VALIDITY OF THE SONDHAUSS EQUATION

by

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INTRODUCTION

Many experimenters have studied the performance of spherical resonators, observing that the sharpness in the tuning makes them extremely sensitive detectors of sounds of a particular frequency, and that any particular resonator has a characteristic frequency called its resonance frequency. These studies, in most cases, have been made with spherical resonators without necks, with only openings in the spherical shell through which the sound energy could enter. Sondhauss, about 1870, investigated the resonance frequency of first partials of spherical resonators with necks. Rayleigh verified the Sondhauss equation which is

$$N = \frac{a}{2\pi}\sqrt{\frac{\sigma}{S\left(L + \frac{1}{2}\sqrt{\pi\sigma}\right)}}$$

where

N = the resonance frequency of the first partial

σ = the area of the wave opening

a = the velocity of sound at the temperature at which the frequency was found

S = the volume of the sphere and

L = the geometric length of the neck.

Sondhouss, after setting up this equation from results obtained from measurements of frequencies of spherical resonators with necks, expressed a conviction that it was no more empirical formula of interpolation but the expression of a natural law (4).

It was thought desirable to test the Sondhauss equation for validity and for frequency range, by experimenting with different sizes of spherical resonators having necks of various lengths and diameters.

The outline of the mathematical treatment was taken from Olsen and Massa (3), supplemented by material from Rayleigh (4) and Stewart and Lindsay (6).

THEORY

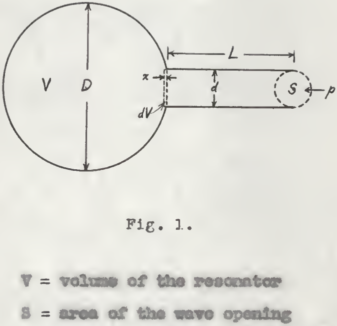

Fig. 1.

V = volume of the resonator

S = area of the wave opening

D = diameter of the sphere

d = diameter of the neck

L = geometrical length of the neck

c = velocity of sound at the temperature the data were taken

p = excess pressure

p_0 = static pressure

p_0' = total pressure (static and excess)

ρ = density of the medium in the resonator

ρ_0 = mean density

ρ_0' = instantaneous density (static and change)

$s = \dfrac{\rho - \rho_0}{\rho_0}$ = ratio of the change in density to original density

γ = ratio of specific heat at constant pressure to the specific heat at constant volume

dV = volume decrease (adiabatic)

λ = wave length of sound

F = force acting upon area (S)

F_d = dissipative force

M = mass of air in the neck

m = particle mass

x = particle displacement at the opening

$\dot{x}$ = velocity of the mass (m)

$\dot{X}$ = rate of volume displacement

$\omega = 2\pi f_r$ = angular velocity

$j = \sqrt{-1}$

f_r = resonance frequency

U = volume current = particle velocity times the area of the wave opening

r_a = acoustical resistance.

To derive the equation for the resonance frequency of a spherical resonator with a neck, it is assumed that the mass of the air in the neck acts as a piston, moving back and forth as a whole due to the sound energy wave, from an external source, which impinges upon the neck opening. This motion is simple harmonic of very small amplitude. As the piston of air in the neck moves inward it compresses the volume of air slightly in the sphere, thus increasing its density. At a certain frequency of the sound energy wave the forces of compression exerted on the air in the sphere will reenforce this wave thus producing resonance.

All the symbols used in the derivation of the resonance frequency equation are given under Fig. 1.

The excess pressure exerted on the wave opening by an incoming sound energy wave will first be derived. If the process of compression and expansion of the air in the sphere is considered to be isothermal, and if Boyle's Law is applied in this case, then

$$c^2 = \frac{P}{\rho_0} \tag{1}$$

If the process is considered adiabatic (this being conceded to be the more accurate) then

$$c^2 = \frac{\gamma P}{\rho_o} \qquad (2)$$

Also the densities will be proportional to the pressures, and

$$\frac{P_o'}{P_o} = \left(\frac{\rho_o'}{\rho_o}\right)^{\gamma} \qquad (3)$$

Introducing the condensation (s) which is the ratio of the density change to the original density, we have

