THE FUNCTION OF RESONANCE AS A PART OF THE PHYSICAL THEORY OF AUDITION:- A STUDY IN EXPERIMENTAL ACOUSTICS.

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The Function of Resonance as a Part of the Physical Theory of Audition:- A Study in Experimental Acoustics.

There are, at present, two outstanding rival theories of audition,- outstanding because they are essentially so very different. These are Helmholt's resonance theory and Sir Thomas Wrightson's displacement theory.

In order to see more fully the significance of the experimental work herein reported, it seemed best to outline each of the theories briefly, pointing out the essential differences and apparent inconsistencies of each, and noting in what manner the results here obtained were related to them.

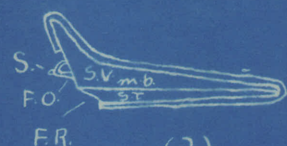
Helmholtz's theory is most briefly outlined by following the course and effects of a sound wave from its source to its termination at the nerve fibres leading to the brain.

A sound wave whether simple or compound, passes from the source of sound through the air into the external ear, through the external auditory canal (meatus), at end of which it strikes a thin circular membrane called the drumskin (membrana tympani). The pressure of the wave is then transmitted through a series of three small bones, or ossicles; the hammer (malleus), the anvil (incus), and the stirrup (stapes), the first of which is attached to the drumskin and the last to the membrane covering the oval window which forms part of the wall of the principle hearing chamber, the cochlea. The three small bones act together as a system of levers, the purpose of which is to transform a motion of great amplitude and little force--such as strikes the drumskin--into one of small amplitude and great force, to strike upon the oval window. This transformation has to take place because the area of the membrane of the oval window is only one-fifteenth to one-twentieth as great as that of the drumskin, and because the liquid or lymph which entirely fills the cochlea is dense and heavy and needs greater force than that striking the drumskin to cause it to moove to any effective extent.

The cochlea itself may be likened in shape to a small bony snail-shell. Its internal structure, however, is very complicated. The entire winding passage in the shell is divided longitudinally into three narrow passages; the vestibular passage (scala vestibuli), the tympanic passage (scala tympani), and the cochlear canal (ductus cochlearis); the entire cochlea, as was previously mentioned, being filled with a dense, heavy, very elastic liquid called the lymph.

The most important of these passages is the cochlear canal. It is roughly triangular in shape. It is bounded on one side by a firm tightly-stretched, very elastic membrane called the basilar membrane (membrana basilaris), on another side

FIG. 1.



(a)

(b)

S.V. - Scala Vestibuli
S.T. - Scala Tympani
D.C. - Ductus Cochlearis
F.O. - Fenestra Ovalis
F.R. - " Rotunda
m.b. - Membrana Basilaris
m.v. - " Vestibularis
S. - Stapes

by a soft membrane incapable of offering much resistance, called Reissner's membrane (membrana vestibularis), and the shell of the cochlea itself, forms the third side of this triangular passage. Fig.1, is a diagrammatic drawing[2] of the cochlea, uncoiled and straightened out; indicating the general arrangements, but not the proportions of the parts:- (a) represents a longitudinal section; (b) represents a transverse section. In (b) the almost triangular shape of the cochlear canal, (D.C.), can very clearly be seen.

The reason that the cochlear canal is of the greatest importance and also of most interest, is because, in it, along the basilar membrane, is situated the organ of Corti, which, according to Helmholtz, is the key to solving the problem of the mystical powers of the internal ear. The organ of Corti consists of a series of arches about forty five hundred[3] in all. Each of the arches has its own natural vibration frequency, and the entire series together with the fibres of the basilar membrane acts as a system of resonators. Thus, when a wave enters the cochlea, the lymph is set in motion; this sets the basilar membrane together with the organ of Corti into motion, and those arches possessing natural vibration frequencies corresponding with those of the entering simple waves, or component waves of the compound wave, are thrown into sympathetic vibration. These vibrating arches stimulate the nerves to which they are attached, which, in turn, send their message to the brain where each individual tone is interpreted as such. The brain thus analyses any compound wave and interprets it in terms of its component simples. The series of resonating arches thus accounts in a very simple manner for the extraordinary analytical power possessed by the ear.

The above, in brief and without detail, is Helmholtz's resonance theory of Audition.

Sir Thomas Wrightson's theory, on the other hand, is a displacement theory. His description of the anatomical structure of the ear is similar to that of Helmholtz; the essential difference between the two theories lying in the extreme differences in function which each theorist ascribes to the contents of the cochlea. We have seen that according to Helmholtz, the sense of hearing is explained by the existence of a resonance mechanism in the ear. According to Wrightson, however, no resonating organ exists. He holds, that when the pressure of any wave is transmitted to the membrane of the oval window into the cochlea, the entire lymph is displaced, and with it, the basilar membrane and all the Corti arches and auxiliary appendages. "These movements", Wrightson says, "are dead beat in their character, being controlled by the constancy of the liquid volume, and its incompressibility".[4] The difference in tone sensation is due to the differences in the nature of the displacements, these being distributed over the whole of the basilar membrane. "The real measure of the power conveyed to the senses is the pressure and displacement of the liquid, and not in the pressure of the air wave, a portion of which is lost through liquid resistance, and ceases to be a moving force."[6]

Wrightson approaches the mechanism of the ear as an engineer approaches a piece of working machinery; his endeavour throughout, being to follow the sequence of every change of pressure and displacement in the liquid particles between the stirrup and the nerve termination.

Dr. Kieth,[6] in his appendix to Wrightson's "The Analytical Mechanism of the Internal Ear" states that, "the whole apparatus of the cochlea is to be regarded as the most delicate weighing machine ever invented------------ a balance for weighing the infinitesimal pressures of sound waves.------------It is a balance which weighs and registers plus as well as minus pressures and displacements. The gradual widening of the basilar membrane as the cochlea is ascended from base to apex, is to provide not a series of resonators," as Helmholtz claims, "but a means of distributing pressure of displacement over an extensive area."

Dr. Kieth, also claims, that on investigating anatomically the structure of the cochlea of the ear of the bird and rabbit,[7] the peculiar structures met with, could not at all be explained under Helmholtz's theory, but that Wrightson's theory explained almost all of them.

The principle differences between the two theories may be summarised as follows:-

First:- where Helmholtz claims that there is a resonance mechanism in the ear, Wrighteon holds that no such organ exists.

Second;-where Helmholtz claims that the organ of Corti and the fibres of the basilar membrane have natural periods of their own, Wrighteon holds that these organs are dead beat.

Third:- where Helmholtz claims that only part of the internal mechanism responds to each individual simple tone, Wrighteon holds that the entire contents of the cochlea is effected and put into motion by each and every wave whether simple or compound.

Fourth:-where Helmholtz claims the lymph is highly elastic, Wrighteon holds that it is highly inelastic.[8]

Both theories have been under the bombardment of the most severe destructive criticism. Each has weathered it to a certain extent,--one standing out stronger that the other, as will be seen.

In a paper by E. G. Boring and E. B. Titchner,[8] Sir Thomas Wrightson's displacement theory was very carefully analysed and so severely criticised that it was literally picked to pieces. The following are a few outstanding points:- Wrightson based his theory entirely upon the principles of analytical mechanics. It was pointed out, however, that he substituted static for dynamic principles[9] in his arguments. Now, since static and dynamic principles of analytical mechanics differ in a great many instances, and in some cases are exactly contradictory,[10] and since the nature of the problem with which he had to deal was purely dynamic, it followed that the arguments put forth by Wrightson in proof of the displacement theory, were without firm foundation.

It was also pointed out in the same paper that Wrightson claimed that the lymph within the cochlea was inelastic and incompressible and "the minute pressures dealt with, would therefore be moved instantaneously in the passages of the cochlea.[11]" Now a liquid cannot be both enelastic and incompressible, because elasticity and compressibility are inversely related;[12] a liquid being highly elastic because of its relative incompressibility.

In the same paper, apparent inconsistencies were pointed out in numerous other instances. These cannot, however, be further gone into in this paper.

Thus, summarising;- Sir Thomas Wrightson's displacement theory, according to Boring and Titchner, although containing many valuable individual points of information, cannot as an entirety be considered a probable theory of hearing.

The Helmholtz resonance theory, on the other hand, in spite of the fact that it is considered by some to have sunk beyond recovery,[13] does still stand, in its essential content, as a probable theory of audition. Whether the resonance mechanism is in the Corti arches primarily, or in the basilar membrane primarily the arches acting as an auxiliary apparatus, or whether the resonating mechanism is one which as yet has not been discovered is not the question; a great deal of experimental evidence leads to the conclusion that such a mechanism probably does xxx exist--and this is the essential content of Helmholtz's theory. Whether his theory in its details embodies and explains, according to the day's interpretation, all the facts concerning our present knowledge of hearing is also not the point. The fact remains that it does explain a great deal that no theory has, as yet been able to do; and which would otherwise still be shrouded in mystery.

Again and again researches have been carried out, the results of which have led to the conclusion that a resonance mechanism exists in the ear. These results are altogether in variance with a displacement theory. For instance, the researches of H. Hartridge,[14] in ghe Cambridge Physiological Labratory, give experimental evidence in favor of the resonance theory. In another of his papers,[15] he answered Perret's objection[16] to the resonance theory. And also in a piece of work by Barton & Browning,[17] the resonance theory of audition was subjected to experimentation with apparent success. The results of my work this year seem also to point very strongly, to a resonance mechanism in the ear. They will also answer a number of current objections to Helmholtz's theory.

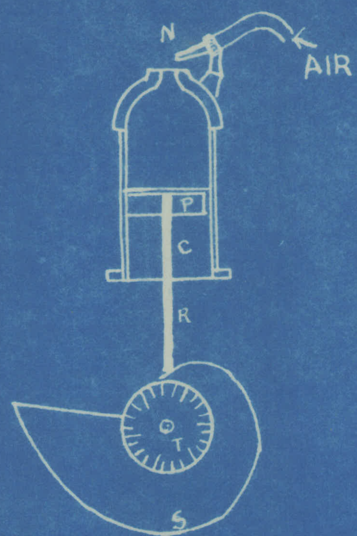


Fig. 2.

Experimental Work Proper

The purpose of the experimentation here to be described, has been to investigate the function of resonance as a part of the physical theory of audition; to see in what manner the results here obtained corresponded with those already established, and if possible, to throw some little light upon the true state of affairs.

Description of Apparatus:-

The essential part of the apparatus is an instrument called a tonvariator, and is diagrematically shown in Fig. 2. It is an instrument by means of which it is possible to obtain any desired note over the range of an octave, without interruption.

The moving piston, P, fits snugly inside of cylinder C. The rod, R, to which the piston is attached, rests upon a peculiarly-shaped cam, S, which, when rotated, caused the piston to move up or down in the cylinder according to a certain definate law embodied in its peculiar shape. The rotation of the cam thus varies the depths of available resonator, and causes the tone emitted to vary in pitch. The instrument can be adjusted to emit any required tone, the vibration frequency of which can be read off from an attached circular scale, T. Air enters the tonvariator through nozzle, N. The range of the tonvariator used is 150-300 D.V.[18]

Fig. 3 is a diagram of the essential parts of the apparatus used throughout the entire experimentation. Tonvariator T, is placed within a closed wooden box which is completely lined

