AN EXPERIMENTAL STUDY OF THE TUNING OF A MUFFLER

by

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NOMENCLATURE

X - position of piston in inches

db - Decibel

Hz - Hertz

P - Acoustic pressure

σ - Density

c - Speed of wave proposition, ft/sec.

T - Absolute temperature

rms - Root mean square

λ - Wavelength

f - Frequency in cyc/sec.

rpm - Revolutions per minute

VITA

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INTRODUCTION

In today's world, air pollution and noise pollution are great problems. Noise is generated by a number of casuses. Some of the greatest noise generators are automobiles and farm equipment.

Most of the farm equipment and automobiles are run on four stroke or two stroke engines. In these engines, noise is created by engine parts such as pistons, cylinders, valves, gears and exhaust systems. At present, mufflers are used to reduce noise of exhaust. In the muffler, we try to equalize the exhaust pressure and atmospheric pressure, but in this process we achieve noise reduction but with a sacrifice of engine efficiency.

In the reduction of noise through the use of the muffler, we have the restictions of availability of space and sacrifice of economy. In order to get noticeable reduction in noise, more attention has to be focused on the design of a muffler.

At present, mufflers are designed to reduce noise by increasing the impedance of the muffler. Importance is not given to the tuning of a muffler which involves having a particular configuration for mufflers. The main purpose of this work is to reduce noise by tuning the muffler by designing a proper configuration in the muffler. If we want to achieve a particular sound level at all speeds of the engine and at all load conditions, we have to design the muffler for the condition when exhaust generates maximum noise. And thus at other conditions, we have quite a low sound level which is not needed and thus we sacrifice economy. So to achieve economy and sound reduction, it seems a good proposition to have a tuned muffler.

The object of this thesis is to focus attention on how to get a practical tuned muffler. Until now the idea of a tuned muffler has not been given much attention, so there is little literature or experimental data on multifrequency tuned mufflers.

PRINCIPLE OF A TUNED MUFFLER

Noise intensity is a function of the amplitude of an acoustical pressure wave as shown in Figure 1. As amplitude increases, intensity of

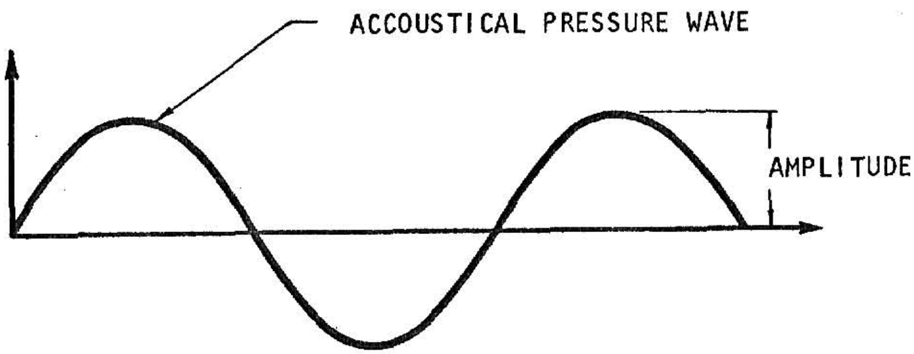


FIGURE 1

sound increases. So to reduce noise, we should have a steady wave, that is, to avoid big instantaneous amplitudes. To achieve small amplitudes, we try to bring compression and tension waves in phase with each other, thereby reducing the resultant amplitude of the wave. Here we don't destroy energy but we try to distribute it more uniformly over time. For if we have resonance, we dissipate energy at a high rate, whereas if we don't have resonance, the energy dissipation rate is low.

To confirm the above statement, the following experiment is performed with a cylindrical tube and a vibrating tuning fork. It is found that when the air column has its natural frequency (that of the fork) there occurs the maximum emission of energy from the system. But since the cylinder can't give out more or less energy than it receives, assuming no dissipation within, the emission of energy from the cylinder must be the same as the energy flowing into it from the fork. Hence, we must conclude that when the fork is placed above the resonating cylinder, the fork emits energy at a greater rate than when alone. This illustrates an important fact not usually understood. Namely, that although resonance doesn't create energy, it may make possible a greater emission from the source. This increase in input can be explained by the phase relationship of the velocity and pressure at the source. An analogous case is setting a swing (pendulum) into vibration by pushing when at the midpoint of the arc or at the maximum velocity. The push and the volocity are in the same phase. It may be remarked that cases may arise in acoustics where the phase relationship is unfavorable rather than favorable. In such an event, the emission of sound is made less by the presence of the resonator near the source.

The above statement that a fork has been caused to emit energy at a higher rate is based not only upon theory but also upon experiment. The literature records experiments by Koenig where in a fork sounded above 90 seconds without a resonator and 10 seconds in the presence of one. Obviously the change that occurs depends upon the internal losses of energy in the fork and upon the dimension of resonator.

Thus, if we can achieve opposite effect of resonance, we will have reduction in noise since amplitude of acoustic pressure will be reduced,

$$\text{Acoustic Intensity} = \frac{P^2_{rms}}{\rho c}$$

thus getting reduction in acoustic intensity.

Quincke has made an experiment on the following configuration as shown in Figure 2 on page 5 . The wave enters at A and either passes out at F or experiences what is equivalent to a reflection at D, for there is no opportunity for the energy to be disposed of otherwise. If the frequency corresponds to the natural period of vibration of the tube DC, then this tube will resonate. At frequency of resonance, the incoming and outgoing waves in such a close tube agree in displacement at the open end, but have pressures that are approximately equal and opposite, forming a "loop" at the end. If this

Quincke's Configuration

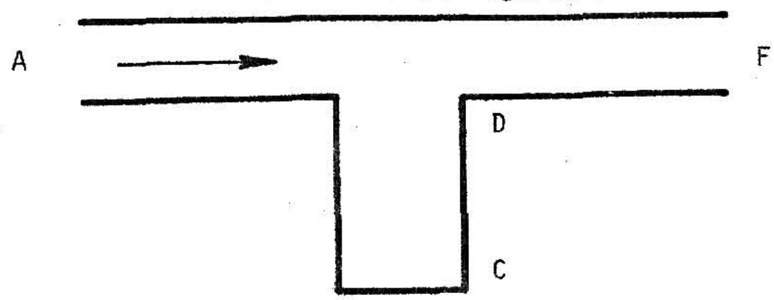


FIGURE 2

occurs, there is approximately no pressure to produce transmission out through DF. Thus the wave of this frequency is eliminated from transmission since the elimination is caused by resonance. The shape of tube DC is inconsequental if the elimination of this frequency only is considered.

Let us consider the number of possible waves involved. There is the flow of energy from A to D, which is wave one, one entering DC is described as two, and one passing on towards F is described as wave three. Let us consider that there are no reflections in tube DC. There is one wave from the tube DC which will pass partly to the left towards A and partly to the right towards F. Denote this wave in the tube by six, the one passing towards A by four, and the one towards F by five. We then see that there are two waves to the right, towrds F, numbered three and five. As noted before, time is required to build up resonance, and, if there is no viscosity, there is only the limiting case of vibration in DC where the energy escaping from the resonator is equal to that entering from the source. Resonance in DC will build up until five is a great as three. But five is opposite in phase to three because it has traversed a half wavelength further. Wave five will not build up any further because at equality of three and five total flow to the right becomes zero. Then the total flow in four must become equal to the flow in one. In other words, wave one is essentially reflected.

Tuned Muffler for all Frequencies

In the above explanation, we have shown that the muffler is tuned for one frequency since DC is a fixed length.

Now let us consider an engine. Instead of attaching a single muffler to it, we will have a wheel with five mufflers (a, b, c, d, e) as shown in Figure 3 on page 7. Let (a, b, c, d, e) be tuned muffler for 500, 1000, 2000, 3000 and 4000 rpm's.

Now start the engine. If it is running at 500 rpm, turn the wheel and bring the muffler "a" in line with the engine, so we have tuned system at 500 rpm. As the engine runs at rpm 1000, 2000, 3000 and 4000 respectively, bring b, c, d, and e mufflers in line with the engine. Thus we have the engine tuned to all five rpm's.

Thus if we want the engine to be tuned at all rpm's we will need an infinite number of mufflers.

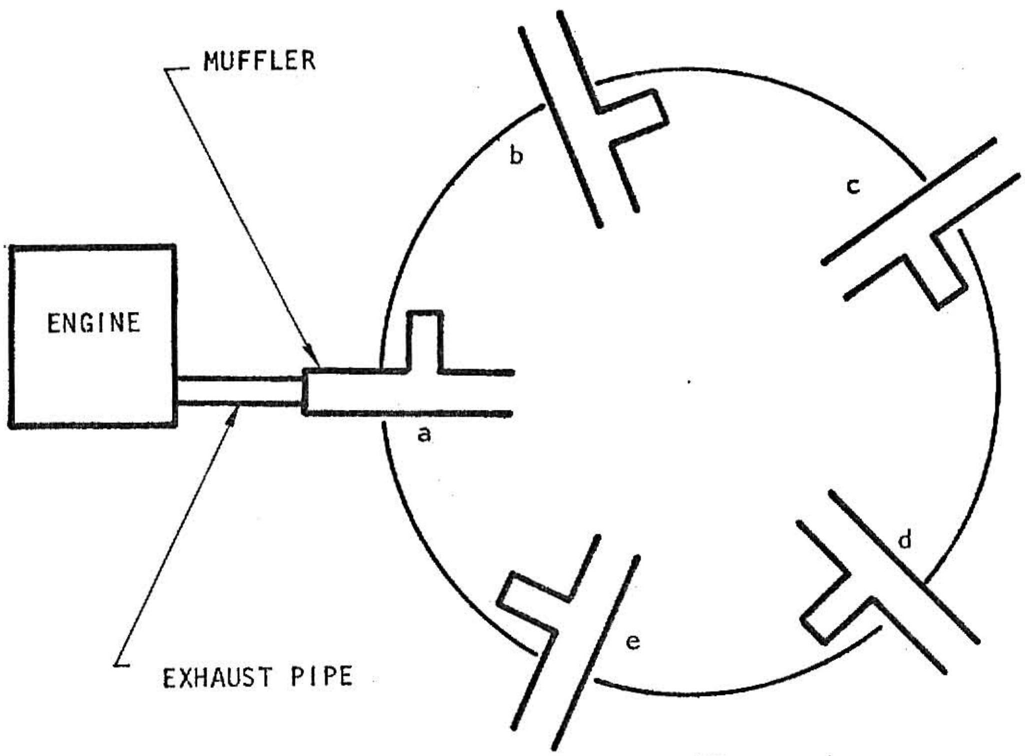
So to obtain a tuned engine muffler, we have one muffler with adjustable length DC.

As the engine rpm changes, the length of DC is adjusted to tune the exhaust stroke frequency. We can say that the system is tuned at all rpm's only if the engine exhaust generates exhaust stroke frequencies at all speeds. The exhaust emits sound waves with a frequency band of 2 to 20000 Hz. Thus, if we

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

tune one frequency, the others would be untuned. To have a desirable sound reduction, we will have to find a frequency band such that if we tune the muffler for the frequency band we will achieve reduction in noise levels.



Set Up for Engine Tuned at Five rpm's
FIGURE 3

As we have seen above that exhaust sound has a wide frequency band, and the intensity of sound at each frequency is different. So to have an equivalent system for exhaust we can have a number of sound generators, each one producing different frequencies and having sound intensity levels that of the exhaust system. Then we can find the resultant of all the sources and that will be the total sound level.

If we have a sound which is a combination of a number of frequencies we can find the sound of equivalent loudness at one frequency with the help of equal loudness contours as shown in Figure 4 on page 8.

It may be possible to eliminate a certain band of frequencies and thereby reduce the total noise.

It is the purpose of this thesis to test the above contention.

Equal Loudness Counters

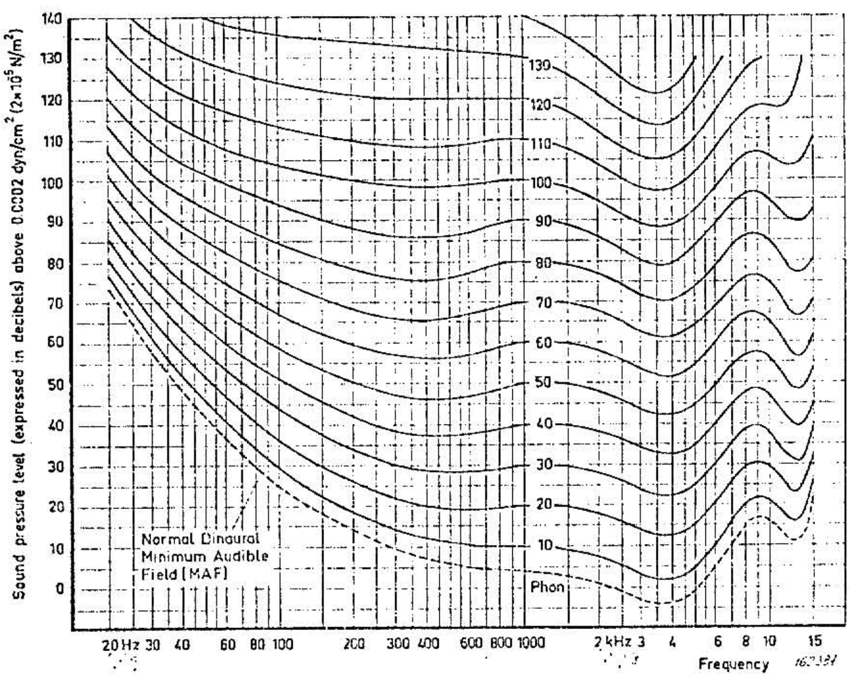


Figure 4

OPTIMIZATION AND RESTRICTIONS

Let us consider a muffler tuned for one frequency. If we want to have zero noise, then the wave "a", as shown in Figure 6 on page 10, which is the tension wave from A, should be out of phase with wave "b", as shown in Figure 6 on page 10, which is a wave which travelled half a wave length distance more than "a". By adjusting the length of CD as shown in Figure 5 on page 9, we can have waves "a" and "b" in out of phase. But to have zero

Quincke's Configuration

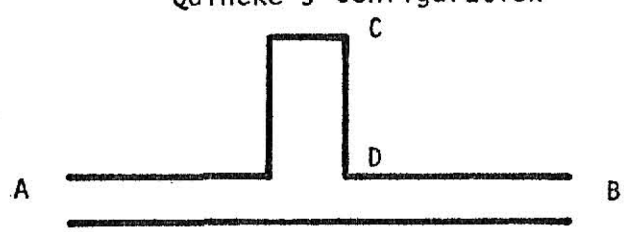


FIGURE 5

noise, the amplitude of "a" and "b" should be the same. But to have the same amplitude we should have complete compression going to "C" and then coming back; but at D part of wave travels to C and part to B. So the amplitude of both waves can't be equal.

We assumed in the last chapter that there are no reflections in tube DC. But this is an ideal case so it is not possible to have a tube DC without any reflections.

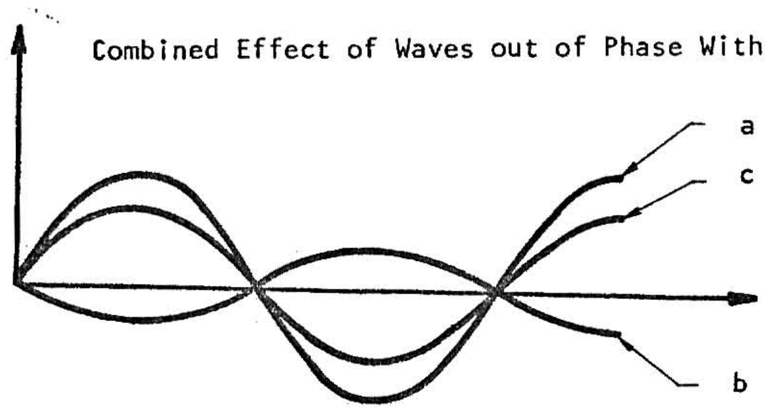


FIGURE 6

Thus the resultant wave C as shown in Figure 6 on page 10 will have some amplitude thereby producing some noise.

If we have a number of reflections in DC then we may have a number of waves with wave a and b and we may end up with resultant wave with larger amplitudes than wave "a".

Although it is impossible to have zero noise, we can reduce noise by having fewer reflections and more resonating tubes like DC.

In the above case we have used a simple construction. Because of space limitations in vehicles, the configuration of the muffler had to be changed. In the modified construction design, one thing had to be kept in mind. Namely, we had to have a design such that minimum relections occur.

We can't reduce exhaust noise to zero since we can't have compression wave amplitude equal to tension wave amplitude because of back pressure limitations. Another reason is that exhaust noise is a combination of sound waves at different frequencies and we can't tune all the frequencies at the same time.

BASIC CALCULATIONS TO TUNE ONE FREQUENCY FOR MUFFLER

If we want to have the muffler tuned for all rpm's, then we will have to find the position of the piston "X" as shown in Figure 7 on page 12 for different rpm's. X denotes the position of the piston. X is the distance of the piston from the main tube. For a tuned muffler, X should be equal to one quarter of a wavelength.

Basic Muffler Configuration

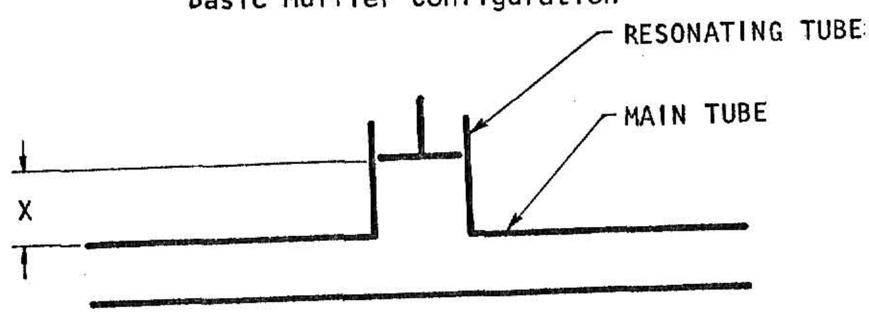


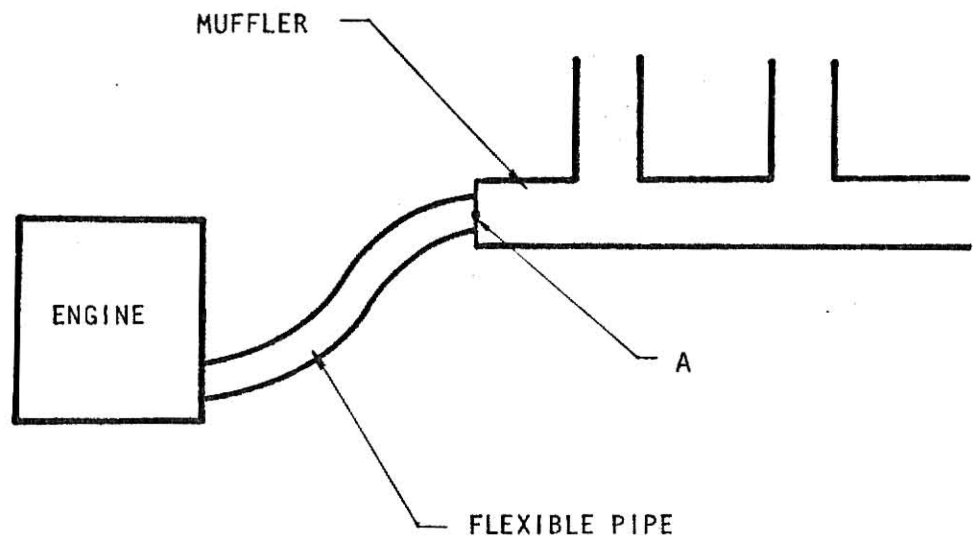
FIGURE 7

Now the speed of sound = wavelength X Frequency.

$$C = \lambda f$$

The speed of sound depends on the temperature of the medium through which sound travels. In our case, the temperature of exhaust gas varies with respect to load and atmospheric conditions. Therefore, the velocity of sound is calculated at the exhaust temperature. The variation in atmospheric temperatures and altitudes will not cause an appreciable change in the value of X.

Velocity of sound V_s = 1132 fps at 0 altitude and at 73.5° F. (23.1° C) As altitude increases the velocity of sound decreases. At 10,000 feet altitude velocity of sound is 1100 fps at a temperature of 43.4° F (6.3°C).



Set Up for Measurement of Exhaust Temperature

FIGURE 8

To find the temperature of gases at point "A" as shown in Figure 8 on page 13. The instrument used to determine the temperature was a Chromel Alumel thermocouple potentiometer. It was found that at the point A. where the muffler is attached, the temperature of exhaust gases was 360° F at rpm 3600 and at low rpm 340°F. This small variation won't affect the value of X. So 360° F is taken as the temperature of gas.

$$\frac{C_1}{C_2} = \sqrt{\frac{T_1}{T_2}}$$

where:

C_1 = speed of sound at temperature T_1 ^oR.

C_2 = speed of sound at temperature T_2 ^oR.

$$\text{Velocity of sound at } 360^\circ \text{ F} = 1100\sqrt{\frac{360 + 460}{460 + 43.4}}$$

$$= 1403 \text{ fps}$$

1403 = wavelength x frequency

$$\text{Quarter wavelength} = X'' = \frac{1403 \times 12}{4 \times \text{Frequency}} \qquad \text{Quarter wavelength} = X'' = \frac{4209}{\text{Frequency}}$$

Frequency Hz	Quarter wavelength X''
250	16.84
300	14.03
350	12.03
400	10.52
450	9.35
500	8.42
550	7.65
600	7.02
650	6.48
700	6.01
750	5.61
800	5.26
850	4.95
900	4.68
950	4.43
1000	4.21

Frequency Hz	Quarter wavelength X"
1050	4.01
1100	3.83
1150	3.66
1200	3.51
1250	3.37
1300	3.24
1350	3.12
1400	3.01
1450	2.90
1500	2.81
1550	2.72
1600	2.63
1650	2.55
1700	2.48
1750	2.41
1800	2.34
1850	2.28
1900	2.22
1950	2.16
2000	2.10

Figure 18 on page 49 shows a graph of piston position as abscissa in inches and frequency as ordinate in Hz.