$$s = \frac{\rho - \rho_o}{\rho_o}$$

or

$$s = \frac{\Delta \rho}{\rho_o} \qquad (4)$$

Combining equations (3) and (4) we obtain

$$\frac{P_o'}{P_o} = \left(\frac{\rho_o'}{\rho_o}\right)^{\gamma} = (1 - s)^{\gamma} = 1 - \gamma s \quad \text{(approximately)}$$

or

$$P_o' = P_o + P_o \gamma s$$

and since

$$P = P_o' - P_o$$

then

$$P = P_o \gamma s \qquad (5)$$

From equations (2) and (5) we obtain the excess pressure

$$p = c^2 \rho_0 s \tag{6}$$

It will be noted that this pressure "p" is a change in pressure and hence is the average pressure causing a change in the potential energy, therefore equation (6) may be written

$$\tfrac{1}{2} p = \tfrac{1}{2} \rho_0 c^2 s$$

while in the equation of motion, derived later, "p" is instantaneous pressure.

To compute the stiffness coefficient, the volume "V" of the resonator is decreased adiabatically by "dV", then

$$p = \rho c^2 s = \rho c^2 \frac{dV}{V}$$

In terms of the area "S" of the wave opening

$$dV = Sx = X$$

Therefore the force acting upon "S" is

$$F_s = pS$$

and

$$F_s = \frac{\rho c^2 S x}{V} \cdot S = \frac{\rho c^2 S^2 x}{V}$$

The potential energy "P.E." of the piston of air in the neck is

$$P.E. = p\, dV = \frac{\rho c^2 S x}{2V} \cdot S \cdot x = \frac{\rho c^2 X^2}{2V} \tag{7}$$

Since the volume current is equal to the particle velocity multiplied by the area of the wave opening,

$$U = S\,\dot{x}$$

and the kinetic energy of the piston of air in the neck of the resonator is

$$K.E. = \frac{1}{2}\frac{\rho L}{S}U^2 = \frac{1}{2}\frac{\rho L}{S}\dot{X}^2 \qquad (8)$$

According to Stewart and Lindsay (6), the dissipative force

$$F_d = \frac{\rho\omega k}{2\pi}S^2\dot{x} \qquad (9)$$

where

$$k = \frac{2\pi}{\lambda}$$

Since

$$\dot{X} = S\,\dot{x}$$

then

$$F_d = \frac{\rho\omega k}{2\pi}\dot{X}\,S$$

The rate of change of kinetic energy is

$$\frac{\rho L}{S}\ddot{X}\dot{X} + \frac{2\rho c^2}{2V}\dot{X}\dot{X} \qquad (10)$$

The rate of dissipation of energy by radiation is

$$\frac{\rho\omega k}{2\pi}\dot{X}\dot{X} \qquad (11)$$

Setting up the equation of motion of the system we have

$$p\,\dot{X} = \rho\,\frac{L}{S}\,\ddot{X}\,\dot{X} + \frac{\rho\omega k}{2\pi}\,\dot{X}\,\dot{X} + \frac{\rho c^2}{V}\,X\,\dot{X}$$

or

$$p = \frac{\rho L}{S}\,\ddot{X} + \frac{\rho\omega k}{2\pi}\,\dot{X} + \frac{\rho c^2}{V}\,X \qquad (12)$$

The steady state solution is

$$\dot{X} = \frac{p}{\dfrac{\rho\omega k}{2\pi} + j\left(\dfrac{\rho\omega L}{S} - \dfrac{\rho c^2}{V\omega}\right)} \qquad (13)$$

The maximum value of the volume current or the rate of volume displacement "$\dot{X}$" occurs when

$$\frac{\rho\omega L}{S} = \frac{\rho c^2}{V\omega} \qquad (14)$$

To determine the resonance frequency we find from equation (14) that

$$\omega^2 = \frac{S c^2}{V L}$$

Since

$$\omega = 2\pi f_r$$

then

$$(2\pi f_r)^2 = \frac{S c^2}{V L}$$

or

$$2\pi f_r = \sqrt{\frac{S c^2}{V L}}$$

and therefore the resonance frequency "f_r" is

$$f_r = \frac{c}{2\pi}\sqrt{\frac{S}{V\ \ L}} \tag{15}$$

In this equation for resonance frequency of spherical resonators with necks, no end correction to the neck is expressed. The Sondhauss equation as given by Rayleigh included the end correction. The equation given below is the same as that given by Rayleigh except for the use of different symbols. It will be noticed that the end correction as used is: $1/2\sqrt{\pi S}$.