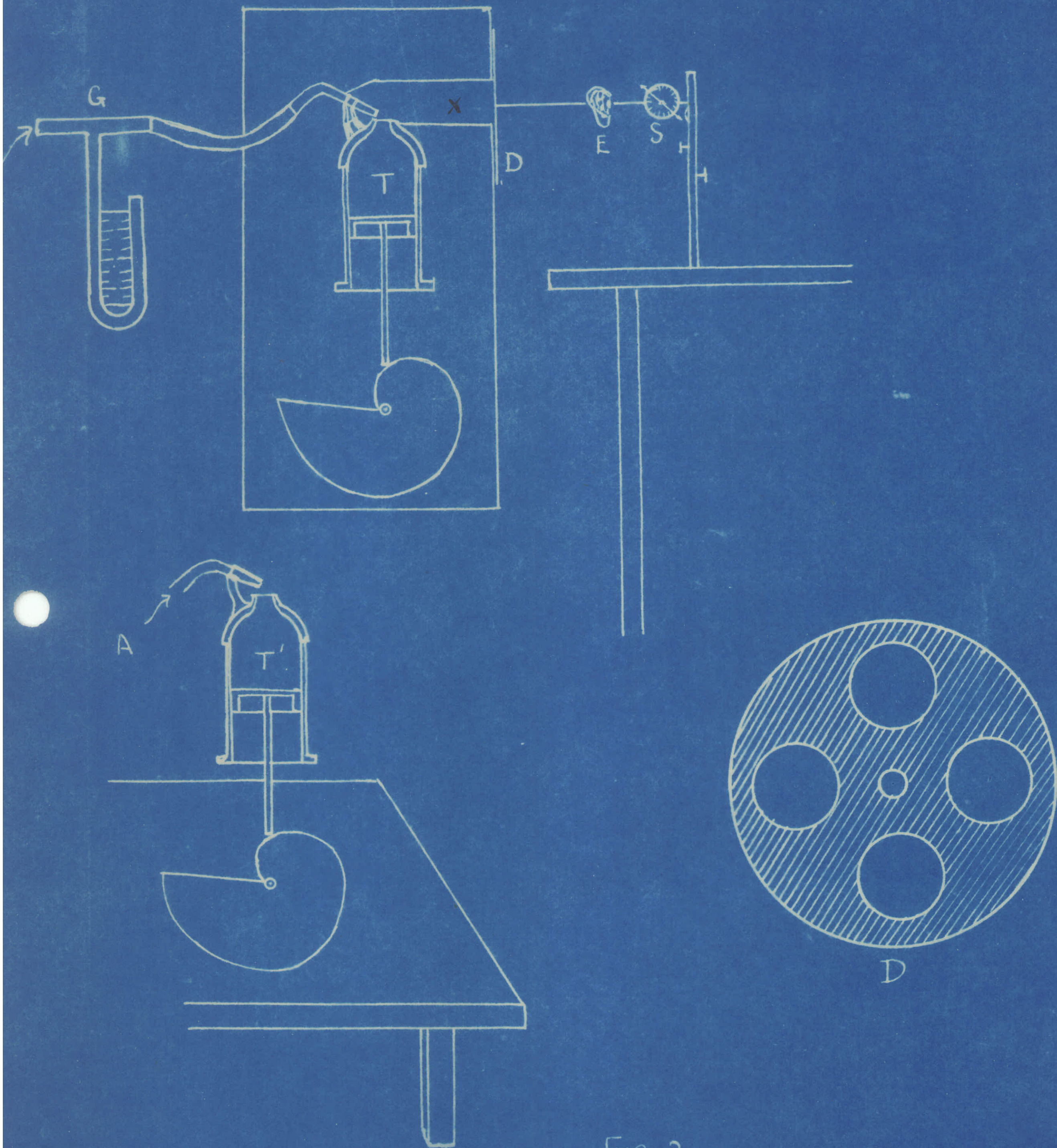


FIG. 3.

on the inside with heavy felt. The purpose of the felt is to absorb any sound except that escaping through cylinderical opening, X. Tonvariator T' is similar in every respect to the one in the box and is used in the latter part of the experimentation for the purpose of fatiguing the ear. Passage X, is the only opening by means of which the sound can leave tonvariator T.

D, is an aluminium disc, so shaped, that sound waves striking it are interrupted four times and allowed to pass through four times each time it revolves. It is covered with velvet in order to keep the sound waves striking it from being reflected back into passage X. The disc is so adjusted, that when revolving, it just does not touch the box, since the closer the disc is to the opening, the more pronounced will be the "flickering" of the sound caused by interruption. The number of revolutions is measured by a speed-counter, S, which makes electrical contact at every fiftieth revolution. This is recorded on the tape of a chronograph. A clock, so modified that it makes and breaks electrical contact every half second, is placed in the circuit and half seconds also are recorded on the tape of the chronograph.

The motor driving the disc is placed in a large wooden box completely lined on the inside and outside with heavy felt this absorbes any whirring or other noises eminating from the motor. The presence of any foreign noise is fatal to the success of the expiriment.

G, is a pressure gauge by means of which the pressure of the air from a constant-pressure tank at A, can be observed. The ear which is always kept in the same position relative to the disc, is represented by E. The speed of the disc, the opening and closing of circuits etc., are controlled by common auxiliary apparatus.

Thus, the air from constant pressure tank at A, passes through the pressure-gauge G,--where the pressure is noted.--into tonvariator T, from which it is emitted as a simple tone, the vibration frequency of which, can be read off on a scale. The simple tone is then forced to pass along passage X, at end of which, it is interrupted at regular intervals by the revolution of disc D. The tone is then ready to be measured.

The arrangement of the apparatus is similar to that used by Dr. Frank Allen in his researches on color vision.

The work fell into two natural divisions:-

A--Investigations into the persistence of audition.

B--Investigations into the resonance of the ear.

A--<u>Investigations into the Persistence of Auditoin.</u>

The word "persistence" is used inthe same sense as when applied to light,(the persistence of vision) namely, the internal of time between two interrupted consecutive trains of sound waves, when the "flicker" [19.] caused by interruption just disappears and the waves seem continuance--or, using another term analogous to that describing the same phenomenon in light, it may be called, the Critical Frequency of "Flicker" of Sound.)

Method of Procedure:-

Adjusted the air to the lowest pressure, (12.5mm.) and the tonvariator to the lowest frequency (150 D.V.). Then caused the disc to rotate at such speed that the "flickering" of the sound became just imperceptible and seemed continuous:--took a chronograph record, from which the persistence of audition was calculated.

The method of calculating from the chronograph tape was as follows:-

A length of tape for 50 revolutions was used for each calculation.

Letting L represent length of tape for 50 revolutions
and t " time in seconds " " "
then L/t is length of tape for one second
and L/50 " " " " " revolution
and L/50 divided by L/t, i.e. t/50 is the time for one revolution.

But there are four interruptions and four passages for each revolution of the disc, therefore, 1/8 of t/50, i.e. t/400 is the time between two successive trains of waves.

The entire calculation thus resolves itself into dividing the number of seconds for 50 revolutions, which can very easily be counted, by 400.

Three calculations were made from each tape record, and the average from three to four such tape records was taken to define the exact point.

Keeping the pressure constant, measurements for seven such points for frequencies between 150-300 inclusive, were obtained. These points were taken to define the normal persistence curve for the given pressure.

In the above manner, measurements for ten such curves were obtained. Each curve represents the relation between the vibration frequency and persistence of audition for the octave 150-300, at a definate pressure. They form a regular family of curves.

The curves thus obtained, were not, however, entirely true; since for a constant adjustment of tonvariator the frequency of the tone emitted was found to vary with the pressure of the entering stream of air. Calibration curves had therefore to be obtained for the purpose of correction. For this purpose, three standard adjustable tuning-forks were used:- and by the process of elimination of beats between the tonvariator and the tuning-fork, the true frequency of the tone variator tones were arrived at. The calibration curves thus obtained are shown in Fig.4, and the table of values in Table 4. It may be of interest to know that the forks used for calibration were made by Herr Rudolph Koenig, himself.

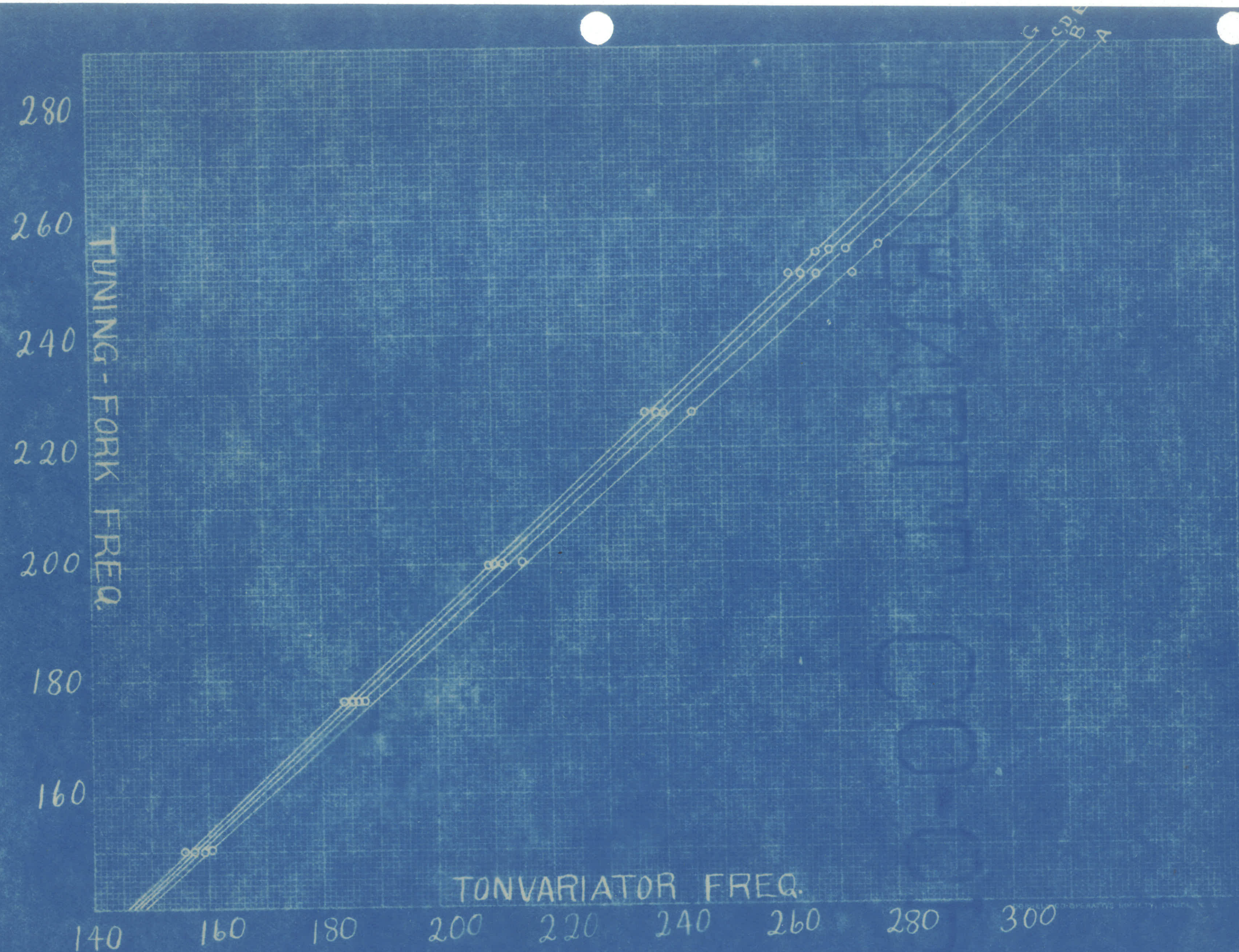

TUNING-FORK FREQ.
TONVARIATOR FREQ.
280
260
240
220
200
180
160
140
160
180
200
220
240
260
280
300
G
C
D
B
E
A

FIG. 4.

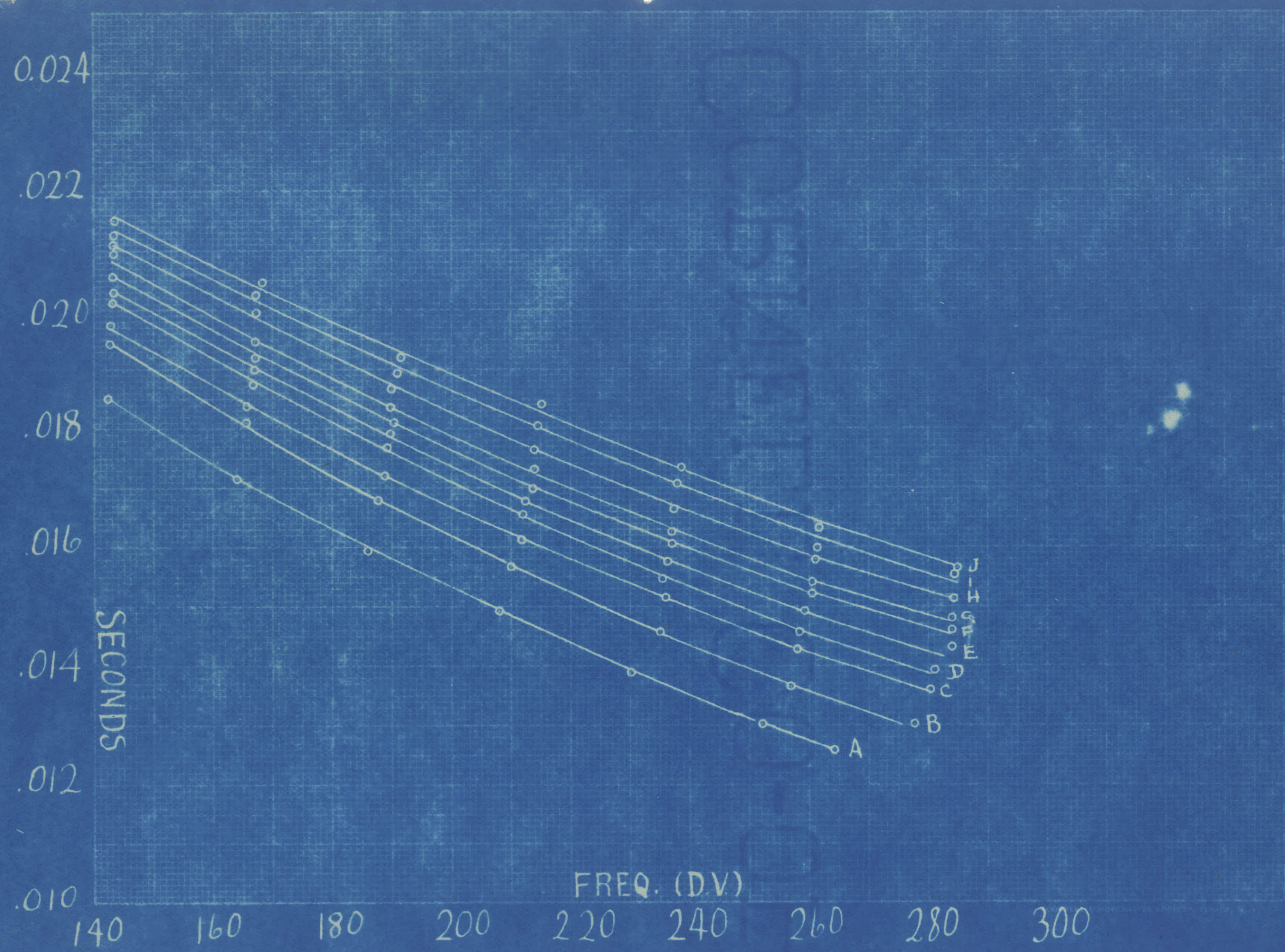
Table 4

Table of Values for Calibration Curves.

