ACOUSTIC INTERACTION WITH THE POSITIVE COLUMN OF A NEON GLOW DISCHARGE

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by

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[redacted]

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 1967

ABSTRACT

Compressive acoustic pulses were produced by an impulsive abnormal-glow discharge and the interaction of these pulses with the positive column of a dc neon glow discharge was studied.

The acoustic pulses are analyzed and are found to be infinitesimal amplitude perturbations.

The mechanism of the acoustic interaction is described in terms of existent theories of the positive column. It is found that the presence of the acoustic pulse in the positive column creates small spatially-separated regions of increased electron temperature and electron density, which move through the plasma in company with the acoustic pulse. It is shown that amplification of the wave of stratification produced in the interaction may, in many cases, depend upon this spatial separation phenomenon.

An attempt was made to observe amplification of the acoustic pulses caused by their propagation through the plasma.

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LIST OF ILLUSTRATIONS

ACKNOWLEDGEMENTS

Many people have helped me very much in the course of this work. I am particularly grateful to:

Professor A. W. M. Cooper, my thesis advisor, who was always available for guidance and counsel, but gave me the freedom to do my own work.

Professors J. V. Sanders and A. B. Coppens, for many hours spent in discussion of acoustic phenomena.

My wife, Jean, for her constant support and encouragement and for her typing of the thesis.

CHAPTER I

INTRODUCTION

For more than one hundred years, it has been well-known that the positive column of a direct current gas discharge is not always homogeneous, but is striated over a wide range of discharge parameters. These striations (regions of increased or decreased light intensity) are of two general types; standing and moving. Moving striations have been studied extensively in the past decade and considerable progress has been made toward understanding the mechanisms which govern their creation and behavior. Oleson and Cooper have written a comprehensive survey of the experimental and theoretical research relating to moving striations.(1)

The use of impulsive electric or magnetic fields and impulsive modulation of the discharge current to perturb a striation-free positive column, thereby generating packets of striations, have been the most common experimental techniques. Using these techniques, Pekarek observed the striation packets and called them "waves of stratification". He further gave an explanation of how the waves of stratification might give rise to a fully striated positive column.(2)

More recently, investigations have been made into the interaction of infinitesimal amplitude acoustic waves with the positive column. Experiments have shown that there exist acoustic disturbances associated with moving striations.(3) Crandall, in his experiments, has shown that waves of stratification can be produced by acoustic perturbation of the homogeneous positive column.(4) Ingard has produced a theory which predicts the existence of striation-generated acoustic waves and also predicts the possibility of amplification of acoustic waves in the positive column.(5)

The investigations undertaken in this work were suggested by the work of Crandall and of Ingard. An examination of the character of the acoustic pulses used by Crandall has been made. A detailed analysis of the interaction of these acoustic pulses with the positive column has been given. An attempt to observe the amplification of the acoustic pulses in the positive column, as predicted by Ingard, was made.

CHAPTER II

EXPERIMENTAL APPARATUS

Investigations of the acoustic pulses observed by Crandall were carried out in the same discharge tube which he had used, with the addition of a second diode microphone between the sound source and the observing discharge. Figure 2-1 shows the arrangement of the equipment. The addition of the second diode allowed the measurement of the time-of-flight of the acoustic pulses and, in addition, made possible the observation of the dispersive effects.

Acoustic waves were generated by a high voltage (variable 0-10kV) pulse discharge operated between electrodes E1 and E2. The electrodes E1 and E2 were 18mm diameter tantalum cylinders with a 1cm gap between them.

The observing discharge was maintained between electrodes E3 and E4, which were also hollow tantalum cylinders of 20mm diameter spaced 40cm apart. This discharge was powered by a 0-1kV, 500ma power supply and the load supplied by an RCA 807 pentode. The use of the pentode, rather than a resistor, as a load in the discharge circuit increases the range of current in which the positive column is homogeneous.(6)

The time-space display method described by Stirand, et. al.(7) was used to observe the discharge in order to check qualitative agreement with the conditions of the previous experiments. In this technique, the oscilloscope sweep is triggered simultaneously with the exciting discharge pulse. The intensity of the oscilloscope beam is modulated by the output of a photomultiplier tube which responds to variation in light intensity in the positive column.