The resonance frequency equation given by Rayleigh is

$$f_r = \frac{c}{2\pi}\sqrt{\frac{S}{V\,(L + 1/2\sqrt{\pi S}\ \ )}}$$

It is evident from this equation that the resonance frequency is directly proportional to the velocity of the sound wave, and to the square root of the area of the wave opening. Also the equation shows that the resonance frequency is inversely proportional to the square root of the volume of the shell and to the acoustic length of the neck. Variation of any one of these factors, at the same time keeping the remaining ones constant, makes it possible to determine the effect of the factor varied on the frequency of the resonator.

CONSTRUCTION OF APPARATUS

A diagram of the apparatus used in this research is shown in Fig. 2. Since the original apparatus which was used was destroyed by fire, part of the description of the essential parts and the diagram of the apparatus was taken from Shenk's thesis (5), several of the same pieces of apparatus having been used in this research as were used by Shenk.

The siren disc (SD) was provided with several rings of holes of the same size and of such number per ring that the tones of a true diatonic scale may be produced by blowing air through them from air jets along the pipe (AT). Compressed air entered at (CAP). The speed of the siren disc was regulated by turning the gears (G_1, G_2, G_3) which moves the rubber clutch roller (CL) back and forth on the two clutch plates (C_1, C_2), the driving plate (C_1) being driven by a motor belted to the pulley (DP).

The speed of the siren disc was determined by a revolution counter (RC) and stop-watch (W) operated simultaneously by a milled head which engaged a tooth (T) of the revolution counter (RC) in the toothed wheel (TW).

The spherical resonators used were made of thin copper with an ear-cone diametrically opposite a circular opening in the shell in which necks were soldered. These spheres

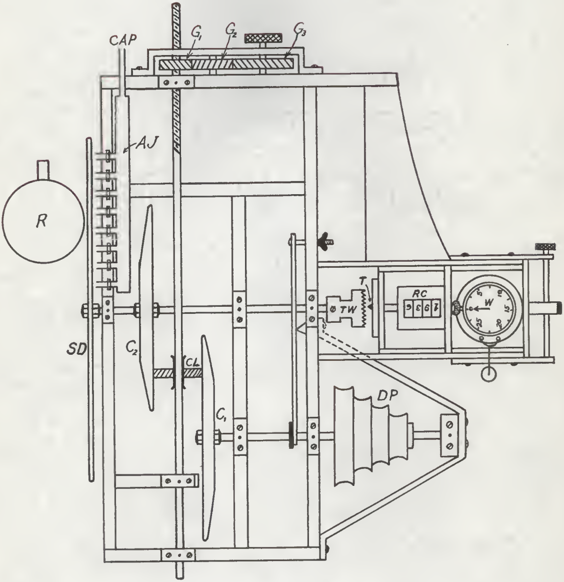

Fig. 2. Diagram of Apparatus.

(R) were mounted on a stand such that they could be easily adjusted as to height and position in relation to the disc.

PROCEDURE

Several preliminary trials were made on a spherical resonator with different shapes of wave openings to determine the optimum air pressure to use and also the optimum position in which the resonator should be placed in relation to the siren disc. These preliminary trials in determining maximum resonance frequency of a spherical shell were made for the purpose of checking the performance of the apparatus and to determine the magnitude of the experimental error.

Two copper spherical shells were used in the research, one of 20.2 cm. inside diameter and the other 9.8 cm. diameter. The inside diameters of the shells were determined by the use of vernier calipers directly and also by calculations based on the mass of water required to completely fill the shells.

One of the spherical shells with a neck attached was set up as close as possible to the siren disc with the axis of the wave opening of the neck at right angles to the axis of the disc. The wave opening was also in such a position that the air coming through the holes of the revolving disc was directed across the opening without any interference.

A rubber tube was attached to the ear-cone of the resonator and extended to the ear of the observer. The best response was observed when the tube was not more than one foot in length.

The maximum resonance was detected by listening to the response through the tubing from the ear-cone while the speed of the siren disc was varied. The exact maximum resonance frequency being difficult to determine, responses of equal loudness on either side of the maximum, as "x" and "y", Fig. 3, were found after which the speed of the disc was taken mid-way between these two points and used in the maximum resonance frequency computations. It may be seen from the general curves in Fig. 3 that for low resonance frequencies the maximum resonance is more difficult to determine than for higher frequencies because of the flatness of the curve.