Table 1

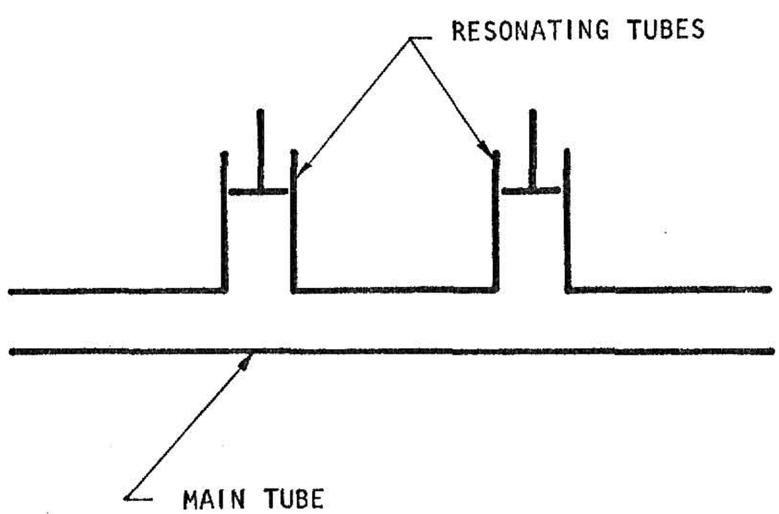
Calculated Values of the Piston Position
at Different Frequencies for a Tuned Muffler

GEOMETRY OF MUFFLER

Because of space restriction in automobiles, geometry of the muffler is one of the important factors to be considered at the time of the design of the muffler.

When we change the geometry of the muffler, we have to consider the following points. When we choose a particular geometry, we don't know how many reflections we are going to get. If we have more reflections, then the tuning effect is sacrificed. We can't find theoretically how much reflection we are going to obtain. Therefore the problem becomes a very complex one. Choose any one configuration; fabricate the muffler and then test it. Repeat the same procedure for different configurations and make inferences from the results of the tests.

In the beginning two configuration are considered. In the configuration



Configuration of a Muffler
FIGURE 9

of Figure 9 on page 16, reflections will be minimum because the resonator tube has a simple configuration. Again, reflections would change as the main tube and resonator tube diameters change. The best combination of main tube diameter and resonator tube diameters is to be determined experimentally.

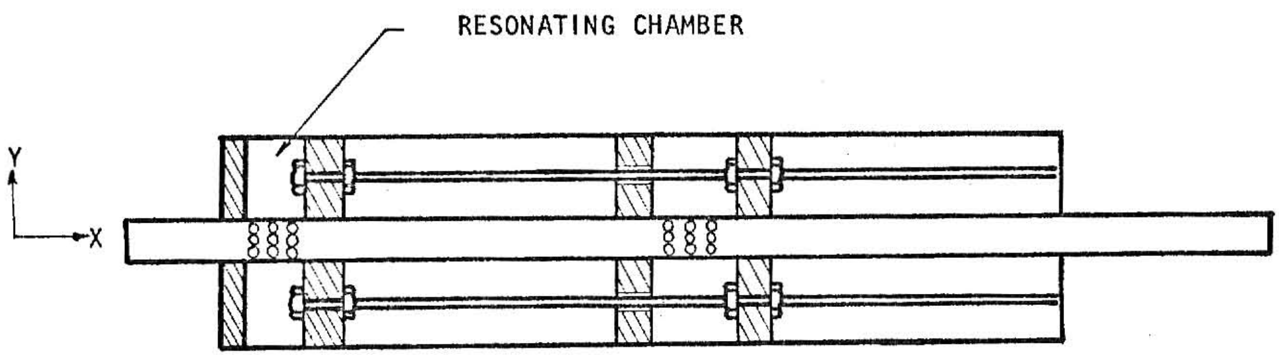


FIGURE 10

Configuration of a Muffler

In the second configuration, shown in Figure 10 on page 17, reflections are more present than in the first case, since the resonating tube has been bent through 90° from the first case position. Then, with little modification, we get the second configuration.

We want the wave to travel in the resonating chamber in the X direction, but as it comes in through the holes the wave hits the outer tube in Y direction and will be reflected and rejoin the flow. Thus we may have exactly opposite effects of tuning if the reflected wave is in phase with the initial wave. Experimental testing will show how good the second configuration is.

The experiment can be considered to be a suitable procedure for determining the best configuration.

EXPERIMENTAL SET UP, READINGS, GRAPHS AND CONCLUSIONS

Experimental Set Up

For the purpose of testing a muffler, a single cylinder four stroke, 10 H.P. gasoline engine, Briggs and Stratton, Milwaukee, Wisconsin, USA, engine is used. A Hasler-Berne tachometer is used to measure the speed of the engine. An electric loading system is used to load the engine. A Precision Sound Level Meter, type 1613 and 2203, and Impulse Precision Sound Level Meter, type 2204, made by Bruel and Kjaer is used to measure the sound intensity level.

The muffler to be tested is connected to the engine by means of a piping arrangement which is shown in the figures for each experiment. The microphone of the sound intensity meter is placed at a place at which it picks up only the sound of the exhaust. Then the engine is started, and the speed and load is adjusted as desired. The movable pistons are moved and necessary types of readings are taken at the desired piston position with variation in speed and load.

The experiments are conducted at night so that external sound disturbances are mostly eliminated.

Variations from the procedure outlined above are mentioned for the particular experiments in which they occur.

Sound Intensity Level Meter

This meter has a wide variety of uses. The functions of the meter which are used in the work are described below.

The instrument is designed according to International Electrotechnical Commission (IEC) standards. It can read the sound intensity varying from 10 db to 130 db. It has a dial which indicates different bands of 10 db of sound level. Although the range of the instrument is from 10 db to 130 db, the full scale deflection is only 10 db, and the increment of the range used is selected by a knob setting. So, the final reading is the addition of the knob setting reading and the scale deflection. The instrumental accuracy depends on the choice of controls used. The meter has three different types of responses, slow, fast and impulsive response. When the sound to be measured is quite steady, without much pulsation, the slow response is used. In this response, instantaneous peaks are filtered out but if peaks are of high amplitudes, the instrument shows overload though the level on the meter doesn't go to extreme positions. This happens because sound intensity peaks are of short duration and in these short time intervals, the needle does not respond. When the overload light flickers, the reading observed is too low. Accuracy of sound intensity level measurement depends on the position of the microphone as well as the frequency range in which sound is to be measured. In general, we can take for granted that the accuracy is $\pm$ 1 db.

Frequency range Hz	Tolerances 30^{o} Incidence db		Tolerances 90^{o} Incidence db	
31.5 - 1000	+.5	-.5	+1	-1
1000 - 2000	+.5	-.5	+1	-2
2000 - 4000	+.5	-1	+1	-3
4000 - 8000	+.5	-1.5	+1	-6
8000 - 12500	+.5	-2	+1	-10

When sound is of short duration as 1 to 100 milli-seconds, then the impulsive scale is used. Hence response time is 35 millisecond. Impulsive reading is alway higher than slow response reading. If sound generated has a very large db variation for a very short period, the impulsive response system is overloaded and the overload is indicated by flickering of overload input or output lights. The accuracy of the measurement of sound intensity level is $\pm$ 1 db.

Intensity of sound is to be measured at a particular frequency, but sound input is a combination of number of frequencies. For this, the filter characteristic of sound intensity level meter is used. The instrument has the following frequency bands: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, 16000 and 31500 Hz. Each particular setting does not filter the given frequency. It has a tendency to filter certain frequencies on either side of the set frequency.

The cut-off frequencies f_1 and f_2 (3 db attenuation) of the filters are equal distances away from the center frequency f_0 on a logarithmic scale as shown in Figure 11 on page 22 . Thus $f_1 = \frac{f_0}{\sqrt{2}}$, $f_2 = f_0\sqrt{2}$ and $f_2 = 2f_1$. That is an octave filter with a center frequency of 1000 Hz has cut-off frequencies of 707 and 1414 Hz. The shape of attenuation curve is shown in Figure 11 on page 22.

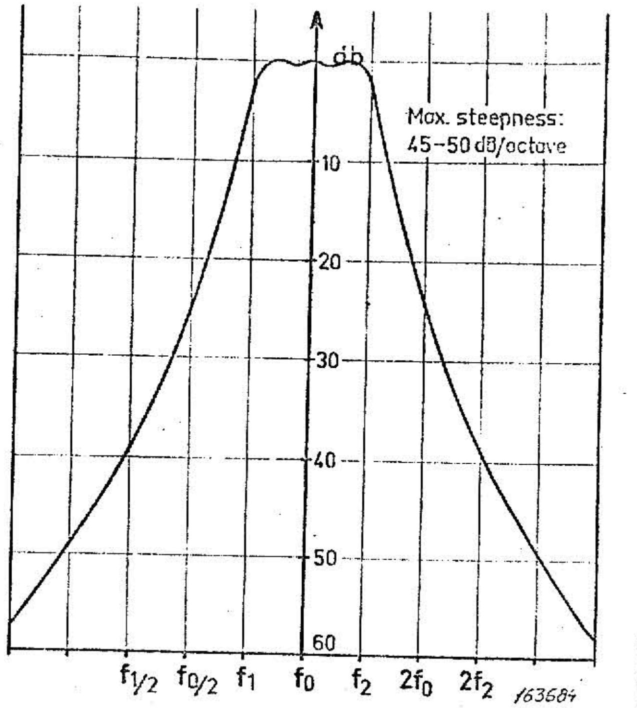


FIGURE 11 Filter Characteristic of One of the Octave Filters

When the combined effect of sound with the combination of number of frequencies with different intensity level is to be studied, the scale A of the precision sound level meter is used. When scale A is used, the instrument behaves as a human ear. Suppose we have a sound with 100 db generated at 1000 Hz. We can then say with the help of equal loudness contours, we will have the same loudness effect at 100 Hz with 104 db sound intensity. The design of scale A is based on equal loudness contours.

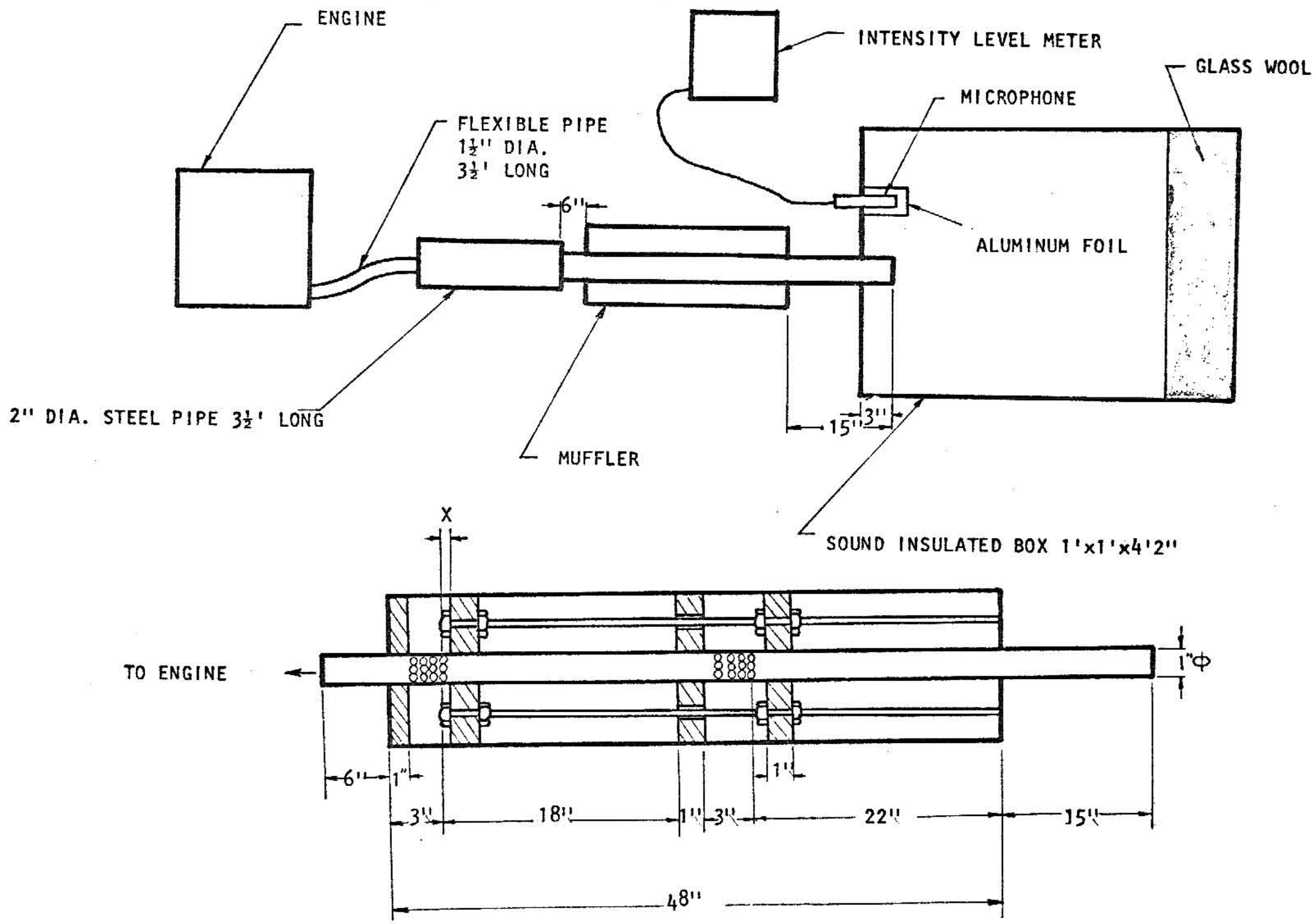
The human ear is a remarkably sensitive instrument for the detection of sound waves. Its response to a certain sound pressure level depends however, upon the frequency of the sound. The sensitivity is greatest at 1000-6000 Hz and falls off both for higher and lower frequencies.

Phase I of Experiment

A muffler was fabricated as shown in the Figure 12 on page 24 . In the first stage, wooden pistons were used. The muffler was hooked to the engine exhaust by use of piping as shown in Figure 12 on page 24. Once the muffler was fitted, the engine was started and the microphone was held near the exhaust. It gave erratic readings because of high surrounding noise made by the engine. Since we are interested in measuring exhaust noise only, the other noise from the engine is considered as surrounding noise. So a tin box was taken which had only four sides and two sides facing each other, which are open. One end of the box was open to the atmosphere and the other end closed by a wooden plate with two holes, one for exhaust pipe and the other for the microphone. Glass wool was used as insulation so that the microphone would pick up only exhaust noise. After this set-up, it was observed that the surrounding noise was low when compared to the exhaust noise. But then the instrument used showd continuous overload. The reason being the condensation , of moisture content in the exhaust, on the microphone. Thereby the microphone lost its sensitivity. A tin box was mounted on the hole of the microphone and the side toward the exhaust was opened and wrapped with aluminum foil, thereby eliminating the condensation of moisture. The engine was started and made to run at 1000, 2000 and 3600 rpm's and an attempt was made to eliminate 500, 1000 and 2000 Hz respectively. The piston position was changed and readings were taken. The readings were taken on every 1" piston position change. A precision sound level meter was used with the appropriate filter and slow response characteristics.

The graphs are plotted with the position of the piston in inches and the intensity of sound in db as the ordinate are shown in Figures 19 and 20 on page 50 and 51.

Experimental Set Up for the Phase I Experiment



SECTIONAL VIEW OF MUFFLER

FIGURE 12

An Intensity level meter was used with external filter and slow response.

The pistons were made of wood.

The engine is running with a partially open throttle, and the readings were taken at 500, 1000 and 2000 Hz at 1000, 2000 and 3650 rpm's respectively.

Position of Piston X"	INTENSITY OF SOUND IN DECIBELS - db				
	WITH LOAD		NO LOAD		
	500 Hz 1000 rpm	1000 Hz 2000 rpm	500 Hz 1000 rpm	1000 Hz 2000 rpm	2000 Hz 3650 rpm
0	87	101	83	83	93
1	86	100	83	82.5	92
2	86	99.5	82.5	82	91
3	85	99	82.5	80.5	90
4	85	99	82.5	81	
5	84	98	81	81.5	
6	82.5	98	80	82	no
7	84	99	82	82	variation
8	83	99	82.5	80	
9	83	98.5	82.5	79	
10	83	97.5	82	80	
11	83	97.5	83	80	
12	85	97.5	83	79	
13	87	97.5	83	80	
14	87	96	84		
15	84.5	95.8			
16	84				
Outside noise	81	92	95	86	

Table 3

Experimental Data of Phase I Experiment

It was observed that as the enigne is loaded, the intensity of the sound level generated by the exhaust system increases and the intensity of sound generated by the engine decreases when compared with no load conditions. This particular engine vibrates more at the no load condition than when the engine is running with a load.

For a system to be tuned at 500 Hz, theoretically, the piston position should be at X = 8.42". But in the experiment it was noticed that the intensity of sound is low at the 4" piston position and the sound level increases up to 13" piston position and then drops down. The above statements are about the engine when it runs at 1000 rpm's without any load. From this set of readings, we conclude that the pressure wave doesn't travel as it should for this particular configuration since the number of reflections is considerable and the tuning effect is not found.

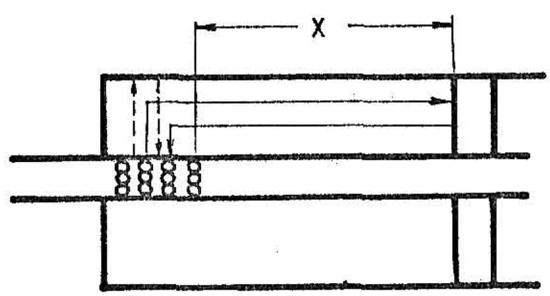


Figure 13

Sectional Part of a Muffler

In the above Figure 13, the desired path of the pressure wave is shown by dark arrows and through dotted line. The actual behavior of the pressure wave is shown, which shows that we have unwanted reflected waves.

When the engine is running at 1000 rpm with a load, we can not predict any particular behavior of the system because we have a large number of reflections. Figure 19 on page 50 supports this statement.

From this stage of the experiment it has been concluded that because of irregular reflections, this configuration is not the best one. An attempt has been made to design a configuration such that the amount of reflections will be considerably less.

Phase II of the Experiment

This new configuration was designed for minimum reflections as shown in Figure 14 on page 29. Here the main tube is the tube in which the exhaust was connected. The side tube is called the resonator. The resonator is a 1" steel pipe and the piston is made of wood which slides inside the tube. For the initial experiment, leakage across the piston was neglected. The instrument and experiment set up are shown in Figure 14 on page 29. For elimination of the external noise, the same method was used as in the first phase of the experiment.

The engine was started and made to run at 1000, 2000 and 3600 rpm with load and without load. An attempt was made to tune the muffler at 500, 1000 and 2000 Hz.

X is the distance of the piston from the main tube once the engine is made to run at the desired condition. Both the pistons are moved simultaneously and the readings are noted. The slow response and the frequency filter characteristics of the instrument was used. Readings are taken at a difference of one half inch in the piston positions.

To understand the configuration, one resonator is made to work. That is the piston in one resonator is moved and the piston in the other resonator is brought near the main tube. The other piston is moved and the first piston is brought near the main tube.

The above experiment will show whether the configuration is good or bad, and will also show whether it is better to have one resonator or two resonators. It will also show if spacing between the resonator tube is important.

We don't have any idea of the diameters of the main tube and the resonating tube. Two more configurations are tried. In one configuration, the diameter of the resonating tube is one half inch and in another it is two inches. From these two similar experiments, we can find out which configuration is not the suitable one.

When all of the readings are taken, graphs are plotted as the position of the piston in inches against the intensity of sound in db. Then conclusions are drawn.

Conclusions From Phase II of the Experiment

Conclusions are drawn from Figures 21, 22, 23, 24 and 25 on pages 52, 53, 54, 55, and 56 respectively. The engine was made to run at 1000 rpm with a load and 500 Hz frequency filters were used. Both resonators were working simultaneously. According to theoretical calculations, for the muffler to be tuned at 500 Hz, the piston position should be at X = 8.42". Experimentally, it is observed that minimum noise intensity level is obtained at the piston position X = 7". This can be explained by the fact that the variation in experimental and theoretical setting is due to the lower and upper bounds of the filter setting. When we want to pass a frequency wave of 500 Hz, it passes a frequency band from 353.7 to 706 Hz. This shows that the experimental tuned position can lie between X = 5.9 and 11.89". Our value of 7" is in the range. As we have minimum noise at the 7" piston position, we can say that the muffler is tuned at the 7" piston position. We can conclude that the tuned frequency has a maximum intensity of sound in the range of 353.7 to 700 Hz.

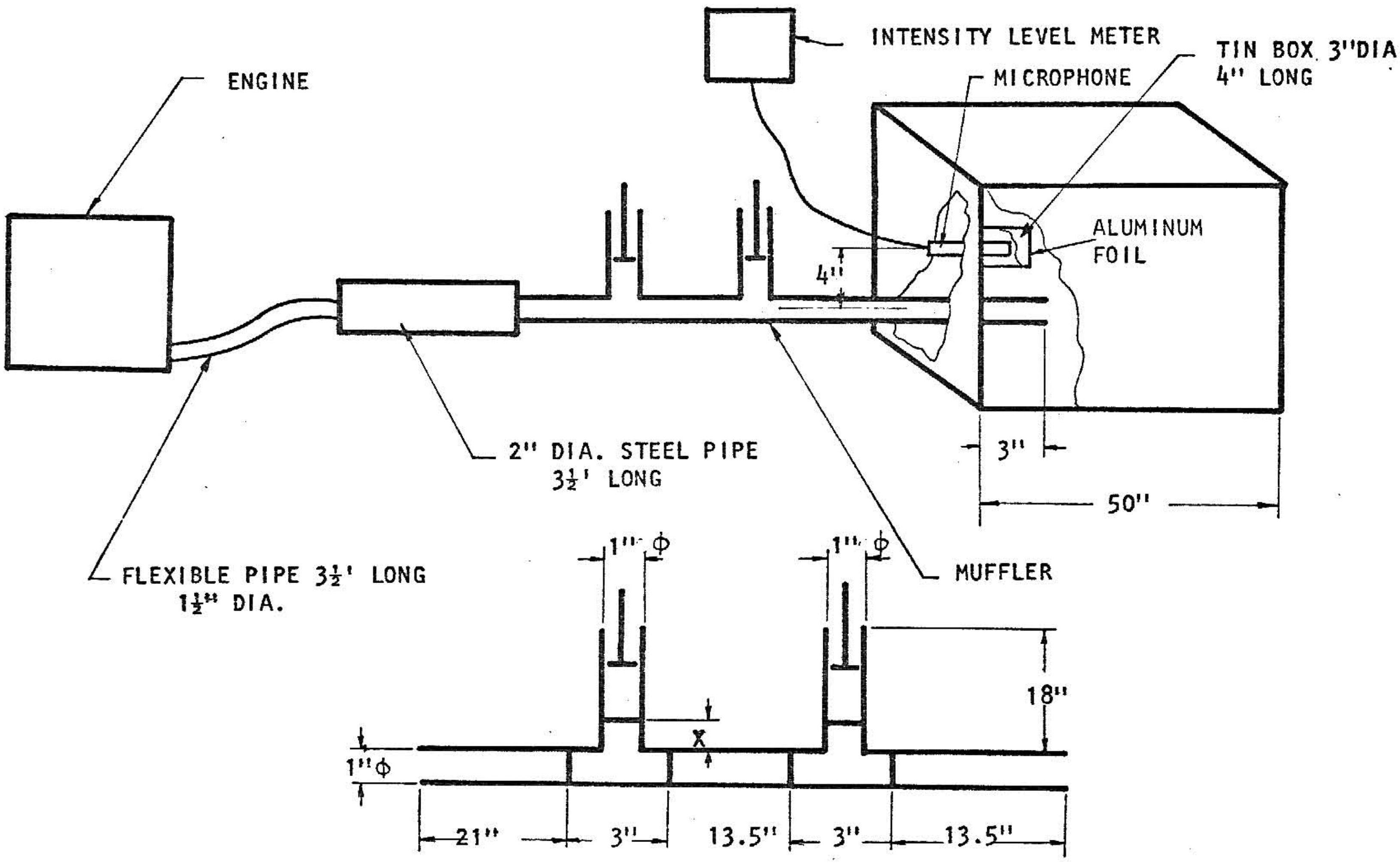


FIGURE 14

Experimental Set Up for the Phase II Experiment

Experimental Data For Phase II

X'' = distance from main pipe (Indicates piston position)

Intensity level meter was used with external filter and slow response.