	Press.	Stand. Tun.Fork.	Tonvar.		Press.	Stand. Tun.Fork.	Tonvar.
	12.5 mm.	150	160		19.8 mm.	150	157
	"	176	187		"	176	184.8
	"	200	215		"	200	211
A	"	226	245	D	"	226	239
	"	250	273		"	250	264
	"	254	277.6		"	254	268
	15.3 mm.	150	157.5		21.0 mm.	150	157
	"	176	186		"	176	184.8
	"	200	211.5		"	200	211
B	"	226	240	E	"	226	239
	"	250	267		"	250	263.2
	"	254	272		"	254	268
	18.2 mm.	150	157.5		22.0 mm.	150	157
	"	176	185		"	176	184
	"	200	211.5		"	200	211
C	"	226	239	F	"	226	238.5
	"	250	264.5		"	250	264
	"	254	269		"	254	268
	24.0 mm.	150	156				
	"	176	184				
	"	200	210				
G	"	226	237				
	"	250	262				
	"	254	267				

The family of normal persistency curves was then corrected from Fig.4. The corrected curves are shown in Fig.5 and the table of values in Table 5.

Each individual curve shows the relation between the persistence of auditon and the frequency of the tones at a definite constant pressure. The position of the curve on the graph defines its relation to the pressure.



0.024
.022
.020
.018
.016
.014
.012
.010
SECONDS
FREQ. (D.V)
140
160
180
200
220
240
260
280
300
A
B
C
D
E
F
G
H
I
J

FIG. 5.

TABLE 5

Normal Curves corrected for Frequency.

	Corr. Freq.	Persist.	Press.		Corr. Freq.	Persist.	Press.
A.	142.0	0.01851	12.5 mm.	F.	143.0	0.02056	18.2 mm.
	164.0	.01716	"		167.0	.01918	"
	186.0	.01595	"		190.0	.01815	"
	208.0	.01491	"		214.0	.01700	"
	230.0	.01388	"		237.0	.01605	"
	252.0	.01301	"		260.5	.01526	"
	264.0	.01269	"		284.0	.01462	"
B.	142.5	0.01941	14.5 mm.	G.	143.0	0.02099	19.8 mm.
	165.5	.01810	"		167.0	.01948	"
	187.5	.01682	"		190.0	.01838	"
	210.0	.01569	"		214.0	.01731	"
	235.0	.01462	"		237.0	.01625	"
	256.7	.01365	"		260.5	.01542	"
	278.0	.01303	"		284.0	.01481	"
C.	142.8	0.01973	15.3 mm.	H.	143.0	0.02106	21.0 mm.
	165.8	.01839	"		167.2	.01998	"
	188.8	.01720	"		190.2	.01866	"
	211.8	.01612	"		214.2	.01770	"
	235.7	.01515	"		237.2	.01663	"
	257.9	.01430	"		260.7	.01580	"
	280.5	.01378	"		284.2	.01513	"
D.	142.9	0.02012	16.2 mm.	I.	143.2	0.02123	22.0 mm.
	166.2	.01874	"		167.3	.02025	"
	189.0	.01770	"		191.0	.01898	"
	212.0	.01658	"		214.6	.01804	"
	235.3	.01549	"		238.0	.01706	"
	258.2	.01458	"		261.2	.01600	"
	280.9	.01395	"		284.2	.01553	"
E.	143.0	0.02028	17.0 mm.	J.	143.5	0.02150	24.0 mm.
	166.6	.01900	"		168.2	.02045	"
	189.7	.01792	"		191.2	.01920	"
	213.2	.01675	"		215.0	.01841	"
	236.2	.01575	"		238.3	.01732	"
	259.3	.01493	"		261.9	.01633	"
	283.0	.01431	"		285.0	.01563	"

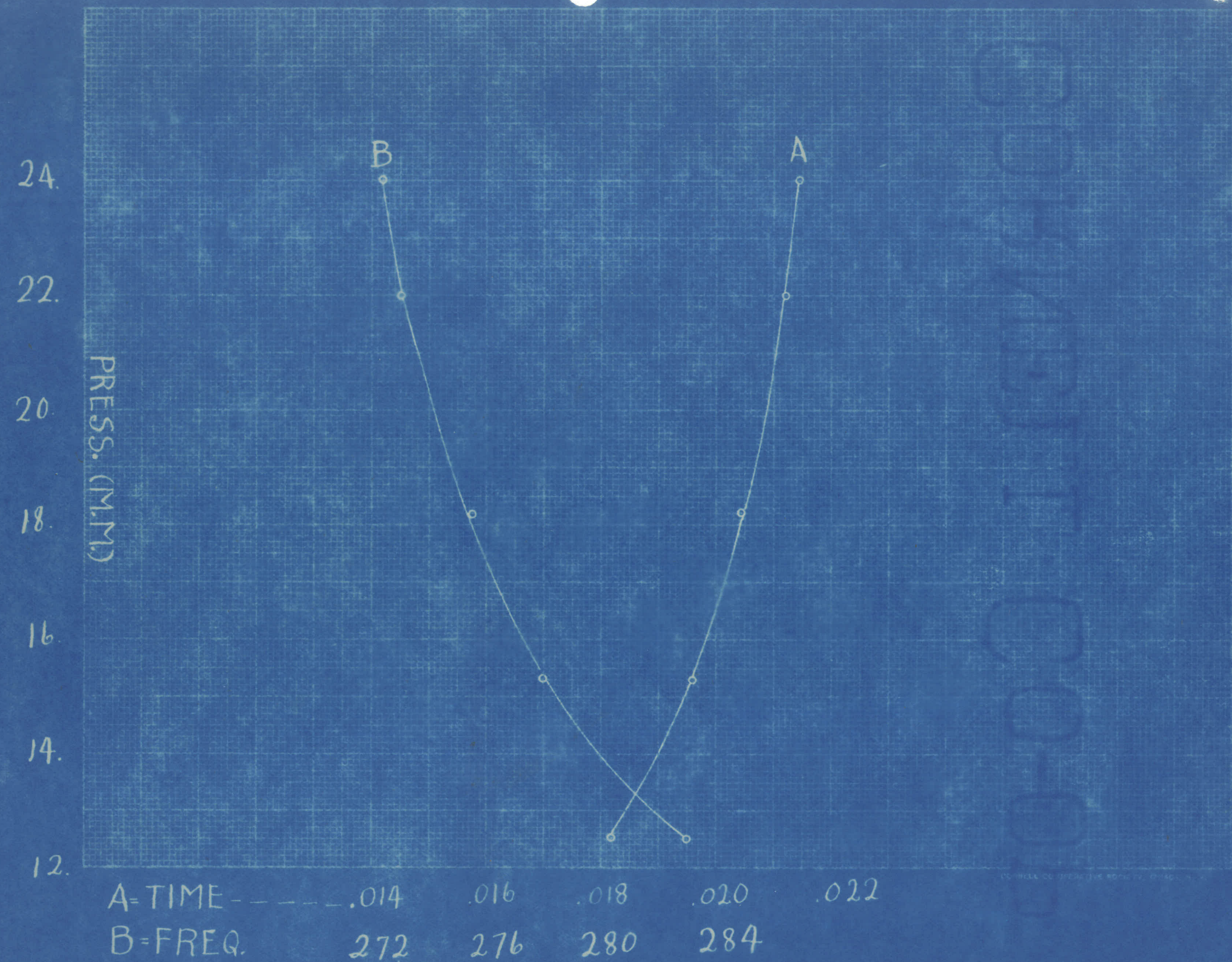
The curves are all of the same type. From frequency 140 to 240, the curves are almost straight lines, indicating an almost constant relationship between the vibration frequency of a tone and its persistence of audition. From 240 to 280 there appears to be a slight increase in curvature.

The curve A, representing the lowest pressure has the lowest persistence and is the lowest curve on the graph. Curves B,C,D--etc. representing pressures each respectively greater than the one before it.

Now, in a piece of research carried by the Misses Love and Dawson,[20] it was shown that the sound intensity of resonators varies with the blowing pressure, i.e. the pressure of the air entering the resonator.

Assuming this to be true, the curves in Fig.5 may be regarded not only as indicating the relation between the vibration frequency persistence of audition, and pressure of a tone, but also as showing a relation between vibration frequency, persistence, and intensity of a tone:- curve A, representing the persistence of tones of lowest intensity, and curve J, of highest intensity; the position of the intermediate curves representing intensities relative to A and J.

It will be noticed that the relative vertical distance between the curves are not equal. The distance between the curves of high intensity is small and gradually increases as the intensity is decreased; the increment of distance becoming



B
A
24.
22.
20.
18.
16.
14.
12.
PRESS. (M.M.)
A=TIME - - - - - .014 .016 .018 .020 .022
B=FREQ. 272 276 280 284

FIG. 6.

greater as the lowest pressure is approached. This increase in vertical distance appeared to be so decidedly regular that a body wondered whether it could not be proven positively that such should be the case.

The method which suggested itself and which was carried out, was to see whether the calibration curves in Fig.4 indicate that the relative distances in Fig.5, should be as actually represented. Now, evidence given by the calibration curves may be regarded as positive proof, because of the manner in which they were obtained. The method used for obtaining them, namely, the elimination of beats, is such that allows of very little error.

From Fig.5, for any given frequency, say 260, a curve may be plotted which shows the relation between the pressure or intensity of that tone and its persistence of audition:- the pressure being represented by the vertical distance. This curve was actually plotted and is shown in Fig.6 curve A'. (Table of values in Table 6A.

Table 6.

Freq. Tuner Fk.	Freq. Tonvar.	Press.	Persist.
260	283.0	12.5 mm. ← A →	0.01820
"		14.5 "	.01925
"	278.0	15.3 "	.01960
"		16.2 "	. 01985
"		17.0 "	.02015
"	275.5	18.2 "	.02045
"		19.8 "	.02075
"		20.0 "	.02100
"	273.0	22.0 "	.02120
"	272.0 ← B →	24.0 "	.02146

Now, the straight lines in FIG.4, represent calibration curves for tones also of different pressure or intensity;- curve A for lowest pressure and C for highest pressure. Therefore, if from Fig. 4, for the same true tone, 260, the pressures (represented in this case by the horizontal distances), be plotted against the tonvariator frequencies, then the resulting curve should be very similar to curve A' (Fig.6):- the curvature, however, should be opposite in sign because of the inverse almost constant relationship which holds between the reequency and persistence of a tone. This curve was also actually plotted and is shown in the same figure curve B'. (Table of values in Table 6(B).) And as can be seen, curve B' lives up to expectations. Thus from evidence given by the calibration curves as shown is Fig.6, the positions of the normal curves in Fig. 5 may be looked upon as accurately relatively placed.

The above serves as more positive experimental proff of theoretical deductions from less positive expiremental evidence;- which makes the less positive experimental evidence more positive.