When the maximum response was heard the adjustment was left undisturbed while the speed of the siren disc was determined by means of the counter and stop-watch. The experimental resonance frequency was then calculated by substituting known values in the equation

$$f = \frac{H\ R}{T_s}$$

where

f = resonance frequency of the sphere

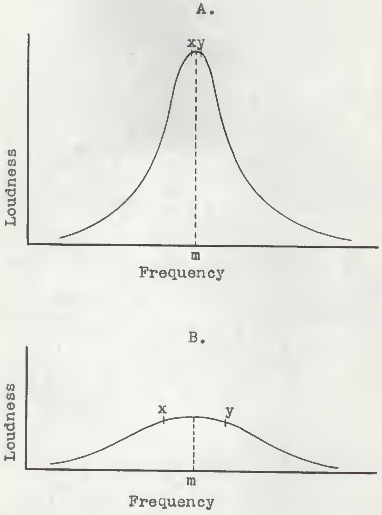

Fig.3. Resonance Frequency Curves.

A. Curve showing sharp peak at maximum loudness for high resonance frequency.

B. Curve showing flat peak at maximum loudness for low resonance frequency.

N = number of holes in the disc per revolution

R = number of revolutions counted

T_s = time interval in seconds.

The resonance frequencies of a sphere of 20.2 cm. diameter, to which necks of diameters 1.9 cm. and 3.2 cm. were soldered, were determined by the method described. In each case the lengths of the necks were varied from zero to 10 cm. Ten trials were made for each resonance frequency and the average frequency was determined. The temperature at the time the readings were taken was observed and recorded.

The above procedure was carried out in a similar manner for a sphere of 9.8 cm. diameter, with necks of the diameters given above and of variable lengths.

One set of readings was taken in each case with no neck on the sphere. The length of neck in those cases was considered as the thickness of the shell which was .05 cm. This thickness of shell was added each time in measuring the geometrical length of the neck. The lengths and inside diameters of the necks were measured with vernier calipers to .1 mm.

The resonators were tested for leaks by placing them under water and blowing compressed air into the sphere through the ear-cone.

Since the frequency of a resonator is a function of the temperature, each resonance frequency was corrected for temperature. The temperature chosen as a normal was 28° C. The velocity of sound at 28° C. was determined by the equation given by Anderson (1)

$$v_t = v_o\sqrt{1 + 0.00367\ t}$$

where

v_t = velocity of sound at temperature "t" which is the same as "a" in the Sondhauss Equation

v_o = velocity of sound at 0° C. = 33,170 cm./sec.

t = temperature (C°) of air at wave opening.

To correct the frequency for temperature the following equation was used

$$C_f = \pm \left[T.C. \times (T_e - T_n) \times N_e \right]$$

where

C_f = the frequency correction to be added or subtracted from the experimental frequency

T.C. = temperature coefficient

$(T_e - T_n)$ = temperature difference, with 28° C. as standard.

The temperature coefficient, which is a change in frequency for 1° C. for one vibration, was determined from experiment and substitution in the equation

$$T.C. = \frac{N_n - N_e}{(T_n - T_e)\ N_n}$$

where

T.C. = temperature coefficient

N_n = frequency determined at normal temperature

N_e = frequency determined at average of 4° C.

T_n = normal temperature

T_e = temperature of 4° C.

Curves of the average experimental frequencies were plotted against the square root of the acoustic length of the necks for the two spheres, each having necks of diameters 1.9 cm. and 3.2 cm. as stated above. Curves of the theoretical frequencies determined by the Sondhauss equation and corresponding to the sizes of spheres and necks used in the experiment, were also plotted against the square root of the acoustic length. The experimental and theoretical curves were compared and studied and conclusions drawn. These curves are shown in Fig. 4 and Fig. 5, pages 27 and 28.

CALCULATIONS AND CURVES

A sample of one set of ten readings taken for a sphere of 9.8 cm. diameter with a 1.9 cm. diameter neck 6 cm. in length is given on page 23.

TABULATED DATA

Table 1. Data of Small Sphere, 9.8 cm. diameter, with Necks of 3.2 cm. diameter.