Pistons are made of wood.

Engine running at partially open throttle.

INTENSITY OF SOUND IN DECIBELS - db

Position of Piston	1000 rpm 500 Hz				2000 rpm 1000 Hz				3600 rpm 2000 Hz		
	No load	With load			No load	With load			No load		
X''	Both tuned	Both tuned	First tuned	Second tuned	Both tuned	Both tuned	First tuned	Second tuned	Both tuned	First tuned	Second tuned
0.0	100.0	102.0	102.0	102.0	93.0	105.0	105.0	105.0	107.0	107.0	107.0
0.5	99.0	101.0	101.5	102.0	93.0	103.0	104.0	105.0	105.0	107.0	105.0
1.0	99.0	100.5	101.0	101.0	92.8	102.5	103.0	103.0	103.0	107.0	104.0
1.5	98.5	100.0	101.0	101.0	92.0	100.5	102.0	102.2	102.0	105.0	103.0
2.0	98.0	100.0	101.0	101.0	92.5	98.5	102.0	102.0	98.5	104.0	102.0
2.5	97.5	99.5	101.0	101.0	92.0	97.0	102.5	101.8	98.0	101.0	101.0
3.0	97.0	99.0	100.0	100.0	91.0	97.5	101.0	101.5	99.0	101.0	104.0
3.5	96.5	98.5	100.0	99.0	91.0	98.0	101.0	102.0	102.0	102.0	105.0
4.0	96.5	98.0	99.0	99.0	90.0	98.0	101.0	102.5	102.0	103.0	105.0
4.5	96.5	98.0	99.0	99.0	90.0	98.5	101.5	102.5	103.0	104.0	106.0
5.0	95.0	96.0	99.0	99.0	90.0	99.0	101.0	103.0	103.0	104.0	105.0
5.5	94.0	95.0	97.0	98.0	89.5	99.5	102.0	102.0	103.0	103.0	104.0
6.0	93.0	94.0	97.0	98.0	90.0	100.0	102.0	102.0	102.0	102.0	103.0
6.5	94.0	93.0	97.0	96.0	90.0	100.0	102.0	101.5	101.0	102.0	103.0
7.0	94.5	93.0	96.0	96.0	90.0	100.5	102.2	101.5	100.0	101.0	104.0
7.5	95.0	96.0	99.0	98.0	90.0	99.0	101.5	101.5	102.0	102.0	105.0
8.0	95.5	99.0	100.0	101.0	89.5	97.5	101.5	101.0	102.0	102.0	106.0

Experimental Data For Phase II

INTENSITY OF SOUND IN DECIBELS - db

Position of Piston	1000 rpm 500 Hz				2000 rpm 1000 Hz				3600 rpm 2000 Hz		
	No load	With load			No load	With load			No load		
X"	Both tuned	Both tuned	First tuned	Second tuned	Both tuned	Both tuned	First tuned	Second tuned	Both tuned	First tuned	Second tuned
8.5	96.0	100.0	101.0	101.0	89.5	97.0	101.0	101.0	102.0	102.0	106.0
9.0	97.0	100.0	101.0	101.0	89.5	95.0	101.0	100.0	102.0	103.0	107.0
9.5	98.0	101.0	102.0	102.0	89.0	96.0	101.0	101.0	102.0	103.0	107.0
10.0	98.0	101.0	102.0	102.0	89.0	96.5	100.2	101.0	102.0	102.0	107.0
Intensity Level Outside The box	69.0	72.0	72.0	72.0	77.5	81.0	81.0	81.0	85.0	85.0	85.0

Table 4

When the resonator near the exhaust inlet is made to work and the other has its piston near the main tube, we find that the minimum sound level (tuned effect) is at X = 7" piston position. But reduction in noise is not as great as when both the resonators are tuned simultaneously.

The tuning effects obtained from either tuning the first resonator or second resonator are not much different. The variation which is seen on the graph is negligible since the accuracy of the sound level meter is 1 db.

In this experiment, wooden pistons are used and we don't have a perfectly air tight sliding fits. The amplitude of the reflected wave won't be as big as it should be. If we have an air tight piston sliding fit, then the reduction of noise will be greater when compared to that obtained using wooden pistons.

In this experiment it was also observed that when the engine is running with a load, the intensity of sound produced is more and the background noise (noise with the exception of exhaust) is less.

It was observed that when an engine is running at 1000 rpm with a load, and when the sound was measured at 500 Hz, the reduction in the noise level was 9 db. Whereas when the engine is running at the same condition without the load, reduction in sound intensity was observed to be 7 db, with both resonators working simultaneously. When either resonator worked it was found that the reduction in sound intensity was 6 db when the engine was loaded. So it can be stated that if we have more resonators, we will have a greater reduction in the sound intensity level.

An engine was running at 2000 rpm and a filtered frequency of 1000 Hz. When both resonators worked, we noticed that minimum noise was found in the range of 3 to 4". The theoretical tuning length for 1000 Hz is 4.21", since the filter passes frequencies from 707 to 1414 Hz. The range of X becomes 2.9" to 5.9" and our reading lies in this range. Thus, experimental and theoretical values match. It was noticed that when the engine was loaded, the intensity of the sound increased and the external disturbance was reduced when the piston position was at 2X distance. The system is untuned and will again be tuned at 3X distance. It has been confirmed from the graphs that the peaks and troughs of the curves are at the same X distance for any condition whether one resonator is working or both resonators are working simultaneously. It has been seen that the operational characteristics for any one resonator working alike.

It has also been noticed that the reduction in noise is 8 db when the engine is loaded and both resonators are working and is 3.5 db when the engine is without a load. When the engine is loaded, the operation of the resonator reduces the noise level by 4 db.

When the engine is running at 3600 rpm without a load, with the filtered frequency set at 2000 Hz, the following results are obtained. With both resonators used for tuning purposes, the reduction in noise levels was found to be 9 db. For the operation of either of the resonators, reduction was 6 db. The intensity level curves for either resonator are similar. The theoretical tuned position of 2000 Hz frequency is X = 2.1. Our experimental values are close to that.

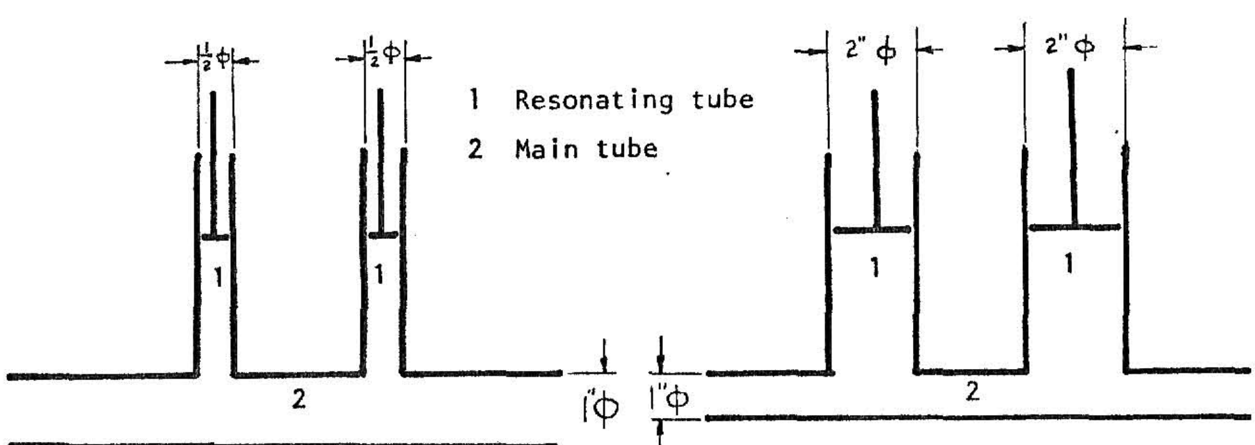


Figure 15

Configuration of a Muffler

It was found that when the engine is fitted with a 2" diameter and a 1/2" diameter, the resonator tubes with wooden pistons, as shown in Figure 15 on page 33, the reduction in the sound level intensity level was low compared to the 1" diameter resonator tube. This was observed for engine rpm's of 1000, 2000 and 3600 with, and without a load at 500, 1000 and 2000 Hz, respectively. The conclusion reached is that one inch diameter main tubes and one inch resonating tubes form a good combination.

Phase III of the Experiment

In phase II of the experiment, we achieved a considerable reduction of sound with the wooden pistons. In this phase, the pistons were made of steel, and an "o" ring used to achieve an air tight seal. In the last phase, a steel pipe was used as the resonator tube. The internal diameter of the steel pipe was not very uniform over a 16" length. Consequently a 1" diameter copper tube is used as a resonator tube. The experiment set up is the same as in phase II of the experiment.

The engine was started, and run at 1000, 2000 and 3600 rpm with a load, and without a load. The piston positions were changed to tune the muffler at 500, 1000 and 2000 Hz. X is the distance of a piston from the main tube. Once the engine is made to run at the desired condition, both pistons are moved simultaneously and the readings are noted. The slow response and the frequency filter characteristics of the instrument are used. Readings are taken at a difference of one half inch in the piston positions.

To confirm the statements made in phase II, one resonator was made to work and the piston in the other was kept near the main tube. This means that the muffler characteristics will be as if it had only one resonator. The same procedure was repeated for the second resonator.

After all of the readings were taken, graphs were plotted. These show the intensity of sound in db as a function of the position of the piston in inches.

Conclusions of Phase III of the Experiment

Conclusions are drawn from Figures 26, 27, 28 and 29 on pages 57, 58, 59 and 60, respectively. The engine is running at 1000 rpm and the sound intensity level is measured at 500 Hz. The engine is loaded and a partially open throttle is used for the experiment.

Here it was observed that the reduction in noise is maximum at the piston position, X = 8" to 9". The frequency corresponding to X = 8" to 9" is withing the theoretical filter band range.

It was found that the minimum intensity of the sound level is at the same piston position X for both resonators working, and for either one working separately. A 13 db sound reduction was achieved at 500 Hz when the engine was loaded. In the last phase of the experimental condition, the reduction in the sound level was 9 db. This difference of 4 db was because of the air tight sliding pistons. When either of the resonators was tuned, the reduction was observed to be 10 db. If we increase the number of resonators, a greater reduction in the sound intensity level is obtained. This statement supports the last statement in the phase ii experiment.

When the engine is loaded, the intensity of the sound is increased and the outside disturbance is decreased in comparison to the no load condition.

The engine had been run at 1000 rpm without a load with the intensity of the sound level measured at 500 Hz. The following observations were made.

X'' = distance from main pipe (Indicates piston postion)

Intensity level meter is used with external filter and with slow response.

Pistons made of steel and fitted with "0" ring to get air tight sealing.

Engine running at partially open throttle.

Readings taken in different frequency bands at different rpm's.

INTENSITY OF SOUND IN DECIBELS - db

Position of Piston	NO LOAD			WITH LOAD				NO LOAD
	rpm 1000 - 500 Hz			rpm 1000 - 500 Hz			2000 rpm - 1000 Hz	3600 rpm - 2000 Hz
X''	Both resonator tuned	First tuned	Second tuned	Both	First	Second	Both	Both
0	102	102	102	101.5	101.5	101.5	120	113
.5	101.5	101.5	102	101.5	100.5	101.5	120	113
1	101.5	101.5	102	100.5	100.5	101.5	120	112.5
1.5	101.5	101.5	101.5	100.5	100.5	101	119	111
2	101	101.5	101.5	100.5	100.5	101	117	108
2.5	101	101.5	101.5	100.5	100.5	102	117	108
3	101	101.5	101	100.5	100.5	101.5	117	108
3.5	101	101.5	101	100.5	100	101.5	116	109
4	100.5	101	101	100.5	99.5	101.5	115	108
4.5	100.5	101	101	100.5	99	101.5	113	108
5	100.5	101	101	100.5	99	101.5	114	108
5.5	99.5	101	101	100	97	101	116	108
6	99.5	101	101	98.5	97	101	118	
6.5	99.5	100.5	101	95	96	100.5		
7	97.5	100	100.5	93	96	97.5		
7.5	96	99	100	92	94	96		

INTENSITY OF SOUND IN DECIBELS - db

Position of Piston	NO LOAD			WITH LOAD			NO LOAD	
	rpm 1000 - 500 Hz			rpm 1000 - 500 Hz			2000 rpm - 1000 Hz	3600 rpm - 2000 Hz
X"	Both resonator tuned	First tuned	Second tuned	Both	First	Second	Both	Both
8	92.5	97	97	91	92	93		
8.5	92.5	97	95	89	92	93		
9	92	96	95	89	93	93.5		
9.5	92	96.5	96.5	89	94.5	94		
10	94.0	96.5	97.5	91	96	97		
10.5	94.5	98	98	92	97	97		
11	94.5	98	98	95	98	98	NO	CHANGE
11.5	94.5	98	98	96	98.5	98		
12	97.5	98	98.5	97	98.5	99	IN	READING
12.5	97.5	99	98.5	97	99	99		
13	99	99	99	98	99.5	100		
13.5	99	99	99	98	99.5	100		
Intensity Level outside the box		70			65		82	85

Table 5

Experimental Data For the Phase III Experiment

The minimum sound intensity level was found to be at X = 8" to 9" at the piston position. The frequency corresponding to X = 8" to 9" lies between the theoretical frequency band. The characteristic curves of either of the resonators are alike. This corresponds with phase II of the experimental conclusion. We can then state that the distance between the two resonators is not important when both resonators work at no load condition. The reduction in the sound intensity level was 9 db, which is less that 13 db. It can then be stated that a greater reduction in the intensity of sound can be obtained when the engine is loaded as compared to the no load condition. When the first resonator operates, the reductions was 9.5 db and when the second resonator operates, the reduction was 8.5 db.

When the engine was running at 2000 rpm with a load and the sound intensity level measured at 1000 Hz, it was seen that the theoretical and experimental piston postitions for the tuning of the muffler agree with each other. Here, reduction in the sound intensity level was found to be 7 db.

When the engine was running at 3600 rpm without a load the intensity of the sound level was measured at 2000 Hz. It was found that the reduction in the intensity of the sound level was 5 db. The theoretical and experimental piston positions X for the tuned effect match quite well.

Phase IV of the Experiment

It has been noted that when the engine runds at any rpm with any load condition, it creates sound waves having a wide band of frequencies. The frequencies which occur range from 2 Hz to 20000 Hz or even greater. But the intensity of the sound isn't the same at all frequencies. It creates a higher sound intensity level at the frequency equal to the exhaust frequency. But the exhaust frequency generally ranges from 10 to 40 Hz. It has been found that the human ear is more sensitive to higher frequencies than at lower frequencies.

If we make an attempt to tune the muffler at the exhaust frequency, the size of the resonating tube becomes very large. Because of the space limitations, we have to drop the idea of tuning the exhaust frequency. If we tune it and have some loudness, the same loudness could also be obtained by tuning a higher frequency which has a considerable amount of sound intensity. We don't know which higher frequency has to be tuned at what particular rpm or load condition. To find this, the frequency scale A on the sound level meter is used. Scale A behaves as a human ear. An attempt is then made to tune the muffler in order to find the value of X, that is the position of the piston at which sound level is low that condition.

When the experiments of Phase I, II, and III are performed, the engine noise was acting as a surrounding noise. To reduce the surrounding noise, the exhaust pipeline is taken through a 1 1/2 ft. thick stone wall. The engine is on one side of the wall and on the other, the muffler, thereby decreasing the surrounding noise. The set up of the experiment is shown in Figure 14 on page 29.

The piping is set up as shown in Figure 14 on page 29 and the exhaust is taken on the otherside of the wall. The engine is then made to run at 1000, 2000, 3000 and 4000 rpm with a load. Readings are taken on an impulsive response of the sound level meter because the meter is overloaded at the slow response.

Then both the pistons are moved and the readings of the sound intensity are noted on Scale A. Either of the resonators is made to work and the readings are noted. The graphs are then plotted; positions of the piston in inches versus the intensity of sound in decibels as shown in Figures 30, 31, 32, and 33 on pages 61, 62, 63 and 64, respectively. Inferences are drawn from these figures.

Experimental Data for Phase IV

X'' = distance from main pipe (Indicates piston position)

Intensity level meter responds like a human ear. Scale "A" is used.

Pistons made of steel and fitted with "O" ring to get air tight sealing.

Impulsive instrument response is selected.

Engine running at partially open throttle except at 4000 rpm.At 4000 rpm it runs full open throttle.

Engine is loaded at all the four conditions.

INTENSITY OF SOUND IN DECIBELS - db

Position of Piston	1000 rpm		2000 rpm		3000 rpm		4000 rpm	
X''	Both tuned	First tuned	Both tuned	First tuned	Both tuned	First tuned	Both tuned	First tuned
0.0	84.00	84.00	127.25	127.25	129.25	129.25	129.25	129.25
0.5	83.50	84.00	125.25	127.25	129.75	129.75	129.00	129.00
1.0	83.50	83.50	124.50	127.25	129.00	129.50	128.50	129.00
1.5	83.00	83.25	120.00	126.00	125.00	129.50	123.00	127.00
2.0	82.50	83.00	118.00	125.00	124.50	127.00	123.00	126.50
2.5	82.50	82.50	118.00	124.50	124.50	127.00	123.00	126.50
3.0	82.00	82.75	117.75	124.50	124.50	127.00	123.00	126.25
3.5	82.00	82.00	117.75	124.50	124.50	127.00	123.00	126.00
4.0	81.75	81.75	118.00	124.75	124.50	126.85	123.00	125.75
4.5	83.00	83.25	118.00	125.00	124.25	126.75	123.75	126.00
5.0	83.50	83.50	121.00	124.75	126.00	126.50	124.50	126.25
5.5	82.50	83.00	123.00	124.75	126.00	126.75	125.00	126.00
6.0	82.00	82.00	123.50	124.75	126.00	126.75	125.00	126.00
6.5	81.50	82.50	120.50	124.50	124.50	126.75	124.00	126.00

Position of Piston X''	1000 rpm		2000 rpm		3000 rpm		4000 rpm	
	Both tuned	First tuned	Both tuned	First tuned	Both tuned	First tuned	Both tuned	First tuned
7.0	81.50	82.00	120.50	124.50	124.50	126.75	124.00	126.25
7.5	80.50	81.75	119.00	124.50	124.25	126.50	123.50	126.25
8.0	80.25	81.75	121.00	124.50	124.25	126.50	123.50	126.00
8.5	80.00	81.00	121.00	124.50	124.25	127.00	123.50	126.00
9.0	80.00	81.00	121.25	124.00	124.25	127.25	123.25	126.00
9.5	79.00	81.00	121.00	124.00	124.25	127.75	123.50	126.00
10.0	79.00	81.00	121.00	124.00	124.00	127.00	123.50	126.00
10.5	79.00	81.00	121.00	124.00	124.00	127.00	123.50	126.00
11.0	79.00	81.00	121.00	124.00	124.00	127.00	123.50	126.00
11.5	79.00	81.00	121.00	124.00	124.00	127.00	123.50	126.00
12.0	79.00	81.00	121.00	124.00	124.00	127.00	123.00	126.00
12.5	79.00	81.00	121.00	124.00	124.00	127.00	124.00	127.00
13.5	79.00	81.00	121.00	124.00	124.00	127.00	124.00	127.00
13.5	79.00	81.00	121.00	124.00	124.00	127.00	124.00	127.00

Table 6

Experimental Data For the Phase IV Experiment

Conclusions of the Phase IV Experiment

The graphs are plotted for both of the working resonators and one working resonator at different rpm of 1000, 2000, 3000 and 4000 as shown in Figures 30, 31, 32, and 33 on pages 61, 62, 63 and 64, respectively.

It is concluded that if we increase the number of resonators we can have more reduction in the sound intensity level. It has alos been found that at all of the rpm's and the load conditions that have 4" long resonator tubes to 1" diameter to the exhaust pipe, reduction of noise is considerable without varying the piston positions. Four inch long resonators means we are trying to eliminate the sound at 1000 Hz.

It has also been observed that at the 4" piston position, 2 1/2 db reduction is obtained at the rpm of 1000. At 2000 rpm with the engine loaded, a 9 db reduction in noise is obtained. At the engine speed of 3000 rpm with a load, a 5.5 db reduction is observed and at 4000 rpm with a load, a 7 db reduction is obtained.

It is noted that at 1000 rpm we had a 5 db reduction if the extension is 9". When all of the data of the Phase IV experiment are considered, the 4" position of the piston is more beneficial.

