probably be more of a hindrance than a help to a blind person; therefore, a series of pure tones would most likely be a poor choice for an echolocation device unless the frequency of separation of the tones is very small.

III. CONCLUSIONS

These experiments have shown that the change in pitch heard as one approaches a flat reflecting surface in the presence of certain sounds is measureable. The pitch that is heard varies inversely with the distance from the surface according to the relation

$$f = c/2d. \tag{5}$$

The particular pitch at a point is due to interference between incident and reflected waves, causing a cancellation of certain frequencies and an augmentation of others. The average difference tone between the frequencies, thus augmented, gives rise to the tone heard.

This same effect can be noticed in many situations that one encounters every day and may be easily detected without the aid of extra devices. It does not necessarily depend on frequencies greater than 10 000 cps. In fact, it is most easily noticed in frequencies in the range from 200 to 2000 cps.

One pure tone alone will not produce a pitch change of this type. A combination of evenly spaced pure tones can be made to produce the same effect if the frequency spacing is not too great. Evenly spaced pure tones, however, cause "false walls," which would be disturbing in echolocation application. The best sound would seem to be a white noise containing essentially all frequencies at equal intensity. The preliminary observations indicate that even a narrow band containing many random frequencies will produce the effect.

This series of experiments does not pretend to cover all of the phenomena in the field of echolocation. There is much more to be explained before a successful method of orientation by sound can be achieved. The pitch-change phenomenon only helps to answer some of the blind man's problems. It can help him to locate some, certainly not all, objects and give him an idea of how close he is to them, but there are many places where it does not aid. It is hoped that this work will be at least a step toward the solution of the problem, and perhaps provide a stimulus for further investigation.

ACKNOWLEDGMENTS

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