Line No.	Geom. Neck Length (cm.)	$\sqrt{\text{Acoustic Neck Length (cm.)}}$	Ave. Temp. (C°)	Ave. Exp.N (vib/sec)	Exp.N Corrected (vib/sec)	Theor.N Corrected (vib/sec)
1	.05	1.603	34.0	462.7	459.5	439.2
2	1.0	1.876	27.5	369.3	369.5	375.3
3	2.0	2.126	26.0	337.6	338.4	331.1
4	3.0	2.349	28.5	303.5	303.3	299.7
5	4.0	2.554	26.0	276.1	276.7	275.6
6	5.0	2.742	30.9	257.2	256,3	256.7
7	6.0	2.920	30.7	240.7	240.0	241.1
8	7.0	3.085	30.4	225.7	226.1	228.2

Table 2. Data of Small Sphere, 9.8 cm. diameter, with Necks of 1.9 cm. diameter.

9	.05	1.240	28.0	343.4	343.4	335.2
10	1.0	1.577	29.0	275.6	275.3	263.6
11	2.0	1.867	31.0	227.1	226.3	222.7
12	3.0	2.118	30.8	197.8	197.2	196.3
13	4.0	2.342	27.7	178.3	178.3	177.5
14	5.0	2.547	29.6	162.6	162.3	163.2
15	6.0	2.736	29.0	150.4	150.2	151.9

Table 3. Data of Large Sphere, 20.2 cm. diameter, with Necks of 3.2 cm. diameter.

Line No.	Geom. Neck Length (cm.)	$\sqrt{\text{Acoustic Neck Length (cm.)}}$	Ave. Temp. (C°)	Ave. Exp. N (vib/sec)	Exp. N Corrected (vib/sec)	Theor. N Corrected (vib/sec)
1	.05	1.603	32.3	153.5	152.7	149.0
2	1.0	1.876	32.4	129.2	128.5	127.3
3	2.0	2.126	32.4	115.5	114.9	112.3
4	3.0	2.349	32.3	104.1	103.6	101.6
5	4.0	2.554	32.5	95.0	94.5	93.5
6	5.0	2.742	30.1	88.9	88.7	87.1
7	6.0	2.920	30.3	83.2	83.0	81.6
8	7.0	3.085	30.8	79.3	79.0	77.4
9	10.0	3.538	28.2	65.9	65.9	67.5

Table 4. Data of Large Sphere, 20.2 cm. diameter, with Necks of 1.9 cm. diameter.

10	.05	1.240	32.1	112.0	111.5	114.3
11	1.0	1.577	32.0	90.9	90.5	89.9
12	2.0	1.867	31.0	77.4	77.1	75.9
13	3.0	2.118	31.2	67.2	66.9	66.9
14	4.0	2.342	29.6	59.6	59.5	60.5
15	5.0	2.547	29.8	54.9	54.8	55.7
16	6.0	2.736	30.0	51.3	51.2	51.8
17	8.0	3.080	30.6	45.6	45.5	46.0

Table 5. Showing % Difference and % Error between the Experimental and Theoretical Frequencies.

Sphere Dia.	Neck Dia.	$\sqrt{\text{Acoustic Length}}$	Exp. N	Theor. N	Freq. Diff.	% Freq.* Diff.	x** %	y*** %
9.8	3.2	1.876	369.5	375.3	14.2	3.6	.3	.5
9.8	3.2	3.085	225.1	228.3	3.1	1.3	1.1	
9.8	1.9	1.577	275.3	263.6	11.7	4.2	1.3	1.1
9.8	1.9	2.736	150.2	151.9	1.7	1.1	1.2	
20.2	3.2	1.876	128.5	127.3	1.2	.9	1.2	1.7
20.2	3.2	3.538	65.9	67.5	1.6	2.4	1.6	
20.2	1.9	1.577	90.5	89.9	.6	.7	1.6	2.6
20.2	1.9	3.080	45.5	46.0	.5	1.1	1.7	

Table 6. Summary of Curves.

Sphere Dia. (D)	Neck Dia. (d)	Ratio D/d	$\sqrt{\text{Acoustic Length}}$ where Exp.N Theor.N	Frequency where Exp.N Theor.N	Neck Lengths where Sondhauss Eq. is Valid
20.2	1.9	10.6	1.46 & 2.13	97.2 & 66.5	.05 to 8.0
20.2	3.2	6.3	3.16	76.0	4 to 10
9.8	1.9	5.2	2.45	170.0	3 to 6
9.8	3.2	3.1	2.70	263.5	2 to 7

* % Freq. Diff. = % differences of frequencies read at extreme points on either side of intersection of experimental and theoretical curves.