The calibrationcurves can be used in another way to show that the normal curves in Fig. 5 are correctly relatively placed. From the calibration curves it can be seen that for a true tone, the pressure varies inversely as the tonvariator frequency;- i.e.

$$P = \frac{K}{F}$$

$$\text{or} \quad F = \frac{K}{P} \text{------------(1)}$$

where P. stands for pressure, F, vibration frequency, and K, an arbitrary constant.

From any of the normal curves it can be seen, the persistence of audition varies inversely as some funtion of the vibration frequency;- i.e.

$$D = \frac{K'}{f(F)} \text{ ----------- } (2)$$

where D. stands for the persistence of audition, f(F) some function of the frequency, and K' another arbitrary constant.

Therefore, substituting the value of F from eqation (1) for f(F) in equation (2), get

$$D = \frac{K'}{K} \cdot P = CP \text{ ---------- } (3)$$

where C is arbitrary constant including K' and K.

Equation (3) is not strictly true, because F cannot be substituted for f (F); it serves to show that the persistence of audition bears a direct realation to the pressure. And this is apparent in Fig. 5, for the higher the pressure of a tone, the higher is its persistence of audition. The curves are thus correctly relatevely placed.

And also, starting from evidence furnished by the calibration curves, the general slope of the normal curves may be shown to be correct.

If D, bears a direct relationship to P, i.e.

$$f(D) = CP \text{ or}$$

$$P = \frac{f(D)}{C} \text{ ------- } (4) \text{ (i.e. equation (3) more correctly represented)}$$

then, substituting value of P from equation (4) into equation (1) get

$$F = \frac{K \times C}{f(D)} = \frac{C'}{f(D)} \text{ -------- } (5)$$

where C' is an arbitrary constant including both K and C, i.e. the frequency of a tone bears an inverse relationship to the persistence of audition.

This relation also becomes apparent by examining any normal curve in Fig. 5:- as the frequency increases, the persistence of audition decreases.---Again, the more positive evidence furnished by the calibration curves, proves the characteristics of the normal curves as exhibited in Fig. 5, to be correct.

And still further examining the normal curves in Fig. 5, convictions as to their relative truth being firmer because of the evidence furnished by the calibration curves, one wonders if there is not a definate law which binds the persistence of audition of a tone with its intensity.

In color vision, Ferry & Porter, independently found that the relation between persistence of vision and intensity of illumination of light can be expressed by the law [21]

$$D = \frac{K}{\text{Log. } I.}$$

where D stands for persistency of vision; I, for intensity of illumination; and K is an arbitrary constant.

This law does not hold true for audition.

Another law, however, similar to that of Ferry & Porter, does seem to apply;- and that is,

$$D = \frac{K}{\sqrt{\text{Log. } I.}}$$

where D stands for persistence of audition; I, for intensity of sound; and K is an arbitrary constant.

In Fig. M, (Table of values in Table M), the reciprocals of the persistencies were plotted against the square roots of the logarithms of the intensities. The results are seen to be straight lines. Each line represents the relation between intensity and persistence for a definite constant frequency. The truth of the above law is thus seen to be very strongly pointed towards.

Table M.

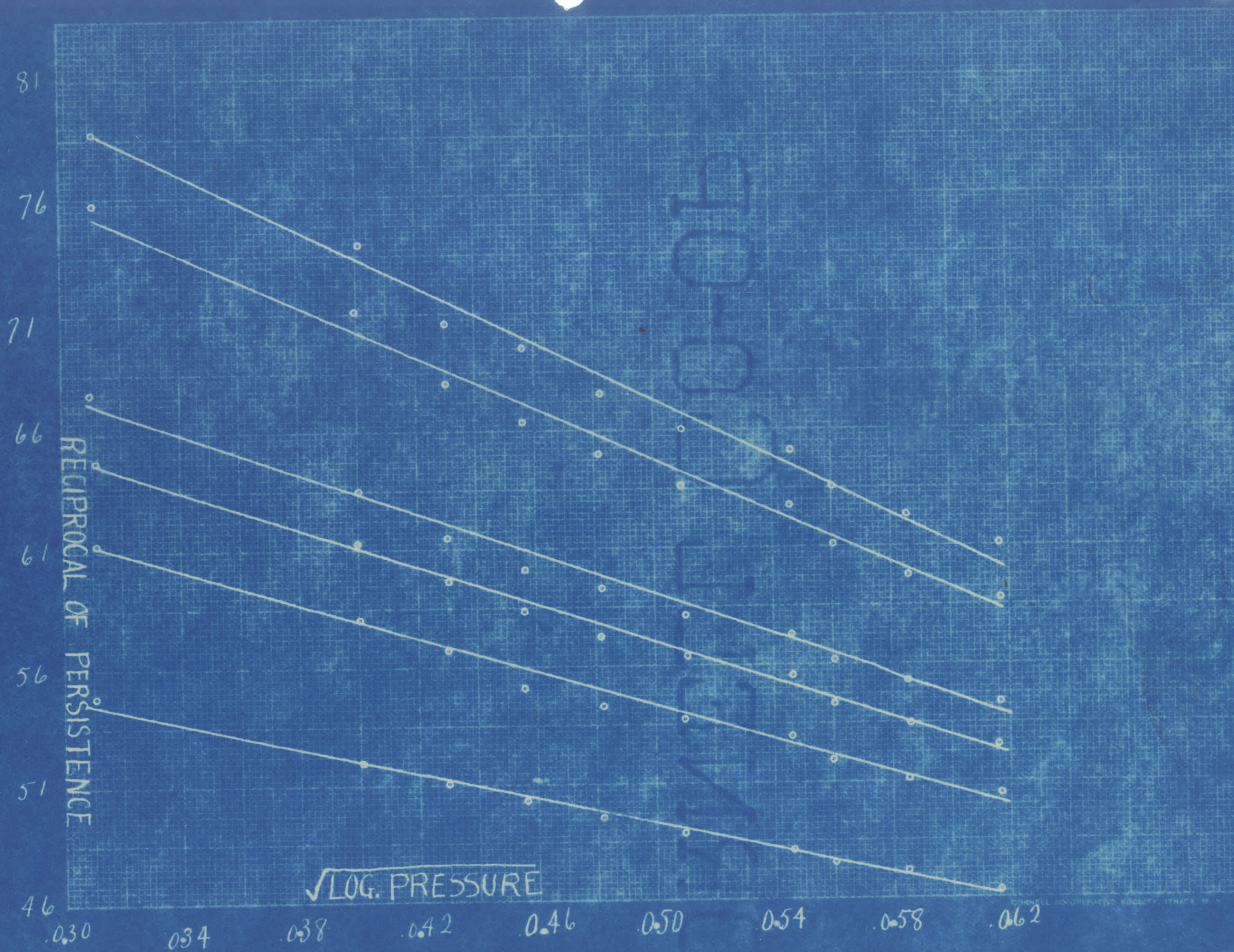
Log. P.R.	1.	2.	3.	4.	5.	6.
.0616	46.60	50.50	52.63	54.34	58.82	61.16
.0585	47.17	51.12	53.42	55.24	59.88	62.30
.0560	47.62	52.03	54.43	56.18	61.16	63.49
.0546	48.19	53.05	55.62	57.30	62.81	65.14
.0510	48.90	53.73	56.46	58.13	63.69	66.00
.0482	49.63	54.41	57.30	59.20	65.02	67.56
.0456	50.38	55.22	58.14	60.06	66.40	69.54
.0430	51.02	56.65	59.66	61.50	68.03	70.52
.0401	51.95	58.14	61.35	63.50	71.07	74.07
.0311	54.95	61.35	64.85	67.75	75.75	78.85

Further exprimentation for verifying the above law, is planned for the near future.

Also, since the number of revolutions per minute of the disc, is inversely proportionat to the persistence of audition, then a relatiin between the number of revolutions of the disc and the intensity may be expressed by

$$n = \sqrt{K \text{ Log. } I} + K'$$ [21]

where n stands for the number of revolutions per minute; K and K'



81
76
71
66
61
56
51
46
RECIPROCAL OF PERSISTENCE
√LOG. PRESSURE
.030
034
038
.042
0.46
0.50
0.54
0.58
.062

FIG. M

are arbitrary constants, and I, the intensity.

In a discussion, the relation between the persistence of audition and the frequency, it may be of interest to know that Professor Mayer[22] of Hoboken N.J., has done extensive experimental work on the subject.[23]

His method was as follows:-[24]

Between a vibrating tuning fork and its resonator he interposed a revolving disc with openings of the same shape as that of the resonator, so that the sound was heard loudly when an opening in the disc came in front of that in the resonator, and faintly when the latter was covered. He found the following law to hold:-

$$D = \left(\frac{53248}{N - 25} - 24\right) \cdot \frac{1}{10,000} \text{ seconds}$$ [24]

i.e.,

$$D = \frac{K}{N} \quad C' \text{ seconds---in general terms--(6)}$$

where D stands for duration of time or the persistence of audition; N, the pitch number or frequency, K and C, arbitrary constants.

The analague relation here obtained is

$$D = \frac{K}{f(N)} \text{-----(7)-----(from equation (2).)}$$

The truth of equation (7) is not only shown from equation (2) with which it is edentical, but from actual plotting. The reciprocals of the persistencies were plotted against the frequencies. Had the result been straight lines, then Dr. Mayer's law, would have applied. The resulting curves were, however, not straight lines. They posed a slight regular curvature very similar to that of the normal curves in Fig. (5), but were opposite in sign.

Equation (7) which states that the persistence of audition is inversely proportional to some function of the frequency, thus holds true for the results here obtained.

The difference between Dr. Mayer's relation and that here obtained is probable due to that fact that in Dr. Mayer's experimentation, a resonator was interposed between the source of sound and the ear; whereas, here the sound was allowed to enter the ear directly.

This finishes division A of the work.

B--<u>Investigations into the resonance of the ear.</u>

The method employed, was to study the effects of fatigue upon the persistence, of audition.

The apparatus used was the same as in the first division of the work, with the addition of another tonvariator, T', similar in all respects to the one in the box. Tonvariator T' was used for the purpose of fatiguing the ear.

In studying the effect of the time of fatigue, on the persistence of audition, the results were too uncertain to warrant the drawing of fatigue-time graph. The maximum fatigue, seemed, however, to be reached at the end of about two minutes. An interval of time of two minutes was therefore allowed for fatiguing the ear, before each measurement was made.

Two methods were used in this part of the work, one the exact converse of the other,--with the hope that the results obtained from one would confirm those obtained from the other. And this, happily, appeared to be the case.

The first method consisted in fatiguing the ear with a tone of constant frequency, and taking measurements on tones varying over a range of twenty vibrations either side of the fatiguing tone. The second method consisted in taking measurements on a tone of constant frequency, varying the fatiguing tone over a range of about twenty vibrations either side of the tone upon which measurement were taken.

Method of Proceedure:-

At definite pressure, adjusted the tone variator in the box to 256, and tonvariator T' to the same frequency by means of eliminating beats. Fatigued the ear with 256 and immediately made measurements on 256. Again fatigued the ear with 256, and made measurements on 259. In the same manner, fatiguing with 256 before each measurement, took chronograph records of 262,270,253,250, and 240.

The persistence curve defined by these points was taken to represent the effect of fatiguing the ear with a tone of constant frequency. It is shown in Fig.7 (a) (Table of Values in Table 7).

