THE CONSTRUCTION OF A POWERFUL ULTRASONIC SIREN GENERATOR AND SOME EXPERIMENTS WITH HIGH INTENSITY ULTRASONIC RADIATION

By

LAWRENCE J. VIERNSTEIN

Bachelor of Science

Oklahoma Agricultural and Mechanical College

Stillwater, Oklahoma

1949

Submitted to the Faculty of the Graduate School of

the Oklahoma Agricultural and Mechanical College

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

1950

THE CONSTRUCTION OF A POWERFUL ULTRASONIC SIREN
GENERATOR AND SOME EXPERIMENTS WITH HIGH INTENSITY
ULTRASONIC RADIATION

LAWRENCE J. VIERNSTEIN

MASTER OF SCIENCE

1950

THESIS AND ABSTRACT APPROVED:

Sherman W Eager
Thesis Adviser

A. D. Pershing
Faculty Representative

D. C. McIntosh
Dean of the Graduate School

PREFACE

This paper brings together most of the author's work at Oklahoma A. & M. College on ultrasonics, including the details of the design and construction of the ultrasonic siren generator.

It is hoped that the mechanical drawings, construction details and experiments on the siren's performance will prove useful to the future workers on the siren.

I wish to express my appreciation to Dr. Sherman W. Eager, Head of the Physics Department at Oklahoma A. & M. College for his encouragement and guidance and to whom must be attributed a large part of what success may be claimed.

TABLE OF CONTENTS

CHAPTER I

APPLICATIONS OF ULTRASONICS

Ultrasonics has seen a wide range of application in recent years. It has received much study in World War II because of its importance for the underwater detection of submarines. Also numerous commercial applications have been found for ultrasonics. The Sperry Company makes an instrument for detecting flaws in large steel castings where x-ray methods are impractical. An ultrasonic pulse is introduced into the casting or part to be tested, the echo pattern is then studied. A flaw will cause a discontinuity in the sound path and send back an echo of its own. The time it takes the echo to return is a measure of the distance the flaw is away from the transducer. The coagulating property of ultrasonics is used in some factories for removing furnace smoke and for collecting carbon black. There is such a unit operating at Kingsmill, Texas installed by the Ultrasonics Corporation of Cambridge, Massachusetts.

In liquids ultrasonics has some important physical as well as chemical effects. It has a strong dispersive power, it can degas a liquid, cause cavitation, and has thermal and oxidizing effects. As a consequence of these properties ultrasonics is finding wide applications in chemical engineering.

Since intense sound has been found to be bactericidal,[1] its possibilities are being studied for pasteurizing milk and sterilizing drinking water.

The biological effects on animals is also receiving study.[2] Airborne

---

[1]N. Gaines, and L. Chambers, "Further Study of Effects of Intense Audio-frequency Sound", Phys. Rev., II (1932), 39, 862.

[2]E. C. Gregg, Jr., "Biological Effects of Ultrasonics, " M. Physics, (1944), 1591-1596.

sound has been found to be lethal to small animals. Other workers are investigating its possibilities for inhibiting or destroying cancerous growths.

The usual difficulties in almost all applications is getting enough acoustic energy in a given place economically. Most of the effects emmerated require a large amount of acoustical energy. This calls for an efficient generator. The siren is one of the most efficient types of sound generators. The Bell Telephone Laboratories has built a siren with an efficiency of 60-80% in the acoustic range.[3]

By certain design changes the siren can be used as an efficient generator of ultrasonics. It is for these reasons the siren was adapted for the construction of a powerful ultrasonic source.

---

[3]R. Clark Jones, "A Fifty Horsepower Siren," J. A. S. A., XVIII (1946), 371-387.

CHAPTER II

THE ULTRASONIC SIREN GENERATOR

In order to facilitate the study of the acoustical phenonema that exist in high intensity ultrasonic radiation, a powerful ultrasonic siren generator was built. The fundamental arrangement decided upon was similar to the one used at the acoustical laboratory at Pennsylvania State College, which was constructed under a Naval contract.[1] Lacking the facilities of that large school the task looked formidable, nevertheless the project was undertaken.

Both the first and second models were built almost entirely on the 9" lathe of the Physics Department by the author, except where it was necessary to secure accurate indexing on a milling machine.

The siren consists of the following components: a source of air, a rotor which interrupts the air flow at a frequency determined by the rotational speed of the rotor, and finally ports in a stator through which the compressed air escapes. The rotor is driven by an electric motor. The frequency of the sound waves is controlled by adjusting the motor voltage. When the rotor turns all the 100 holes open simultaneously giving an effective area of opening of .503 square inches. The sound intensity is adjusted independently of the frequency by regulating the chamber air pressure, the higher pressures giving the louder sounds.

The Design and Construction of Model I

Figure I is a cross section of the first siren built. This drawing is ½ scale. The rotor was driven by a ¼ horsepower motor. The upper bearing

---

[1] C. H. Allen, and I. Rudnick, "A Powerful High Frequency Siren" J. A. S. A., XIX (September, 1947), 857-865.

Ultrasonic Siren

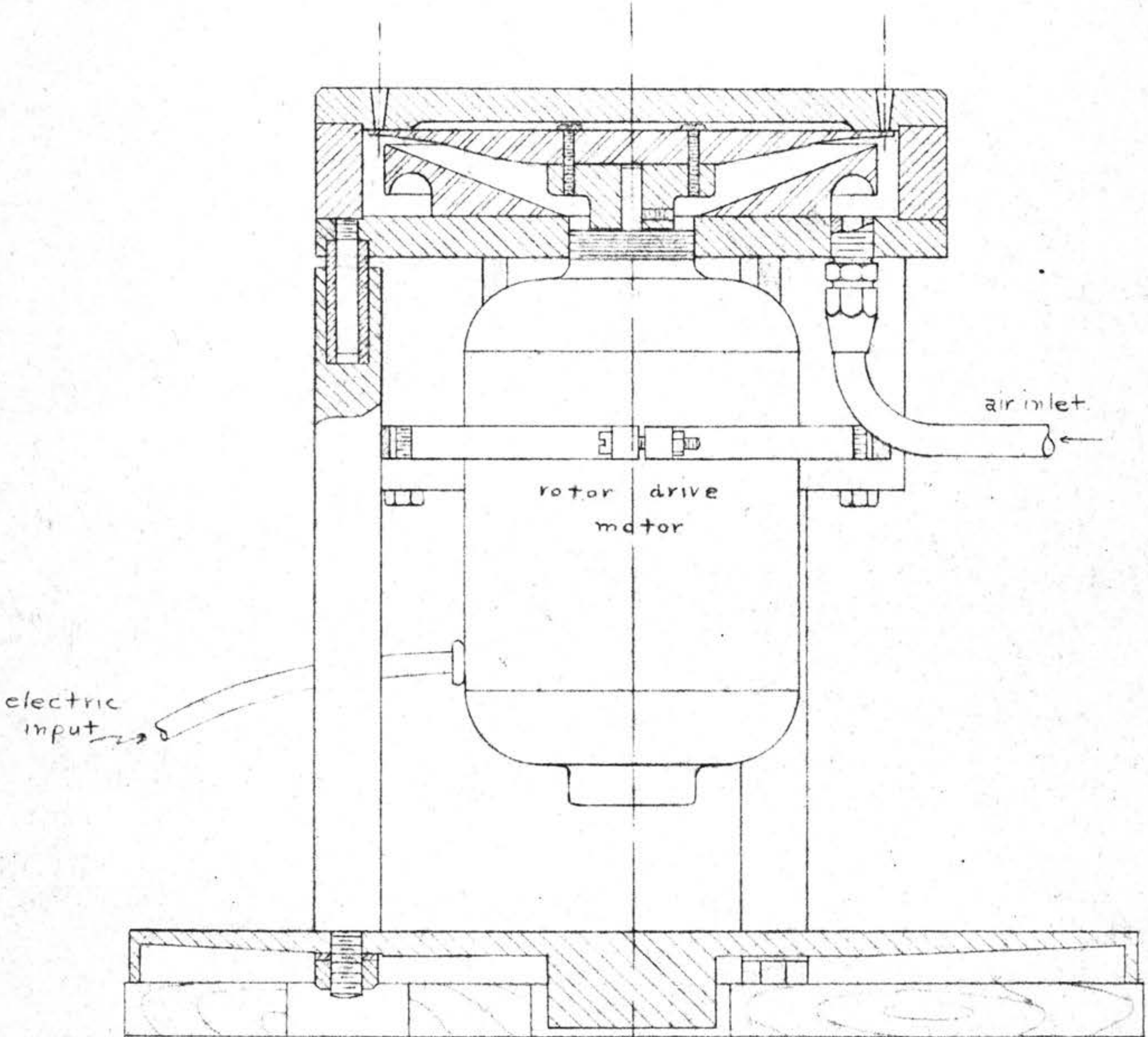


Figure I

Model I	L. J. V.

housing of the motor was threaded and the motor was screwed into the underside of the pressure chamber. By rotating the motor the rotor-stator spacing could be adjusted. The usual spacing was set at .001". After this adjustment the motor was locked into position by three hold down clamps. Three pipes leading to the underside of the chamber brought in air at a pressure of 3 to 5 lbs/sq. in. The air deflector insured a uniform distribution of air to the 100 holes in the top of the chamber. The entire chamber assembly and motor was shock mounted in rubber and it ran vibration free.