** x % = % experimental error within which readings were taken at extreme points on either side of the intersection of experimental and theoretical curves.

*** y % = % experimental error within which readings were taken at the point of intersection of experimental and theoretical curves.

Trial	Holes	Rev.	Freq.	Diff. from Ave. f.	Temp. ° C.
1	96	93.6	149.8	- .6	29.0
2	"	93.4	149.4	-1.0	
3	"	94.6	151.3	+ .9	
4	"	94.4	151.0	+ .6	
5	"	94.1	150.5	+ .1	29.0
6	"	93.7	150.9	+ .4	
7	"	93.9	150.2	- .2	
8	"	93.5	149.6	- .8	
9	"	94.6	151.3	+ .9	
10	"	94.0	150.4	.0	29.0
		Average	150.4		29.0° C. (1)

To find the frequency "f" the first line of data in the above table is taken as an example and substituted into the equation

$$f = \frac{H\ R}{T_s}$$

$$f = \frac{96 \times 93.6}{60}$$

$$f = 149.8 \text{ vib./sec.}$$

The velocity of sound in air was determined by substituting experimental values in the equation given on page 18.

$$a = v_t = v_o \sqrt{1 + 0.00367\ t}$$

$$a = v_{28^\circ} = 33{,}170 \sqrt{1 + .00367 \times 28}$$

$$a = 34{,}828.5 \text{ cm./sec.}$$

The temperature coefficient was found by substituting

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(1) Refer to line 15, table 2, p. 20.

experimental values into the equation, also given on page 18.

$$T.C. = \frac{N_n - N_e}{(T_n - T_e)\ N_n}$$

$$T.C. = \frac{277.6 - 270.6}{(25.29 - 3.86)277.6}$$

$$T.C. = .00116$$

This value of "T.C." was used in determining the frequency correction to be used for each experimental resonance frequency. Sample calculations are shown below for the resonator the readings of which are given at the beginning of this section, page 23.

$$C_f = \pm\ \left[T.C.\ (T_e - T_n)\ N_e\right]$$

$$C_f = -\ \left[.00116\ (29^\circ - 28^\circ)\ 150.4\right]$$

$$C_f = -\ .175 \text{ vib./sec.}$$

The corrected frequency is

$$N_c = N_e - C_f$$

$$N_c = 150.4 - .175$$

$$N_c = 150.2 \text{ vib./sec.}^{(1)}$$

To determine the theoretical frequency for the spheres at 28° C., the Sondhauss equation was used, substituting the values which correspond to the ones used in the experiment, for example, to find the theoretical frequency corre-

(1) Refer to line 15, table 2, p. 20.

sponding to the experimental frequency of 150.4

$$N = \frac{a}{2\pi}\sqrt{\frac{\sigma}{S\left[L + \frac{1}{2}\sqrt{\pi\sigma}\right]}}$$

$$N = \frac{34828.5}{2 \times 3.1416}\sqrt{\frac{\pi\left(\frac{1.9}{2}\right)^2}{4315.73\left[6 + \frac{1}{2}\sqrt{\pi\cdot\pi\left(\frac{1.9}{2}\right)^2}\right]}}$$

$$N = \frac{238.76}{\sqrt{\text{acoustic } L}} = \frac{238.76}{2.736}$$

$$N = 151.9 \text{ vib./sec.}^{(1)}$$

To find the per cent difference between the experimental and theoretical frequencies at various points on the curves the following equation was used

$$\%\ \text{Diff.} = \frac{\text{Exp.N} - \text{Theor.N}}{\text{Exp.N}} \times 100$$

Taking line 4, table 5, page 22, as an example:

$$\%\ \text{Diff.} = \frac{150.2 - 151.9}{150.2} \times 100$$

$$= 1.1\%$$

For column "x" page 22, in determining the per cent error within which readings were taken at extreme points on either side of the intersection of the experimental and theoretical curves, the following equation was used:

$$x = \frac{D_1 + D_2}{f}\ 100$$

(1) Refer to line 15, table 2, p. 20.

where

D_1 = the largest negative departure from the mean

D_2 = the largest positive departure from the mean

f = the average frequency of 10 trials.