When the first resonator is working at 1000 rpm, we have a reduction in the sound level by 2 db. At 2000 rpm, the reduction is 2.5 db. At 3000 rpm, the reduction in the sound level is 3 db and at 4000 rpm, the reduction is 4 db. When all of the readings are considered, the conclusion is to increase the number of resonators. So in Phase V, a muffler with three resonators is constructed.

Experimental Set Up for the Phase IV Experiment

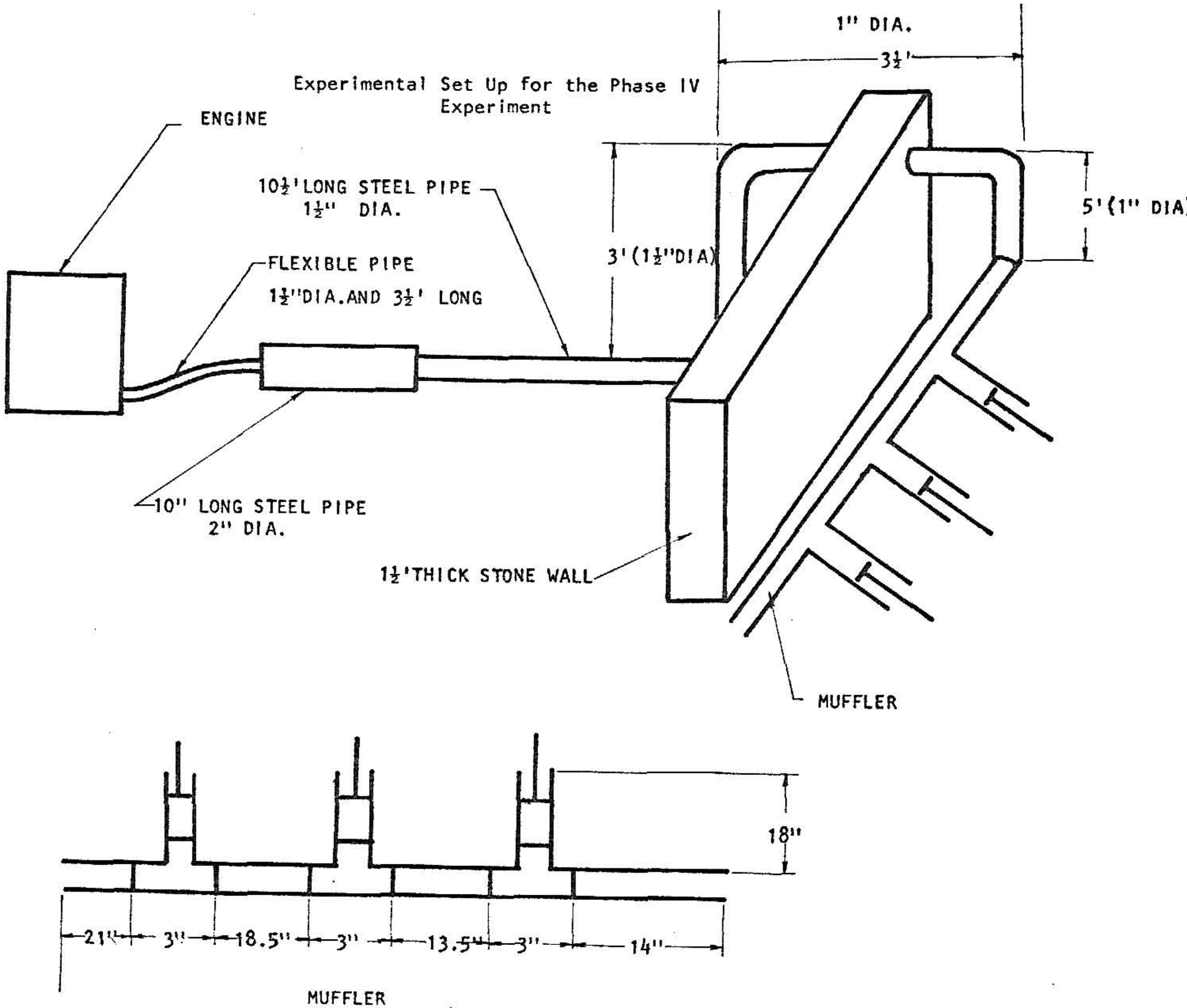


FIGURE 16

Phase V of the Experiment

It has been noted from the Phase IV experiment conclusion that a muffler with three resonators gives more reduction in sound than with two resonators. A muffler with three resonators has been set up as in Phase IV. The engine is made to run at 1000, 2000, 3000 and 4000 rpm with a load. Scale A and the impulsive response properties of the sound level meter are used. All of the three resonators are made to work simultaneously and readings are taken as in the previous phases of the experiment.

Then the piston position in inches versus the intensity of the sound are plotted in Figures 34, 35, 36 and 37 on pages 65, 66, 67 and 68. And the conclusions are drawn. With the engine running at 1000, 2000, 3000 and 4000 rpm with a load, the maximum reduction obtained is 7 db, 9.5 db, 10.2 db, and 10.5 db, respectively. These reductions are obtained when all three resonators are moved simultaneously. These reductions are comparitively high when compared to the Phase IV experiment reductions.

All of the maximum reduction in the intensity of sound are obtained at the X = 4'' piston position. So if we have a 4'' long extension on a one inch diameter exhaust pipe, we will be able to reduce quite a large amount of the impulsive load. This will be comforting to the human ear.

When all phases of the experiments are studied, the following empirical statements can be made.

For all engine speeds and all load conditions, the intensity of the sound level of a 1'' diameter exhaust muffler can be considerably reduced by having the number of 4'' long tubes used as resonators on the muffler.

That means if we eliminate the frequencies near 1000 Hz (707 to 1414 Hz) we can have quite a low intensity of sound, this will be comfortable to the human ear.

Experimental Data for Phase V

X" = distance from main pipe (indicates piston position)

Intensity level meter responds like a human ear. Scale "A" is used.

Pistons made of steel and fitted with "O" ring to get air tight sealing.

Impulsive instrument response is selected.

Engine running at partially open throttle except at 4000 rpm.

Engine is loaded.

Position of Piston X"	INTENSITY OF SOUND IN DECIBELS - db			
	1000 rpm	2000 rpm	3000 rpm	4000 rpm
0	92	126.5	127	126.25
.5	92	126.4	125.5	124
1	92	125	124	123.75
1.5	91.5	123.4	117	116.5
2	89	117.5	119	118
2.5	88	117.5	119	122
3	86	119.5	117	117
3.5	85	115.5	117	116
4	85	116	116.75	116
4.5	85	117.5	117	116.25
5	85	117	116.75	116.25
5.5	86	117.5	116.75	118
6	86	117.5	118.5	116
6.5	88	118.5	117	116
7	88.5	117.5	118	116
7.5	88.5	119.5	117	119
8	88.5	119.5	118	116
8.5	88.5	119.5	117.5	117.75
9	88	120	117.5	116.5
9.5	87.5	121.5	118.5	116.5
10	86.5	121.5	118.25	116.5
10.5	86.5	121.5	118.25	115.5
11	86.5	121.5	118	115
11.5	86.5	121.5	118.5	115
12	86.5	121.5	118.5	115.5
12.5	86.5	121.5	118.5	115.5
13	86.5	121.5	118.5	115.5
13.5	86.5	121.5	118.5	115.5

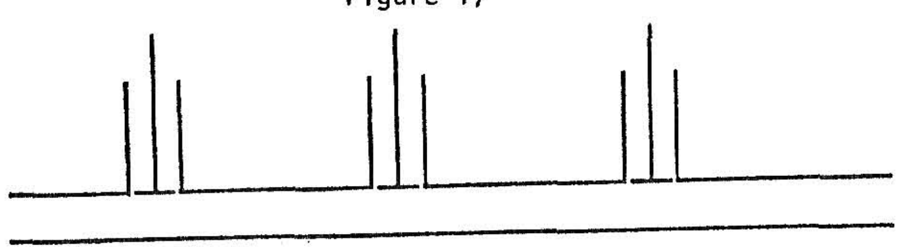
Table 7

Intensity of Sound Generated by the Engine in the Frequency Spectrum (31.5 Hz to 16000 Hz)

Procedure: Start the engine and steadily load it to get the rpm of the engine to be equal to 1000. Measure the intensity of the sound at the exhaust end, keeping all of the pistons near the main tube as shown in Figure 17 on page 47. Using the appropriate frequency filter band, measure the intensity of the sound at the different frequencies. At each frequency band, two readings are taken. One is slow response and the other is the impulse setting. The same procedure is repeated to get the set of readings at 2000, 3000 and 4000 rpm.

The graphs are then plotted; the frequency versus the intensity of sound as the ordinate. From the graphs it is clear that the engine emits a large band of frequencies at all speeds. Graphs are shown in Figures 38, 39, 40 and 41 on pages 69, 70, 71, and 72, respectively.

Figure 17



Set Up of a Muffler for Finding the Frequency Spectrum Emitted by the Engine

The engine is running at a partially open throttle.

Scale A is used so the instrument responds like the human ear.

Pistons are made of steel and are fitted with "0" ring to get air tight sealing.

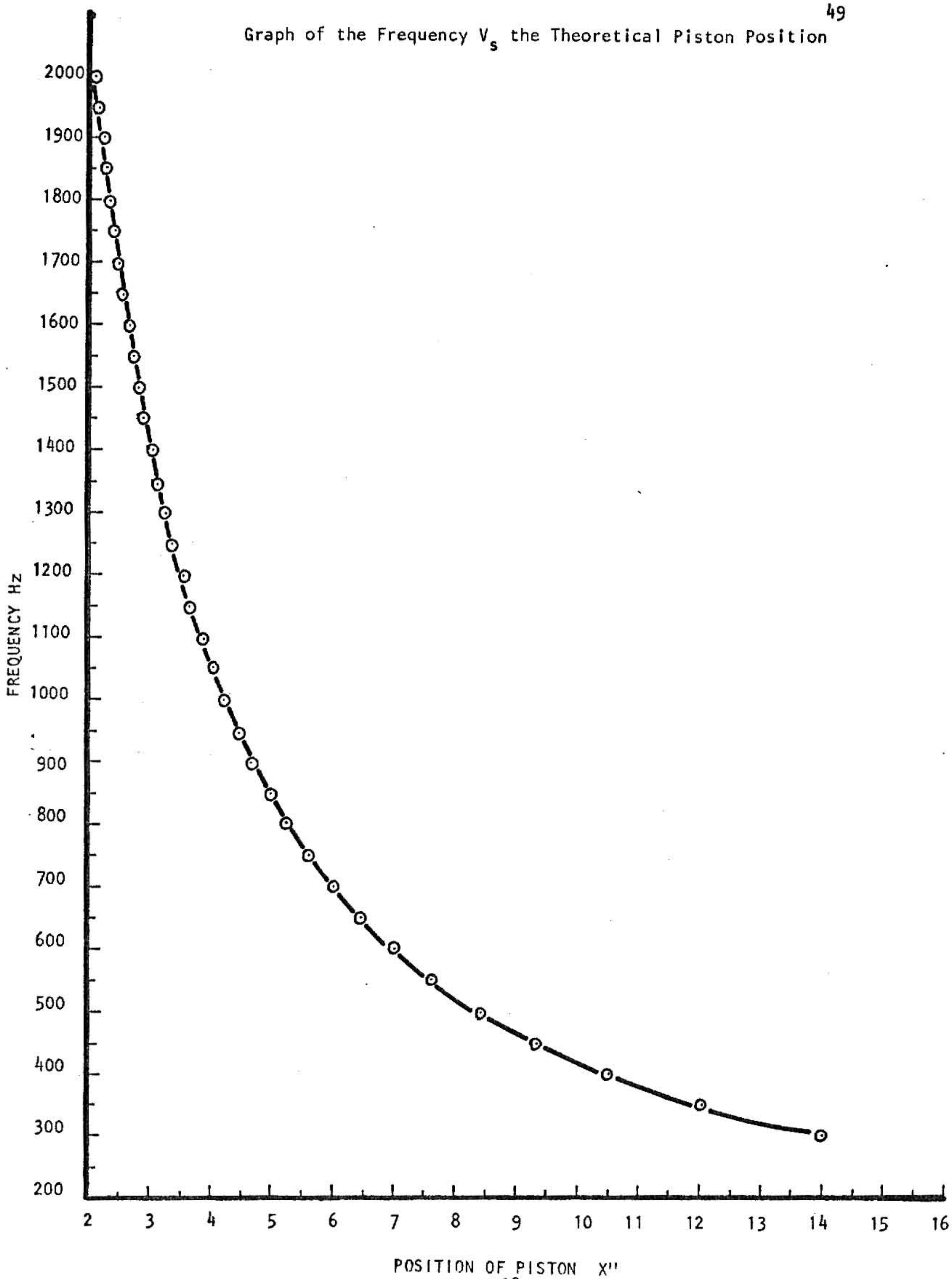
Impulsive responses and slow responses are used.

INTENSITY OF SOUND IN DECIBLES

Freq. Hz	1000 rpm Impulsive Response	1000 rpm Slow Response	2000 rpm Impulsive Response	2000 rpm Slow Response	3000 rpm Impulsive Response	3000 rpm Slow Response	4000 rpm Impulsive Response	4000 rpm Slow Response
31.5	76	71	77	74	91	87	86	85
63	85	75	90	85	85	81	91	88
125	85	77	99.5	88.5	99.5	92.5	100	94
250	84	74	102.5	95	99	90	104	94
500	83	72	107	96.5	105	92.5	109	99.0
1000	83	69	108.5	95.5	108	92	114	99.5
2000	71	59	106.5	94	105	90	113	98
4000	72	54	115.5	94	112	87	115	98
8000	66	47	115	91	114	85	119	90
16000	56	46	110	81	110	80	113	88

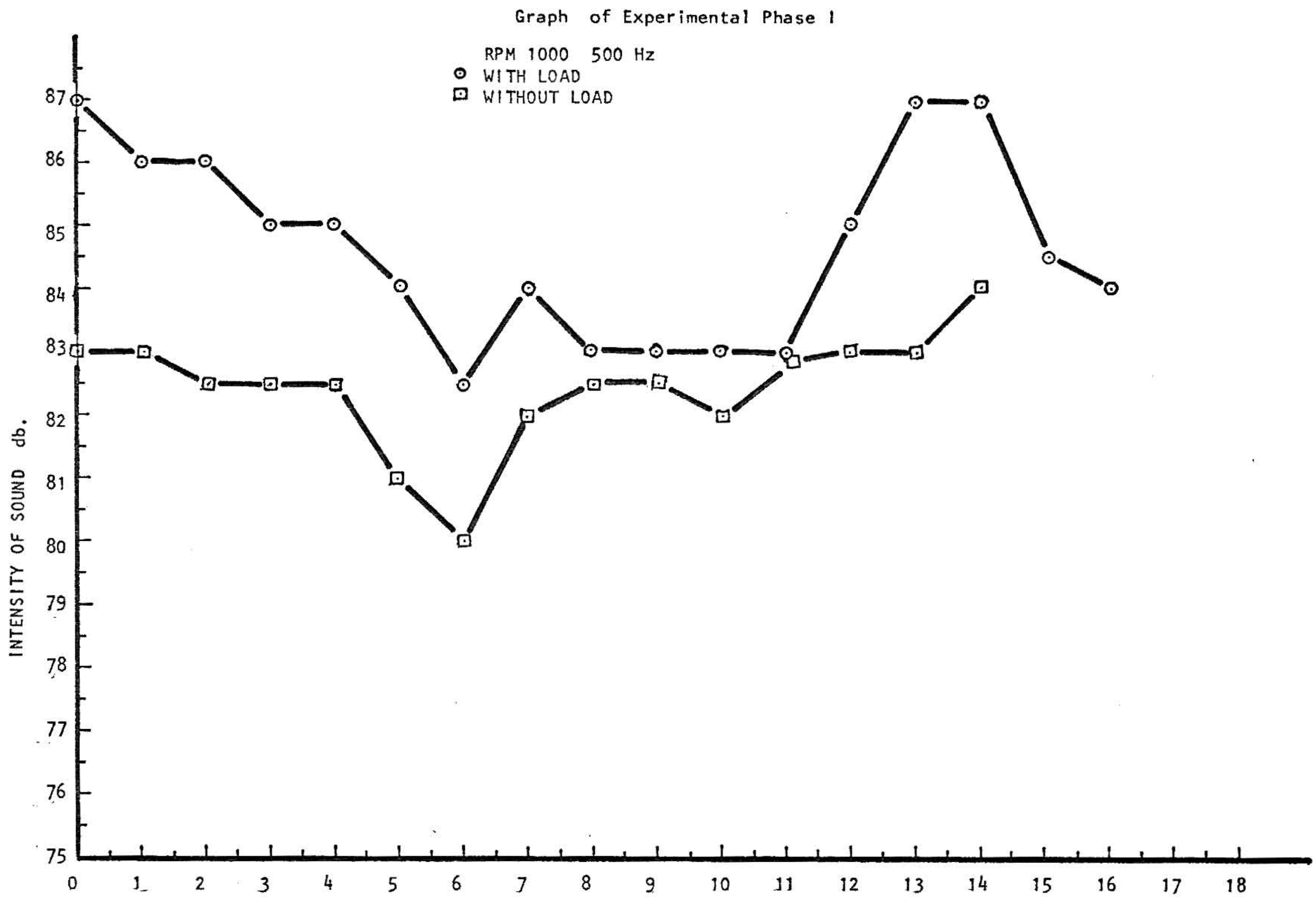
Table 8

Experimental Data for Finding the Frequency Spectrum Emitted by the Engine



Graph of the Frequency V_s the Theoretical Piston Position
FREQUENCY Hz
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
POSITION OF PISTON X"

FIGURE 18



Graph of Experimental Phase I
RPM 1000 500 Hz
WITH LOAD
WITHOUT LOAD
INTENSITY OF SOUND db.
87
86
85
84
83
82
81
80
79
78
77
76
75
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
POSITION OF PISTON X"

FIGURE 19

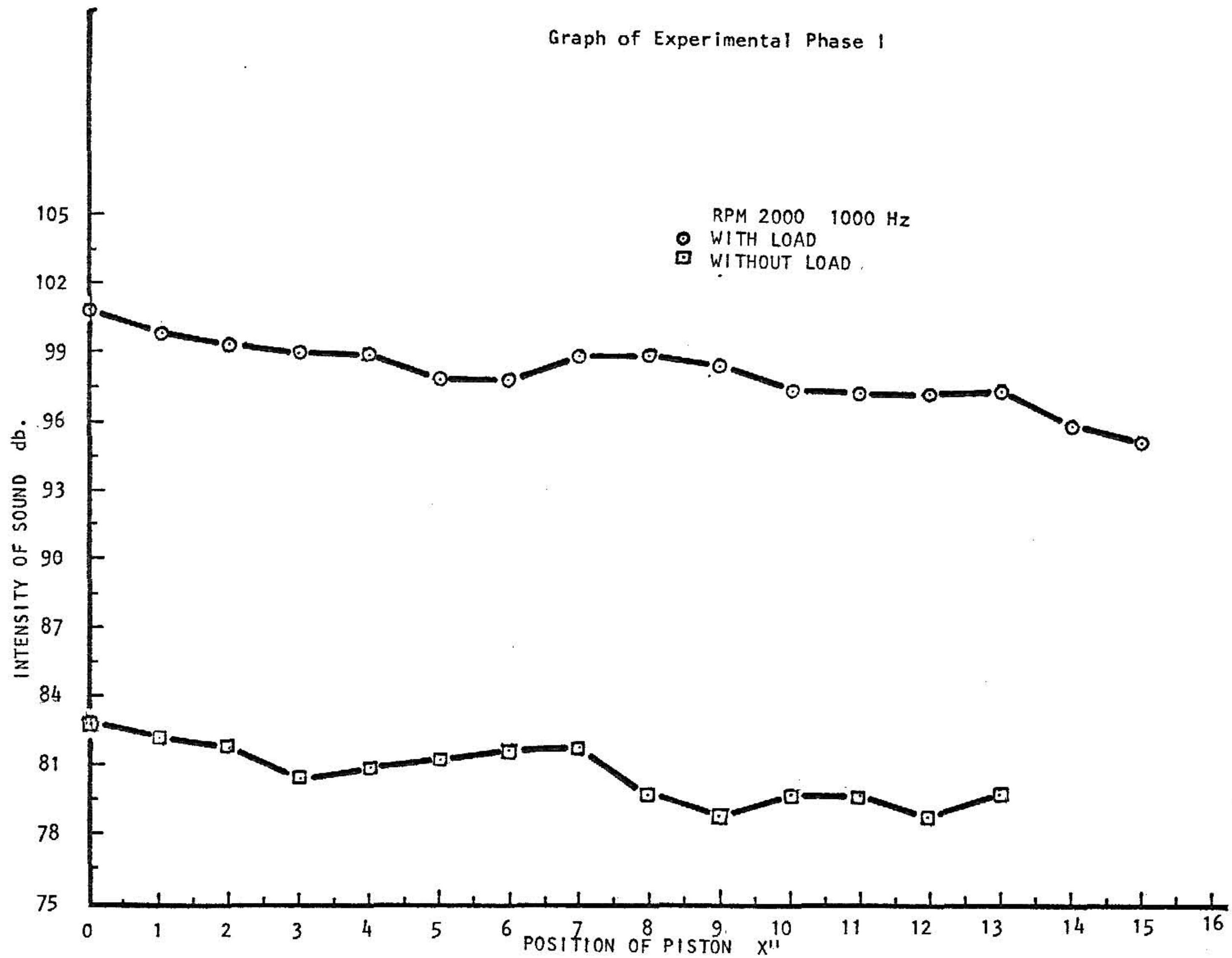

Graph of Experimental Phase I
RPM 2000 1000 Hz
WITH LOAD
WITHOUT LOAD
INTENSITY OF SOUND db.
105
102
99
96
93
90
87
84
81
78
75
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
POSITION OF PISTON X''