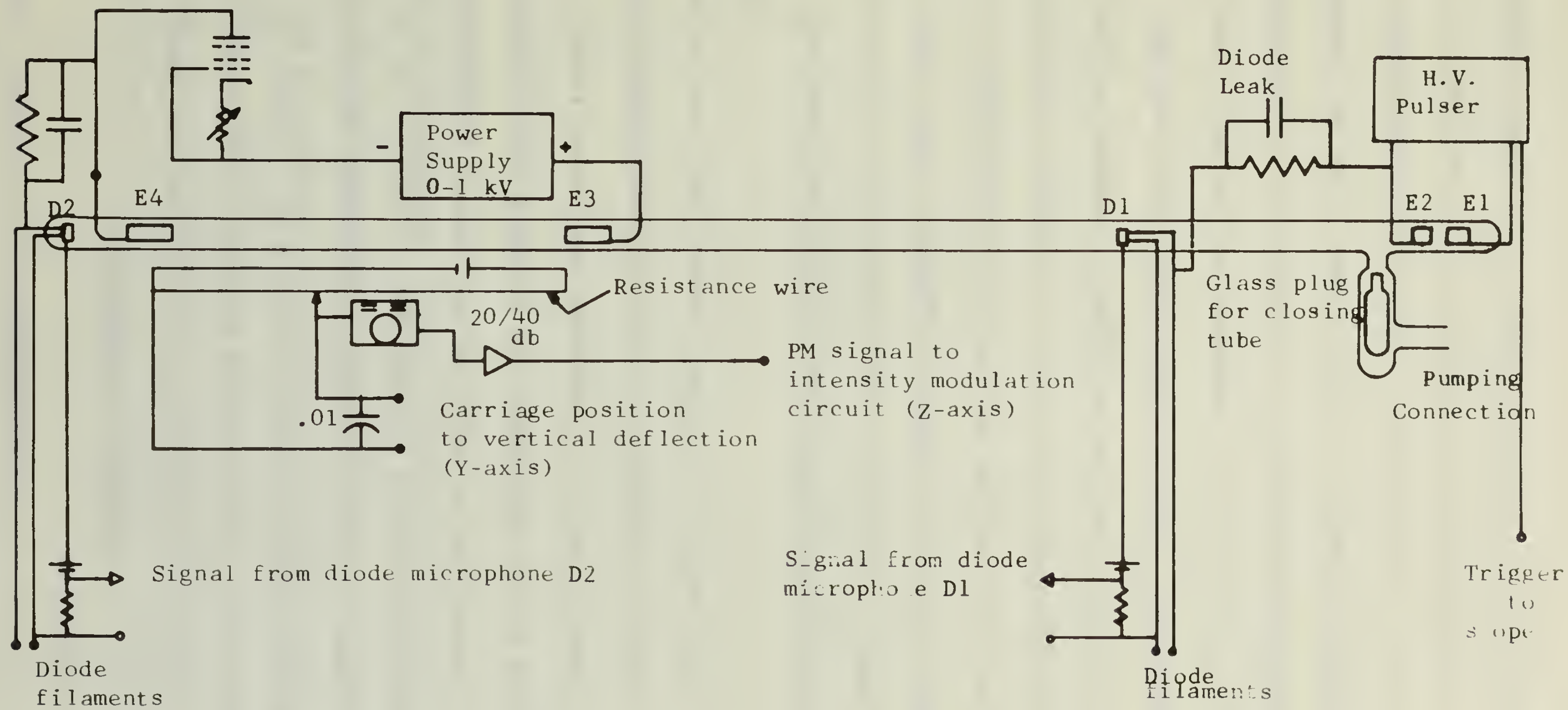
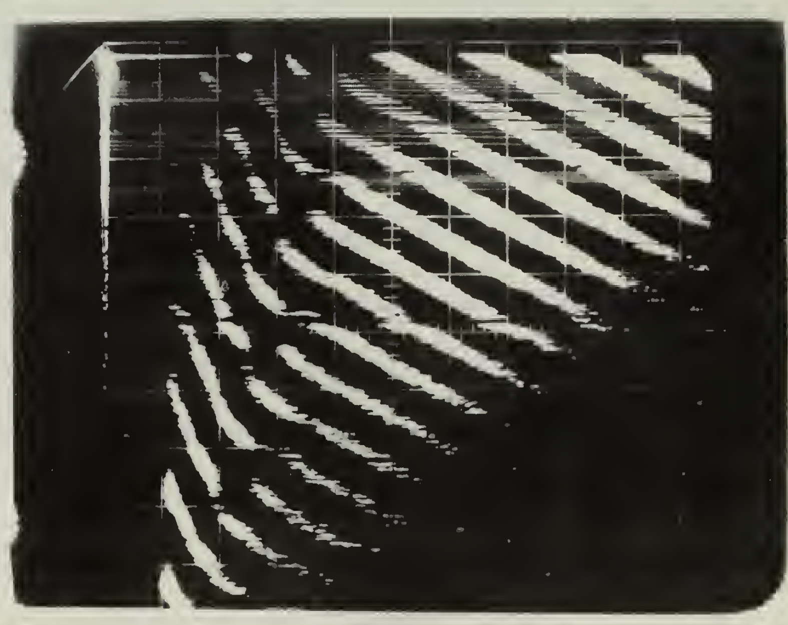


Figure 2-1. Experimental arrangement, showing Z-modulation and diode circuits.

The particular circuitry used here gives oscilloscope beam intensity out of phase with light intensity, so that regions of greater light intensity in the positive column are presented as darkened areas on the scope face. The photomultiplier is mounted on a moveable carriage so that it can be moved parallel to the observing discharge and the vertical position of the oscilloscope trace is made to correspond to carriage position along the discharge by means of a slide wire resistor incorporated in the carriage mounting. Thus with the carriage fixed, a single-line horizontal trace will be seen on the oscilloscope with intensity variation caused by any time variation in light intensity in the discharge. If a camera is used, and the shutter is left open while the carriage is moved slowly from one end of the discharge to the other, a photograph of any striation phenomenon which is coherently related to the sweep trigger will be made. Figure 2-2 is an example of the use of this technique, showing the space-time development of a wave of stratification caused by impulsive modulation of the discharge current.

The acoustic pulses were detected in the two diode microphones. These devices are, in essence, simple thermionic diodes with cylindrical anodes of 1 cm diameter and 1 cm length and cathodes made (in this case) from a single strand of 3 mil thoriated tungsten wire suspended on the axis of the anodes. The use of thermionic diodes as microphones, first noted by Dayton, et. al., (8) gives increased sensitivity over piezo-electric or capacitance microphones in the 1-10 torr pressure range and provides ease of handling in the high temperature baking of the vacuum system, which is required to ensure purity of the discharge. The diodes are operated in a partially mobility-limited regime, thus

Anode



Cathode

Figure 2-2. Time-space development of light intensity in a previously homogeneous positive column, following impulsive perturbation of of the discharge current.

density variations in the acoustic pulses cause corresponding changes in the conductivity of the diode which appear as current variations in the anode circuit. The equation governing the diode current is

$$i = A(\mu)V^m , \tag{1}$$

where V is the plate voltage and $A(\mu)$ is a constant involving the mobility. The parameter, m, varies from 1.5 to 2.0 as quiescent gas pressure increases, reflecting the change from the Child-Langmuir law (space charge limited) to the mobility limited region. In this latter region, since the mobility is a function of neutral gas density, the relation between current and density may be written as

$$i = \frac{a}{\rho^k} , \tag{2}$$

The diodes were calibrated by plotting current as a function of pressure with fixed plate voltage. Since pressure and density are related by the ideal gas law for this static calibration, equation 2 is also the relation between current and pressure. Thus, the slope k found from the static calibration curves, figures 2-3 and 2-4, may be applied to equation 2. If fractional current changes are read as voltage variations across the load resistor R we have the following relation:

$$\frac{d\rho}{\rho} = -\frac{di}{k i_0} = -\frac{dV}{k R i_0} . \tag{3}$$

In contrast to this quasi-static calibration relation between density and pressure, the pressure and density are considered to be related adiabatically in the acoustic pulse of infinitesimal amplitude.(9) Thus