The Performance of Model I

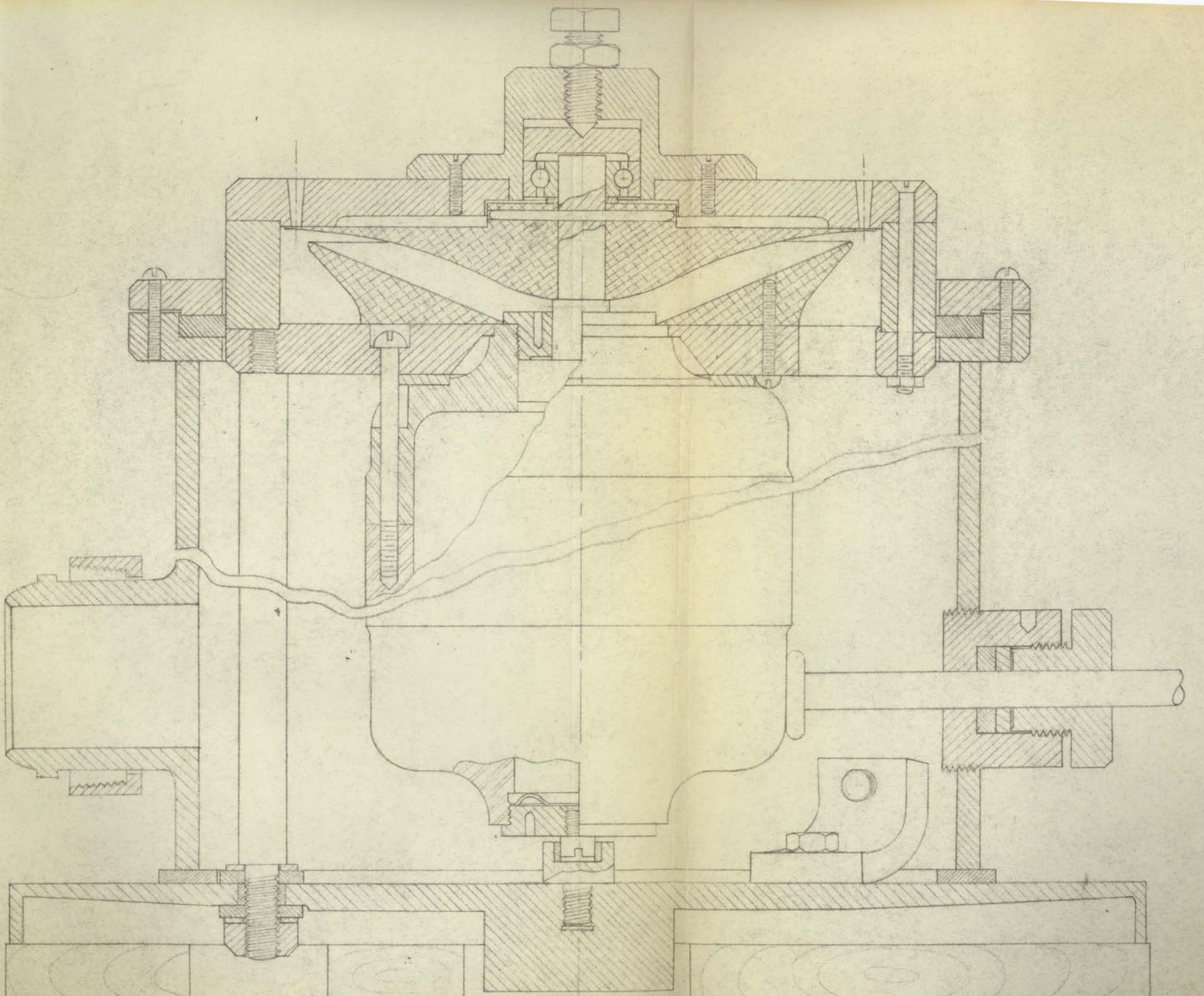
Some difficulties arose on the first runs with the first model of the siren. There was an 80% drop in pressure between the compressor storage tank and the siren pressure chamber. This was due to the high resistance to the air flow offered by small hoses used to admit the air and the construction of the connectors for this tubing. The connectors used had a bore of $\frac{1}{4}$" diameter, which for the three connectors gave only a cross sectional area of .15 sq. in. to admit the air. This is small compared to the .503" cross section of the openings that generate the sound. Another difficulty noted was the large decrease in frequency that occurred when the pressure was raised. This trouble was attributed to the thickness of the rotor teeth (.040") and the small size of the drive motor ($\frac{1}{4}$ h. p.).

To remedy these troubles the rotor teeth were trimmed down to .015" thick. This is over a 60% decrease in thickness. The small hose, the small connectors and the three way distribution system was eliminated, since the latter had right angle bends in it. Large connectors, and ordinary garden hose of good quality was substituted for the small hose and all constrictions and right angle bends were eliminated. The new cross section of the inlets was equal to .93 sq. in., an increase of over 500% in cross sectional area.

With these modifications there was only a 20% drop in pressure between the compressor storage tank and the siren. Considerable improvement was noted in the siren performance. No instruments were available for quantitative measurements but cotton could be scorched in the sound field, demonstrating a high level of sound intensity.

The Design and Construction of Model II

It was decided to make some radical improvements on the siren which were based on our own experience and the experience of the group who were doing similar work at Pennsylvania State College with whom we were in contact. Figure II is a cross section of the Model II siren designed and built by the author. This drawing is a 1:1 scale. A new and more powerful motor was obtained. It was the Dumore W-2 type motor which has a rating of 2/3 of a horsepower with an input of 710 watts and a speed of 8000 r.p.m. The motor is of the A.C.-D.C. type whose speed is controllable with a Variac on A.C. or a rheostat on D.C. In the new design a new type of motor mounting is used. The motor itself is encased in a steel jacket through which the compressed air circulates. This has the advantage of providing increased cooling for the motor and it helps suppress the motor noise. To accomplish this it was necessary to provide air tight seals on the top and the bottom of the large jacket and also to provide an airtight seal for the electrical input to the motor. For the electrical cable a screw cap is brought up against a steel washer which compresses a rubber washer around the input cable making an effective pressure seal. About the top of the jacket two rings were mounted. The lower ring was welded to the jacket and the upper ring compresses a ring



Ultasonic Siren Model II Figure II

of rubber to provide an airtight seal between the jacket and the siren chamber. The lower pressure seal was made by bolting the jacket down on a rubber gasket by means by three brackets, one of which can be seen in Figure II. The siren chamber is held down against the pressure by three $\frac{1}{2}$" steel rods. (There is a force of 1326 lbs. on this siren chamber when it is operating at 30 lbs./sq. in.). The air is introduced into the jacket by a 2" pipe line. The air rushes past the motor and then passes through the base plate which has six 13/16" holes. The air deflector was machined with a smoother curve so it would offer little resistance to the flow of air.

The Rotor

Much care had to go into the design of the rotor since it has to rotate at very high speeds. There always exists the possibility that the rotor might explode because of the very high stresses to which it is subjected. Figure III is a drawing of the rotor. The teeth and spaces on this rotor have the same width (.094). The teeth are wider than the ports (.080") to minimize air leakage during the time the teeth are covering the ports. The use of teeth rather than holes in the rotor is for the purpose of reducing the mass on the periphery of the rotor and thus reduce the stress in this area. The forces to be considered in the design of the rotor is centrifugal force and the cantilever force due to the periodic stopping of the flow of air through the 100 openings. To produce a sound of 30 KC the speed of the rotor would be as follows:

$$S = \frac{30{,}000 \times 60}{100} = 18{,}000 \text{ r.p.m.}$$

If we consider the radial and cantilever forces to be of equal magnitude

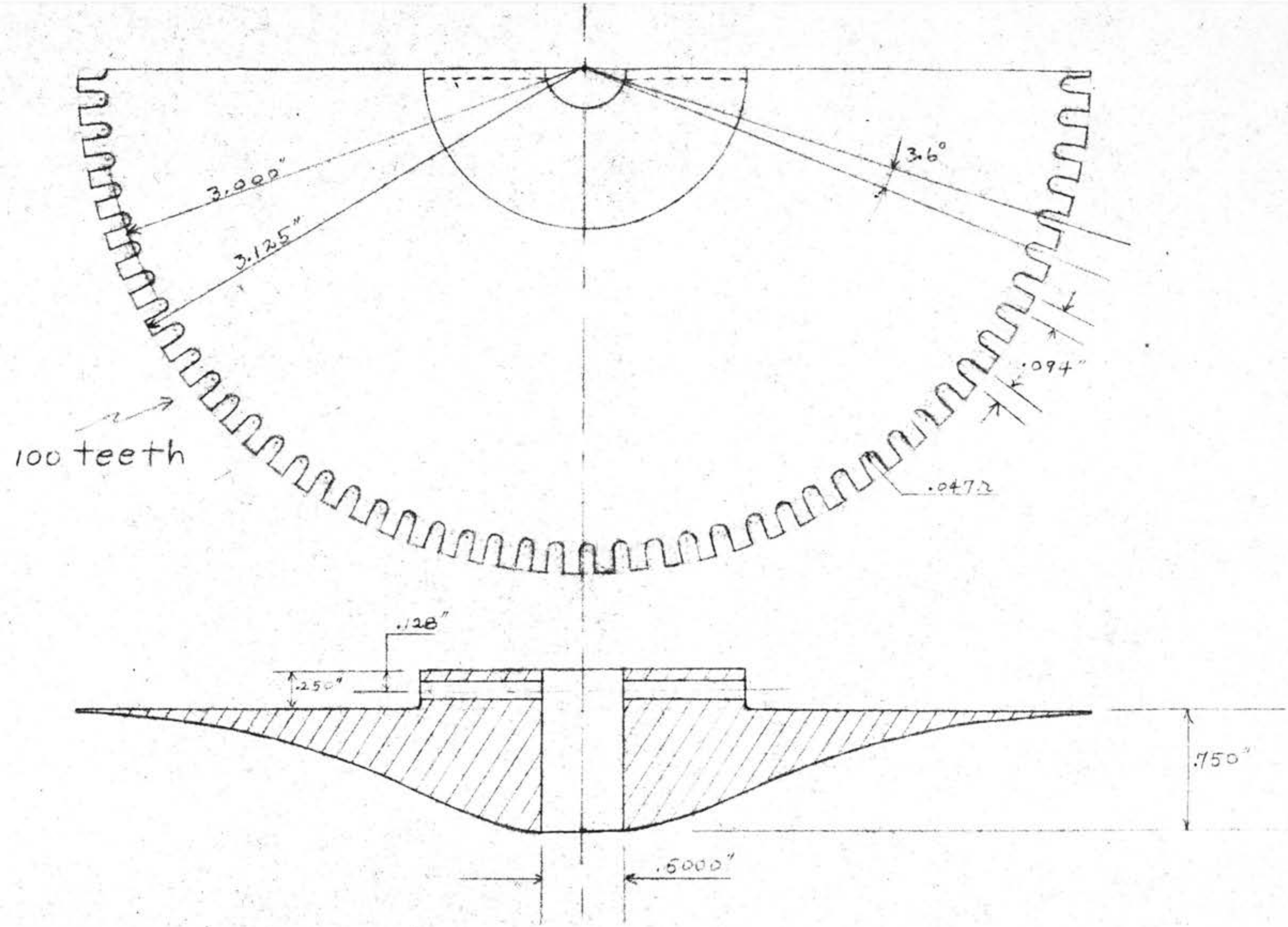


Figure III

Siren Rotor 75 ST aluminum

we have a "disc of uniform strength" so that we get the following:

$$\sigma_a = \sigma_r = \sigma = \text{constant}$$

The shape of such a rotor is given by the following formula:[2]

$$y = y_a e^{-\frac{\mu \omega^2}{2\sigma} x^2}$$

σ = stress (lbs./sq. in.)
μ = specific density
γ = density (lbs./cu. in.)
g = 32.17 $\times$ 12 in./sec.
ω = angular velocity (radians/sec.)

It can be seen from the formula that the material used for the rotor should have a high tensile strength and a low density to obtain the greatest safety factor. The best material obtainable for this purpose was 24 S-T aluminum. This material has a yield strength of 68,000 lbs./sq. in. and a density of 0.1 lbs/cu. in.

The value $$\frac{\mu \omega^2}{2\sigma} = k$$

is a constant determined by the material and the operating conditions. Values are now chosen for the center thickness and the thickness of the rim of the rotor.

y_a (thickness at the center) = .750

y (thickness at a 3 1/8" radius) = .015

With these values we can now determine k.

[2]Stodola and Loewenstein, Steam and Gas Turbines, p. 376.

$$y = y_a e^{-Kx^2}$$
$$.015 = .75e^{-K(3.125)^2}$$
$$.02 = e^{-K9.78}$$
$$K = .40$$

Hence the formula for construction is

$$y = .75e^{-.40x^2}$$

It now remains to show what the safety factor will be. This can be done in the following way:

$$K = .40 = \frac{\mu \omega^2}{2\sigma}$$

To find the safety factor at 30,000 cycles/sec. we have the following values:

$\mu = \gamma/g$
$\gamma =$ 0.1 lbs./cu.in.
$g =$ 32.17 12 in./sec.^{2}
$\omega = 2\pi 300 =$ 1885 radians/sec.
then

$$.40 = \frac{2.59 \times (1.885)^2 \times 10^6 \times 10^{-4}}{2\sigma}$$

$\sigma =$ 1150 lbs./sq.in. (required strength)

$$\text{Safety factor} = \frac{68,000}{1150} = 59$$

where

$$\text{Safety factor} = \frac{\text{actual strength}}{\text{minimum required strength}}$$

The actual safety factor will be less due to the hole in the center of the rotor for the shaft. The design of the rotor for the first siren had a computed safety factor of 22. This later design is nearly three times stronger.

The rotor is secured to the motor shaft by a tapered pin. The actual values used to construct the rotor follow on the next page.

These figures made it possible to fabricate the pattern from which the rotor was made. The curve was first made in a flat piece of brass plate 1/8" thick. This plate was secured to the lathe bed. A small pin was mounted on the cross-slide of the lathe. When the cross feed was fed in the pin followed the curve and guided the cutting tool. The result was that it was possible to produce the surface of revolution of the curve on the aluminum piece which was rotating on a supporting fixture. As a final step the rotor powered by its own motor was turned and ground after it was mounted to assure that it would run true. The stator was ground and lapped so that very close spacing could be effected. The rotor ran vibration free after mounting, demonstrating a good condition of balance.

Assembly

The shaft is spring loaded at the bottom with a third bearing on the top of the shaft providing a positive stop. When expansion occurs in the shaft this upper bearing prevents the rotor from coming in contact with the stator. The adjusting screw on the top of the siren makes it possible to adjust the spacing between the rotor and the stator.

Figure IV is a photograph showing the parts that go into the construction of the siren.

Figure V is a photograph of the assembled unit. The hose to the upper pressure chamber is a line to a pressure gauge. The base plate is a salvaged vacuum chamber base plate. The jacket is a section of high pressure steam

$$y = .75e^{-.40x^2}$$

x	y	x^2	$.4x^2$	$e^{-.4x^2}$
0	.75	0	0	1
.1	.75	.01	.004	1
.2	.735	..04	.016	.98
.3	.72	.09	.036	.96
.4	.705	.16	.064	.94
.5	.677	.25	.1	.904
.6	.653	.36	.144	.87
.7	.615	.49	.196	.82
.8	.577	.64	.256	.77
.9	.545	.81	.324	.726
1.0	.503	1.0	.4	.67
1.1	.465	1.21	.484	.62
1.2	.42	1.44	.576	.56
1.3	.382	1.69	.676	.51
1.4	.344	1.96	.784	.458
1.5	.308	2.22	.888	.411
1.6	.27	2.56	1.02	.36
1.7	.239	2.89	1.14	.319
1.8	.202	3.24	1.3	.27
1.9	.178	3.61	1.44	.237
2.0	.152	4.0	1.6	.202
2.1	.129	4.41	1.76	.172
2.2	.108	4.84	1.94	.144

x	y	x^2	$.4x^2$	$e^{-.4x^2}$
2.3	.090	5.29	2.12	.120
2.4	.075	5.76	2.3	.100
2.5	.060	6.25	2.5	.08
2.6	.0503	6.76	2.7	.067
2.7	.0405	7.29	2.92	.054
2.8	.0322	7.84	3.14	.043
2.9	.0262	8.41	3.36	.035
3.0	.0202	9.00	3.6	.027
3.1	.0158	9.61	3.84	.021
3.125	.015	9.77	3.9	.020

pipe. There was very little cost for material since all of the material was obtained on the campus.

It might be mentioned in concluding this section that great care had to be exercised in maintaining concentricity between the rotor and the various structures which supported these two very important pieces.

The Compressor for the Air Source

A large compressor was installed in the Physics Department to serve the need for the large quantities of compressed air that is needed for various equipment such as the ultrasonic siren and the ultracentrifuge. The compressor is a Chicago Pneumatic Type T. It is equipped with a 25 horsepower motor and it can pump 100 cu. ft. per minute. Since the compressor has a very large storage tank the required 200 cu. ft./min. can be supplied to the siren by storing the air at 100 to 200 p.s.i. A pressure regulator was installed in the air line to the siren but it had to be removed since it would not work properly with the very large volumes of air demanded by the siren. An ordinary valve was found to work much better, and is now being used to regulate the pressure in the siren chamber.

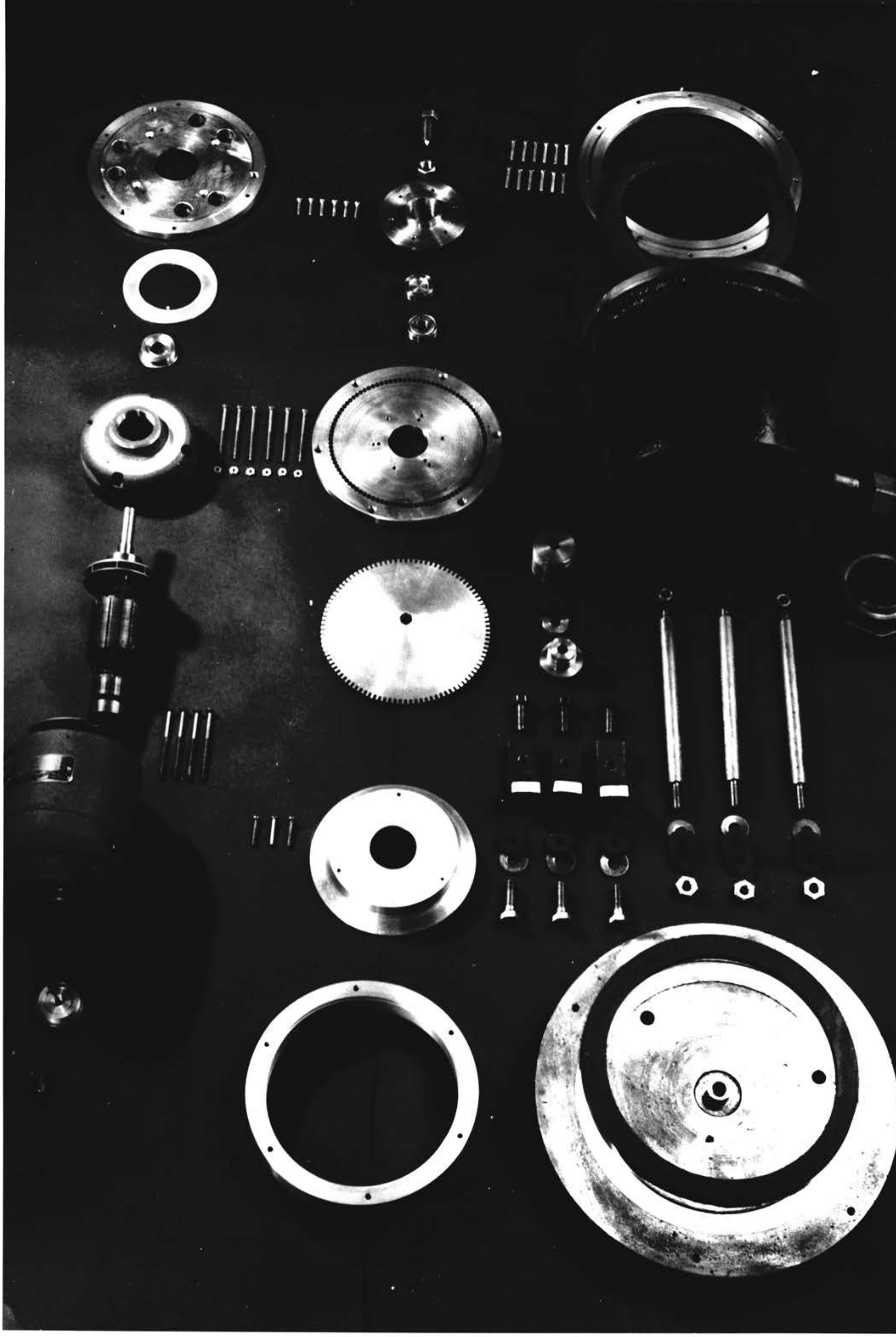


Figure IV

CHAPTER III

SOME EXPERIMENTS WITH THE MODEL II SIREN

Frequency Studies

The frequency characteristics of the siren were studied as a function of the motor voltage and the chamber pressure.