FIGURE 20

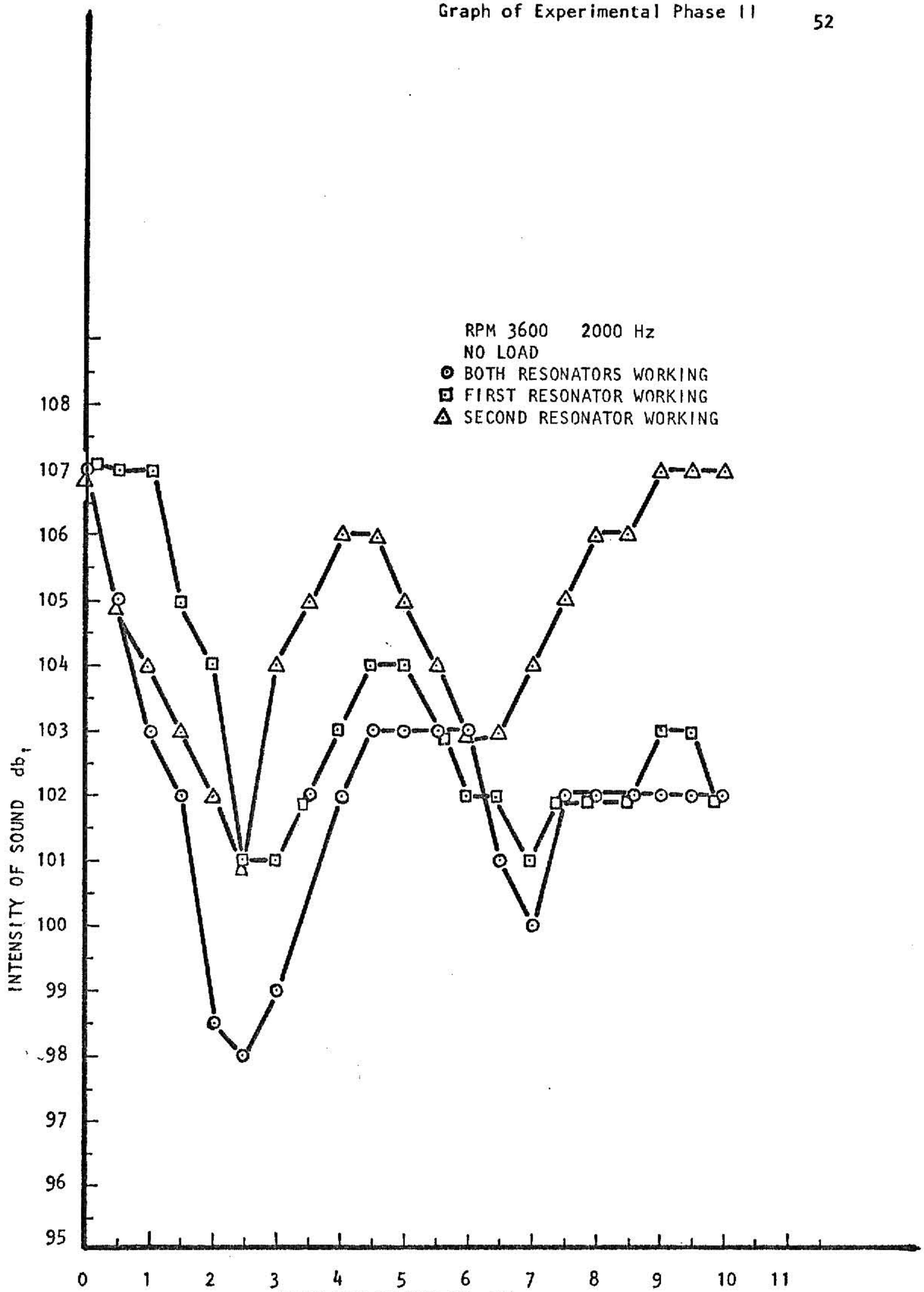

RPM 3600 2000 Hz
NO LOAD
BOTH RESONATORS WORKING
FIRST RESONATOR WORKING
SECOND RESONATOR WORKING
INTENSITY OF SOUND db
95
96
97
98
99
100
101
102
103
104
105
106
107
108
0
1
2
3
4
5
6
7
8
9
10
11
POSITION OF PISTON X''

FIGURE 21

Graph of Experimental Phase II

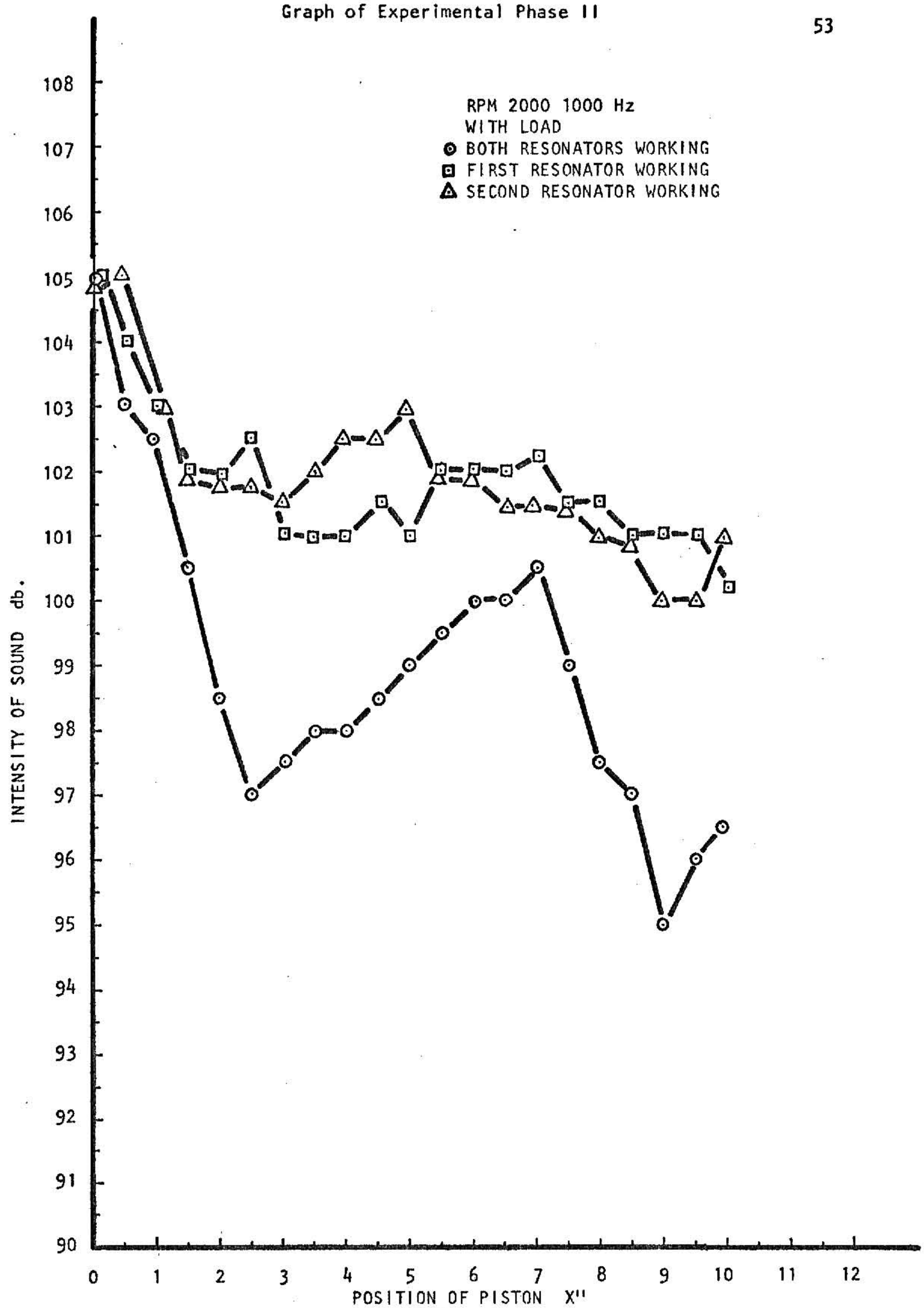


FIGURE 22

Graph of Experimental Phase II

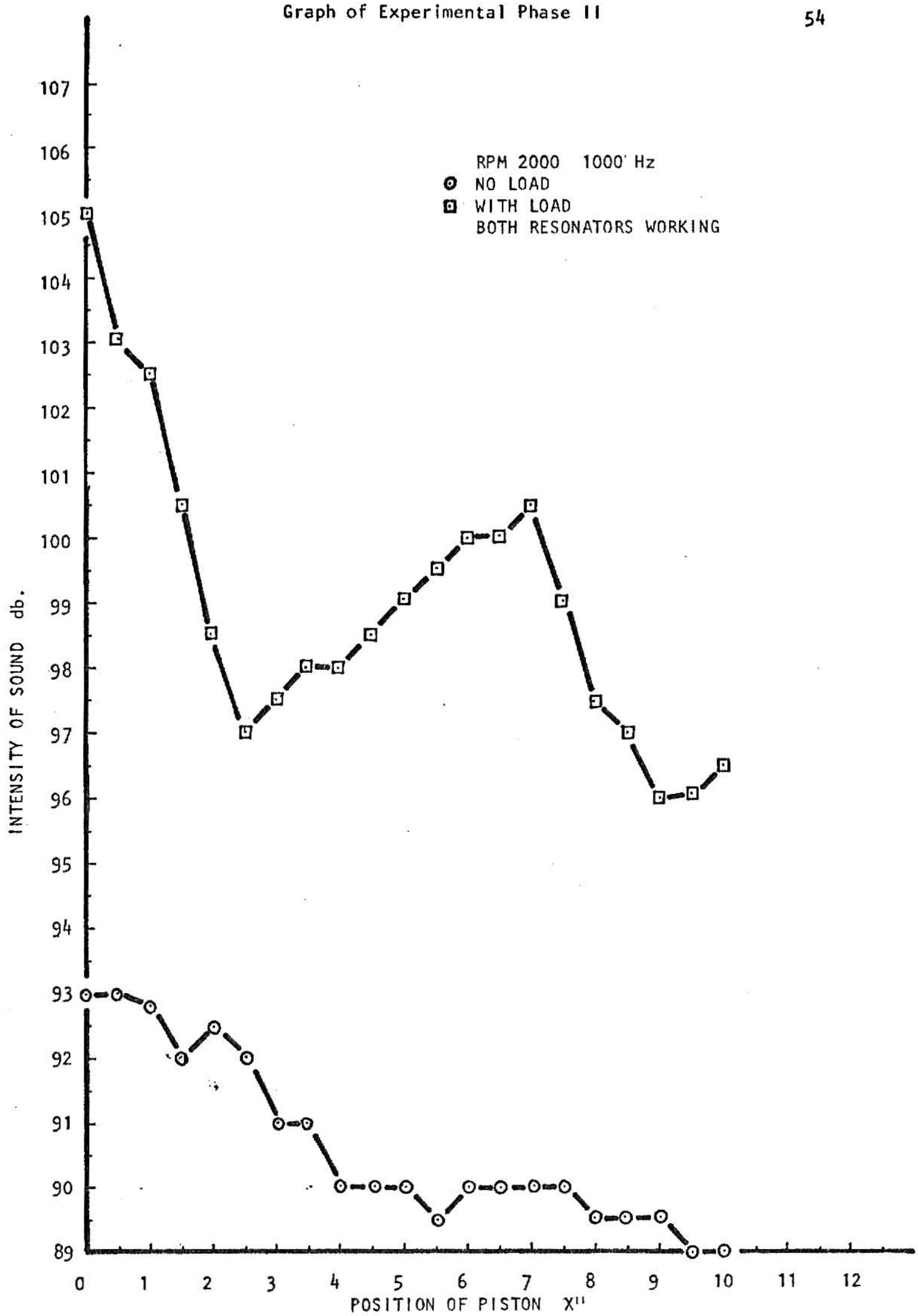


FIGURE 23

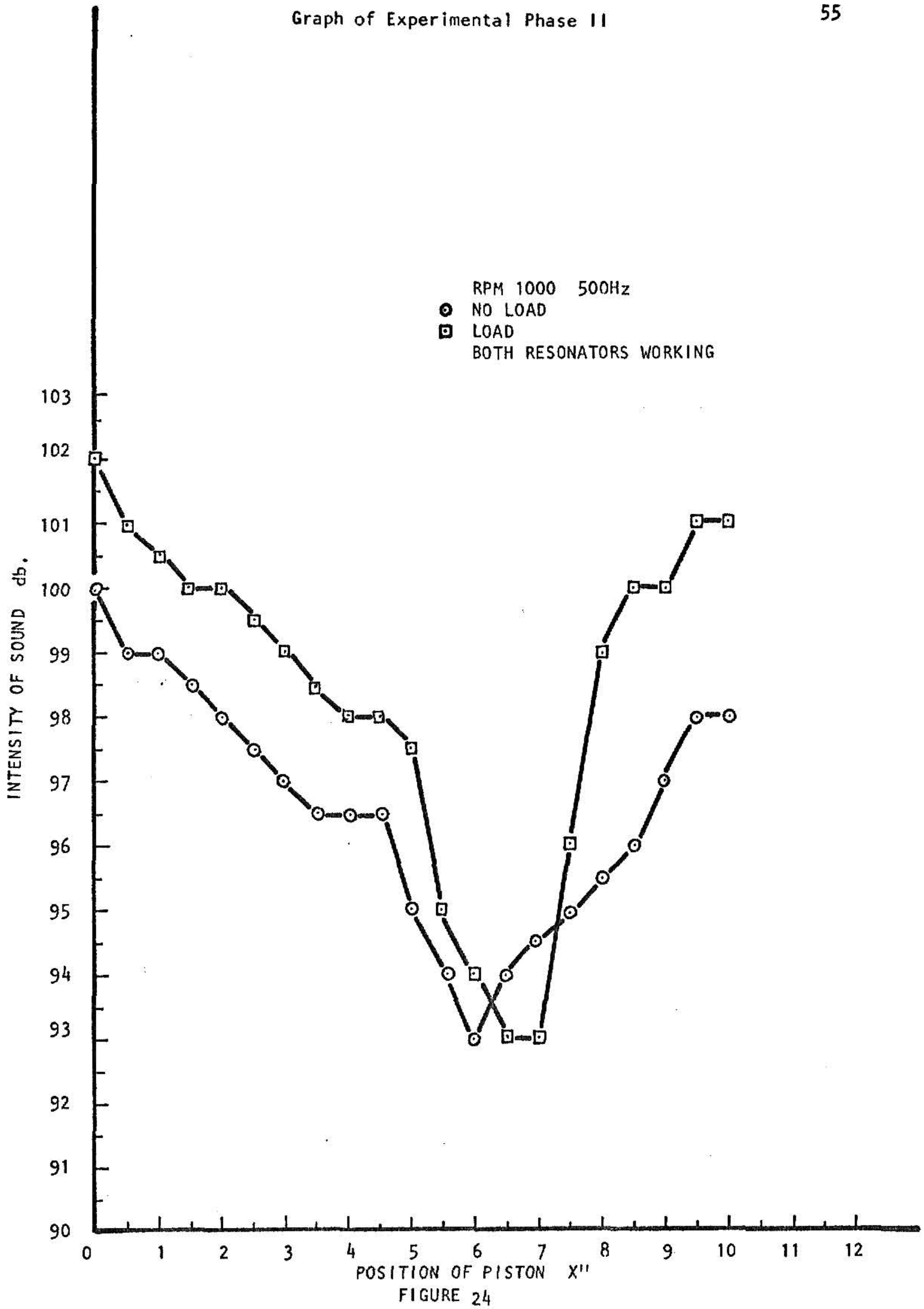

Graph of Experimental Phase II
RPM 1000 500Hz
NO LOAD
LOAD
BOTH RESONATORS WORKING
INTENSITY OF SOUND db.
103
102
101
100
99
98
97
96
95
94
93
92
91
90
0
1
2
3
4
5
6
7
8
9
10
11
12
POSITION OF PISTON X''

FIGURE 24

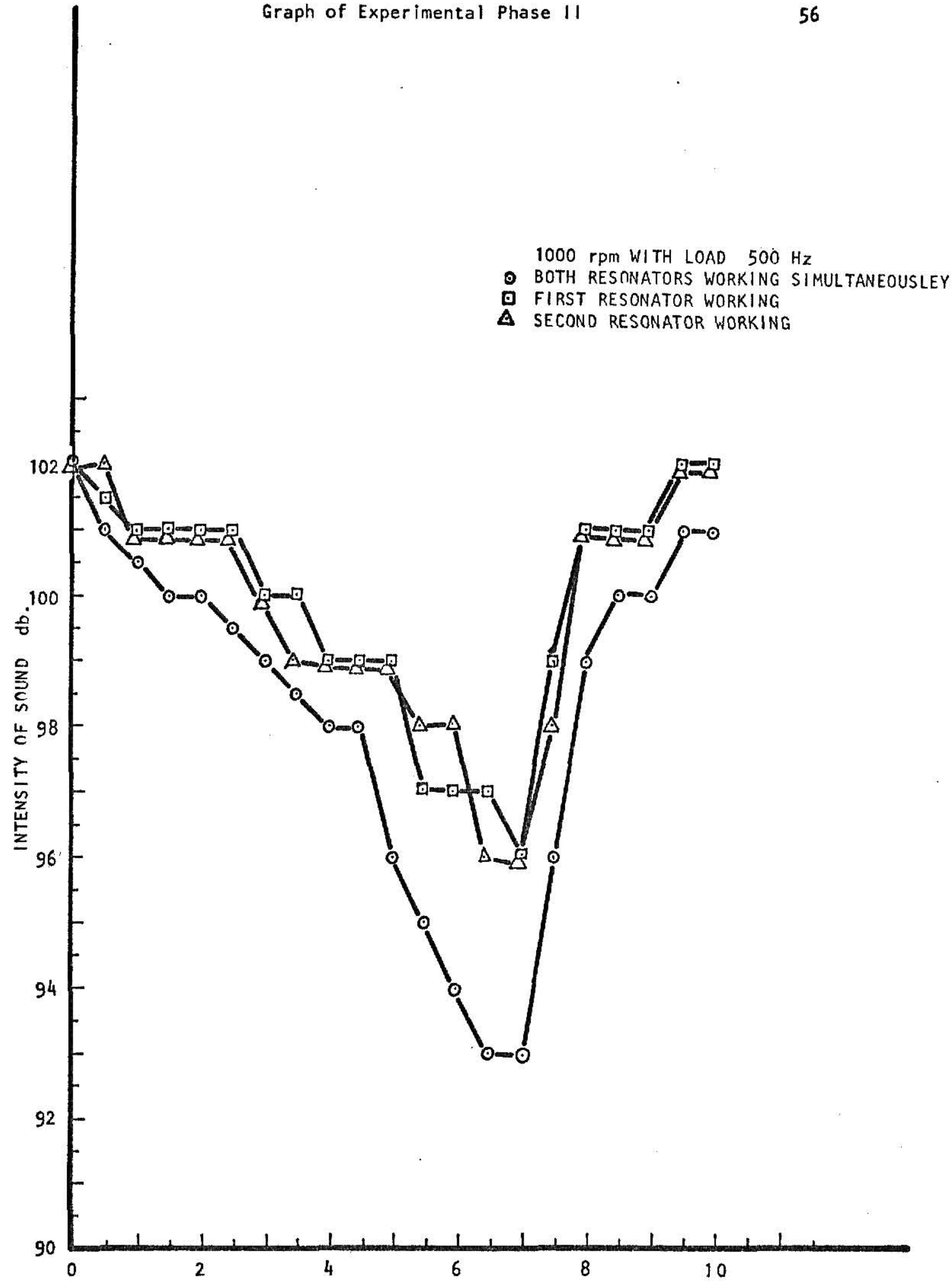

1000 rpm WITH LOAD 500 Hz
BOTH RESONATORS WORKING SIMULTANEOUSLEY
FIRST RESONATOR WORKING
SECOND RESONATOR WORKING
INTENSITY OF SOUND db.
102
100
98
96
94
92
90
0
2
4
6
8
10
POSITION OF PISTON X"