$$\frac{P}{\rho^\gamma} = \text{const.} \tag{4}$$

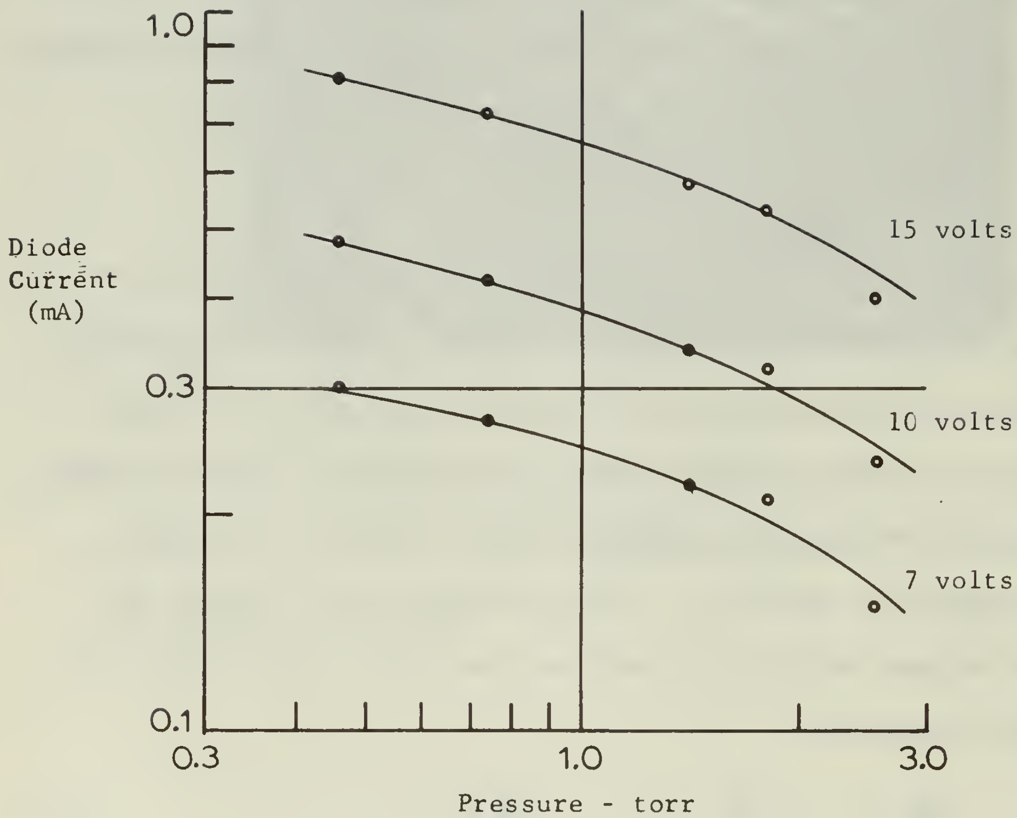


Figure 2-3. Diode plate current as a function of pressure for constant plate voltage. Calibration for diode D1.

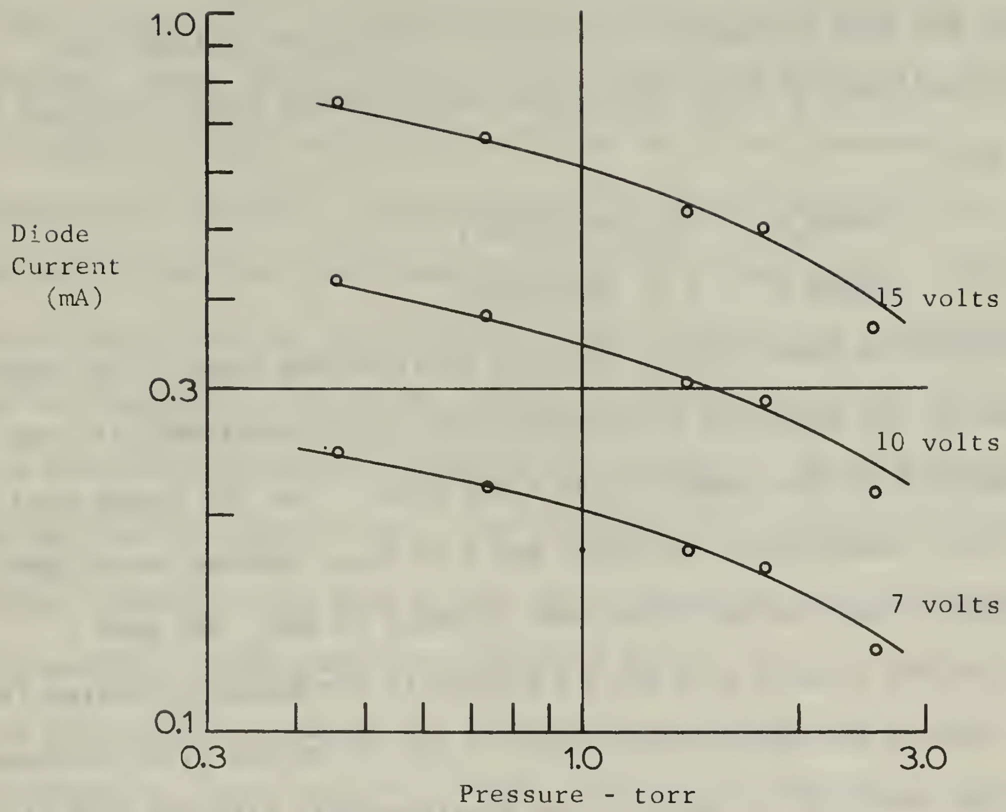


Figure 2-4. Diode plate current as a function of pressure for constant plate voltage. Calibration for diode D2.

and

$$\frac{\delta p}{p} = \gamma \frac{\delta \rho}{\rho} , \qquad (5)$$

so that the sensitivity of the diode can be derived from

$$\frac{\delta p}{p} = \gamma \frac{\delta V}{K R i_o} , \qquad (6)$$

giving

$$S = \frac{dV}{dp} = \frac{K R i_o}{\gamma p} . \qquad (7)$$

From the data in figures 2-3 and 2-4; using plate voltage 15V, R = 1000 ohms, p = 1.0 torr; diode sensitivities were calculated to be:

Diode D1 S = 107 mV/torr

Diode D2 S = 80 mV/torr

It should be noted that an accurate oscilloscope trace of the waveshape of the sound may be obtained only if the wavelength is long compared with the length of the diode plate. For the diodes used in these experiments, the plate was 1 cm long, leading to an upper frequency limit on the sound wave of about 40 kHz. For good resolution, a limit of 4 kHz (λ = 10cm) is a reasonable working limit.

One of the major difficulties in the use of the diode microphones was the inability to operate them simultaneously with the glow discharge, because there was a marked tendency for breakdown to occur between the anode of the discharge and the diode filament (the filament being at the minimum potential in the diode). In order to avoid this unwanted discharge, total isolation of the power supplies for diodes and discharges was effected. The exciting and observing discharge power supplies were operated from different line sources with "floating" ground in order to eliminate return paths from one to another. The diodes were operated from isolated battery power supplies. In spite of this, breakdown still occurred periodically (about once per second) between the exciting discharge anode E2 and the diode D1, and between the observing discharge electrode E4 and diode D2. This breakdown was visually observed as a glow in the areas described and interfered strongly with the output of the diodes. Since the electrodes at either end of the undesired discharges were electrically isolated, it was apparent that the discharge was caused by an electrostatic mechanism. Under the influence of the nearby high potential, there was negative charge build-up on the diode until the breakdown condition was reached. Upon breakdown, the diode would return to equilibrium potential and charge build-up would begin again. This problem was solved by the inclusion in the circuit of a leakage path for the charges on each of the diodes, so that build-up was limited to a value well below that required for breakdown. The circuit used was the familiar "grid-leak", used in vacuum tube circuits to prevent charge build-up on the grid of the tube, consisting of a 10k resistor with parallel .02mfd capacitor connected between the low potential side of the diode filament and the nearest discharge anode. Thorough investigation showed that the "diode leak" had no observable effect on the operation of the discharges or of the diodes, other than the suppression of the unwanted breakdown. Figure 2-1 shows the circuits used for simultaneous generation of acoustic pulses, observation of acoustic pulses in diodes D1 and D2, and observation of waves of stratification in the observing discharge.