The best way to measure frequency is to compare the unknown frequency with some reliable standard. In this experiment the General Radio Audio Oscillator was used as a standard. The unit has an internal calibration checker. At the factory this unit has been calibrated on every point on the dial. As a further check the unit was found to agree very closely with the primary standard audio signals that are transmitted by WWV from Washington, D. C.

The sound of the siren was picked up with a microphone and fed into the vertical amplifiers of the oscilloscope. The G. R. Audio oscillator voltage was fed into the horizontal amplifier of the oscilloscope. The oscillator frequency is adjusted until a circle appears on the oscilloscope. Under these circumstances the oscillator frequency is exactly the same as the siren frequency. Since the G. R. Audio oscillator has an upper limit of 20,000 cycles a figure eight was used as an oscilloscope pattern. With a figure eight pattern laying on its side the frequency of the audio oscillator will be $\frac{1}{2}$ of the frequency of the siren. The only limitation of accuracy is the closeness with which the audio oscillator frequency can be determined by reading its dial.

Figure VI is a sketch of the set up used to determine the frequency characteristics of the siren.

For the first run the chamber pressure was set for a constant 2 lbs./cu. in. The motor voltage was set at various values and the resulting frequency

The setup for checking siren frequency as motor voltage and air pressure is varied

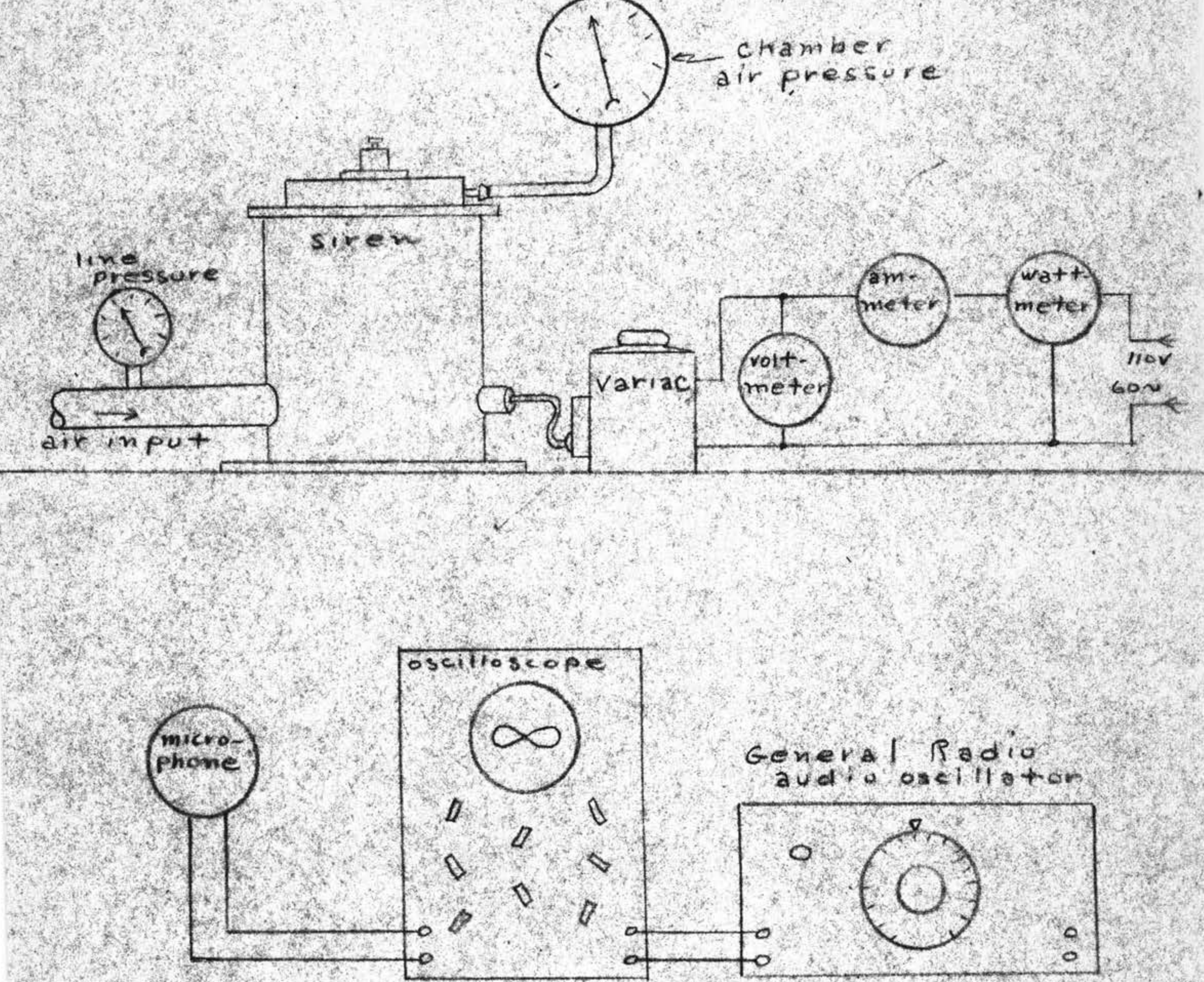


Figure VI

was recorded. The power consumption of the siren drive motor was also recorded.

The data for a constant pressure of 2 lbs./sq. in. is as follows:

	Voltage input to siren motor	Power consumption of drive motor	Frequency of siren
1	144 volts	625 watts	26,600 cycles
2	140 volts	580 watts	26,000 cycles
3	135 volts	550 watts	25,000 cycles
4	130 volts	530 watts	24,000 cycles
5	125 volts	500 watts	23,000 cycles
6	120 volts	460 watts	26,600 cycles
7	115 volts	425 watts	22,000 cycles
8	110 volts	400 watts	21,000 cycles
9	105 volts	365 watts	20,400 cycles
10	100 volts	335 watts	19,200 cycles
11	95 volts	315 watts	18,400 cycles
12	90 volts	227 watts	18,000 cycles
13	85 volts	250 watts	17,400 cycles
14	80 volts	225 watts	16,400 cycles

The curves that result from these figures are drawn in Figure VII.