As an example, using the same sphere and neck as in the tables shown at the beginning of this section:

$$x = \frac{.9 + 1.0}{150.4} 100$$

$$x = 1.2\%$$ [1]

CONCLUSIONS

From the curves plotted it was observed that for spheres of large diameter and with necks of small diameter the experimental curve and the theoretical curve coincided within experimental error. Whereas when the resonator was small in diameter and had a neck of large diameter the curves coincided at only one point; the failure to coincide becoming greater as the resonance frequency became higher and the lengths of the necks shorter.

Therefore, it was concluded that the Sondhauss equation is valid for only certain sizes of spherical resonators which have necks of small diameter in comparison with the diameters of the spheres; namely, large spheres and small

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(1) Refer to line 5, col. "x", p. 22.

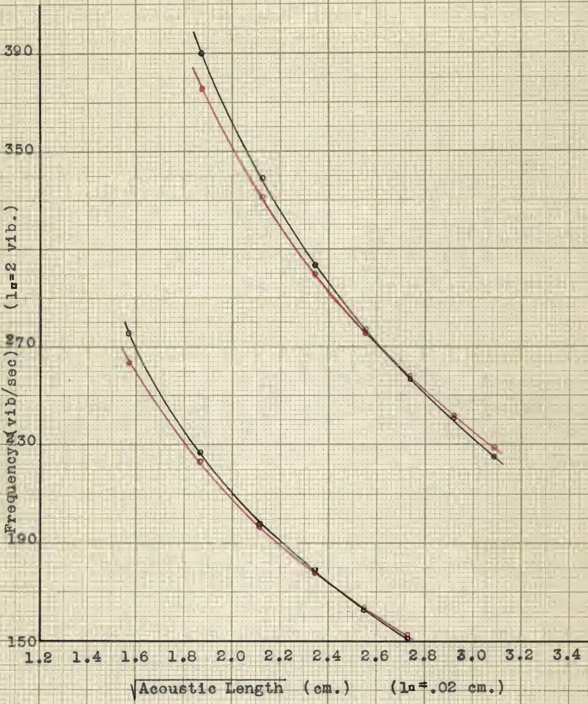

Fig. 4. Experimental and Theoretical Curves of the Sondhauss Equation.

A. Experimental Curve, Sphere of 9.8 cm. diameter, with Neck of 3.2 cm. diameter.

B. Theoretical Curve, same sphere, Neck of 3.2 cm.dia.

C. Experimental " " " " " 1.9 " ".

D. Theoretical " " " " " 1.9 " ".

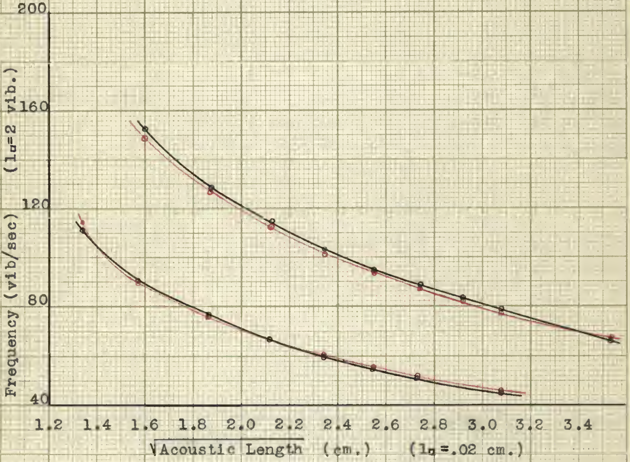

Fig.5. Experimental and Theoretical Curves of the Sondhauss Equation.

A. Experimental Curve. Sphere of 20.2 cm. diameter, with neck of 3.2 cm. diameter.
B. Theoretical Curve, same sphere, Neck of 3.2cm.dia.
C. Experimental " " " " " 1.9 " ".
D. Theoretical " " " " " 1.9 " ".

necks of variable length, this ratio being approximately 11.

It was also found that within small variations of length of neck, either longer or shorter than one certain length, that the Sondhauss equation was also valid for spheres and necks having ratios less than 11. Other than within these small limits the curves showed that the Sondhauss equation would not hold.

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