The investigation into the possibility of amplification of sound pulses in the positive column (plasma) was carried out in a second discharge tube, constructed especially for that purpose. This second tube (tube II) was similar to the first (fig. 2-1), but was of 41mm diameter (vice 25mm) and the observing discharge electrodes were modified. The diameter was increased in order to decrease the attenuation of the sound pulses so that net amplification would be more readily observed. The discharge electrodes were modified in an attempt to achieve increased current and so increased current and ion density in the positive column. The electrodes in tube I became alarmingly hot when operated above 100ma and this caused the walls of the glass tube to become very hot. New electrodes were constructed as shown in figure 2-5. It was hoped that this design would give increased current with lower operating temperature because of the increase in surface area and would reduce the high local temperature at the edges of the cylinder by greatly increasing the available effective "edge". A discussion of the performance of these electrodes is given in Chapter V.

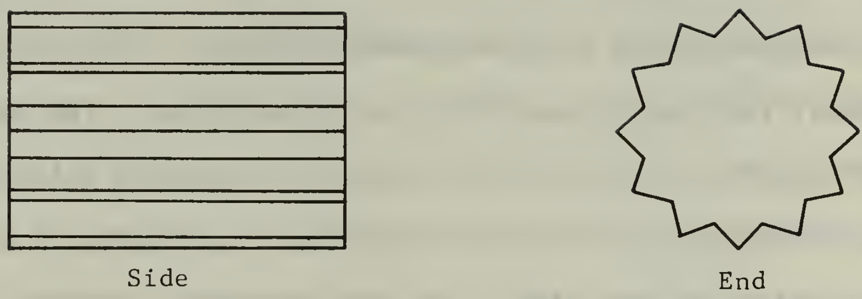


Figure 2-5. Sketch of discharge electrode design for discharge tube II. Electrode formed from 5 mil sheet tantalum. Nominal diameter, 30 mm.

CHAPTER III

ANALYSIS OF THE ACOUSTIC PULSES

Acoustic pulses were observed in tube I (fig. 2-1). Crandall, using this same tube, had observed a variation in the arrival times of pulses at the end of the tube opposite the exciting discharge. With the oscilloscope sweep triggered by the pulse trigger, it was observed that the higher intensity pulses arrived at the receiver somewhat earlier, leading to the hypothesis that the propagation velocity was greater for the higher amplitude pulses. Since a variation of sound velocity is not a characteristic of small amplitude sound waves, Crandall had suggested the inclusion of the second diode microphone, so that the acoustic pulses might be analyzed and a determination of their specific character made. This analysis was made in the following manner:

a) The time of flight between diodes D1 and D2 was measured for several pulse intensities.

b) The speed of sound was measured experimentally and compared to that calculated for small amplitude acoustic waves.

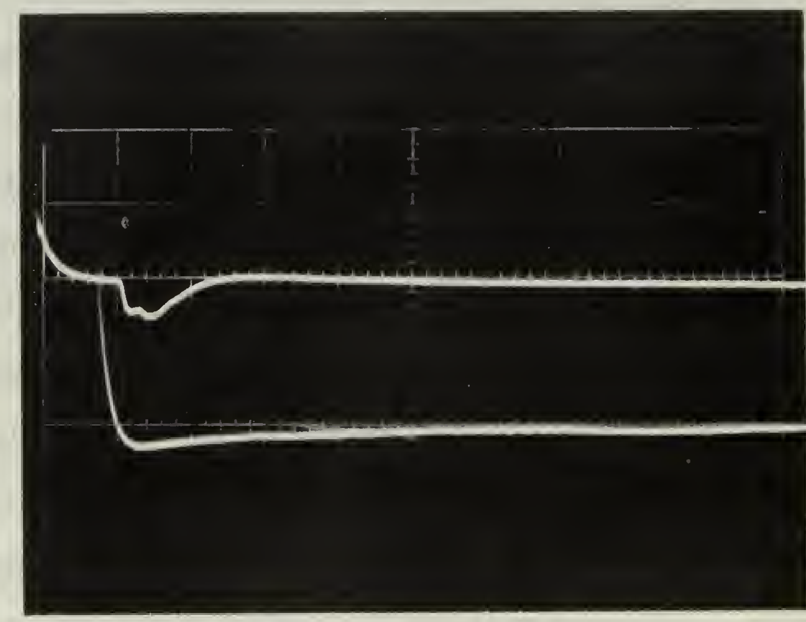
c) The attenuation was measured and compared with the theoretical value.

d) The waveforms were examined to see if any steepening took place during the propagation.

e) The shock-formation distance was calculated and compared with tube length.

Initial observations disclosed a significant variation in the amplitude and waveshape of the acoustic pulses depending on the pulse-repetition-rate (PRR) selected. Figure 3-1a shows the wave at D1 with a PRR of ten per second. Figure 3-2a shows the wave observed when the pulser was manually triggered with at least five seconds delay between pulses. Qualitatively, it is seen that the non-repetitive pulse is nearly four times as great in amplitude and that the rise time of the leading edge of the pulse is less, indicating an increase of high frequency components in the Fourier spectrum. Since it was desired to examine the maximum amplitude pulsed available from the source in order to detect possible non-linear effects, the non-repetitive pulse trigger was used in all subsequent investigations. It was also observed that the wave shape was somewhat dependent upon the voltage applied to the exciting discharge, higher voltage giving slightly steeper wave forms (see figures 3-2a and 3-3a) and that the peak pressure at D1 was not linear with applied voltage.