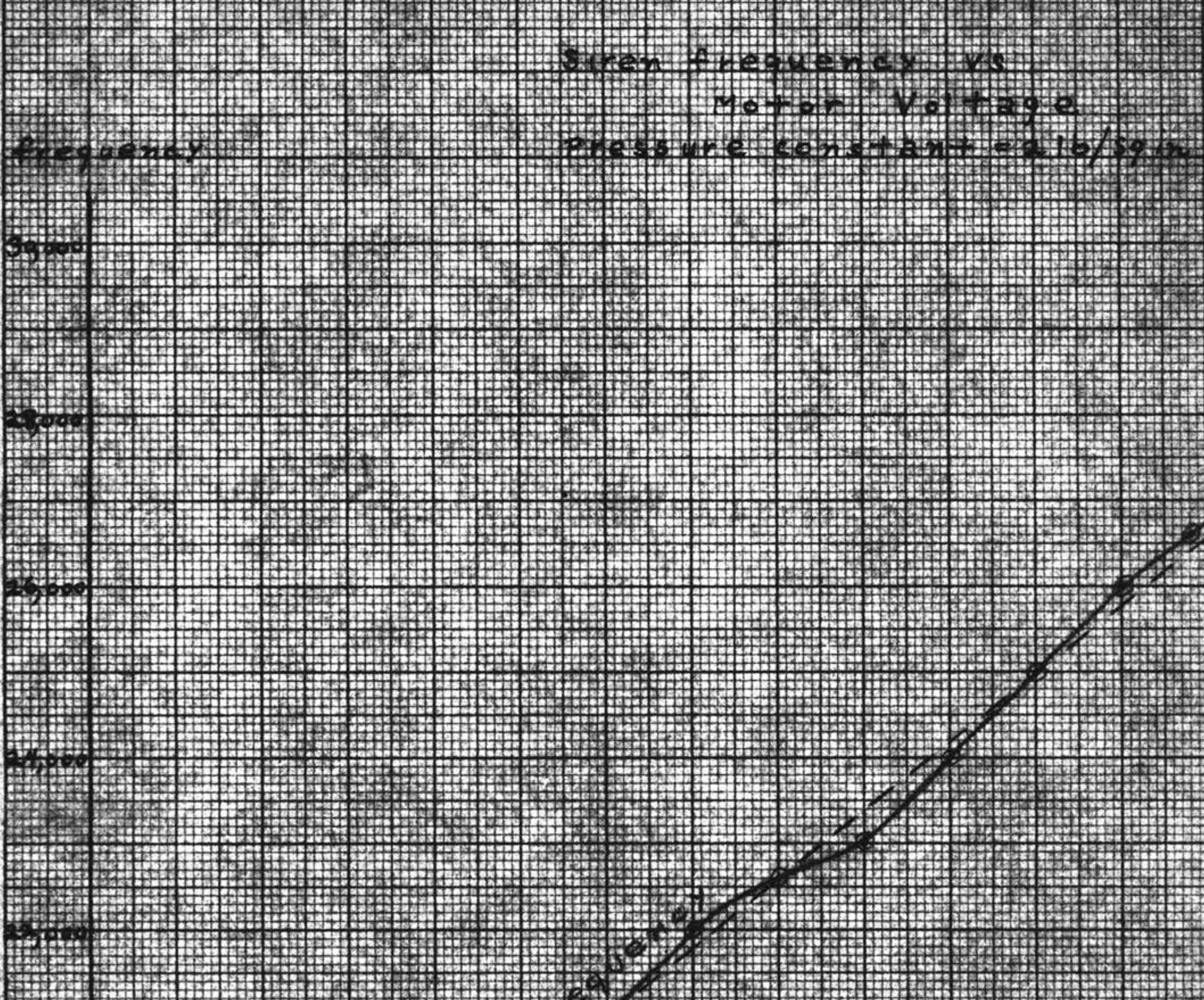

Siren frequency vs
Motor Voltage
Pressure constant = 2 lb/sq in
frequency
30,000
28,000
26,000
24,000
22,000
20,000
18,000
16,000
watts
700
600
500
400
300
200
frequency
Power
80
90
100
110
120
130
140
Motor Voltage

Figure VII

The second run was made with a constant pressure of 5 lbs./sq. in. The data is as follows:

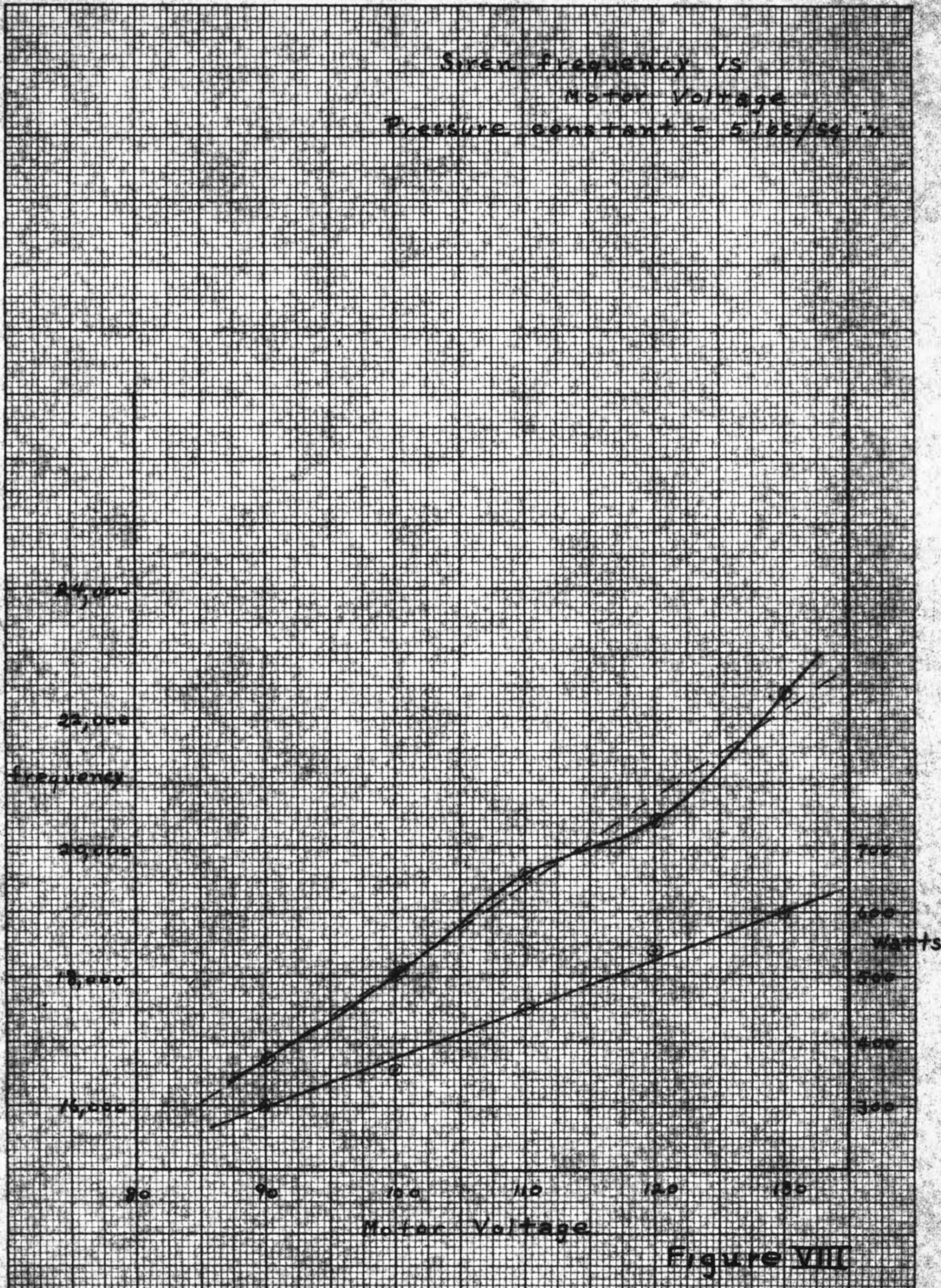
	Voltage setting	Power input	Frequency (cycles)
1	130 volts	600 watts	22,400
2	120 volts	540 watts	20,400
3	110 volts	450 watts	19,600
4	100 volts	356 watts	18,000
5	90 volts	300 watts	16,800

This curve is plotted in Figure VIII.

The third run was made using a chamber pressure of 10 lbs./sq.in. All of these runs particularly on the high intensities were limited because the sound came down too far in the hearing range.

	Motor voltage	Power consumption of siren motor	Siren frequency
1	130 volts	720 watts	20,000 cycles
2	125 volts	660 watts	19,600 cycles
3	120 volts	610 watts	18,600 cycles
4	115 volts	550 watts	18,400 cycles
5	110 volts	500 watts	18,000 cycles

The above was plotted in Figure IX.


Siren frequency vs
Motor Voltage
Pressure constant - 5 lbs/sq in
24,000
22,000
frequency
20,000
18,000
16,000
700
600
watts
500
400
300
80
90
100
110
120
130
Motor Voltage
Figure VIII

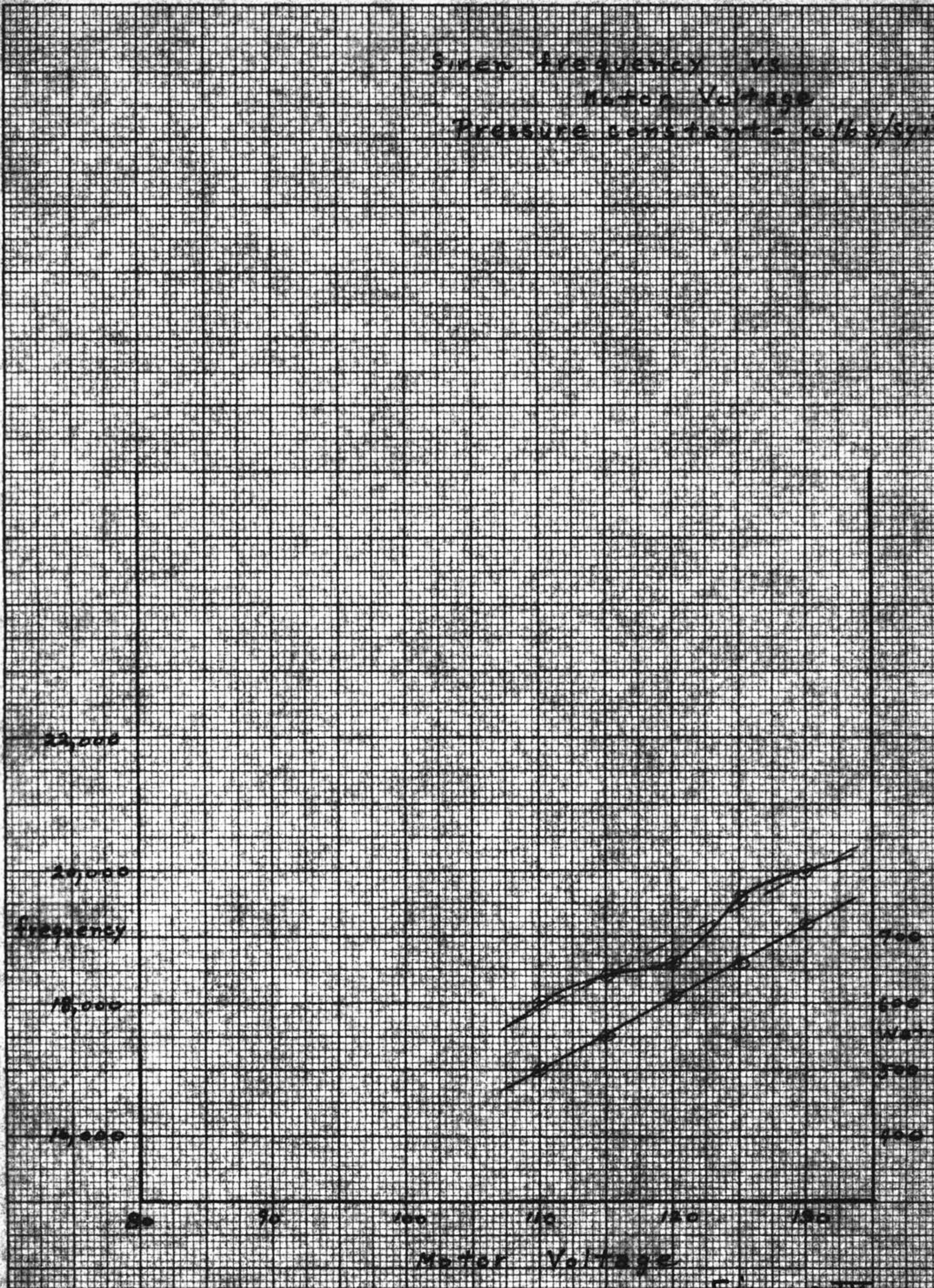

Siren frequency vs
Motor Voltage
Pressure constant = 10 lbs/sq in
22,000
20,000
Frequency
18,000
16,000
700
600
Watts
500
400
80
90
100
110
120
130
Motor Voltage

Figure IX

The final run was made by holding the motor voltage constant at 130 volts and increasing the chamber pressure. The effect on the frequency was noted.