FIGURE 25

Graph of Experimental Phase III

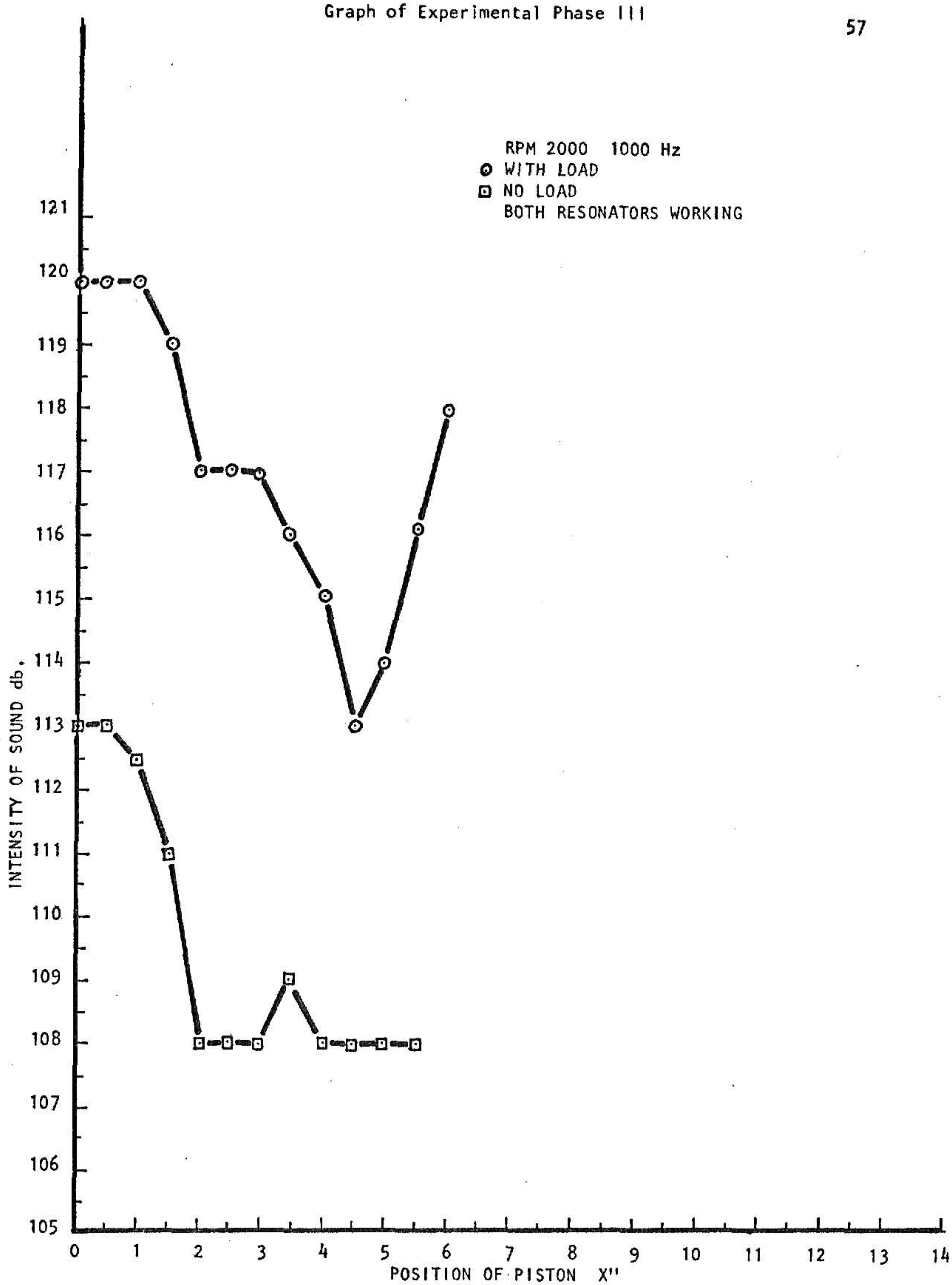


FIGURE 26

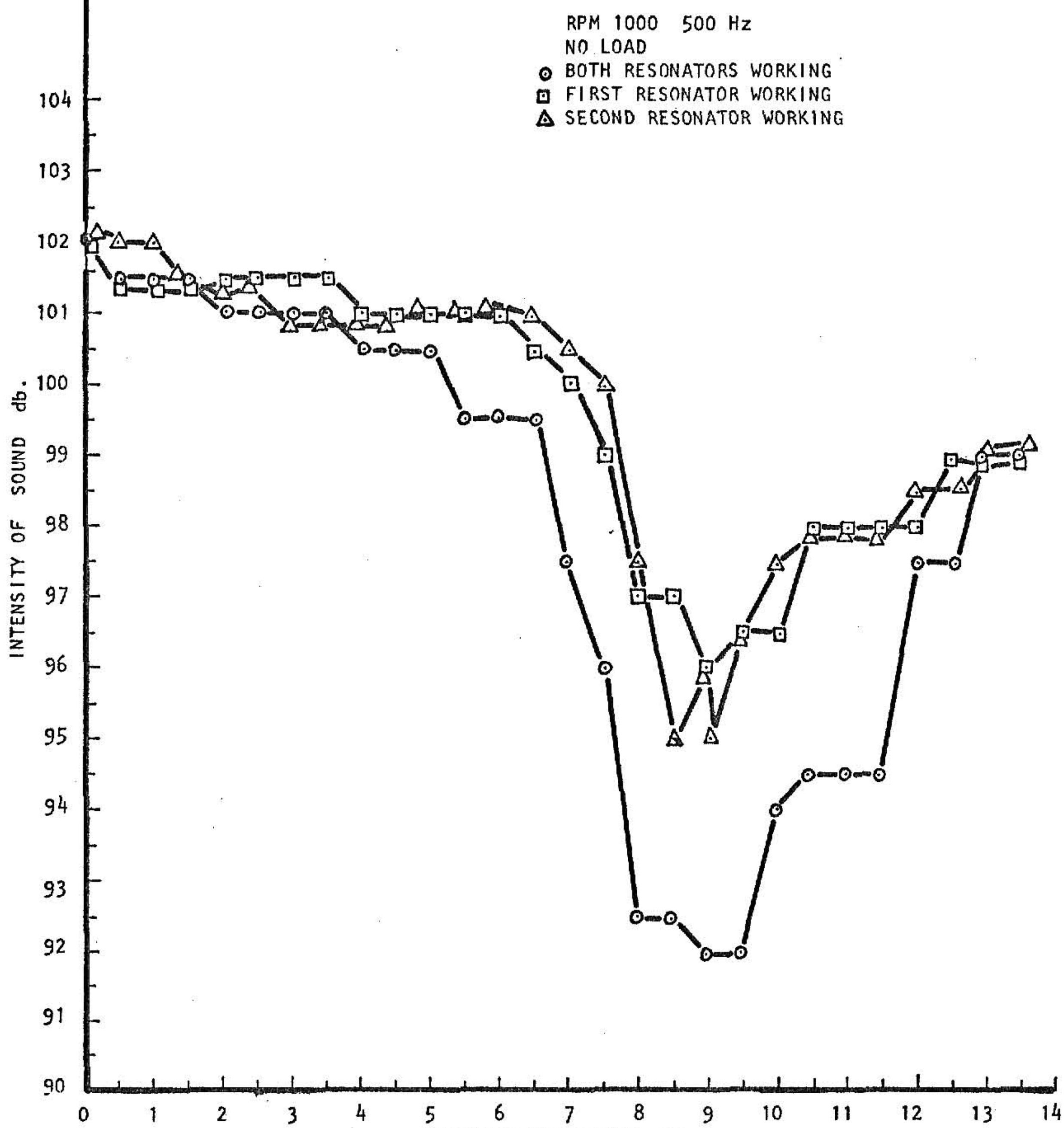

RPM 1000 500 Hz
NO LOAD
BOTH RESONATORS WORKING
FIRST RESONATOR WORKING
SECOND RESONATOR WORKING
INTENSITY OF SOUND db.
104
103
102
101
100
99
98
97
96
95
94
93
92
91
90
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
POSITION OF PISTON X''