Figures 3-2 and 3-3 are oscilloscope photographs of the sound pulses observed at diodes D1 and D2. Figure 3-2 shows the pulse at both positions with 2kV applied between the electrodes E1 and E2. Figure 3-3 shows the pulse with 3kV applied. A dual trace oscilloscope was used with the horizontal sweep triggered simultaneously with the high-voltage pulse generator. The large deviation in vertical displacement prior to 0.5 millisecond is caused by an electrostatic interaction between the HV pulser and the diodes. That this interaction is electrostatic was verified by operation of the pulser and diodes with tube pressure at 3×10^{-7} torr and at this pressure, with no exciting discharge and essentially no gas as a medium to support current flow or acoustic propagation, the same



a

b

Figure 3-1. Acoustic pulses due to 2kV pulser voltage.

a) Acoustic pulse detected in diode D1. Pulse-repetition-rate is ten per second. Time scale .5 ms per division. Vertical scale .5 mV per division.

b) Diode D2 signal. Vertical scale .5 mV per division.

a

b

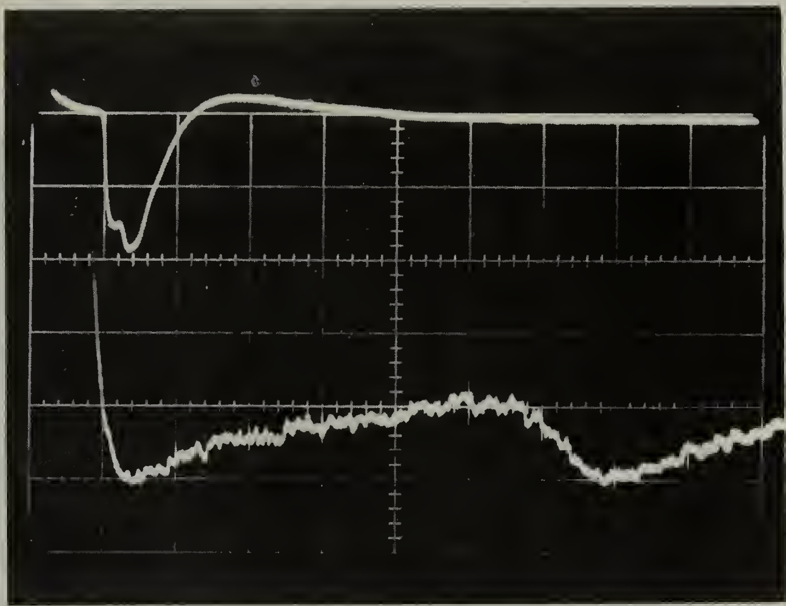


Figure 3-2. Acoustic pulses due to 2kV pulser voltage.

a) Acoustic pulse detected in diode D1. Pulse manually triggered. Time scale .5 ms per division. Vertical scale .5 mV per division.

b) Acoustic pulse detected in diode D2. Vertical scale .05 mV per division.

a

b

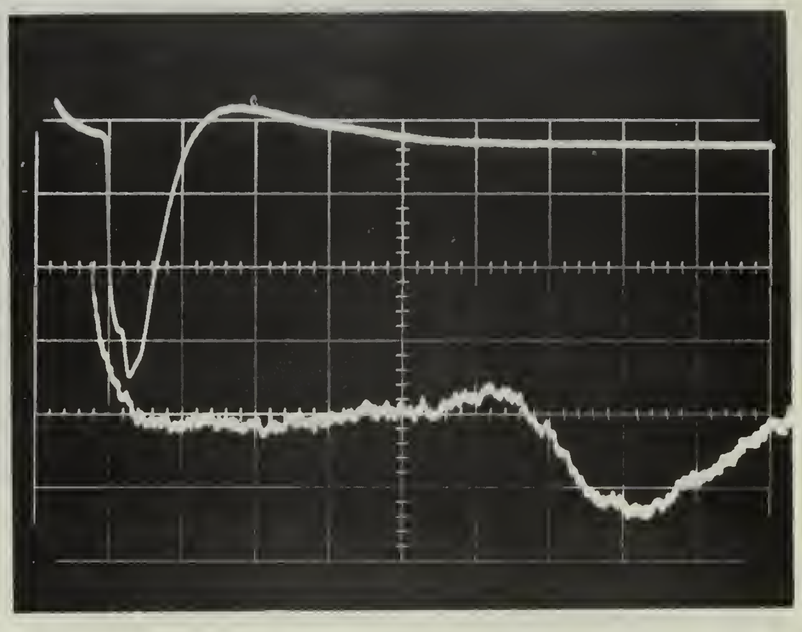


Figure 3-3. Acoustic pulses due to 3kV pulser voltage.

a) Acoustic pulse detected in diode D1. Pulse manually triggered. Time scale .5 ms per division. Vertical scale .5 mV per division.

b) Acoustic pulse detected in diode D2. Vertical scale .05 mV per division.

vertical deflection prior to 0.5 millisecond was seen. If the initial vertical deflection of each acoustic pulse is used as the reference, the speed of sound calculated from the pulses in figures 3-2 and 3-3 is about 430 metres per second and is the same, within the resolution capability of the diode, for both pulses. Indeed for all values of pulse voltage, from 1 to 6 kV, the same speed was obtained. Using the adiabatic approximation, which is so closely associated with small amplitude acoustic phenomena that it is virtually definitive, the sound velocity is obtained from (9)

$$c = \sqrt{\frac{\gamma p_0}{\rho_0}} , \qquad (8)$$

where p_0 and ρ_0 are the quiescent pressure and density respectively. From equation 8, the acoustic velocity in neon at 1 torr and 20°C is 444 m/s. This figure agrees with the experimental value within the resolution capability of the photographic data.

The observed attenuation of the peak pressure in the pulses was approximately -23.8 db over the 114 cm travel of the pulses. A Fourier spectrum of the waveform of figure 3-3a was obtained. The pulse was approximated by a sinusoidal pulse, the half period of the sinusoid being 0.5 ms, and the Fourier integral was solved. The spectrum showed that the major Fourier component was 2 kHz, and all other frequency components were small with respect to this fundamental frequency. Therefore, it was decided to approximate the pulse by 2 kHz for calculation of attenuation, as the primary interest was to establish order of magnitude correspondence between observation and calculation. At the pressure of these observations, wall losses dominate bulk losses in the attenuation constant.(10)

As a good approximation, the pressure attenuation constant may be written (5)

$$\alpha \approx \frac{1}{d}\left[2\left(\frac{\omega}{c}\right)\left(\frac{\eta}{\rho c}\right)\right]^{1/2}, \tag{9}$$

where d is the tube diameter, c is sound velocity from equation 8 and η is the coefficient of viscosity. This may be further reduced to

$$\alpha \approx \frac{1}{d}\left[2\left(\frac{\omega}{c}\right) \ell_m\right]^{1/2}, \tag{10}$$

where ℓ_n is of the order of the mean free path of the neutral particles. (5) Then, solving equation 10, with $\omega = 4\pi \times 10^3 \text{ sec}^{-1}$, d = 2.5 cm and $\ell_n = 5 \times 10^{-3}$ cm, the attenuation constant is $\alpha = 2.14 \times 10^{-2} \text{ cm}^{-1}$. Using this value, the attenuation over 114 cm will be -21.2 db. It was felt that the agreement, in sound velocity and attenuation, between observation and theory served to validate the procedures and approximations.