Table 7

	Press.	Tonv.T.	Tonv.T'	Pers't.		Press.	Tonv.T.	Tonv.T'	Pers't.
(a)		Normal Curve			(b)		Fatigue Curve		
	18.2mm	214.0		0.01700		17.8mm	242.8	242.8	0.01705
	"	236.8		.01605		"	"	245.8	.01550
	"	260.5		.01526		"	"	248.2	.01520
	"	284.0		.01463		"	"	251.0	.01486
						"	"	254.0	.01510
		Fatigue Curve				"	"	256.8	.01494
						"	"	265.0	.01498
	18.2mm	242.8	242.8	0.01803		"	"	240.0	.01568
	"	245.5	"	.01610		"	"	237.0	.01500
	"	248.2	"	.01580		"	"	234.5	.01508
	"	255.8	"	.01552		"	"	231.6	.01501
	"	240.0	"	.01750		"	"	228.7	.01479
	"	237.0	"	.01628		"	"	226.0	.01483
	"	227.8	"	.01642		"	"	218.4	.01494

The curve through the circles is the normal, and the curve through the x's, is the fatigue curve. It will be noticed that the fatigue curve is hump-shaped, and fits quite

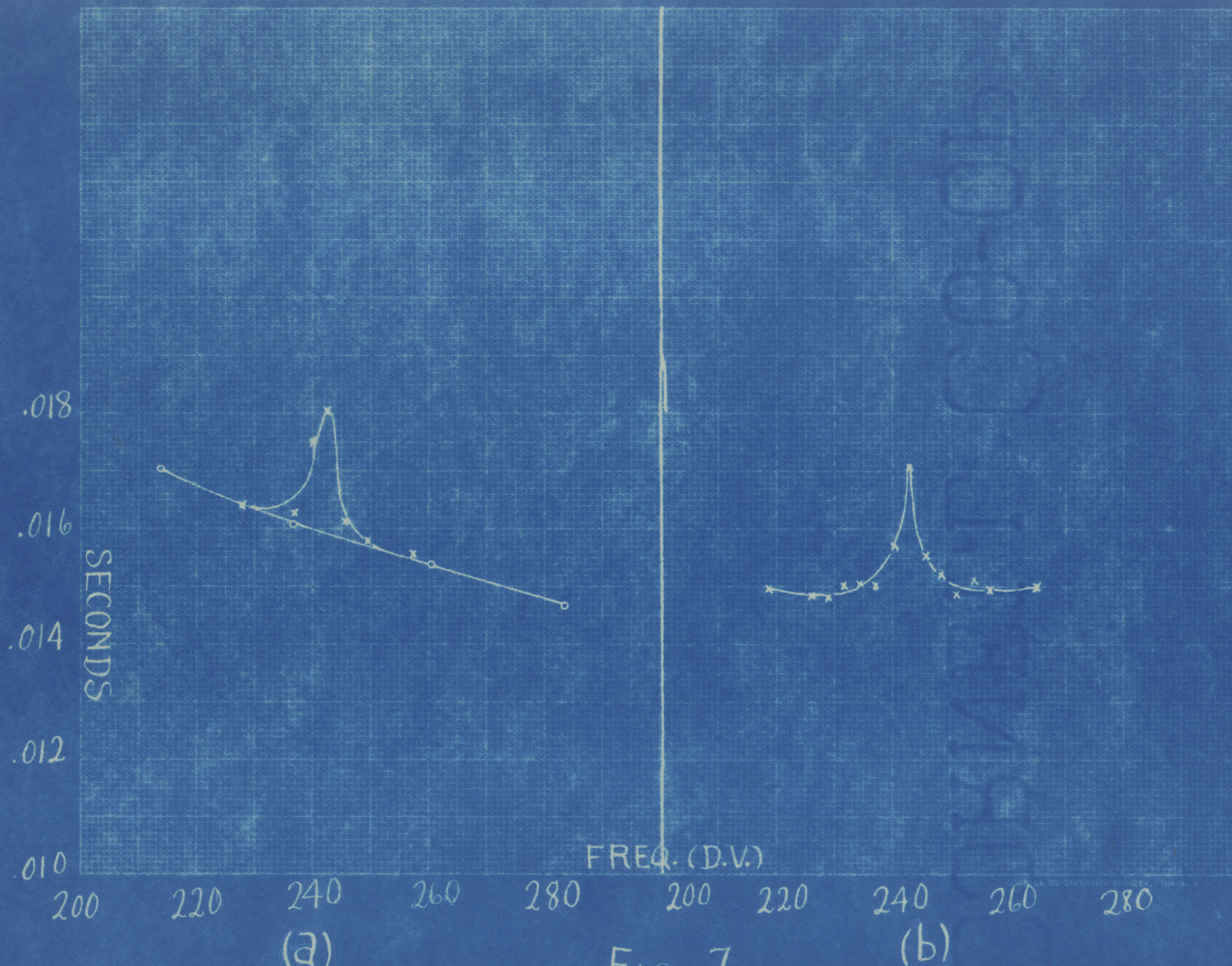

.018
.016
.014
.012
.010
SECONDS
FREQ. (D.V.)
200
220
240
260
280
(a)
200
220
240
260
280
(b)

Fig. 7.

accurately on the normal persistency curve of the same pressure.

A series of such fatigue-persistency, for different frequencies and pressures, were obtained. These will be dealt with later.

Fig. 7 (b), is a fatigue curve for the same frequency and pressure, but obtained by the second method,- i.e. all measurement were taken on 256, the fatiguing tone being varied. It will be noticed that the hump drops on a horizontal normal. This should be so, since, the horizontal line represents the persistence of the constant tone 256.

The curves indicate that, as a result of fatigue, the persistency of sound impressions is greatly increased. This increase is a maximum, when the frequency of the fatiguing tone is the same as that upon which measurements were taken, and diminishes very rapidly as the the distance from the frequency of the fatiguing tone is increased. The entire range effected is about thirty vibrations. The steepness of the slope, indicates that only a few vibrations immediately either side of the maximum, are stimulated, to any great extent.

The above phenomenon is not only very readily explained by a resonance theory, but points directly towards the existance of resonance mechanism in the ear. It cannot in any manner be explained by a displacement theory.

Let us assume, for the sake of argument, that the organ of Corti, is that mechanism, the forty five hundred arches acting as a series of resonators. And also, for the sake of brevity, let us call those arches possessing natural vibration frequencies corresponding exactly to that of an entering wave, the *resonal arches* of that wave, and the few adjacent arches corresponding to about two vibrations either side of the resonals, the *auxiliary arches*. The, evidence from Fig. 7, may be interpreted as follows:-

When a train of simple waves enters the cochlea, the resonal arches are set into viblent vibration. Arches corresponding to about fifteen vibrations either side of the resonals are also effected, but the intensity of their tone very rapidly dominishes as the distance from the resonals is increased. Allowing the ordinates to represent the intensity of the vibrating arches and assuming that the intensity of vibration varies as a square of the ordinates, then the intensity of the resonals and the auxiliary arches will be very great as compared with those farther away. And, if the intensity of vibration is proportional to the degree of stimulation of the auditory nerves then the effect in the brain due to the resonals and the auxiliary arches, would altogether drown out the effect due to the arches farther away. The only effective motion may therefore be said to be in the resonals and in the auxiliary arches.

Granted that the above is the case, then the following objection arises;----since the auxiliary arches occupy points of relatively maximal intensity, why should they not give experiences peculiar to their own vibration frequencies when they are vibrating in subordination to their relative maximums, the resonals. In fact, this is the principle objection that Professor Watt[25] has against Helmholtz's theory. Dr. Kieth,[27] in his appendix to Wrightson's book, mentions the fact that Professor Watt rejects Helmholtz's conception of resonators in the ear.

The above objection, may be explained in two ways. First, from an expériment carried out by Helmholtz,[26] who writes;-"an elastic body set into sympathetic vibrations by any tone, vibrates sympathetically in the pitch number of the exciting tone;- but as soon as the exciting tone ceases, it goes on sounding in the pitch number of its own proper tone. This fact, which is derived from theory may be perfectly verified on tuning forks by means of the vibration microscope."

Helmholtz's conclusion, when applied to the present instance, indicates that the reason the auxiliary arches are not heard in their own natural vibration frequency, is because they vibrate in the same frequency as the resonals. As soon as the exciting tone ceases, the entire range effected also ceases to vibrate;- and the tones due to the natural frequency of the auxiliaries are therefore again, not experienced.

The fact that the auxiliaries are not heard in their own natural frequency, may be explained in another manner.

It is a well know fact that only an exceptionally well-trained ear can distinguish the interval of a coma,-i.e. a difference of one vibration in 80. To the average ear, this interval is not at all distinguishable. Now, in the case under consideration, looking upon the auxiliary arches as the only ones whose intensity may be considered comparable to that of the resonals, then we have only about three to four frequencies to consider. If each arch vibrates in its own natural frequency, we have a difference of three to four vibrations in 256,- i.e. a difference of one in about seventy five;

which is approximately the interval of a coma.--And this, according to universal experience, as stated above, is indistinguishable to the average ear.

And here an experiment suggests itself, which, if it could be carried out, would give rather strong evidence as to the existence of resonators in the ear. If, when the arches are responding to an exciting tone, the resonals could in some manner be damped, then the intensities of arches, farther distant from the resonals, would appear comparatively more prominent, and the differencies in audible frequency being greater, beats should be heard. The above might perhaps be done by changing the phase of the exciting wave, by π , (as described by H. Hartridge in his, " A Vindication of the Resonance Hypothesis of Audition." 2.) [23] This would cause momentary cessation of the audibility of the resonals:- and if beats were then heard, then the evidence would point towards the existance of resonators in the ear.

As was mentioned before, Watt's main objection to a resonance theory is that the arches either side of the resonals do not give experiences in conformity with the law of specific energies of sense. Watt may have been justified in his objection, since according to Helmholtz himself, in a graph indicating the distribution of intensity over the range of frequencies set into motion by an exciting tone, he has the effect spread over a range of two whole equally tempered tones;-i.e. approcimately sixty four vibrations. Graph A, Fig. 8, is an exact reproduction of Helmholtz's graph. The abscissae represents the frequencies effected and the ordinates the intensity of vibration. Graph B, Fig. 8, is plotted in the same scale as that of Helmholts's. It is the fatigue curve for frequency 256, pressure 18.2 mm.

Table 8

Comparison between Helmholts's Intensity Curve and Fatigue Curve.

Pressure	Tonvariator T'	Tonvariator T	Persistence
17.8 mm.	242.8	242.8	0.01705
"	245.5	"	.01550
"	248.2	"	.01520
"	251.0	"	.01486
"	254.0	"	.01510
"	256.8	"	.01494
"	265.0	"	.01498
"	240.0	"	.01562
"	237.0	"	.01500
"	234.5	"	.01508
"	231.6	"	.01501
"	228.7	"	.01479
"	226.0	"	.01483
"	218.4	"	.01494

A

B Helmholts's curve taken directly from Book page 144.

The difference in range affected is thus very strikingly shown in Fig. 8. It is apparent from the figure, that Helmholts did not assign to his resonators powers of functioning over such comparitively narrow limits, as curve B, seems to indicate.

Objections such as Watt's, may therefore have been justified. However, since Helmholts's curve was purely hypothetical and not confirmed by actual experiment, and since curve B was obtained experimentally, above objections cannot any longer be raised.

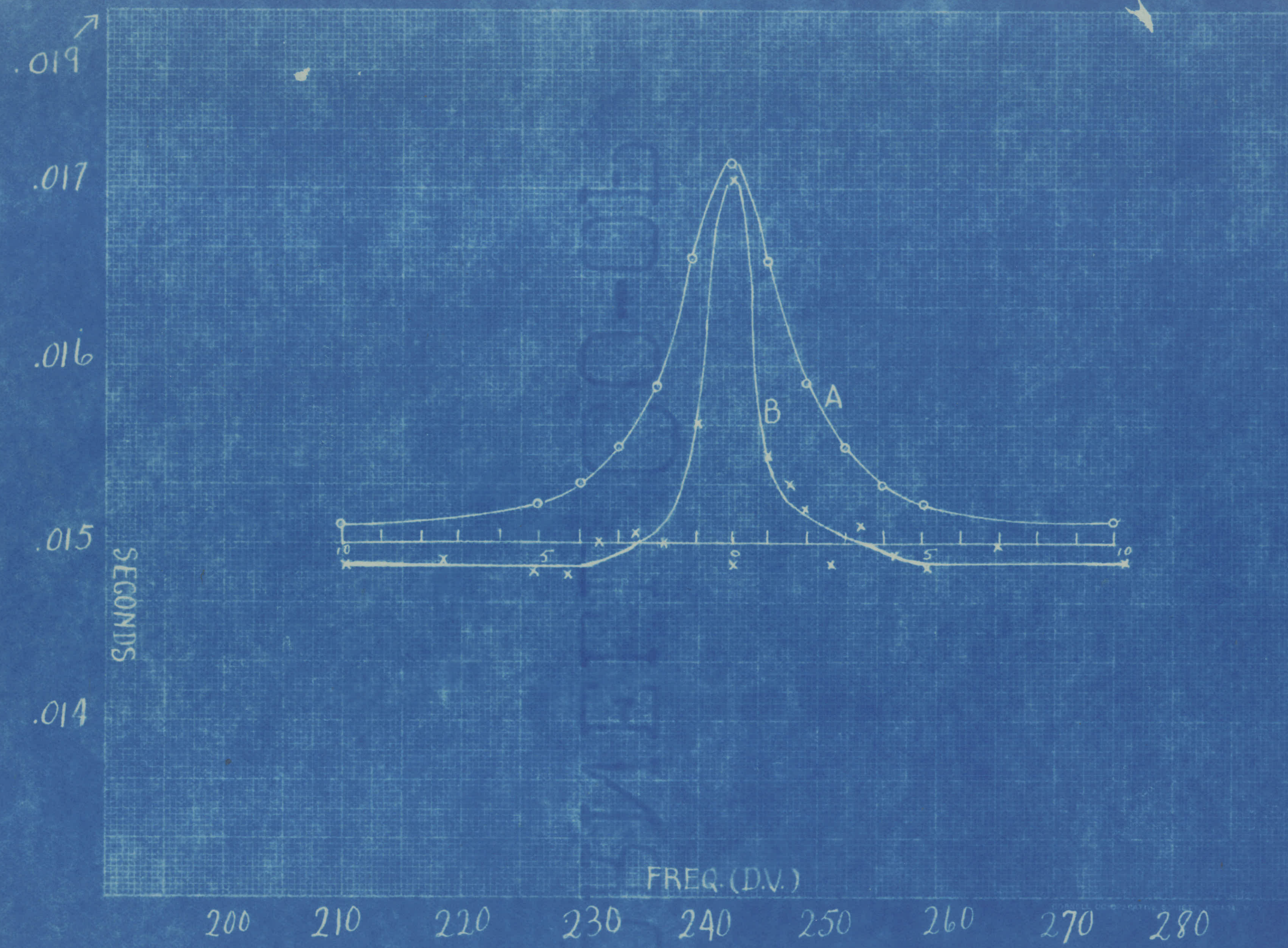

.019
.017
.016
.015
.014
SECONDS
A
B
10
5
0
5
10
FREQ. (D.V.)
200
210
220
230
240
250
260
270
280

Fig. 8.