	Pressure	Frequency of siren (cycle)
1	2 p.s.i.	24,000
2	5 p.s.i.	22,000
3	10 p.s.i.	20,000
4	15 p.s.i.	19,400
5	20 p.s.i.	18,000

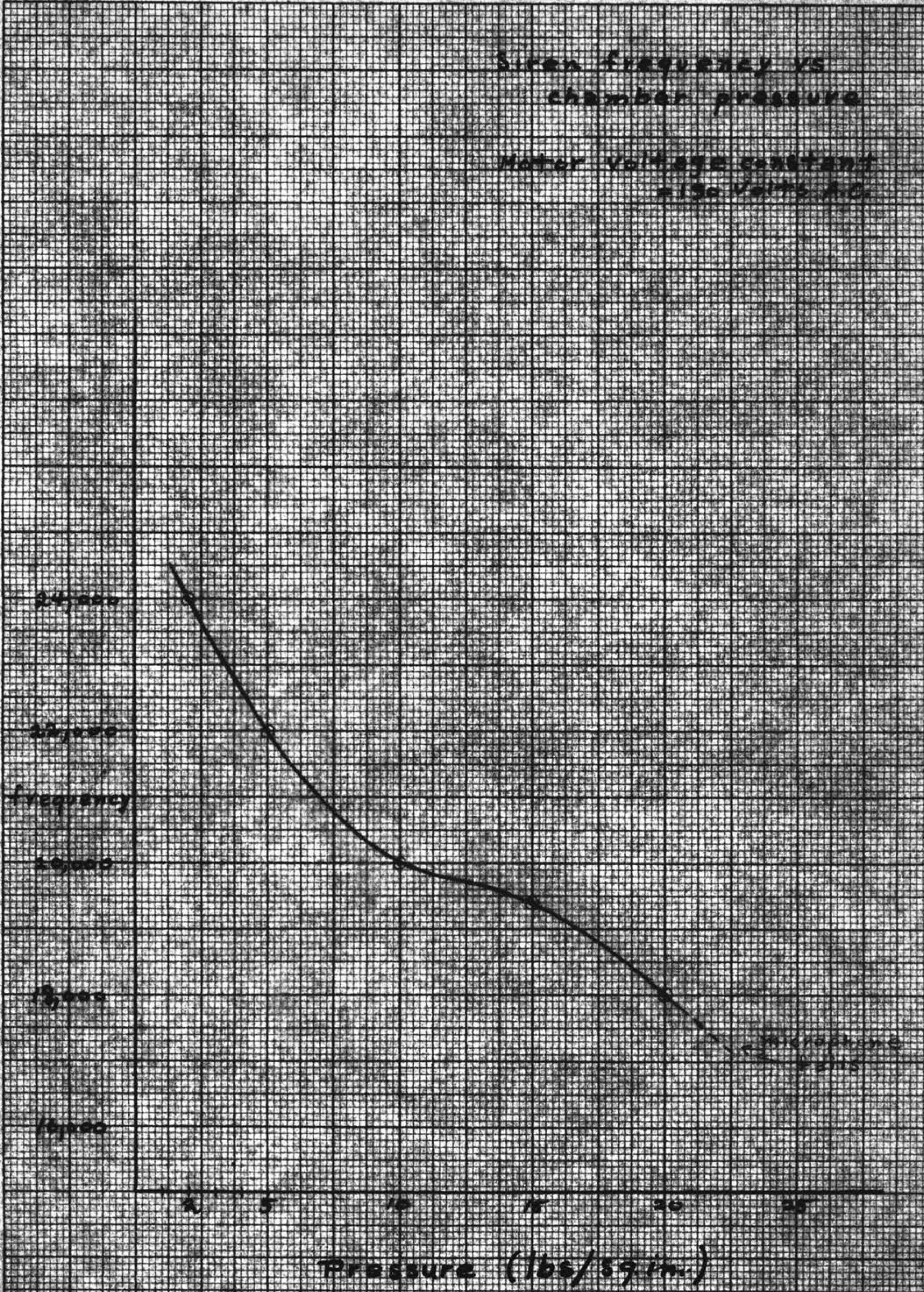
This last curve is given in Figure X. It can be seen in this curve that the higher pressures put a substantial load on the siren motor. The microphone did not operate well on the high intensities. Since it was badly overdriven considerable distortion resulted in the signal. The purest sine wave is obtained when the microphone was close to the siren. When the microphone was moved away from the siren the wave approached a saw toothed shape. This non-linearity has also been observed by other workers.[1]

Wave Shape of the Radiated Wave

The shape of the sound wave will be strongly affected by the instantaneous area of the openings as the rotor revolves. By changing the shape of the teeth on the rotor and the shape of the ports on the stator it is possible to produce quite a variety of wave-shapes from a pure sine wave to a square

---

[1] A. L. Thuras, R. T. Jenkins, and H. T. O'Neil, "Extraneous Frequencies Generated In Air Carrying Intense Sound Waves," J.A.S.A., VI (1935), 173-180.

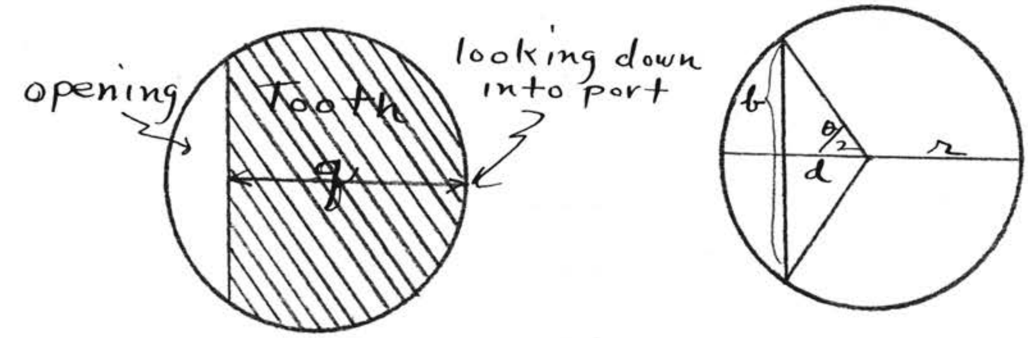


Siren frequency vs
chamber pressure
Motor voltage constant
=130 Volts A.C.
24,000
22,000
frequency
20,000
18,000
16,000
2
5
10
15
20
25
microphone
Pressure (lbs/sq in.)

Figure X

wave. Any wave shape other than a sine wave will have harmonies of the fundamental frequency.

In order to plot the curve of the area of opening at every instant, the formula for this area will be derived.



Let $q = d + r$

$$A_{seg} = \frac{\theta r^2}{2} \qquad A_{tri} = \frac{bd}{2} = \frac{b(q-r)}{2}$$

but $b = 2r \sin \theta/2$

$$A_{tri} = r(q-r) \sin \theta/2$$

$$A_0 = A_{seg} - A_{tri}$$

$$A_0 = \frac{\theta r^2}{2} - r(r-q) \sin \theta/2$$

but $d = r \cos \theta/2 = q - r$

$$\theta = 2 \cos^{-1}\left(\frac{q-r}{r}\right)$$

$$\boxed{A_0 = r^2 \cos^{-1}\left(\frac{q-r}{r}\right) - r(q-r) \sin \cos^{-1}\left(\frac{q-r}{r}\right)}$$

The above formula can now be used to plot the increase of area with time. For the size of the bottom of the port we have r = .040". It is assumed in this analysis that the tooth makes a straight line in the hole, which it does to a very close degree. Curve 1 on Figure XI shows a plot of the above formula. The flattening out of the top and bottom of the waveform is due to the fact that the tooth (.094" wide) is wider than the hole (.080" wide). Consequently for .014" travel of the tooth, the hole remains closed. Also since