FIGURE 27

Graph of Experimental Phase III

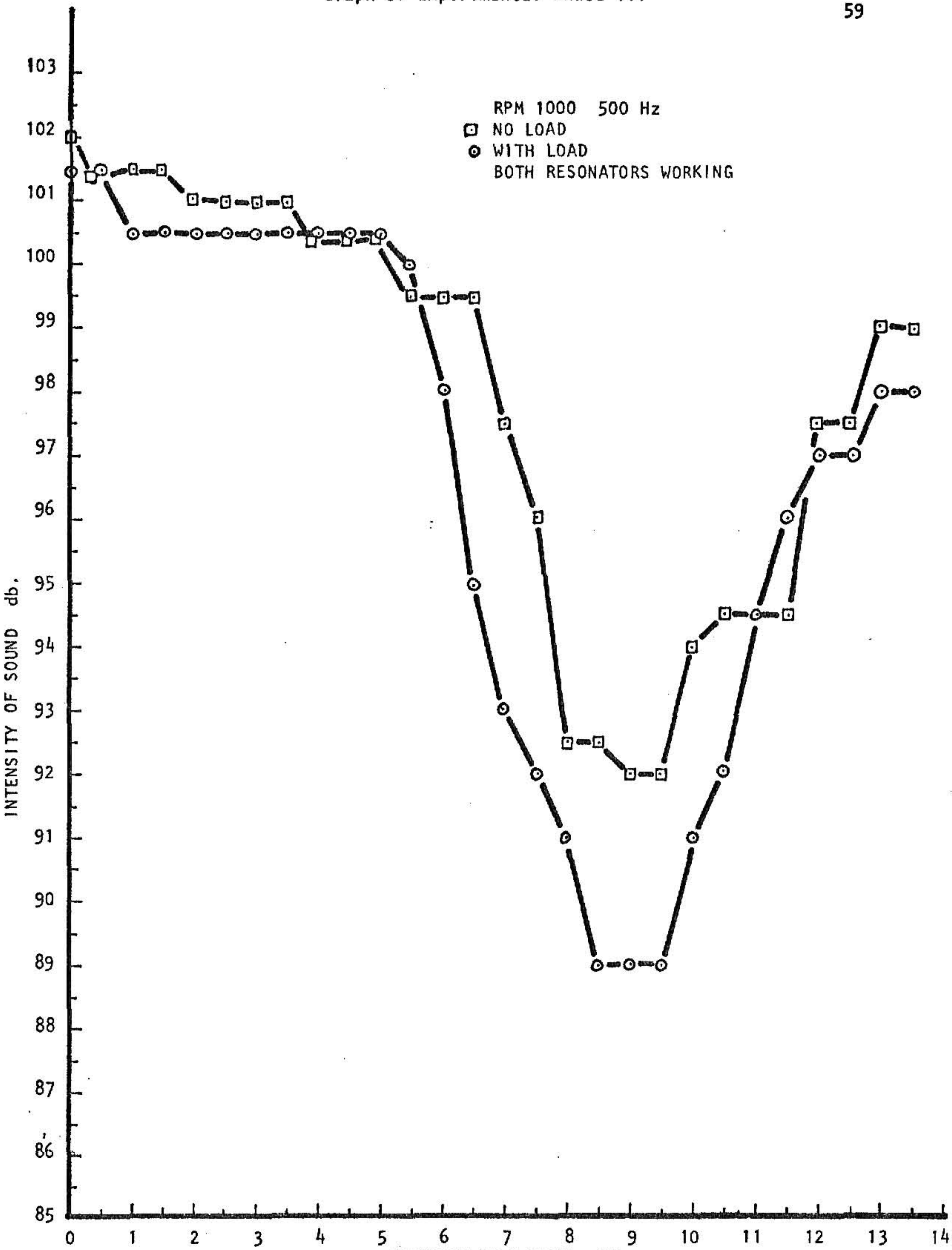


FIGURE 28

Graphs of Experimental Phase III

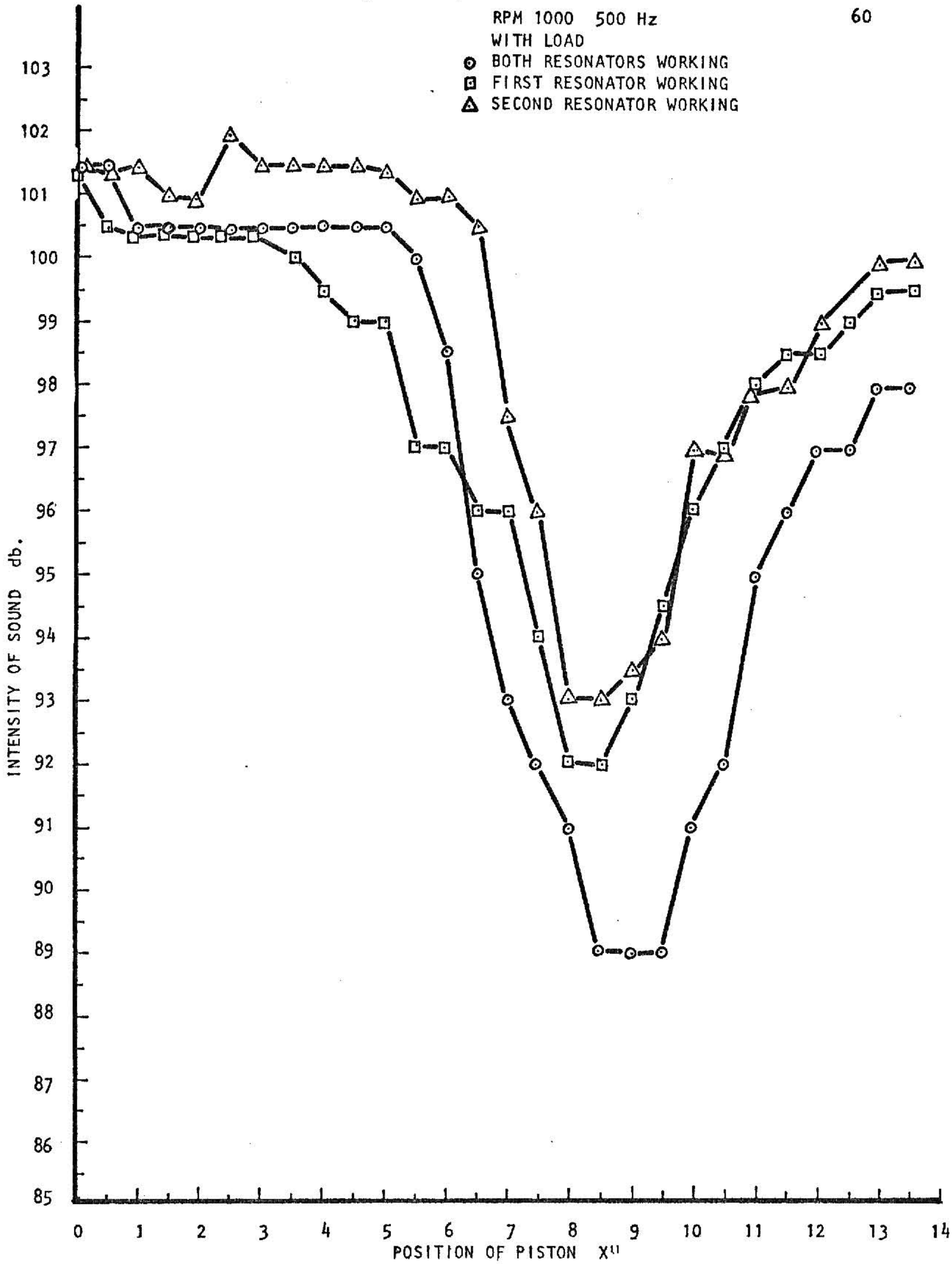


FIGURE 29

Graph of Experimental Phase IV

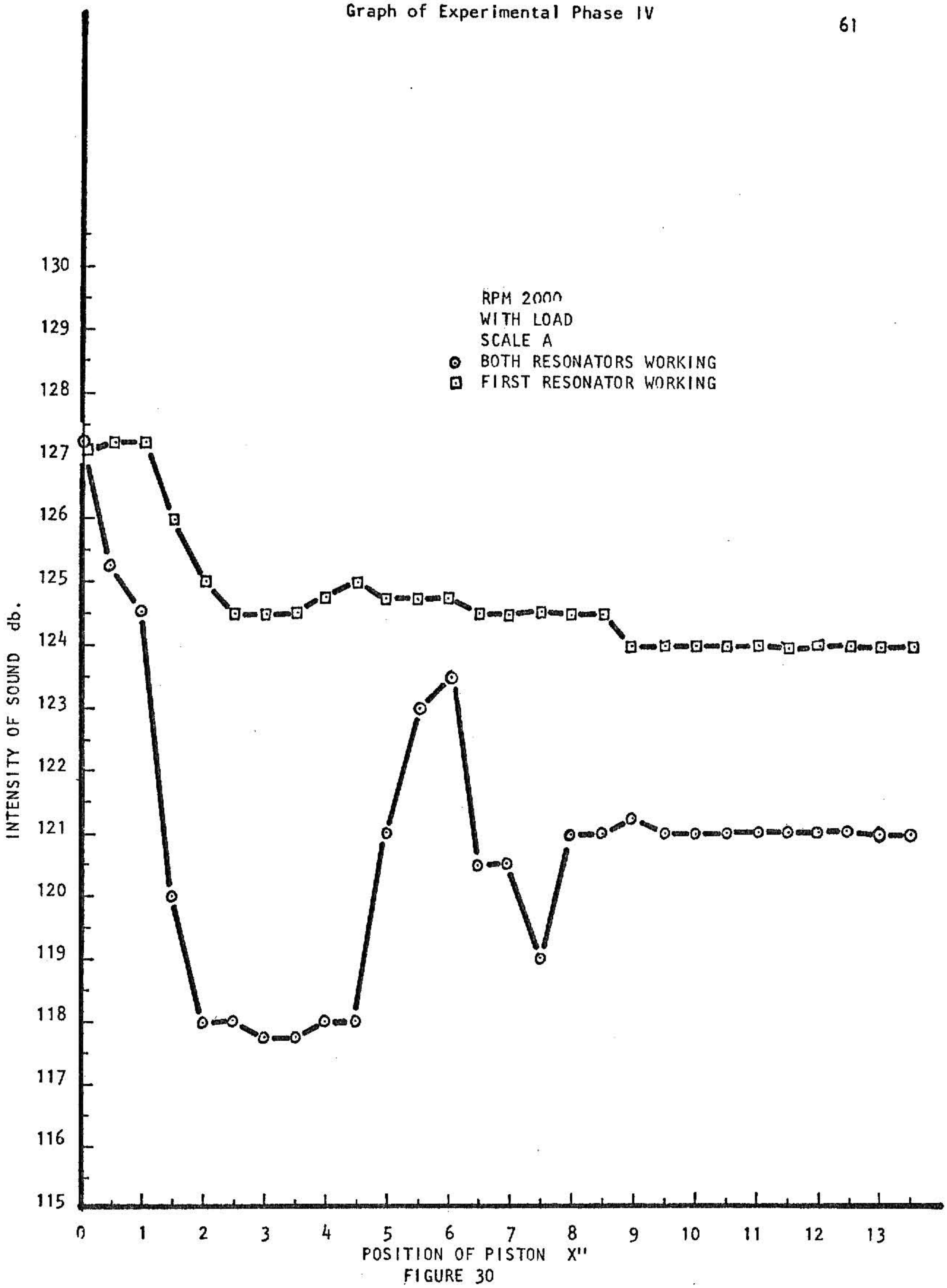


FIGURE 30

Graph of Experimental Phase IV

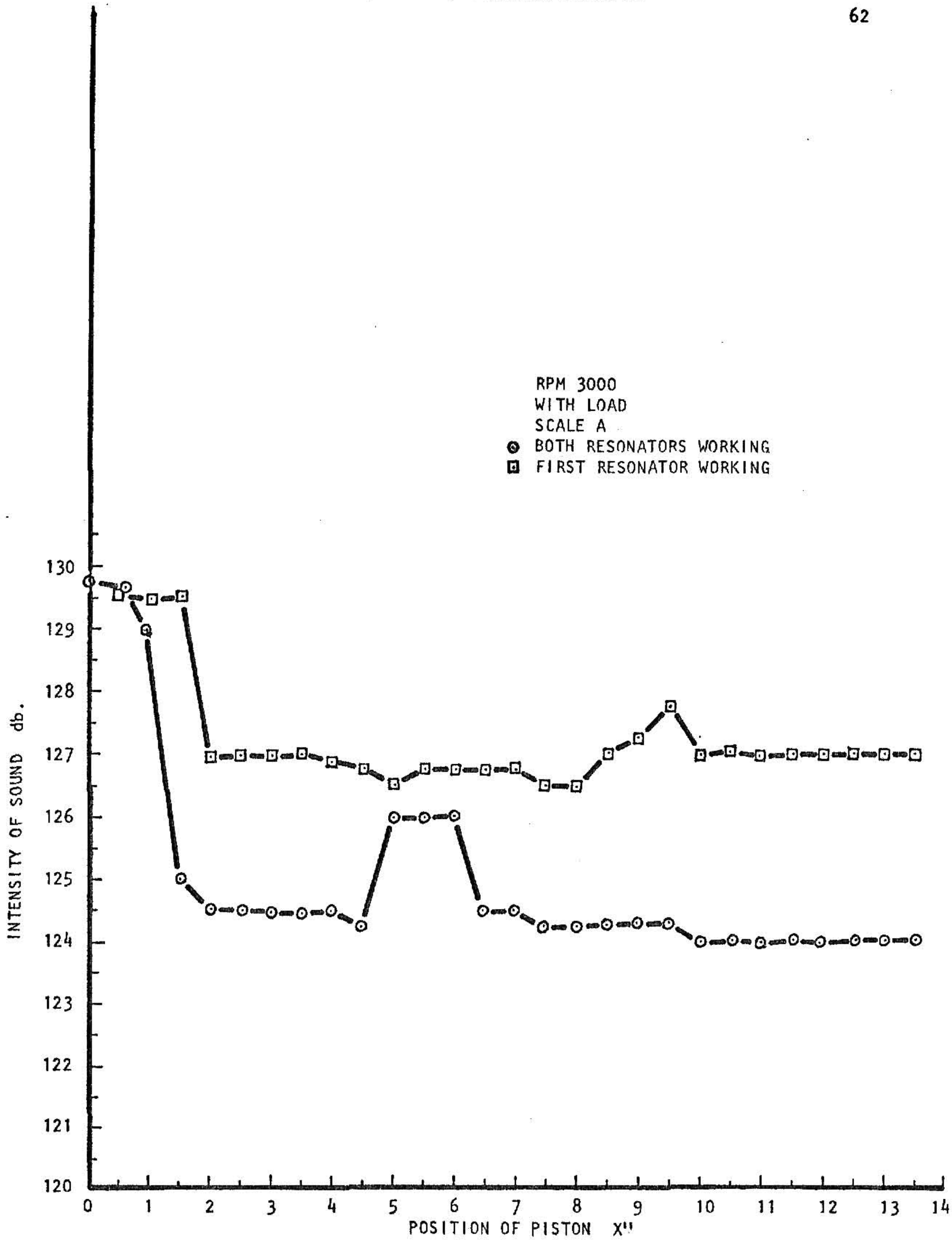


FIGURE 31

Graph of Experimental Phase IV

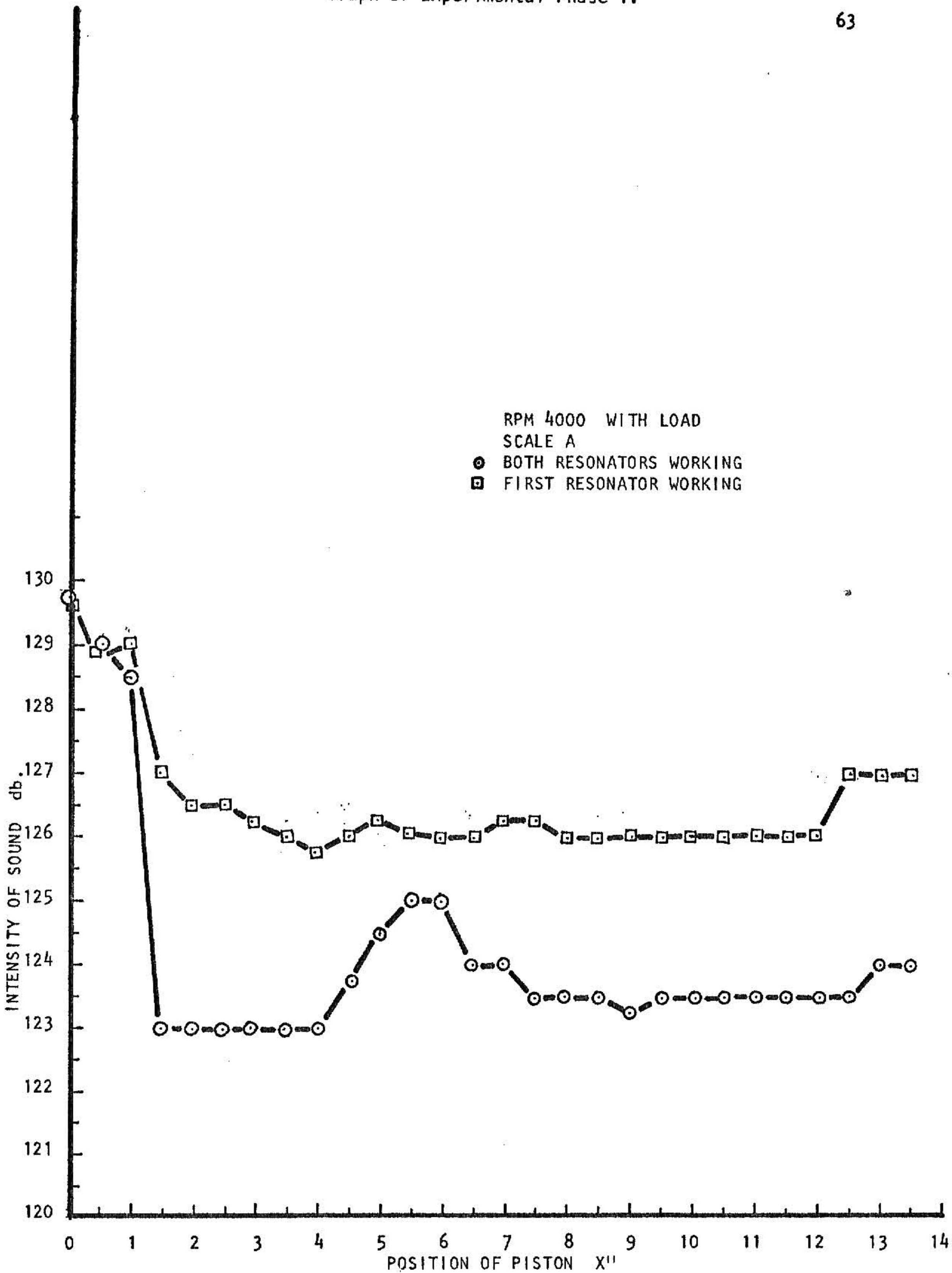


FIGURE 32

Graph of Experimental Phase IV

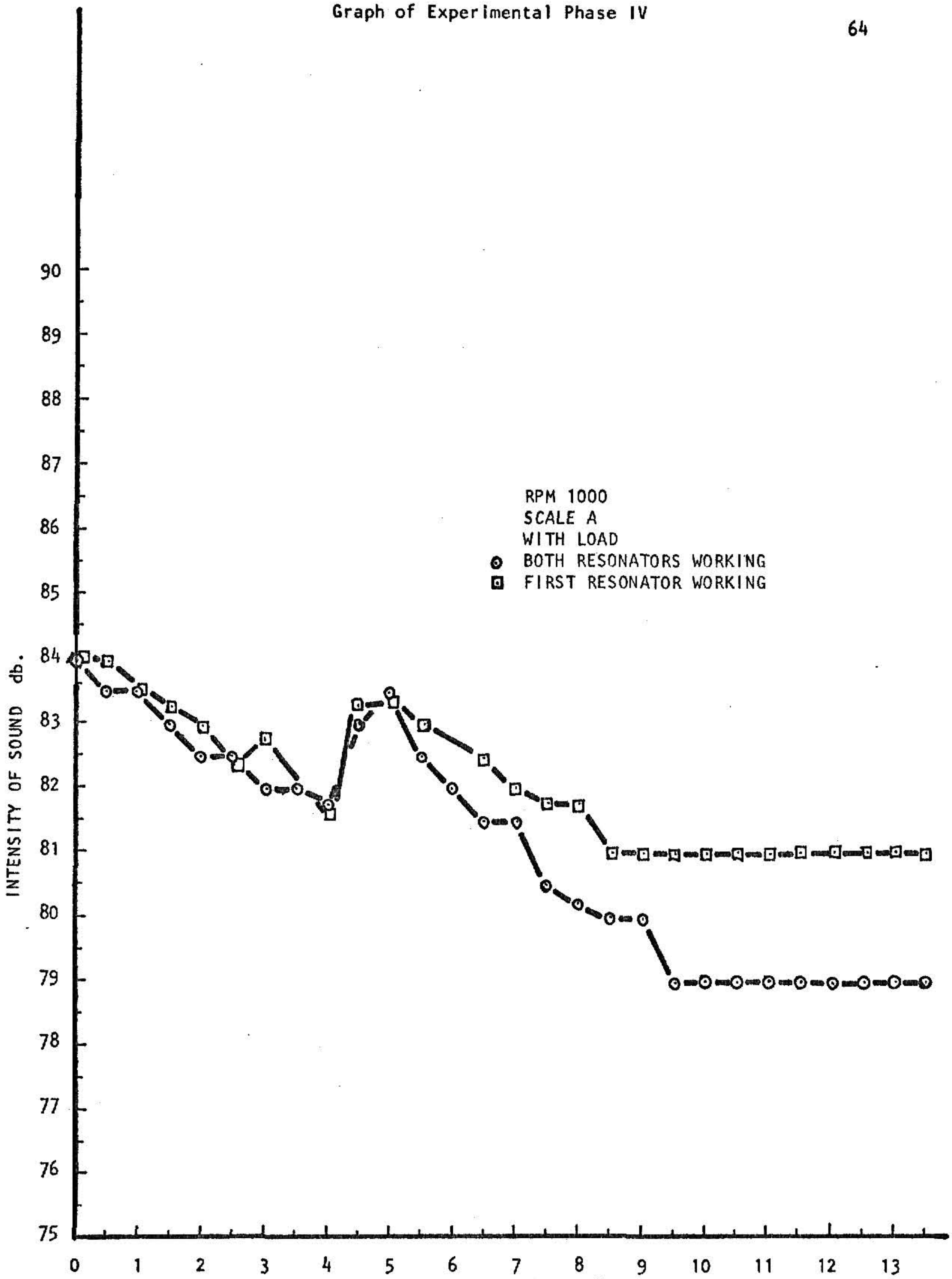


FIGURE 33

Graph of Experimental Phase V

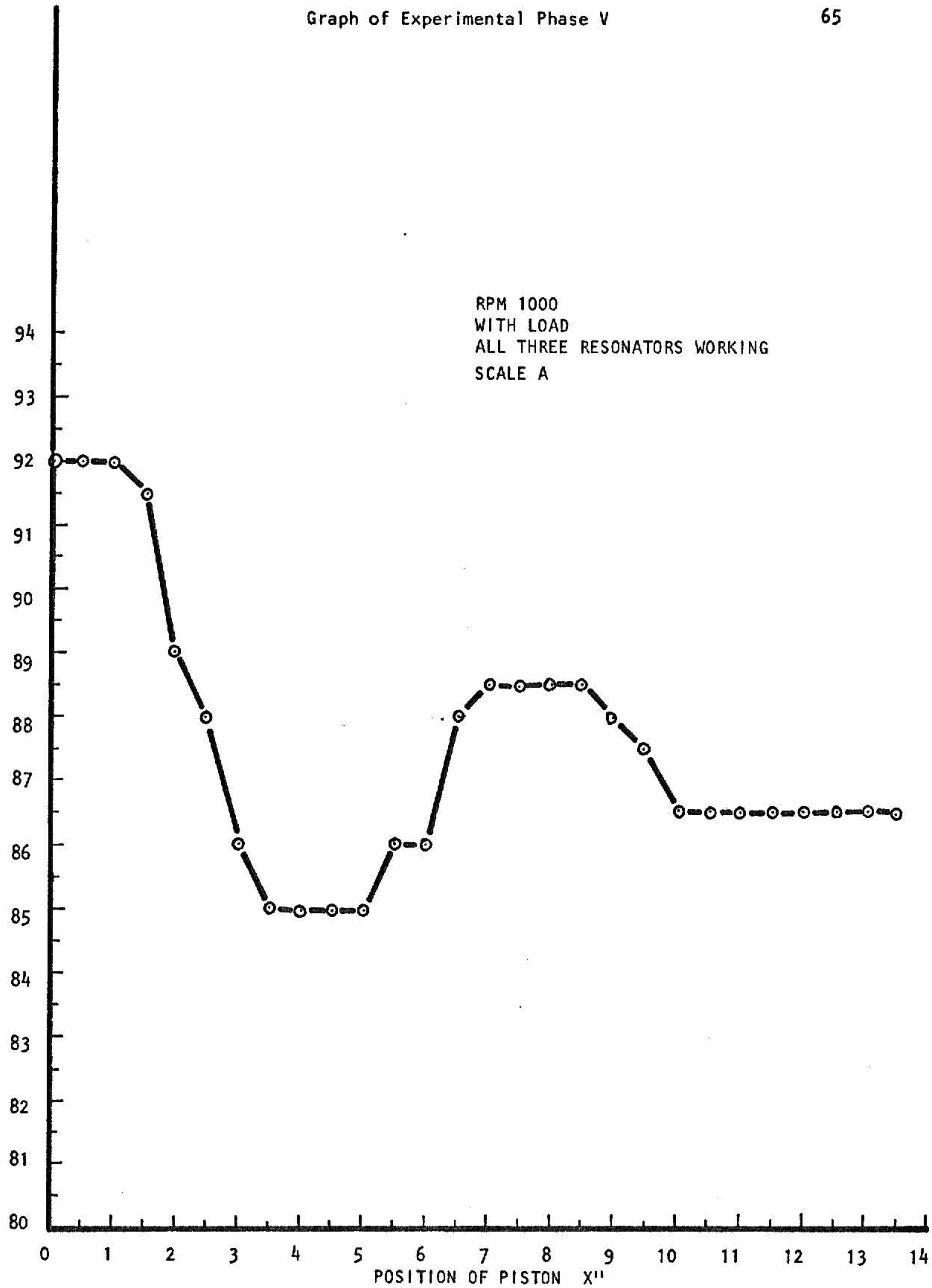


FIGURE 34

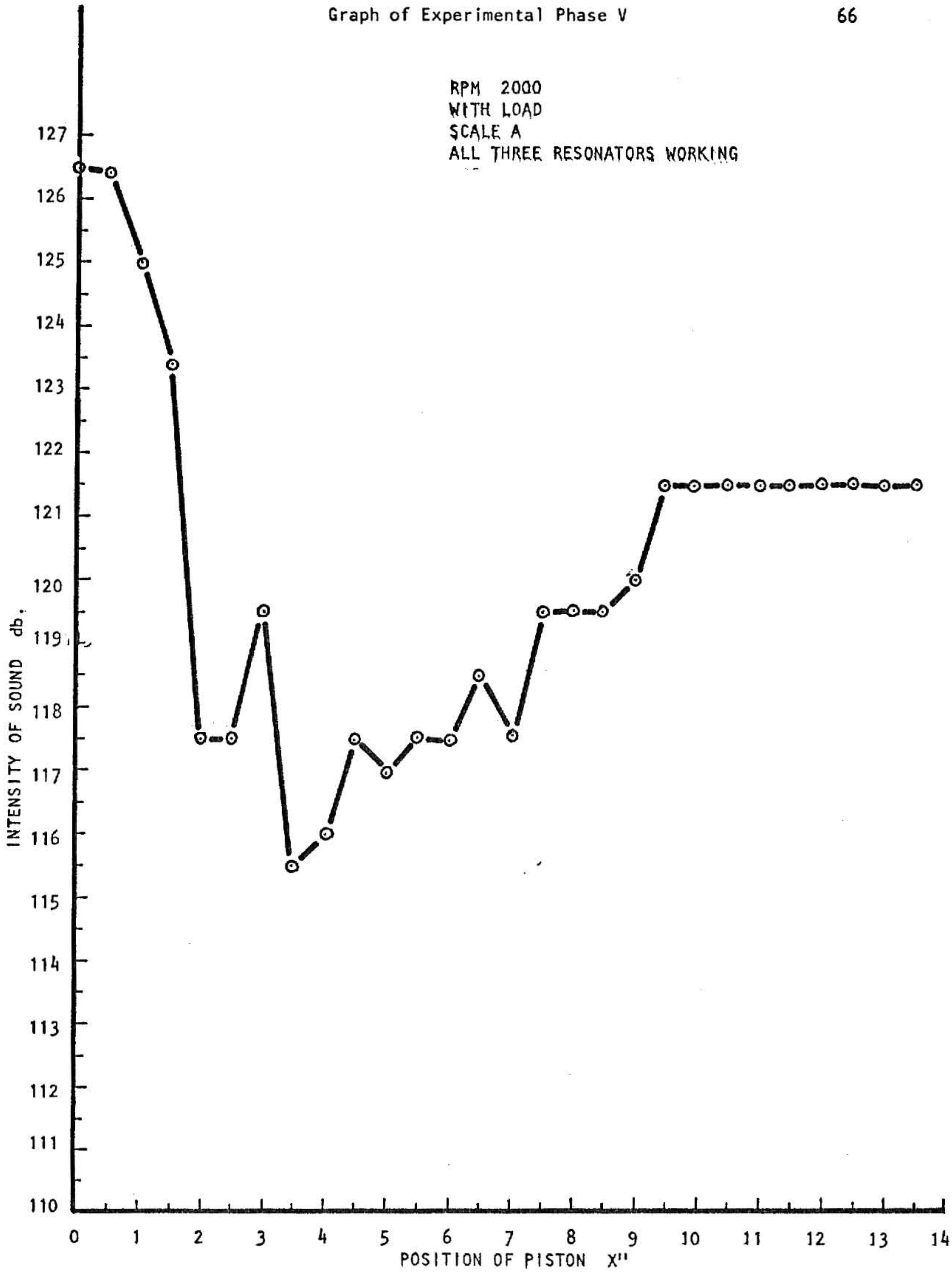

RPM 2000
WITH LOAD
SCALE A
ALL THREE RESONATORS WORKING
INTENSITY OF SOUND db.
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
POSITION OF PISTON X"

FIGURE 35

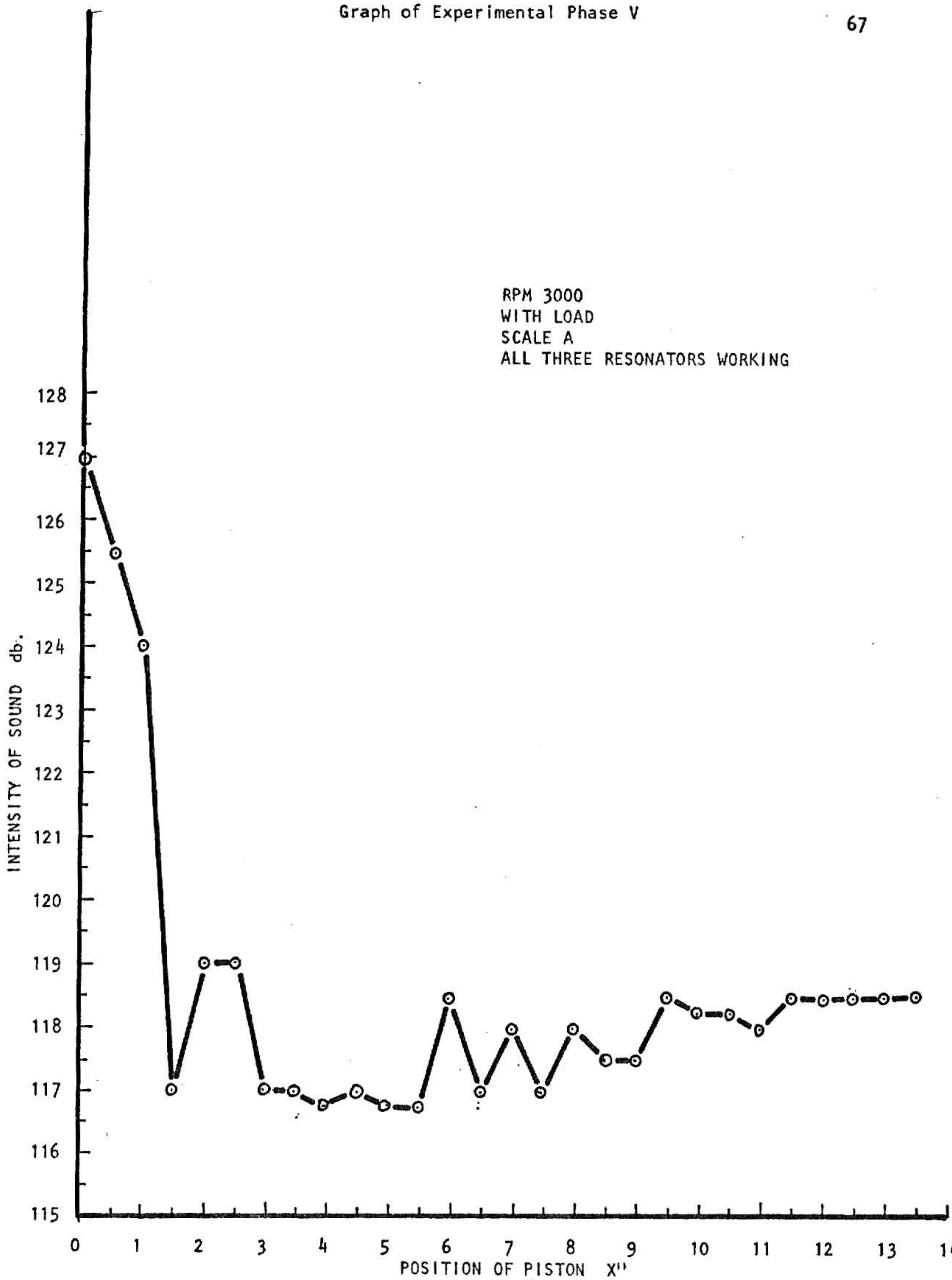

RPM 3000
WITH LOAD
SCALE A
ALL THREE RESONATORS WORKING
INTENSITY OF SOUND db.
128
127
126
125
124
123
122
121
120
119
118
117
116
115
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
POSITION OF PISTON X''