There is another point that could now, perhaps, be more clearly explained;- and that is the lack of clearness and brilliance when making quick runs or shakes in the base.

It is universally known, that shakes in the bass are not clear, but that the tones merge into one another. This is independent of the instrument upon which the runs are attempted.

Helmholtz, in his own words,[29] explains it as follows:-"---------. Since the difficulty of shaking in the bass is the same for all instruments; and for individual instruments, is demonstably independent of the manner of which the tones are produced,-we are forced to conclude that the difficulty lies in the ear itself. And this, " he claims, "is a plain indication that the vibrating parts of the ear are not damped with sufficient force and rapidity to allow of successfully affecting such a rapid alternation of tones."

The blurring or merging of tones in the bass is not due to the peculiar construction of the ear and to the insufficient damping of the resonance mechanism, - but to the very nature and defination of musical tones, even before they enter the ear.

The difference in vibration frequency between two successive tones in the treble is very large when compared with the difference between two such tones in the bass; e.g. the difference between c'' 512, and d'' 576, is 64 vibrations; whereas the difference between C, 32 and D, 36, is only 4 vibrations. In a run in the treble therefore, each tone is so far moved from the one preceding it, that the arches stimulated by the first tone are altogether outside the region of influence of the second. It can very clearly be seen, therefore, that when c'', d'', e'', f'' etc. are sounded in rapid succession, the effect will be distinct and brilliant. And the higher the pitch in which the runs are made, the more distinct will each tone be from the other, and the more brilliant the total impression.

In the base, on the other hand, this is not the case. The difference in vibration frequency between two successive tones is comparitively very small;- e.g. the difference between C, 32 and D, 36, is only four vibrations; and even in an octave higher, the difference between C 63 and D 72 is only eight vibrations. Now, since the difference in frequency between two consecutive tones is so small, the arches responding to one tone will be influenced by the arches responding to the other:- in fact, nearly the same range will be influenced by the each tone. The arches most clearly distinguishable will be the resonals of each tone. And these are themselves not far distant from each other. In Fig. 9, in which fatigue curves for five frequencies at the same pressure are indicated, it will be noticed that the humps for 160 and 170 overlap to a great extent. The difference in frequency in this instance is ten vibrations. If the difference were smaller, the overlapping would be greater:- therefore the farther down the base one attempts to produde a succession of tones, the more nearly will the same range of resonators be influenced by each of the tones,- and the more indistinct and blurred will be the general impression made. Thus, when A, B, C, D,----etc. are sounded in rapid succession in the bass, the impression of blurredness and indistinctness is experienced. The blurredness is however, not due to the peculiar construction of the ear, but to very nature of sound and defination of tones.

The fact that the ear does experience this blurring of tones in the bass, is further proof that a resonance mechanism exists in the ear; for, if air be blown into a set of resonators for bass tones, in rapid succession, the same effect will be produced.

Fig. 9, shows a set of five fatigued-persistency curves taken from frequencies 160, 170, 210, 256 and 285; at same pressure 18.2 mm.

Table 9

Fatigue Curves for different Frequencies at same Pressure.

Press.	Tonv. T.	Pers't.	Press.	Tonv. T.	Pers't.
	Normal Curve				
18.2 mm.	143.0	0.02056	18.2 mm.	162.2	0.02115
"	167.0	.01918	"	165.0	.01982
"	190.0	.01815	"	168.0	.01917
"	214.0	.01700	"	176.5	.01870
"	237.0	.01605	"	159.2	.02050
"	260.5	.01526	"	156.4	.01985
"	284.0	.01462	"	149.0	.02012
	Fatigue Curves.				
18.2 mm.	152.5	.02131	18.2 mm.	200.0	.01952
"	155.5	.02060	"	202.8	.01833
"	158.2	.01959	"	205.6	.01762
"	167.0	.01927	"	213.8	.01710
"	149.5	.02022	"	197.2	.01905
"	146.7	.02045	"	194.5	.01823
"	153.8	.02062	"	185.8	.01832

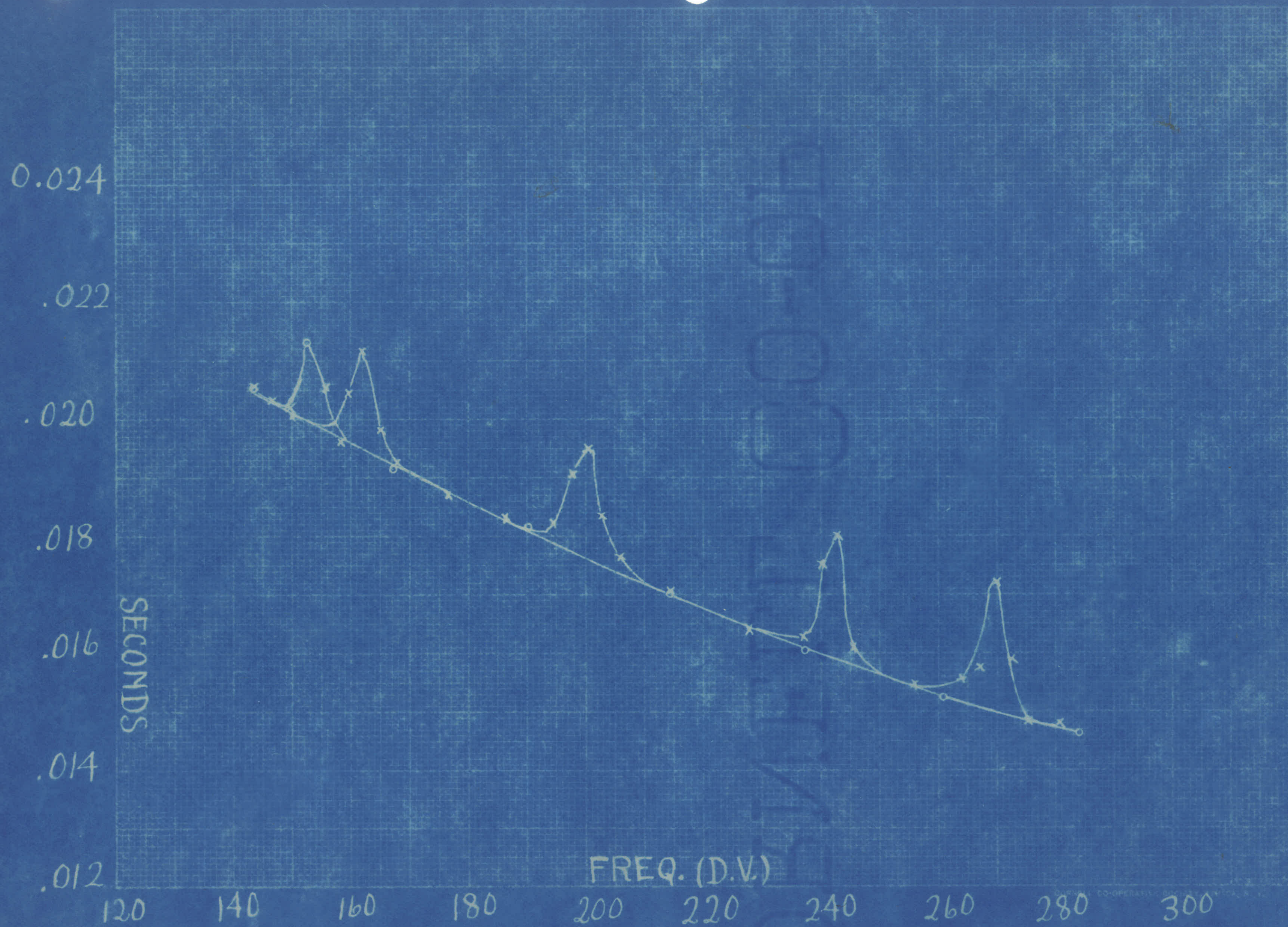

0.024
.022
.020
.018
.016
.014
.012
SECONDS
FREQ. (D.V.)
120
140
160
180
200
220
240
260
280
300

Fig. 9.

Table 9 (Continued)

Press.	Tonv. T.	Pers't.	Press.	Tonvt.T.	Pers't.
		Fatigue Curves (Continued)			
18.2 mm.	242.8	0.01803	18.2 mm.	269.6	0.01707
"	245.5	.01610	"	272.4	.01591
"	248.2	.01580	"	275.2	.01482
"	255.8	.01552	"	281.0	.01481
"	240.0	.01750	"	267.0	.01577
"	237.0	.01628	"	264.0	.01557
"	227.8	.01642	"	255.8	.01545

The nature of the curve, is seen to be the same for each frequency. It will be noticed, that, as the frequency is increased, there is a gradual increase in the persistence of the resonal arches. This can be more clearly seen, if a curve defined by the five persistencies of the resonals is drawn and compared with the normal for the same pressure. This is shown in Fig. 10 (Table of values in Table 10).

Table 10

Comparison between Normal Curve and Curve through Resonals.					
Press.	Tonv. T.	Pers't.	Press.	Tonv. T.	Pers't.
A	Normal Curve.		B	Curve Through Resonals	
18.2 mm.	143.0	0.02056	18.2 mm	152.5	0.02131
"	167.0	.01918	"	162.2	.02115
"	190.0	.01815	"	200.0	.01952
"	214.0	.01706	"	242.8	.01803
"	237.0	.01605	"	269.6	.01707
"	260.5	.01526			
"	284.0	.01462			

Curve A, represents the curvethrough the persistencies of the resonals. B, represents the normal curve for the same

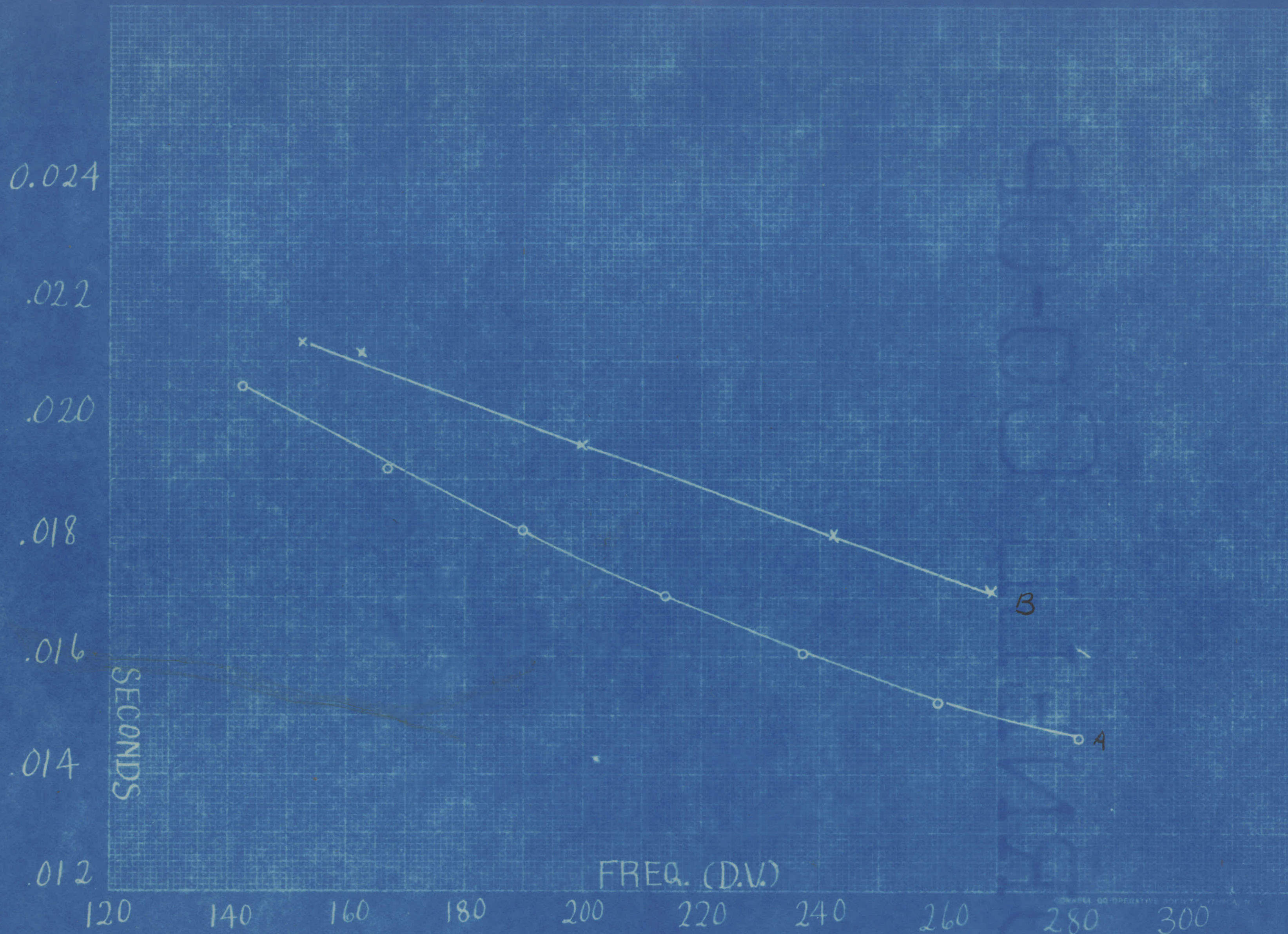

0.024
.022
.020
.018
.016
.014
.012
SECONDS
B
A
FREQ. (D.V.)
120
140
160
180
200
220
240
260
280
300

Fig. 10.