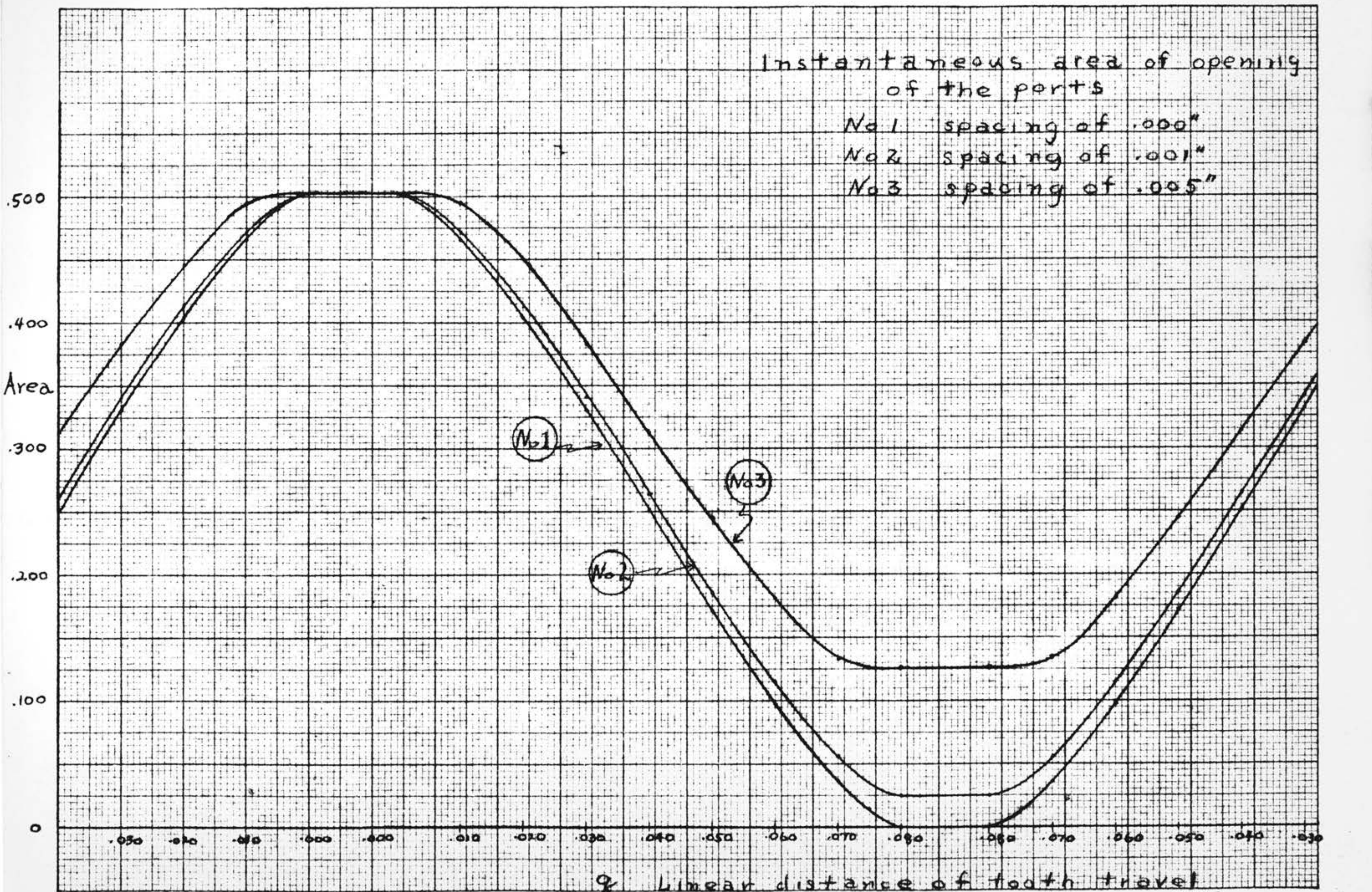

Instantaneous area of opening of the ports
No 1 spacing of .000"
No 2 spacing of .001"
No 3 spacing of .005"
.500
.400
Area
.300
.200
.100
0
No 1
No 2
No 3
℄ Linear distance of tooth travel

Figure XI

the space between the teeth is .094" wide the hole will remain totally uncovered for .014" of tooth travel. The above assumes that no leakage exists between the rotor and stator.

The Effect of Leakage Around Rotor Teeth

It must be considered now what effect leakage has on the wave form of the siren. To the original formula will be added the increase in the free area due to the spacing between the rotor and stator. If S is the spacing, then the leakage area when the port is covered will be given by:

$$A_e = 2\pi r S$$

This area will decrease as the tooth advances so that:

$$A_e = \theta r S$$

$$\text{but } \theta = 2\cos^{-1}\left(\frac{g-r}{r}\right)$$

$$A_e = 2rS\cos^{-1}\left(\frac{g-r}{r}\right)$$

This area is then added to the area of the uncovered part of the hole. Curves 2 and 3 in Figure XI show the resulting waveform for spacings of .001" and .005". Thus it can be seen that the area amplitude is rapidly decreased with increased spacing. This of course results in less sound output.

Curve No. 2 with the .001" spacing is a practical value for construction and as can be seen provides a 95% closure of the hole.

Curve 3 is for a spacing of .005". The leakage here is becoming excessive, and only a 75% closure will be obtained.

When the spacing is .010" the closure is 50%. At .020" there is no closure at all, the resulting area amplitude will be zero. At this spacing sound can still be produced due to the pumping action of the blades and the

Calculations for Instantaneous Area of Opening

q	$\frac{q-r}{r}$	A_o	θ $2\cos^{-1}\left(\frac{q-r}{r}\right)$	θr	A_e/S
.080	1	.0000	0.000	.0000	.2515
.070	3/4	.0365	1.446	.0578	.1930
.060	1/2	.0984	2.095	.0838	.1670
.050	1/4	.1718	2.635	.1052	.1460
.040	0	.2515	3.140	.1257	.1257
.030	-1/4	.3307	3.645	.1460	.1052
.020	-1/2	.4044	4.180	.1670	.0838
.010	-3/4	.4663	4.830	.1930	.0578
.000	-1	.5030	6.280	.2515	.0000

A_e/S	A_e for .001"	A_e for .005"	A_T for .001"	A_T for .005"	
.2515	.02515	.1258	.02515	.1258	
.1930	.01930	.0965	.05580	.133	
.1670	.01670	.0835	.1151	.1819	
.1460	.01460	.0730	.1864	.2448	
.1257	.01257	.0628	.26407	.3143	
.1052	.01052	.0527	.34122	.3834	
.0838	.00838	.0419	.41278	.4463	
.0578	.00578	.0289	.47208	.4952	
.0000	.0000	.000	.5030	.5030	

turbulence. Such curves are useful for producing a definite waveform. It has been shown by R. Jones[2] that the sinusoidal output which this siren approximates, has a maximum efficiency of 50%. The siren with a square wave output has a possible efficiency of 100%.

No intensity measurements were made on the siren since no equipment was available for such work.

The Radiation Pattern Rendered Visible

Some work was done on the Schlieren method for detecting the variable density of the standing wave pattern. Successful runs were made with ultrasonics in oil, but the method failed when it was applied to airborne sound. Figure XII shows the standing wave pattern that was obtained with 450 KC ultrasonic waves in oil. The lack of results for airborne sound was attributed to the poor lens that was used.

Another method was used to study the radiation pattern. A microphone and neon lamp was attached together on the end of a long oscillating arm. The microphone neon lamp combination was made to scan the area over the siren while the camera was set for a time exposure. The gain of the accompanying amplifier was set so the neon lit at the antinode and it extinguished at the nodes. The standing waves were produced by placing a heavy brass plate over the siren. The vertical travel of the neon lamp-microphone combination was 15".

Figure XIII shows the appearance of the radiation pattern. Since the arm was swept through a vertical plane across the center of the siren (the covered siren may be seen in the bottom of the picture) the pattern is a cross section of the circular pattern.

In Figure XIII it can be observed that the siren on this frequency

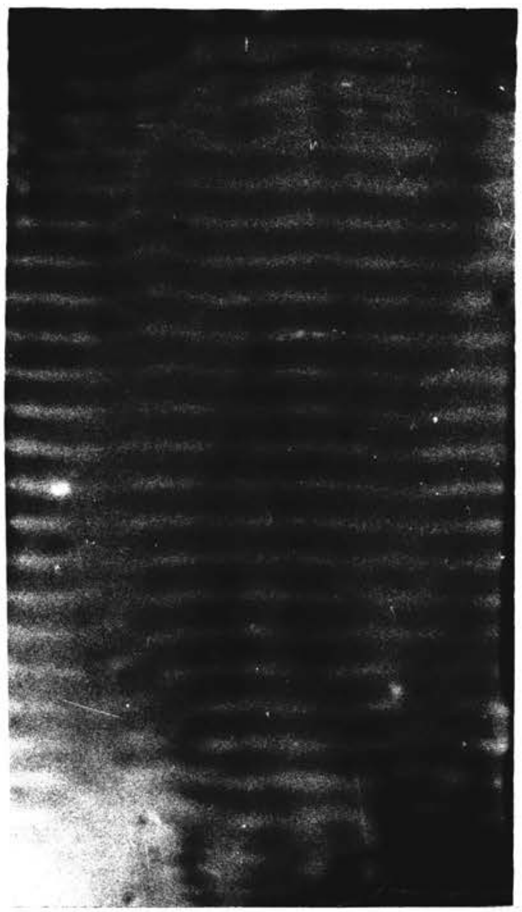


Figure XII

This is the 450 KC standing wave pattern produced on the Physics Department's Ultrason. It was rendered visible by optic means through an improvised chamber with windows sealed against oil leakage.

Figure XIII

(5500 cycles) produces a strong central lobe and two side lobes. The side lobes can be seen to be 180° out of phase with the standing waves in the central lobe.

This technique can be used for studying the effectiveness of horns, acoustic lenses, and acoustic zone plate.

Floating Objects in the Sound Field

When objects such as corks, balls or coins are placed in the sound field they were found to float on the velocity antinode. It was noted that the objects in the same level attract each other and tend to cling together. The objects could be sent flying out of the field by a fast variation of the frequency. These objects are easily held in the field with a glass cylinder. Another interesting experiment was to blow powder into the field. The powder collected at the nodes rendering their location visible.

Coins laid on a sheet stood up on end, corks stood up on their corners when the frequency is adjusted so they are over a velocity antinode. If the frequency is varied the objects jump, all at the same time.

Heating Effects of Intense Ultrasonic Waves

To discover the heating effect one had only to hold his hand in the strong sound field. The hand will get hot very fast. If cotton is held in the sound waves path it will burst into flames in about 30-45 seconds. The burning cotton cannot be extinguished by smothering. Even after wetting, the interior of the cotton is still very hot. Thus the heat generated is penetrating.

The lethal effect that the radiation has on small animals is most likely due to this heating effect although in small insects some physical damage can be observed such as broken wings and antennae.