FIGURE 36

Graph of Experimental Phase V

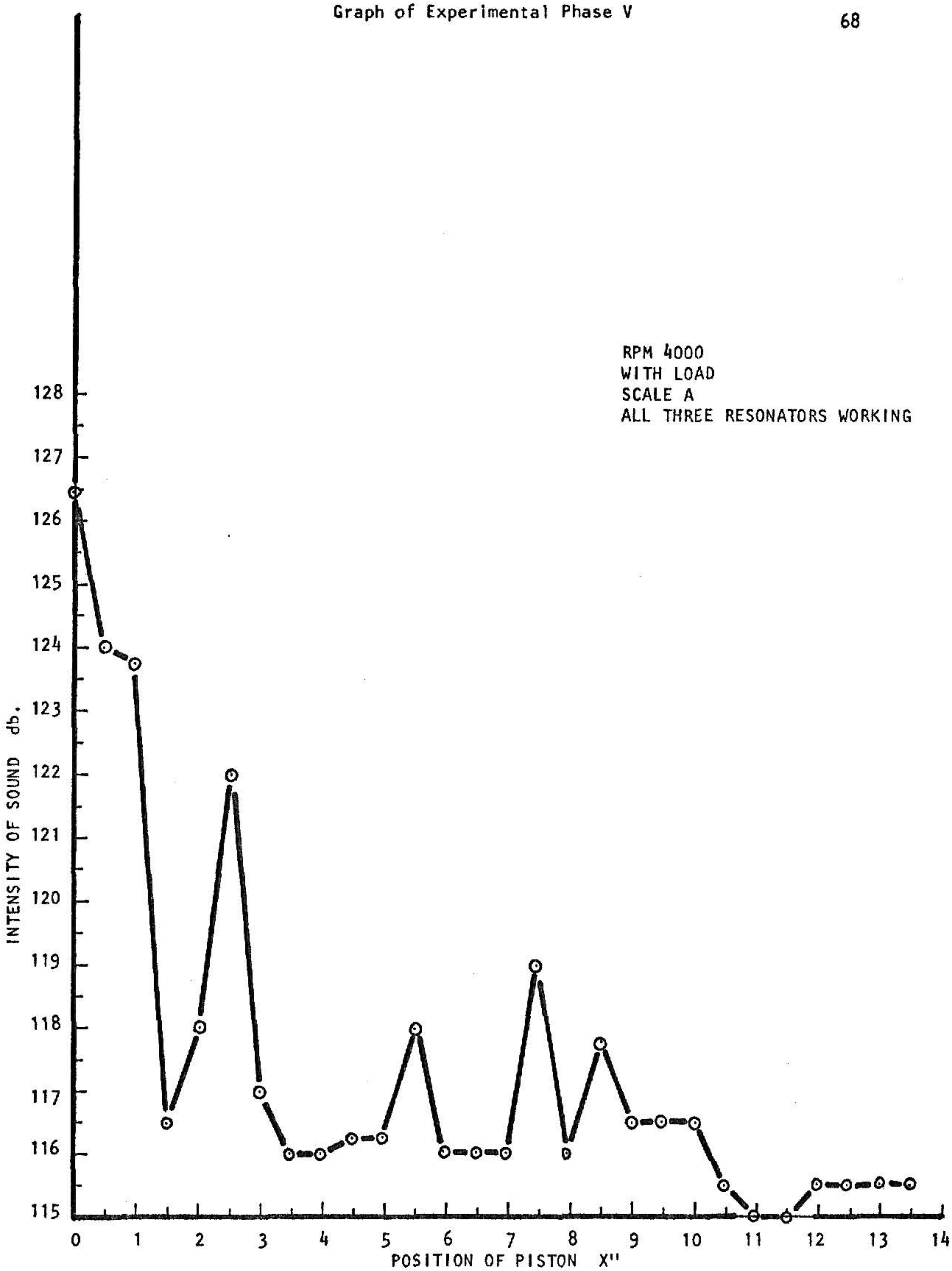


FIGURE 37

Graph of Frequency Spectrum at Different rpm's

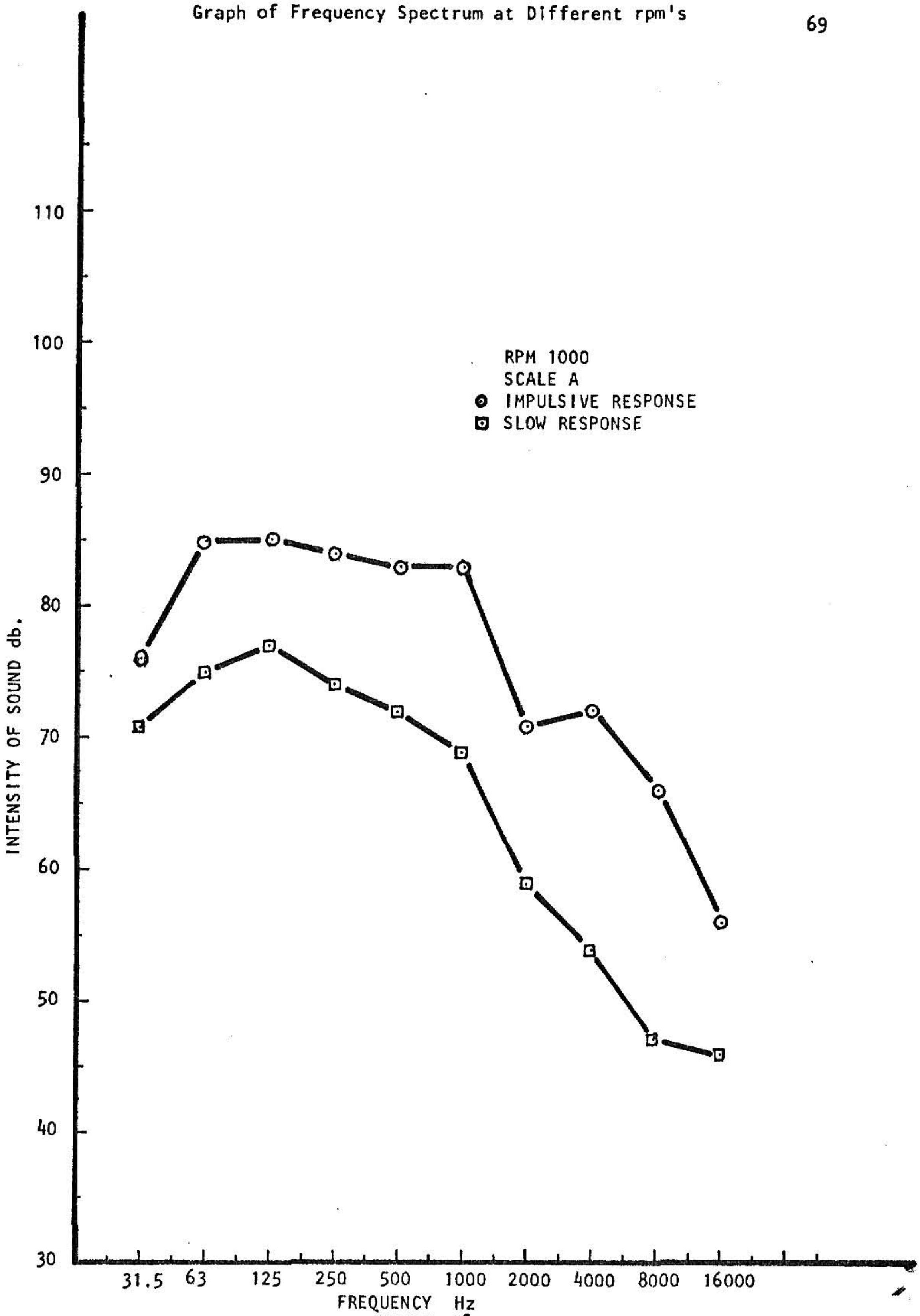


FIGURE 38

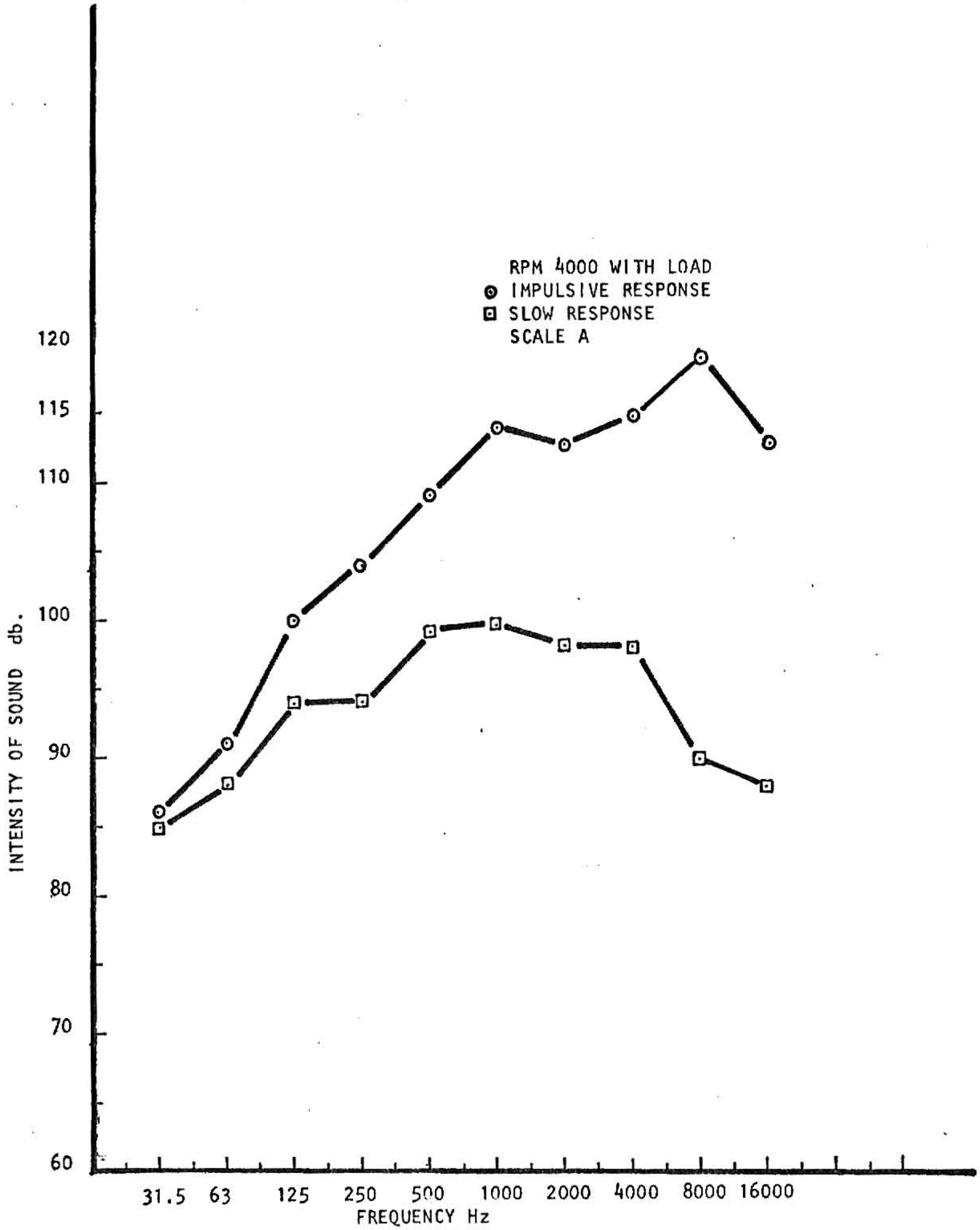

RPM 4000 WITH LOAD
IMPULSIVE RESPONSE
SLOW RESPONSE
SCALE A
INTENSITY OF SOUND db.
120
115
110
100
90
80
70
60
31.5
63
125
250
500
1000
2000
4000
8000
16000
FREQUENCY Hz

FIGURE 39

Graph of Frequency Spectrum at Different rpm's

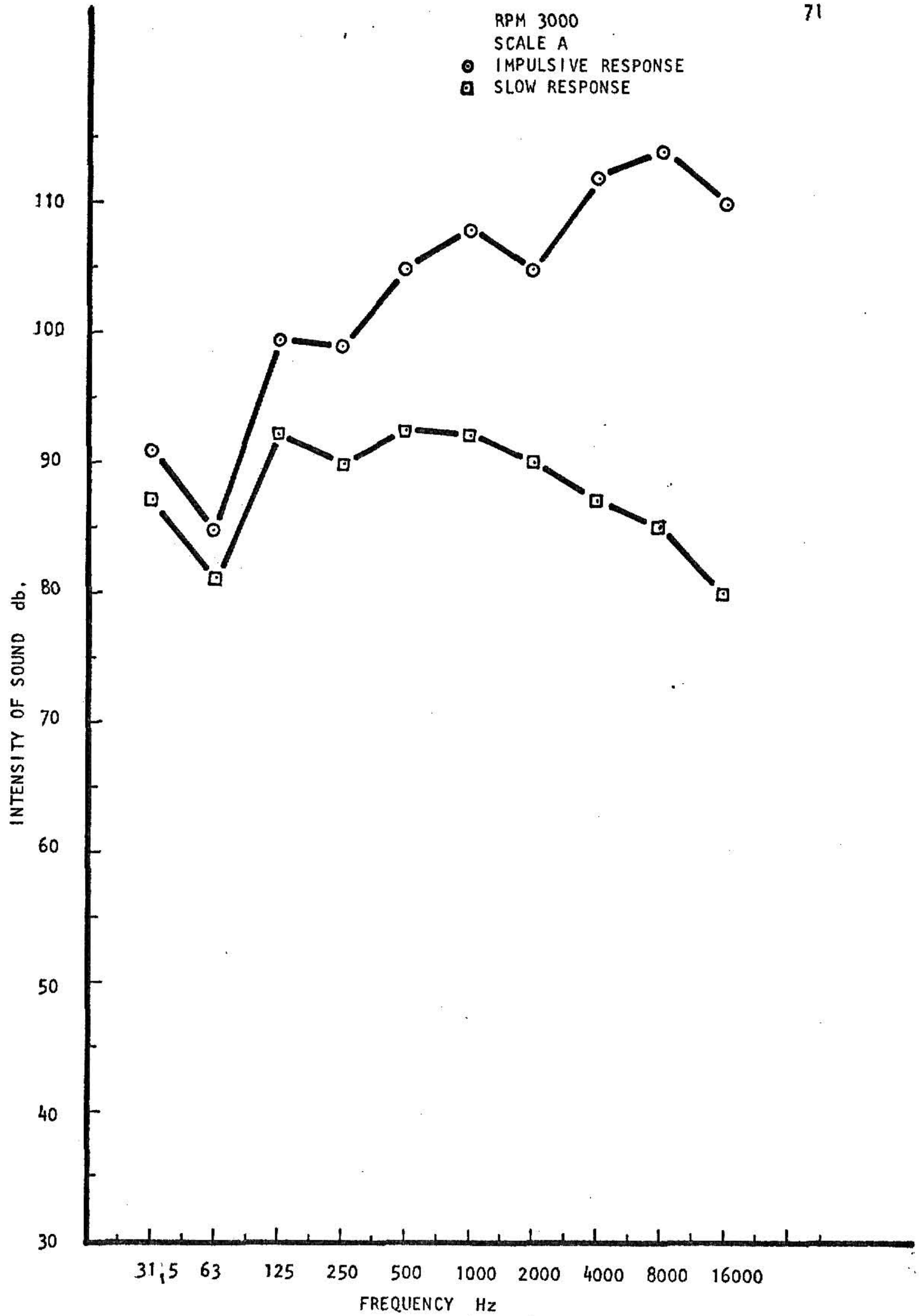


FIGURE 40

Graph of Frequency Spectrum at Different rpm's

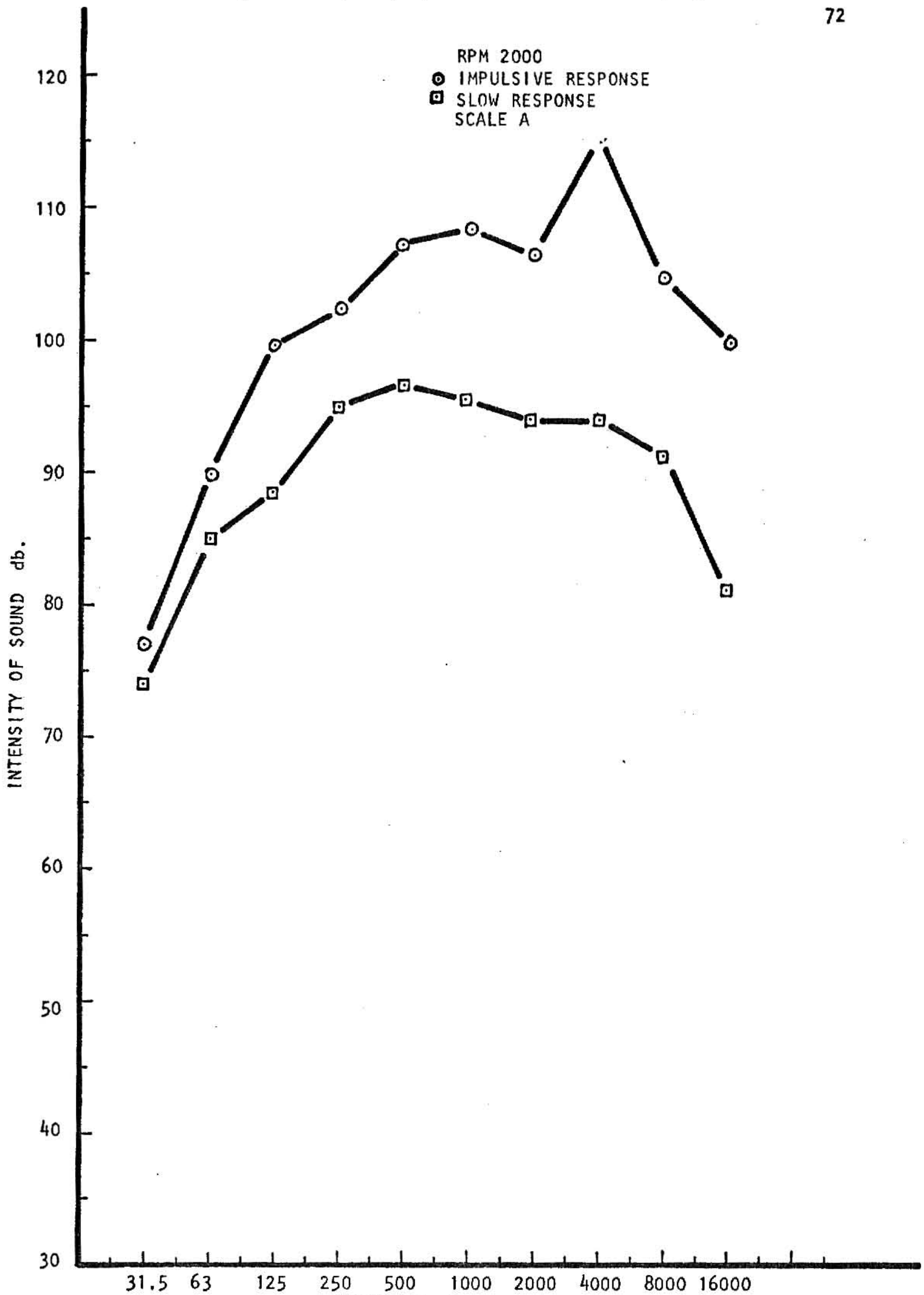


FIGURE 41

RECOMMENDATIONS FOR FUTURE WORK

For the type of engine which was used in the experiment with the same type of mounting, the following configuration was found to be the most suitable. If we have a 1" diameter exhaust pipe with a number of 1" diameter and 4" long extension tubes (resonating tubes), we get the maximum sound reduction at all speeds of the engine with different load conditions. The distance between the extension tubes is not very important.

Even if we change the engine mounting, the above configuration may not be the best one, because the vibration characteristic of the engine changes as we change the engine mounting. If we want to design a tuned muffler for any engine for a given engine mounting, the method employed in this research work could be used.

If instead of a 1" diameter exhaust pipe we have different diameter pipes or an oval pipe, the best cross-section of the resonator tube and the proper length of the resonating tube can be determined by the above method for an optimum design of a tuned muffler.

In future work, it has to be investigated as to why a 4" long extension tube gives a considerable amount of reduction in noise at all speeds with different load conditions. It can be determined by finding the reduction in noise with the change in the position of a piston at different frequencies and taking into consideration the combined effect of different frequencies.

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5. Bruel and Kjaer. Instructions and Applications, "Impulsive Precision Sound Level Meter Type 2204." 1971, pages 6, 10, 11, 16 and 21.

6. Bruel and Kjaer. Instructions and Applications, "Precision Sound Level Meter Type 2203 Octave Filter Set Type 1613." 1971, pages 7 - 12.

7. Bolz and Tuve. Handbook of Tables for Applied Engineering Science, 1970, pages 10 - 19.

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I would like, also, to express my appreciation to Dr. Paul L. Miller and Dr. Garth J. Thompson for providing me with financial assistance which made this project possible.

Also, I would like to express my thanks for the willing co-operation of Mr. Gary Thronton and Mr. Neil Weybrew who have been more than helpful in fabricating the equipment.

I will have to render a special thank you to my dear sister, Marjorie Olson for typing this thesis at such short notice with such patience. I thank Mr. K. P. Premnath for editing the manuscript.

Last, but not the least, I must thank my father, Ratanlal Kotecha and my mother, Shanta Kotecha and my sister, Rekha, who have been a constant source of inspiration in my endeavors to strive to reach greater heights.

AN EXPERIMENTAL STUDY OF
TUNING OF A MUFFLER

by

SHIRISH RATANLAL KOTECHA

B.S. MYSORE UNIVERSITY, 1973

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976

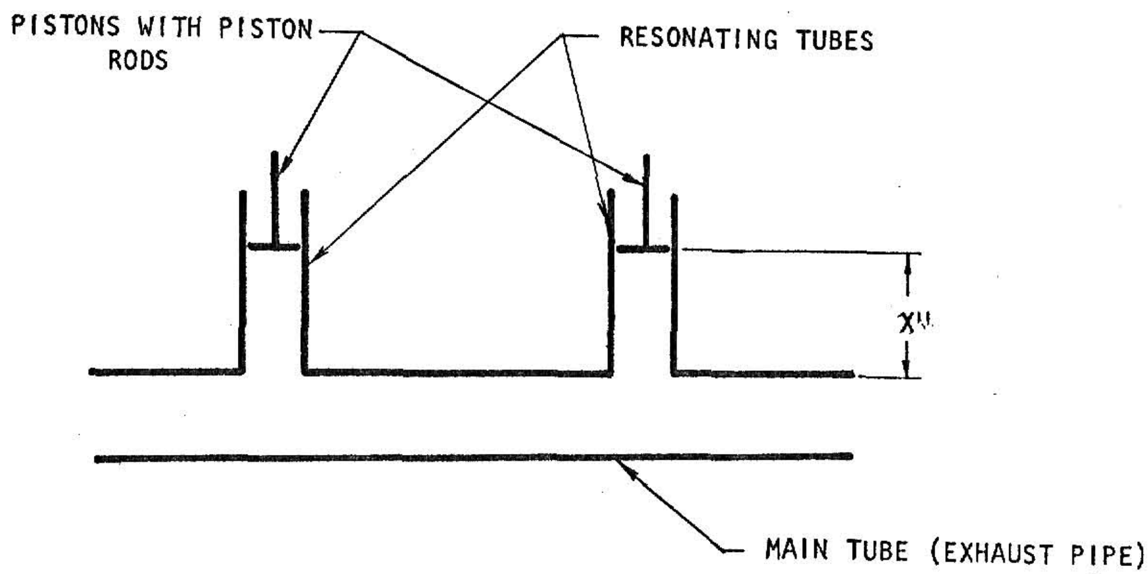
ABSTRACT

At present, air pollution and noise pollution are some of the greatest problems to modern man. Noise is generated by a number of means. Some of the greatest noise pollutants are automobiles and farm equipment. Most of the farm equipment and automobiles are run on internal combustion engines. The main noise pollutant in internal combustion engines is the exhaust system. Presently, noise is reduced by use of a muffler which is designed on the basis of an increase in muffler impedance which increases back pressure and there by reduces enigne noise. This research has been designed on the principle of tuning of the muffler.

When we say the muffler is tuned for a particular frequency we have a reduction in intensity of the sound. This effect is due to compression and tension waves being out of phase with each other. We can't reduce the exhaust noise to zero for two reasons. The first reason is that we can't have the tension wave and the compression in phase with each other with equal amplitude. The second reason is that the intensity of sound of the exhaust of an engine doesn't have just one frequency. It is a combination of a wide frequency band. This band is from 2 Hz to 20,000 Hz or even more. So if we try to tune one frequency, other frequencies would be untuned. And for one particular configuration all the frequencies can't be tuned.

Different configurations are tried and an attempt is made to tune that configuration. If configurations are as in phase I experiments, we have a lot of reflections and consequently we can't have a reduction in noise. In the design of a muffler, configuration should be based on *minimum reflections* principle.

In phase II configuration is an important stage of experiments as shown in Figure 42 on page 77. The first stage was to tune one frequency by changing



Configuration of a Muffler used in Phase II

FIGURE 42

position of piston X. In the initial stage, wooden pistons were used. With wooden pistons also considerable amount of intensity of sound was reduced. Because of wooden pistons there was not an airtight sliding motion for the pistons. Then airtight sliding pistons were prepared. Airtight sliding pistons used were steel pistons with '0' rings. In this case more reduction in sound level is obtained when engine is loaded compared with unloaded engine. And as the number of resonators are increased more and more sound reduction is achieved.

As we know, exhaust sound is a combination of a number of frequencies which have different intensity of sound. At the exhaust frequency, the intensity of sound is more than at other frequencies generated by the engine.

In the next stage, the muffler and engine were separated by a wall, enabling the microphone to pick up only exhaust noise. A precision sound level meter was used to measure intensity of sound. Accuracy of the meter was $\pm$ 1 db. Intensity level meter has a scale A. When the meter is used with scale A, it behaves as a human ear. It has slow and impulsive response. Impulsive response is used when intensity of sound increases for a short duration of time.

In the last state, the muffler with three resonator tubes was designed and tested with scale A and impulsive response of sound level meter. And it was found that a reduction of nearly 10 db sound level was obtained at all speeds with all loaded conditions. It was found that for a main tube of 1" dia. extenstion tubes (resonating tubes) of 4" length tune the muffler at all speeds and load conditions. This is an empirical result obtained from experiments. It can be stated in another way, that if we tune the exhaust system of a given engine at 1000 Hz, we have minimum sound level.

Future prospects in this field of research are pretty vast. It has to be shown theoretically why the empirical result for this engine behaves like this. For this, a sound wave generator can be used to create one frequency at a time and a number of readings of this sort of experiment can be combined to give the theory behind the behavior.

Here the configuration for a 1" dia. main pipe exhaust system was found but if we have a different cross-section for the main pipe we might not get minimum noise with the above mentioned empirical statement. So this configuration is one of the good configurations and it will differ with changes in the main pipe (pipe in which exhaust is brought from the engine) dimensions.