Examination of all oscilloscope data showed no tendency toward steepening of the pulse as it propagated.

In order to examine the likelihood of occurrence of shock formation, the experimental attenuation data were used to extrapolate the sound pressure pulse observed at D1 back to the source. A calculation of the shock formation distance (without attenuation) was made. Once this distance was calculated, the effect of attenuation was considered in a qualitative way. (Attenuation can only increase the shock formation distance).(11) For the wave of figure 3-3a, the peak pressure deviation is .0145 torr. Using the experimental attenuation constant, the extrapolated peak pressure at the source, 30 cm away, was .0276 torr. The shock formation distance is given by (11)

$$x_s = \frac{2c}{\omega(\gamma+1)}\left(\frac{1}{M}\right), \tag{11}$$

where M is the Mach number. The Mach number may be obtained from

$$M \approx \left| \frac{\rho_o}{\rho} - 1 \right| \tag{12}$$

$$\approx \left| \left\{ \frac{p_o}{(p + p_o)} \right\}^{1/\gamma} - 1 \right| . \tag{13}$$

Then

$$x_s \approx \frac{2c}{\omega(\gamma+1)} \left| \left(\frac{p_o}{p + p_o} \right)^{1/\gamma} - 1 \right|^{-1} , \tag{14}$$

where p_o is the ambient pressure and p is the acoustic pressure. Solution of equation 14 for the pressure and frequency of this experiment yields

$$x_s \approx 5.1 \text{ metres} .$$

Including the effect of attenuation, it may be concluded that $x_s > 5.1$ metres. Since this distance is more than twice the length of the entire tube, the possibility of both formation and attenuation of pulse steepening occurring between the diodes can be ruled out.

From the foregoing, it may be concluded that only small amplitude acoustic effects occur in the discharge. The differences in arrival time of the pulses of different amplitude which were observed by Crandall were most likely not due to differences in propagation velocity. Considering the anomalies observed in the operation of the pulse generator, it seems most reasonable to attribute the observed arrival-time differences to differences in the pulse formation time within the pulse generator circuit itself and perhaps, to a lesser degree, the dispersion of the medium coupled with the noticeable differences in the waveshapes of different intensity pulses (fig. 3-2a and 3-3a).

Of further interest in the analysis of the acoustic pulses and their interaction with the positive column is the phase difference between pressure and condensation which is found in dissipative media. For our experiments, since the attenuation is dominated by wall losses, the phase angle is obtained by considering the effect averaged over the entire cross section. The condensation, or fractional density variation, will lag the pressure by a phase angle θ given by (9)

$$\tan\theta = \frac{\sqrt{2\eta\rho\omega}}{2d\rho\omega} \, . \tag{15}$$

Using the approximations of equations 9 and 10 this may be written

$$\tan\theta = \left[\pi\left(\frac{\ell_m}{d}\right)\left(\frac{\lambda}{d}\right)\right]^{1/2} . \tag{16}$$

Solving equation 16 for the same conditions as previously described, the value obtained is

$$\theta \approx 12.5^\circ .$$

This results in a spatial separation of the pressure and condensation on the order of 1 cm. The significance of this spatial separation of the pressure and condensation will be examined in the following section.

CHAPTER IV

ANALYSIS OF THE ACOUSTIC INTERACTION WITH THE POSITIVE COLUMN

In the previous section it was shown that there exists a phase difference between the pressure and condensation in the acoustic pulse. In keeping with the approximations used, the pressure leads the condensation by a phase angle of approximately 15° for the experiments performed. The work of Pekarek et. al. (12, 13, 14, 15), Vesely (16), and more recently, Sicha et. al. (17) suggests that this phase difference in the acoustic wave may be an important phenomenon in the formation and amplification of the moving striations within the wave of stratification produced by the acoustic pulse.

In seeking the interaction mechanism between the acoustic wave and the plasma, we begin by relating the observations of Crandall to the characterization of the sound wave made here. Crandall mentions the presence of a region of increased light intensity traveling immediately in front of the decreased light intensity region expected in the compressive portion of the acoustic pulse. This region of increased light intensity was always present, but is most clearly evident in his figure 3-6, which is reproduced here, figure 4-1. Examination of Crandall's data shows good correlation between the spatial separation of the increased and decreased light intensities and the calculated spatial separation ($\sim$ 1 cm) of the pressure and condensation in the acoustic wave. Whether it is possible to associate the increase in light intensity leading the pulse with the pressure leading the condensation remains for further experiment to determine. However, if we associate energy of the particles with the thermodynamic