pressure. A, appears to be a straight line sloping farther away from B, as the frequency is increased.

There also appears to be a slight gradual widening of the basses of the fatigue curves as the frequency is increased. This would seem to indicate that the range influenced is slightly greater for higher frequencies. There is too much uncertainity, however, to make any definate statement.

Fig. 11 (Table of Values in Table 11) , (shows) three series of fatigue persistence curves each series representing the effects of fatigue on approximately the same frequency, for seven different pressures:- series one, for frequency 170, series two for frequency 210, series three for frequency 256.

All three series indicate in remarkable manner that the effect of fatigue is to increase the persistency of a tone. This increase becoming less as the pressure becomes greater.

It was thought that if a set of fatigue curves at a pressure above the maximum here used, could be obtained, a point might be reached where no visible effect of fatigue could be graphically shown. This was not practical experimentally, because when a tone for such a pressure was produced, it possessed a hissing quality which made measurement of persistency, with any degree of uncertainty practically impossible.

If measurements could be taken and the expected results should be obtained, then the disappearance of the visible effect of fatigue might point, not to the absence of fatigue upon the ear, but to the fact that at a higher pressure, the ear is fatigued in a shorter time; that is, during the time the observer

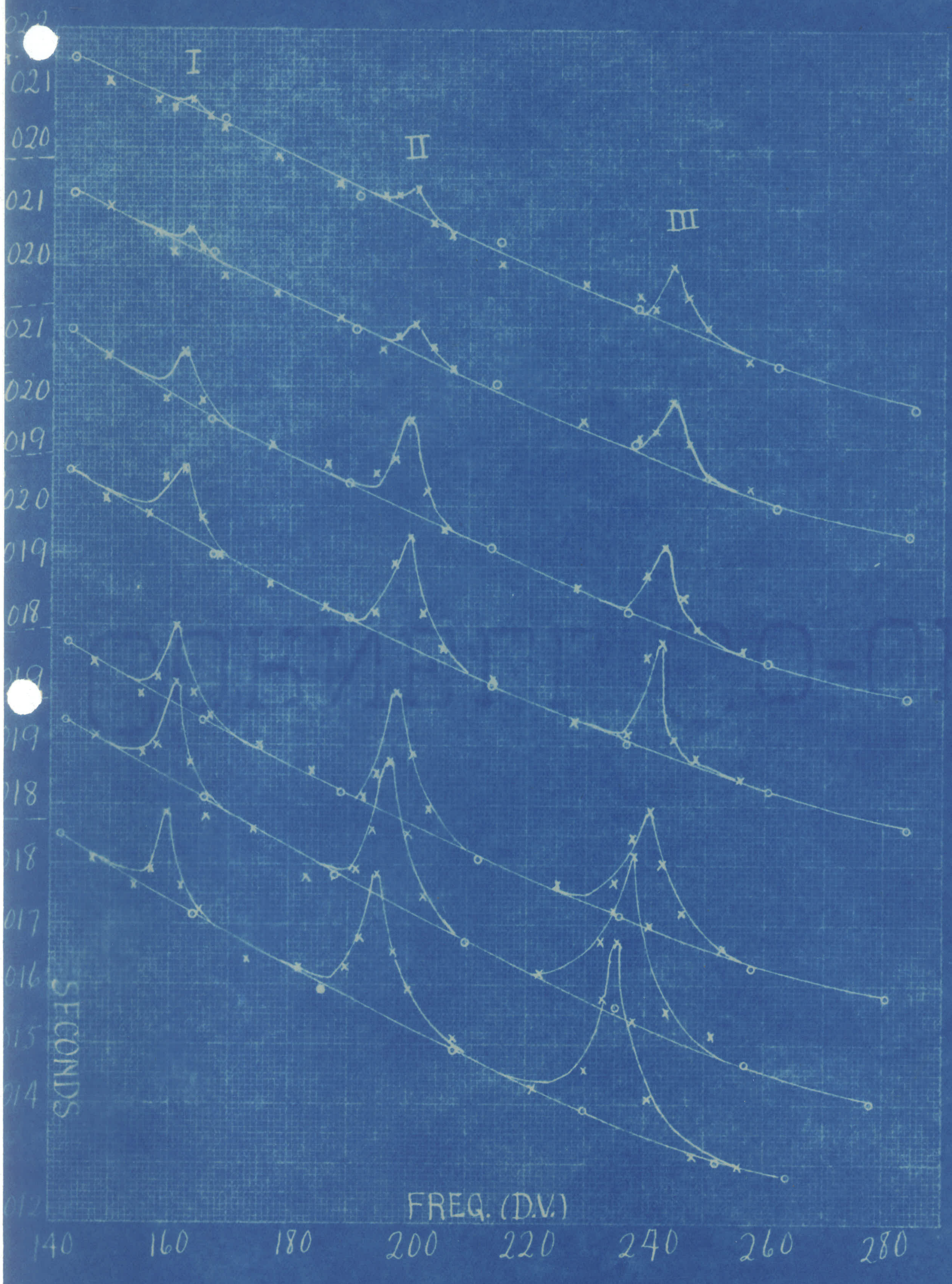


Fig. 11.

Table 11

Persistence of Fatigue Curves.

Tonv.T.	Pers't.	Tonv.T.	Pers't.	Tonv.T.	Pers't.
12.5mm(235.2)		**14.5mm(160.8)**		**18.2mm(200.0)**	
235.2	0.01677	160.8	0.02005	200.0	0.01952
238.0	.01540	163.6	.01871	202.8	.01833
240.6	.01410	166.0	.01776	205.6	.01762
247.8	.01310	174.3	.01763	213.8	.01710
232.7	.01576	158.0	.01900	197.2	.01905
230.0	.01456	155.2	.01889	194.5	.01823
221.2	.01427	147.3	.01920	185.8	.01832
12.5mm(159.4)		**15.3mm(240.3)**		**18.2mm(162.2)**	
159.4	.01887	240.3	.01692	162.2	.02067
162.0	.01765	243.0	.01605	165.0	.01982
165.0	.01725	246.0	.01519	168.0	.01917
173.0	.01640	253.0	.01462	176.5	.01870
156.9	.01791	237.6	.01650	159.2	.02050
154.0	.01762	235.0	.01570	156.4	.01985
147.0	.01810	225.8	.01571	149.0	.02012
12.5mm(195.0)		**15.3mm(198.0)**		**19.8mm(242.8)**	
195.0	.01785	198.0	.01887	242.8	.01733
197.6	.01654	200.8	.01784	245.5	.01649
200.0	.01592	203.5	.01694	248.2	.01597
208.0	.01516	211.8	.01619	255.8	.01562
192.0	.01678	195.0	.01752	240.0	.01687
189.6	.01629	192.3	.01718	237.0	.01629
181.8	.01637	184.0	.01764	227.8	.01667
14.5mm(238.0)		**15.3mm(161.0)**		**19.8mm(200.0)**	
238.0	.01715	161.0	.02000	200.0	.01845
240.8	.01600	163.9	.01889	202.8	.01721
243.6	.01459	166.6	.01850	205.6	.01671
251.0	.01423	175.0	.01809	213.8	.01632
235.2	.01623	158.0	.01914	197.2	.01779
232.4	.01575	155.0	.01882	194.5	.01755
222.8	.01520	147.5	.01939	185.8	.01775
14.5mm(197.0)		**18.2mm(242.8)**		**19.8mm(162.2)**	
197.0	.01875	242.8	.01803	162.2	.02060
199.8	.01750	245.5	.01610	165.0	.01979
202.5	.01646	248.2	.01580	168.0	.01948
210.0	.01580	255.8	.01552	176.5	.01900
194.0	.01757	240.0	.01750	159.2	.01978
191.2	.01692	237.0	.01628	156.4	.01996
183.0	.01678	227.8	.01642	149.0	.02054

Tonv.T.	Pers't.	
244.00	.01778	
247.0	.01704	22.0mm
249.8	.01652	(244.0)
257.0	.01638	
241.2	.01727	
238.4	.01714	
229.0	.01741	
201.0	.01902	
203.8	.01865	
206.7	.01830	
215.0	.01790	22.0mm
198.0	.01885	(201.0)
195.2	.01857	
186.7	.01913	
163.0	.02062	
165.9	.02029	
168.0	.01983	
177.2	.01953	22.0mm
160.0	.02025	(163.0)
157.2	.02069	
149.0	.02103	
244.0	.01802	
247.0	.01750	
249.8	.01702	24.0mm
257.0	.01638	(244.0)
241.2	.01735	
238.4	.01753	
229.0	.01777	
201.0	.01932	
203.8	.01876	
206.7	.01855	24.0mm
215.0	.01803	(201.0)
198.0	.01925	
195.2	.01925	
186.7	.01941	
163.0	.02082	
165.9	.02068	
168.0	.02037	24.0mm
177.2	.01983	(163.0)
160.0	.02068	
157.2	.02079	
149.0	.02110	

was making a measurement of normal persistence, the ear, apparently in a normal condition, was being fatigued.

Fig. 12, (Table of Values in Table 12) shows a set of four persistency fatigue curves obtained by the second method; i.e. taking measurement on a constant tone, the fatiguing tone being varied.