There is some question as to the source of this generated heat. Filamentous materials seem to be best for converting sound energy into heat. The heat is most likely caused by friction. A good acoustical resistor is a long narrow pipe, or a small hole. A fibrous substance like cotton or steel wool has a multitude of such tortuous channels through its interior. The rapid viscous flow through such channels would result in a large loss of energy through friction. To test this idea the cotton was held in various parts of the field and it was found that the velocity antinode produced the greatest heating effect.

CHAPTER IV

THE DESIGN OF AN ACCESSORY EXPONENTIAL HORN

To effect a closer coupling between the sound generator and the air an impedance matching device should be used. The exponential horn is such a device in acoustics.

The design of such a horn should be such that the increase in area per unit length should be proportional to the area itself. Stated mathematically we have the following:

$$\frac{dA}{dl} = KA$$

Solving $$\int \frac{dA}{A} = \int K\,dl$$

$$\log A = Kl + \text{const.} \qquad \text{let const} = \log B$$

$$\log A = Kl + \log B$$

$$\log A/B = Kl$$

$$A = B \exp Kl$$

This last equation can be used to design the horn.

Another factor to be considered is the diameter of the large end, it should be greater than a quarter wave for the lowest frequencies to prevent reflections.

The rate of flare determines the cut off frequency. Thus if the horn area doubles for every 2 feet of length the cut off is 32 cycles. If it doubles every one foot of length the cut off will be 64 cycles etc.

This horn has to be designed in a different manner since the source of the sound is from a ring of holes. Hence the horn must be made in two parts (see Figure XIV).

A design formula must now be found for this type of horn.

$r =$ mean radius = 3"
$\Delta r =$ the increase or decrease in radius with an increase in length
$r_2 =$ radius of the outer piece
$r_1 =$ radius of the inner piece

The Area will be

$$A = \pi(r_2^2 - r_1^2)$$

but

$$r_2 = r + \Delta r$$
$$r_1 = r - \Delta r$$
$$A = \pi[(r^2 + 2r\Delta r + \Delta r^2) - (r^2 - 2r\Delta r + \Delta r^2)]$$
$$A = 4\pi r \Delta r$$
$$A_{min} = 4\pi 3 \times .094$$

(since the diameter of the upper part of the port is .188")

$A_{min} =$ 3.54 sq. in.

$$A_{max} = \pi 36 = 113 \text{ sq. in.}$$

From these areas one can determine K since the length chosen is 5".

Using the horn equation we get

$$113 = 3.54\, e^{K5}$$
$$31.9 = e^{K5}$$
$$K = .693$$

This gives a horn with a cut off of about 1,000 cycles/sec. Below this frequency the horn is ineffective.

The diameter of the large opening is 1 ft. at a 1,000 cycle/sec. A quarter wave length is .3 feet, so no trouble should arise from reflections.

The equation can now be put into a form for calculation.

$$A = 3.54\, e^{.693l}$$

but

$$A = 4\pi 3 \Delta r$$
$$4\pi 3 \Delta r = 3.54\, e^{.693l}$$
$$\Delta r = .094\, e^{.693l}$$

The calculations follow.

Figure XIV shows a drawing of the horn. At this writing the horn was still under construction.

Calculations for the Exponential Horn

l (inches)	lk .693l	e^{kl}	Δr .094e^{kl}	r_2 $(r+\Delta r)$	r_1 $(r-\Delta r)$	l (inches)
0	0	1	.094	3.094	2.906	0
¼	.17325	1.185	.1113	3.111	2.889	¼
½	.3465	1.419	.133	3.133	2.867	½
3/4	.51975	1.68	.159	3.159	2.841	3/4
1	.693	1.994	.187	3.187	2.813	1
1.250	.866	2.38	.224	3.224	2.776	1¼
1.5	1.0395	2.83	.266	3.266	2.734	1½
1.75	1.21275	3.35	.315	3.315	2.685	1 3/4
2	1.386	4.01	.377	3.377	2.623	2
2.25	1.559	4.76	.448	3.448	2.552	2¼
2.5	1.733	5.64	.53	3.530	2.470	2½
2.75	1.90575	6.75	.635	3.635	2.365	2 3/4
3	2.079	8.00	.752	3.752	2.248	3
3.25	2.25225	9.49	.892	3.892	2.108	3¼
3.5	2.4255	11.36	1.07	4.070	1.930	3½
3.75	2.59875	13.46	1.265	4.265	1.735	3 3/4
4	2.772	15.959	1.50	4.500	1.500	4
4.25	2.945	19.106	1.800	4.800	1.200	4¼
4.5	3.1185	22.65	2.135	5.135	.865	4½
4.75	3.29175	26.84	2.52	5.520	.480	4 3/4
5	3.465	32.14	3.02	6.020	0	5

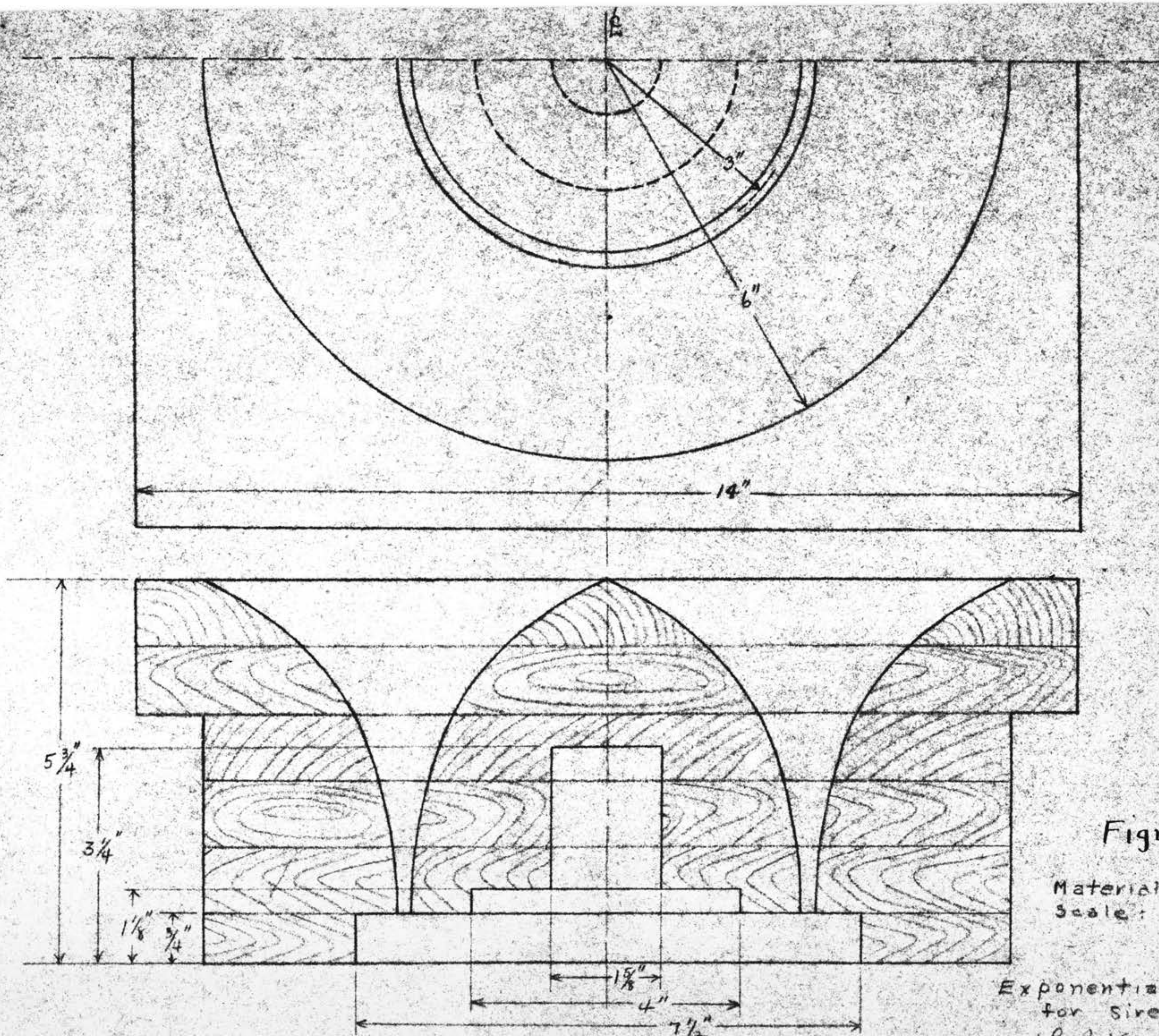


Figure XIV

Material: wood
Scale: 1" = 1/2"

Exponential horn
for siren

F. J. V.

BIBLIOGRAPHY

Allen, C. H., and Rudnick, I. "A Powerful High Frequency Siren", XIX (Sept. 1947), 857-865.

Beranek, Leo L. Acoustic Measurements. Cambridge, Mass., John Wiley and Sons, 1949.

Bergmann, Dr. Ludwig. Ultrasonics and Their Scientific and Technical Applications. Germany: John Wiley and Sons, 1938.

Colby, M. Y. Sound Waves and Acoustics. New York: Henry Holt Co., 1937.

Gaines N., and Chambers L. "Further Study of Effects of Intense Audio Frequency Sound," Phys. Rev. II.(1932), 39, 862.

Gregg Jr., E. C. "Biological Effects of Ultrasonics," M. Physics, (1944), 1591-1596.

Olson, H. F. Elements of Acoustical Engineering. New York: Von Nostrand, (1947).

Olson, H. F. Dynamical Analogies. New York: Von Nostrand, (1938).

Thuras, A. L. Jenkins, R. T., and O'Neil, H. T. "Extraneous Frequencies Generated in Air Carrying Intense Sound Waves," J. A. S. A., VI (1935), 173-180.

Typist: Jo Fowler