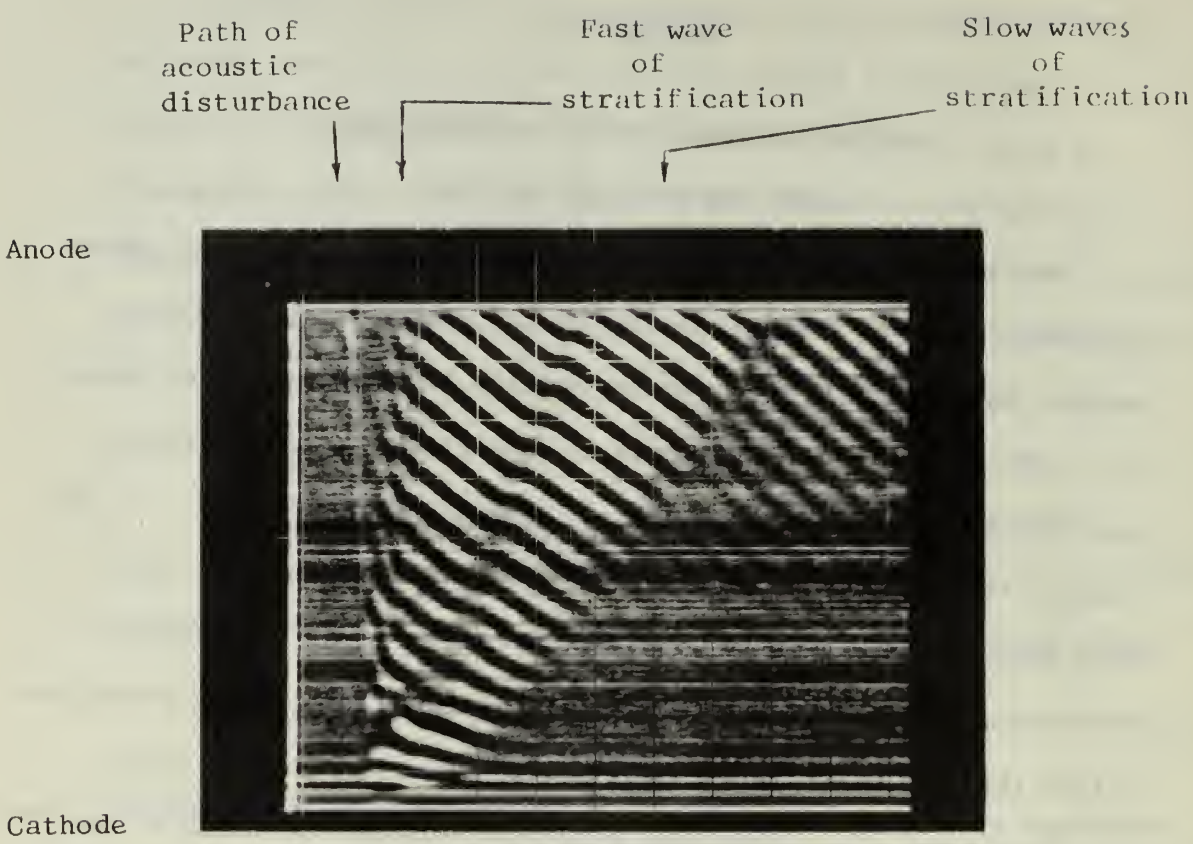


Figure 4-1. Time-space development of light intensity in a 2.2 torr neon discharge at 3.1 ma. Anode to cathode propagation of a compressive acoustic disturbance. Time scale is 2 msec/ division. Thin dark line preceding bright line in acoustic interaction indicates a slight increase of ionization rate.

pressure, it seems reasonable to expect an increase in electron temperature and, correspondingly, an increase in excitation and light output, with a region of increased pressure. It has been observed (4) that the increase in density in the condensation phase of the acoustic pulse reduces light output in the positive column. This may be explained in terms of the increased collision frequency causing a greater rate of energy loss which leads naturally to lower electron temperature and hence to lower excitation and reduced light output. Then, if we assume electron density to follow neutral density we may make the following assertion: as the sound pulse propagates through the positive column from anode to cathode, it will carry with it in the plasma a region of increased electron temperature, spatially separated from a region of increased electron density having a lower temperature. As will be shown, this spatial displacement between electron temperature and concentration is precisely the condition required by the theory of Pekarek for the amplification of the wave of stratification which is observed in the experiments of Crandall. In addition, the phase difference calculated for the sound pulse for our experiments agrees qualitatively and to some extent quantitatively with the phase angles between electron temperature and density observed by Sicha et. al. (17) in moving striations.

Pekarek and Krejci (12) describe the mechanism for production of a wave of stratification by an impulsive perturbation, beginning with three phenomena which have been found to be decisive. These are:

a) the dependence of the ionization coefficient on mean electron energy, and thus on the local electric field,

b) the production of space charges due to different diffusion rates of the charged particles, and,

c) creation of additional electric fields due to creation of space charges.

These phenomena are expressed in the following equations:

a) $$\frac{dn_+}{dt} = Z'_e N_o e \qquad (17)$$

b) $$\frac{de}{dx} = 4\pi \rho_o n_+ , \qquad (18)$$

where

$$n_+ = N_+ - N_o$$

is the deviation of ion density from equilibrium,

$$e = E - E_o \quad , \quad |e| \ll E_o$$

is the electric field perturbation, and

$$Z'_e = \left(\frac{dZ}{dE}\right)_{E_o}$$

is the slope of the dependence of the ionization coefficient Z on the electric field. The positive X direction is from anode to cathode. The solution of this system of equations with an initial ion density perturbation in the form of a step function in space and time gives

$$n_+ \sim \sqrt{\frac{2}{\pi\sqrt{4\pi\rho_o N_o Z'_e}}\,\frac{1}{4\sqrt{-xt}}}\,\cos\left(\sqrt{4\pi\rho_o N_o Z'_e}\sqrt{-xt} - \frac{\pi}{4}\right), \qquad (19)$$

which when plotted on a space-time diagram gives an excellent approximation of the experimentally observed waves of stratification, provided very long or very short wavelength striations are neglected. Now if we make the usual assumption that ion density closely follows neutral density, we may attribute the formation of waves of stratification to the density perturbations caused by the acoustic pulses.

We next desire to examine the condition for amplification of the moving striations and the relationship between this condition and the character of the acoustic pulse. Pekarek and Krejci (13) have described the process of amplification of the moving striations by the inclusion, in the equations of the previous work (12), of terms relating to processes not considered earlier. This leads to a set of more sophisticated equations,

a) $$\frac{\partial n_+}{\partial t} = Z'_\theta N_o \theta - \frac{1}{\tau} n_+ - Z_o n_- \quad (20)$$

b) $$\frac{\partial e}{\partial x} = 4\pi \xi \quad (21)$$

c) $$\xi = \rho_o (n_+ - n_-) \quad (22)$$

d) $$\theta = \frac{1}{C_o} e \quad (23)$$

e) $$n_- = 0 \quad (24)$$

where the notation is the same as equations 17 and 18, but with additional terms; n_-, the deviation of electron density; τ, the mean lifetime of ions; ξ, the space charge; θ, the deflection of electron temperature from the equilibrium T_e; $Z'_\theta = \left(\frac{\partial Z}{\partial T_e}\right)_{T_{eo}} = C_o Z'_e$. Various solutions to this set of equations are obtained assuming a harmonic form for the perturbations. Then the approximation of equation 24 is replaced by

$$n_- = A'_D n_o \sin(Kx + \varphi) \quad (25)$$

and more solutions obtained. It is found that solutions to these equations with an assumed spatial separation of the electric field e and the electron temperature θ are the only solutions which give amplification of the moving striations. In fact, the following statement is made: "the only phenomenon which can lead to amplification of the stratification of the positive column is the space shift of the temperature curve of the electrons with respect to the electric field."

It can be shown that there is an electric field perturbation associated with the neutral density perturbation. We assume that for the acoustic frequencies of our experiments, the ion density closely follows the neutral density. Pekarek and Masek (15) have shown that the electron density does not follow ion density exactly, but is displaced longitudinally a small amount (very much less than the displacement measured between electron temperature and neutral density in the acoustic pulses). This displacement is the result of the differences in diffusion rate between ions and electrons. The result of the displacement is a local electric field perturbation which is phase-separated from the ion density by a small amount (again much less than the phase separation in the acoustic pulses). For our experiments, the position of the electric field perturbation may be considered to be the same as the position of the neutral density perturbation of the acoustic pulse. Thus it appears that the propagation of the acoustic pulse, causing a phase separation between electron temperature and electric field in the positive column, provides, intrinsically, the very condition required for amplification of the moving striations which is observed in the acoustic interaction.