Table 12

Fatigue Curves---By Second Method.-(Constant Pressure)

Press.	Tonv. T'.	Pers't.	Press.	Tonv.T'.	Pers't.
	(242.8)			(190.5)	
17.8 mm.	242.8	0.01705	17.8 mm	190.5	0.01882
"	245.5	.01550	"	193.2	.01777
"	248.2	.01520	"	196.0	.01713
"	251.0	.01486	"	198.5	.01697
"	254.0	.01510	"	201.7	.01698
"	256.8	.01494	"	204.5	.01699
"	265.0	.01498	"	213.6	.01693
"	240.0	.01568	"	187.5	.01750
"	237.0	.01500	"	185.0	.01721
"	234.5	.01508	"	182.0	.01721
"	231.6	.01501	"	179.3	.01709
"	228.7	.01479	"	176.6	.01739
"	226.0	.01483	"	167.0	.01727
"	218.4	.01494	"		

Press.	Tonv. T'.	Pers't.	Press.	Tonv.T'.	Pers't.
17.8 mm.	199.8	.01862	17.8 mm.	218.4	.01747
"	202.6	.01727	"	221.3	.01571
"	205.3	.01655	"	224.0	.01543
"	208.1	.01653	"	226.6	.01544
"	218.4	.01665	"	229.8	.01544
"	196.9	.01721	"	237.1	.01535
"	194.0	.01674	"	215.7	.01582
"	191.2	.01678	"	212.7	.01553
"	181.0	.01658	"	210.0	.01544
"			"	207.1	.01546
			"	200.0	.01535

As in Fig. 9, the curves in Fig. 12 indicate that the effect of fatigue on persistence becomes greater as the

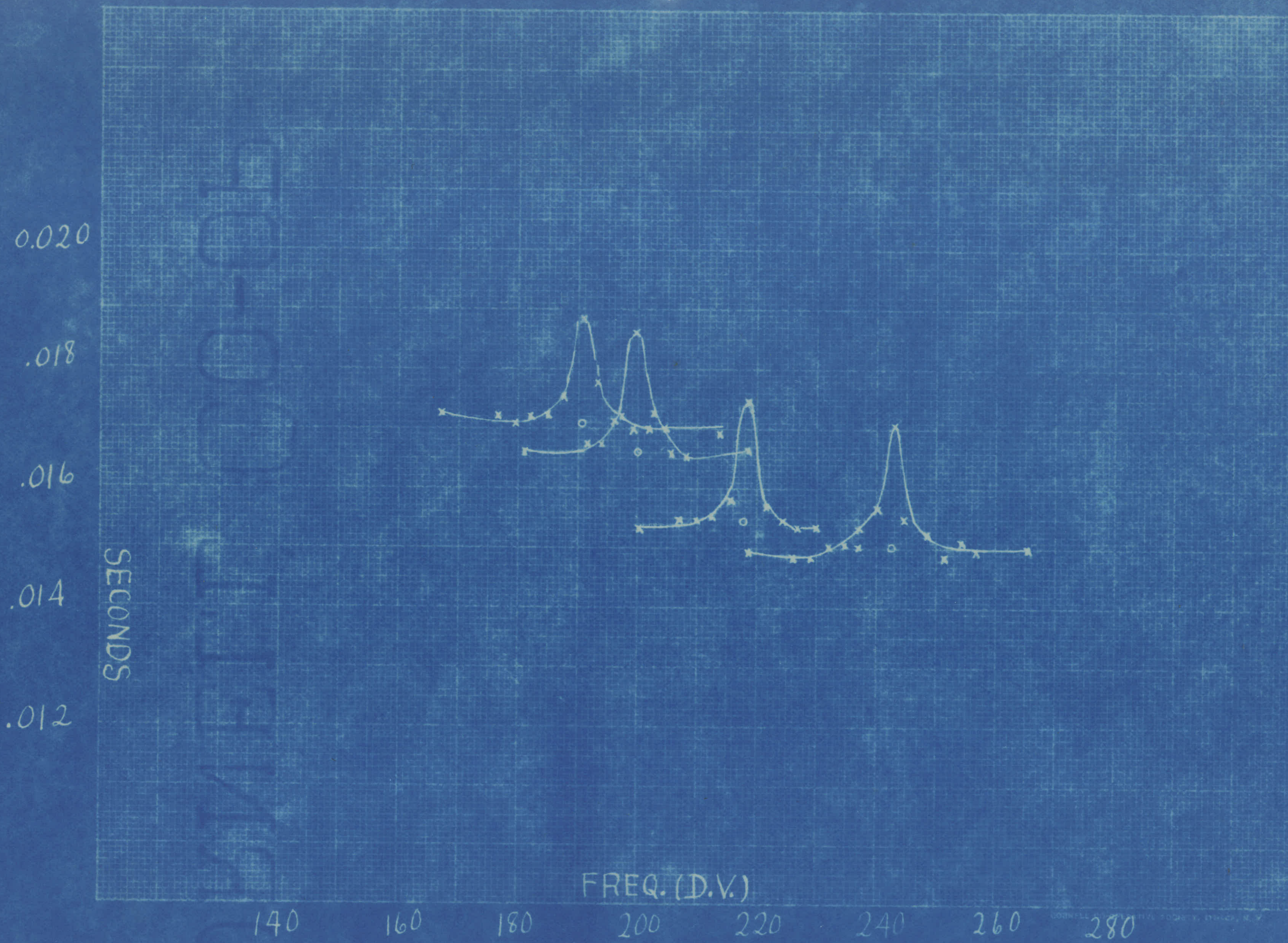

0.020
.018
.016
.014
.012
SECONDS
FREQ. (D.V.)
140
160
180
200
220
240
260
280

Fig 12.

musical scale is ascended. The narrowness of the range effected is seen more clearly in this figure, because the normal upon which the humps drpp is horizontal.

Fig. 13, (Table of Values in Table 13), shows two series of fatigue curves, each for an approximately constant frequency, but for varying pressures. Again the decrease in the apparent effect of fatigue is very clearly indicated as the pressures is increased; e.g. the vertical height of A, is less than that of B, is less than that of C,-------etc. The increase in the effect of fatigue, as the frequency is increased, is also apparent in this figure:- e.g. the vertical height of A' is greater than that of A, of B' is greater than that of B, etc.

The effects of fatigue as indicated by the results of the second method, are thus very consistant with those of the first method:- the results of one, confirming those of the other.

The effect of fatigue as indicated by the effect on the persistence of audition, may be summorised as follows. Due to fatigue, the persistency of any tone is increased, the increase being greatest at the lowest pressure, decreasing as the pressure is increased; and smallest at the lowest frequency, increasing as the frequency is increased. The range effected is approximately the same forall frequencies and pressures, there appearing, however, slight but not very certain indications that the range at high pressures and low frequencies is a little less than

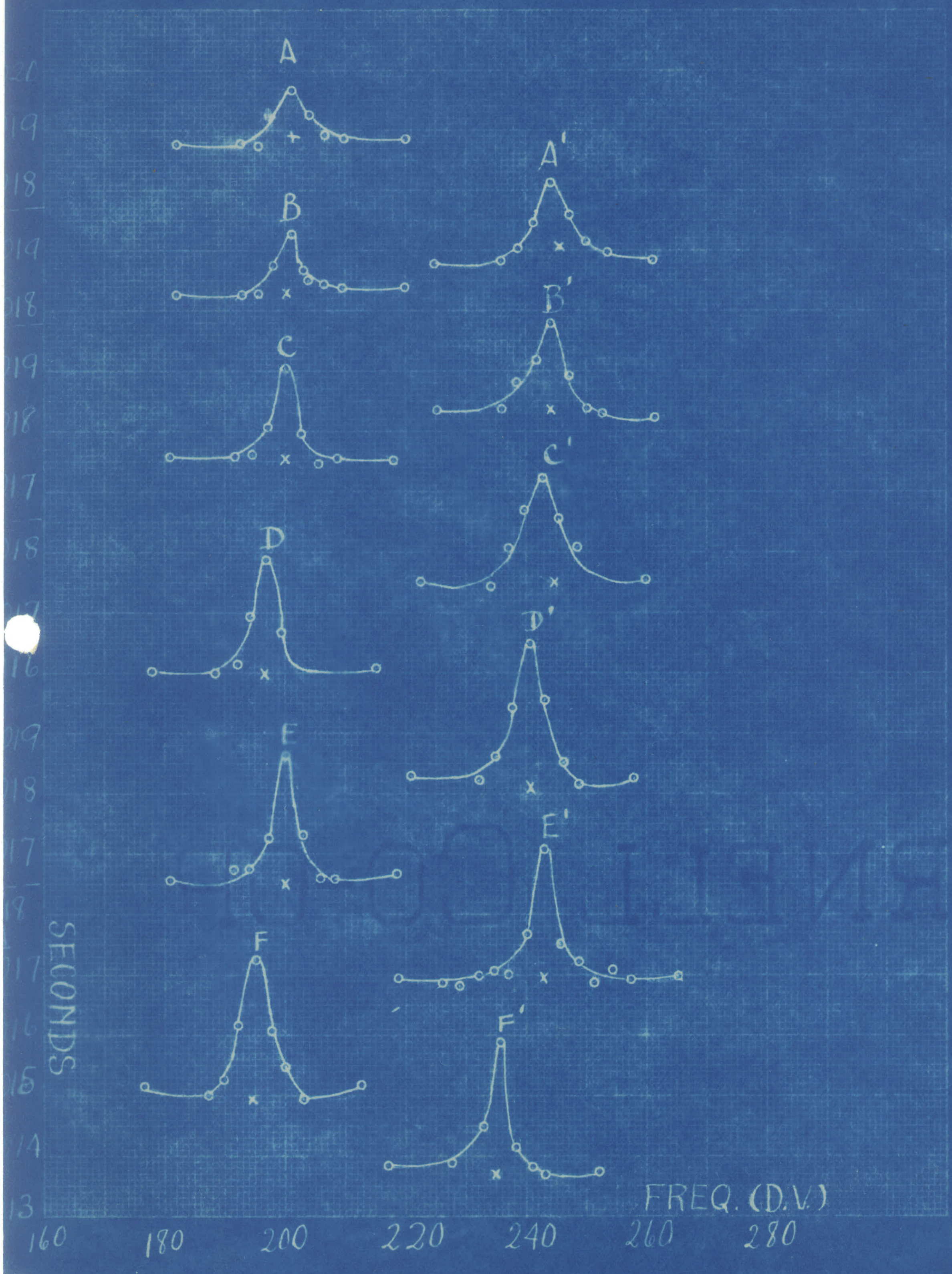


FIG. 13.

Table 13

Fatigue Curves---By Second Method.

Conv.T'	Pers't.	Conv.T'	Pers't.	Conv.T'	Pers't.	Conv.T'	Pers't.
11.6mm(195.0)		15.0mm(240.3)		19.8mm(200.0)		21.0mm(244.0)	
195.0	0.01725	240.3	0.01649	200.0	0.01902	244.0	0.01781
197.6	.01604	243.0	.01554	202.8	.01795	247.0	.01691
200.0	.01542	246.0	.01453	205.6	.01745	249.8	.01636
203.0	.01494	248.5	.01414	208.4	.01755	252.5	.01630
212.3	.01520	258.0	.01425	218.0	.01750	261.5	.01620
192.0	.01618	237.6	.01545	197.2	.01807	241.2	.01712
189.6	.01525	235.0	.01462	194.5	.01760	238.4	.01679
187.0	.01500	232.0	.01420	191.8	.01755	236.0	.01637
177.0	.01515	221.0	.01430	181.0	.01752	225.0	.01633
11.6mm(235.2)		17.8mm(199.8)		19.8mm(242.8)		24.0mm(201.0)	
235.2	.01585	199.8	.01862	242.8	.01724	201.0	.01962
238.0	.01413	202.6	.01727	245.5	.01652	203.8	.01925
240.6	.01380	205.3	.01655	248.2	.01607	206.7	.01892
243.0	.01358	208.1	.01653	251.0	.01556	209.5	.01886
252.0	.01373	218.4	.01665	260.0	.01552	219.0	.01881
232.7	.01450	196.9	.01721	240.0	.01670	198.0	.01905
230.0	.01415	194.0	.01674	237.0	.01605	195.2	.01872
227.3	.01390	191.2	.01675	234.0	.01542	192.5	.01873
217.0	.01383	181.0	.01658	223.0	.01550	182.0	.01875
15.0mm(197.0)		17.8mm(242.8)		21.0mm(201.0)		24.0mm(244.0)	
197.0	.01788	242.8	.01705	201.0	.01926	244.0	.01810
199.8	.01667	245.5	.01550	203.0	.01865	247.0	.01759
202.5	.01592	248.2	.01520	206.7	.01841	249.8	.01713
205.2	.01597	251.0	.01486	209.5	.01838	252.8	.01692
215.0	.01607	254.0	.01510	219.0	.01838	261.0	.01680
194.0	.01656	256.8	.01494	198.0	.01871	241.2	.01746
191.2	.01611	265.0	.01498	195.2	.01825	238.4	.01698
188.2	.01599	240.0	.01568	192.5	.01828	235.8	.01679
178.0	.01603	237.0	.01500	182.0	.01834	224.5	.01675
		234.5	.01508				
		231.6	.01501				
		228.7	.01479				
		226.0	.01483				
		218.4	.01494				

that of low pressures and high frequencies.

In interpreting the graphical effects of fatigue, in turns of the probable nature of the structure of the ear, it may be stated that the entire evidence points very strongly to a resonance mechanism in the cochlea of the ear.

An attempt was made to investigate whether any relation or bond exists between the two ears. The method of procedure was to fatigue one ear and take measurements with the other. Measurements up to the present, were, however, too uncertain to warrant any definite conclusions.

Conclusion:-

In conclusion, it may be stated that the results of the expermental work here reported, as does the work of H. Hartridge[1A], Barton and Browning[11] and others, very strongly support a resonance theory of audition; and do not in any manner fit in under displacement theory. Whether the Corti Arches, principally, or the basilar membrane, or both in conjunction or some organ not yet discovered, act as the resonators, cannot as yet be definately stated. One may feel on the right road towards a most probable theory, however, when it is approached by way of resonance mechanism.

I wish to acknowledge my indebtedness, to the kindness and valuable advise of Dr. Frank Allen, Director of the Department of Physics of the University of Manitoba; at whose suggestion the investigations here described were undertaken.

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University of Manitoba.

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