It is of interest to consider here the experimental result which cannot be explained by the theories of Pekarek et.al. That is, that the waves of stratification are produced only at the cathode in the homogeneous column or at the site of standing striations in the inhomogeneous column. The previously mentioned theories are positive column theories and predict production and amplification of striations at any point in the column whenever the correct conditions are met. It remains for further experiment and broader theory to specify the effect of particle density gradients and magnitude of the perturbation upon the production and amplification of the striations.

Vesely (16) measured a phase displacement between intensity of radiated light and electron concentration in moving striations in both helium and neon discharges. In a neon discharge, under conditions similar to those of our experiments, he found that the peak light intensity was displaced from electron concentration by $\sim 12^{\circ}$ with light intensity leading from anode to cathode. This agrees in direction with the phase separation of the acoustic pulse propagated from anode to cathode, but is much less in magnitude. The $\sim 15^{\circ}$ phase angle in the acoustic pulse would represent $\sim 150^{\circ}$ phase angle in the striations, since the acoustic wave length is about ten times the wavelength of the striations. More recently, Sicha (17) has measured this same phase angle and finds that it is $\sim 180^{\circ}$. It may be then, that the acoustic pulses of our experiments, when propagated from anode to cathode, arrive at the cathode and create a phase separation in electron temperature and concentration which is not only correct in direction, but has a magnitude approximately the same as that preferred by the striations. It is noteworthy that Crandall's observations showed that the amplification was less when the pulses were propagated from cathode to anode. Further investigation will be necessary to discover the way in which the characteristics of the sound pulses, including the phase lag and propagation direction, are related to the production and degree of amplification of the wave of stratification. It seems reasonable to assert that such a relationship does exist.

CHAPTER V

EXPERIMENTS RELATING TO THE AMPLIFICATION OF ACOUSTIC PULSES IN THE PLASMA

Ingard (5) predicts the amplification of sound waves by propagation through a plasma. He finds, in solving the acoustic propagation equations for the weakly ionized medium, that the character of the medium introduces energy source terms into the acoustic equations. That is to say, there is a mechanism through which energy may be transferred from the charged particles to the neutral particles in such a way that amplification of the acoustic wave may result. Ingard calculated a condition necessary for net amplification of the acoustic wave, which is

$$\left(\frac{1}{4\gamma}\right)\left(\frac{d^2}{\ell_m \ell_e}\right)\left(\frac{T_e}{T_m}\right)^{3/2}\left(\frac{m_e}{m_m}\right)^{1/2}\left(\frac{N_e}{N_m}\right) > 1 \quad , \qquad (26)$$

where d is the tube diameter; ℓ_n is of the order of the mean free path of the neutral particles; ℓ_e is of the order of the mean free path of the electrons; T_n is the neutral gas temperature; T_e is the electron temperature; m_e and m_n are the masses of electrons and neutral particles respectively; and N_e and N_n are the concentrations of the electrons and neutral particles in the plasma.

An attempt was made to observe amplification of the acoustic pulses in tube I. No amplification was observed, but an examination of equation 26 shows that the conditions in tube I were probably not correct for such an observation to be made. Equation 26 represents the requirement that the ratio of the amplification constant β to the attenuation constant α must be greater than one for net amplification to occur.(5) In tube I, the region in which the discharge or plasma was generated represented approximately one-third of the acoustic wave travel distance between diode D1 and diode D2. Since only the amplification constant β is a function of the plasma parameters, and the attenuation constant α is dependent only upon neutral gas parameters and boundaries, it was apparent that we required the ratio $\beta:\alpha$ to be greater than three in order to observe net amplification. Equation 26 was solved using this criterion. Each of the terms in equation 26 was a known constant for the conditions of our experiment, except for N_e/N_n which, in the absence of Langmuir probe measurements may be approximated only to within two orders of magnitude. The ratio may be written

$$\frac{N_e}{N_m} \sim 10^{-6} \text{ to } 10^{-4} \tag{27}$$

for the conditions of the experiments. The solution to equation 26, under the same experimental conditions yields

$$\frac{N_e}{N_m} > 4 \times 10^{-4} \tag{28}$$

for net amplification. The fact that amplification was not observed, coupled with the low current handling capability of the discharge electrodes in tube I (maximum 100 ma) indicates that for this tube, sufficient electron density was probably not attained.

Tube II was constructed with modified discharge electrodes and greater diameter in an attempt to satisfy the amplification condition. It was hoped that the modified electrodes might permit discharge currents on the order of 500 ma to 1 amp. Since $N_e \propto I$, the increased current would provide the required electron density. Increased tube diameter would also enhance the ratio of equation 26. Unfortunately, the maximum current for tube II was only 200 ma. Even at this current, severe overheating of the electrodes and nearby glass tubing was encountered.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Acoustic interactions with the positive column of a neon glow discharge were studied and analyzed. The theories of Pekarek were used as a basis for the analysis. The interaction mechanism between a compressive acoustic pulse and the homogeneous positive column for the case of anode to cathode acoustic propagation may be described as follows:

a) The acoustic pulse enters the positive column and creates in the plasma phase-separated regions of increased electron temperature and increased electron density which are carried along by the neutral perturbation.

b) The neutral perturbation carries the phase-separated electron temperature and density regions to the cathode, which provide at the cathode the precise conditions required for production and amplification of a wave of stratification.

c) The wave of stratification propagates and is amplified.

The theories of Pekarek are not complete, in that they do not describe the role of the cathode in the above described mechanism. Further experiment is necessary to establish this role.

An unsuccessful attempt to observe amplification of sound pulses in the plasma as predicted by Ingard was made. Failure was attributed to insufficient electron density in the plasma used.

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DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Naval Postgraduate School Monterey, California 93940	Unclassified
	2b. GROUP

3. REPORT TITLE

Acoustic Interaction with the Positive Column of a Neon Glow Discharge

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Thesis, Master of Science, December 1967

5. AUTHOR(S) *(Last name, first name, initial)*

MELVILLE, Richard D. S., Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1967	42	17

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. AVAILABILITY/LIMITATION NOTICES

[redacted]

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

Compressive acoustic pulses were produced by an impulsive abnormal-glow discharge and the interaction of these pulses with the positive column of a dc neon glow discharge was studied.

The acoustic pulses are analyzed and are found to be infinitesimal amplitude perturbations.

The mechanism of the acoustic interaction is described in terms of existent theories of the positive column. It is found that the presence of the acoustic pulse in the positive column creates small spatially-separated regions of increased electron temperature and electron density, which move through the plasma in company with the acoustic pulse. It is shown that amplification of the wave of stratification produced in the interaction may, in many cases, depend upon this spatial separation phenomenon.

An attempt was made to observe amplification of the acoustic pulses caused by their propagation through the plasma.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Glow discharge						
Positive column						
Moving striations						
Stratification						
Wave of stratification						
Plasma						
Acoustic						
Acoustic Interaction						
Diode microphone						

[redacted]