ACOUSTICALLY ENHANCED MULTICHANNEL SPARK GAP SWITCH

James P. O'Loughlin
Captain Jack D. Sidler
Captain Peter M. Ranon
Air Force Weapons Laboratory
Kirtland Air Force Base, NM 87117-6008
(505) 844 0121

ABSTRACT

The inductance of a gas switch is reduced by causing it to operate in a multichannel mode. The reduced inductance is desirable to increase the switching speed. Normally, multichannel operation is achieved by careful alignment of the electrodes, use of special gas mixtures and by application of a trigger which is faster than the arc channel formation time.[1] Under normal circumstances multichannel formation is of a somewhat random and unpredictable nature. By establishing an acoustic standing wave along the electrodes the molecular number density is modulated at a precise number of positions corresponding to the nodes of the standing wave. By synchronizing the trigger with the density modulation very predictable multichannel performance and other advantages are obtained. The electrical breakdown of the gas is determined primarily by the ratio of the electric field (E) to the molecular number density (N), i.e. E/N. In conventional gaps the sites where the emission initiates on the cathode are established by the fact that the cathode surface has small irregularities resulting in local E field enhancement. The gas pressure is static so N is the same everywhere. The resulting local E/N enhancements induce the initiations at these sites. The discharge erodes the cathode surface and thus the number and location of these enhanced sites are random. An experimental rail gap was constructed with acoustic drivers at each end. The drivers were powered with a dual channel audio amplifier rated at 200 watts per channel up to 20 kHz. Experiments were conducted at ambient air density using both DC and pulse excitation of the gap electrodes. It was found that a driver excitation power of less than 10 watts per channel was sufficient to establish absolute control of the position of the arc channel. The position of the standing wave node was controlled by changing the drive frequency or the phase between the drive amplifier channels. By applying a continuous phase modulation between the drivers it is possible to cause a gliding of the arc channel along the electrodes and thus establish a more uniform erosion rate and thus a longer electrode life. The gliding arc channel also should improve the recovery time of the switch.

INTRODUCTION

Shown in Fig.1 is a rail gap switch which has an acoustic driver loacated at the end of the enclosure and an acoustically reflecting termination or a second driver at the other end. When an acoustic wave of a given frequency is impressed by the driver an acoustic standing wave will be established along the rail gap electrodes. This standing wave is by definition the interaction between the forward wave propagating from the driver and the wave from the termination end which is propagating in the opposite direction. The standing wave has nodes which are spaced along the electrodes at a distance of one half of the acoustic wavelength. By adjusting the frequency such that an integral number of half wave lengths are included between the driver and opposite end, the standing wave is optimized. If the gap is triggered or overvolted in synchronization with the standing wave pressure minima at the nodes, then arc channels will be preferentially induced at these node locations. The improved implementation using two drivers, one at each end of the rail gap enclosure, is also shown in Fig.1. By controlling the relative phase of the two drivers as well as the frequency, both the number and the location of the standing wave minima, and thus the arc channels, can be precisely located and/or caused to move along the electrodes.

THEORETICAL ANALYSIS

In a gas, such as air, the relation between pressure and volume due to acoustic modulation is taken to be adiabatic and is expressed as:

$$p\,V^{g} = K = \text{(constant)} \qquad (1)$$

where:
p = pressure (in volume V)
V = volume increment
g = ratio of specific heat at constant pressure to the specific heat at constant volume

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The inductance of a gas switch is reduced by causing it to operate in a multichannel mode. The reduced inductance is desirable to increase the switching speed. Normally, multichannel operation is achieved by careful alignment of the electrodes, use of special gas mixtures and by application of a trigger which is faster than the arc channel formation time.]1] Under normal circumstances multichannel formation is of a somewhat random and unpredictable nature. By establishing an acoustic standing wave along the electrodes the molecular number density is modulated at a precise number of positions corresponding to the nodes of the standing wave.

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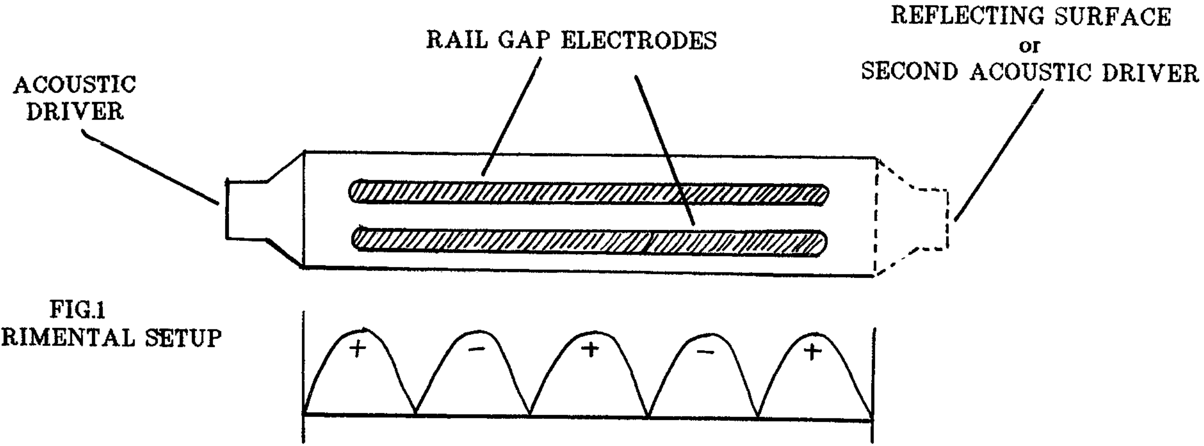

FIG.1
EXPERIMENTAL SETUP

If the number of molecules in the volume V is constant then the molecular density is inversely proportional to V and is related to the pressure as:

(2) $$RHO = \text{constant}\ \ (p)^{1/g}$$

where: RHO = the molecular density
g = as above (about 1.4 for air)

A density change of about plus or minus 20% corresponds to a pressure change of about plus or minus 28.5%. There is a nonlinearity at this level which is less than .5% and is negligible for the purpose at hand. In fact for most of our work here a linear approximation is sufficient:

(3) $$RHO/RHO_o = p/(g * p_o)$$

The pressure due to plane acoustic waves propagating in the x (+/−) directions is given by:

(4) $$p(x,t) = \mathrm{Re}[p+ \exp(jk(x-ct))+ p- \exp(jk(x+ct))]$$

where: p^+ = pressure of the + x wave
p^- = pressure of the − x wave
k = wave number
c = speed of sound
t = time

In Fig.1 a rail gap is shown enclosed in a tube with an acoustic driver at one end and a reflecting wall or driver at the other. The entire structure is made of highly acoustic reflecting material such that a strong standing wave is established with a minimum of acoustic power input required from the driver. Typically metals, glass, plastics and such materials have acoustic absorbtion coeficients of about .02 (energy) in the audio spectrum. This corresponds to a pressure reflection cofficient, R, of about .99. If the initial pressure from the driver is p^+ then the amplitude of the first reflection will be $R*p^+$, with no phase reversal. If the length of the structure between the driver and the end wall is an integral number of wavelengths, then the reflection of the wave from the driver will be in phase with the driver and it will have an amplitude of $R*R*p^+$. In the limit the sum of all such reflections becomes:

(5) $$p(x,t) = p^+(\exp(jk(ct-x))+R \exp(jk(ct+x)))/(1-R^2)$$

Thus there is a "Q" of the structure which causes an increase in the pressure level due to the standing wave which is equal to the factor $(1+R)/(1-R^2)$ or about a factor of 100 for a R=0.99. The actual acoustic power delivered by the driver is thus 40 dB less than the power required to establish the same pressure level if the wave were a plane wave propagating in one direction.

The intensity, or watts per square meter, of a plane wave is given by:

(6) $$I = (p^+)^2/(2\ \ RHO\ \ c)$$

where: RHO = mean density of the gas
c = speed of sound
I = intensity, watts / sq meter

For a configuration as in Fig.1 the power intensity of the driver is given by:

(7) $$I_D = \frac{A(p_o)^{3/2}(1-R^2)S^2}{(2(1+R)RHO_o^{1/2})}$$

where:
I_D = driver, watts / sq meter
A = density relative to STP (Amagat)
p_o= STP pressure, 100,000 n/sq meter
g = 1.4 (air)
S = density modulation percentage
RHO_o = STP density, 1.29 kg/cu meter
R = reflection coefficient

Equation (6) is plotted in Fig.2 for a reflection coefficient of R=.99 and a range of S from .01 to .2.

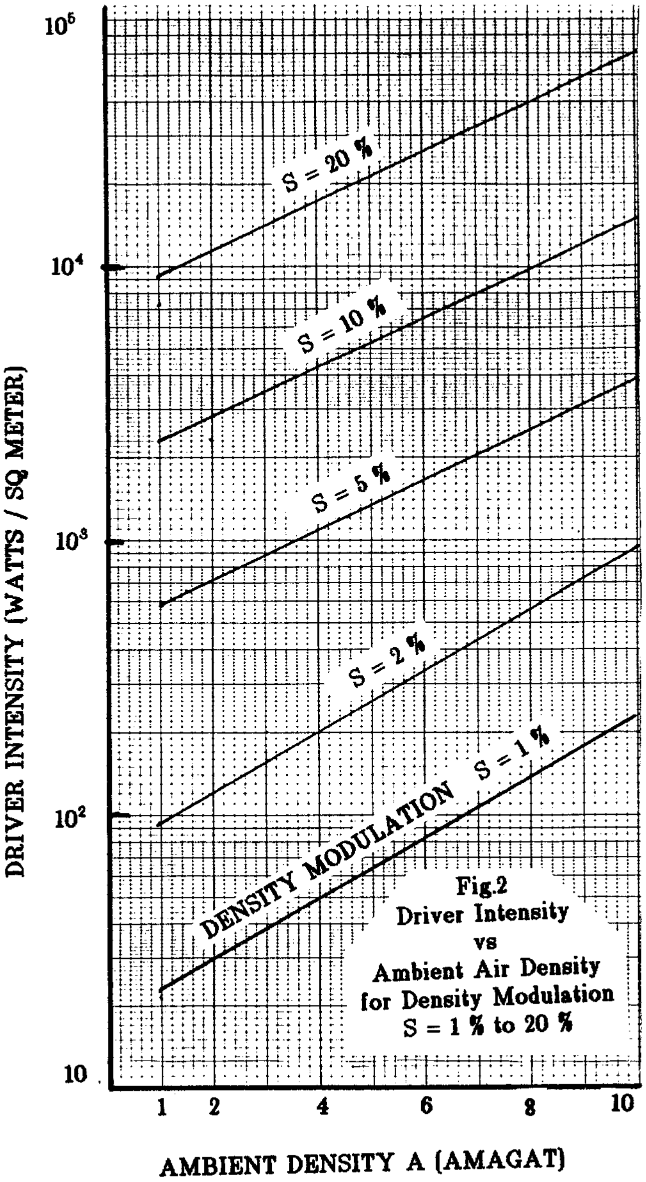

Fig.2
Driver Intensity
vs
Ambient Air Density
for Density Modulation
S = 1 % to 20 %

The electrical breakdown of a gas is directly proportional to the density of the gas [2]. With the density being modulated at the nodes of the acoustic standing wave the breakdown strength will be minimum at the nodes when the density (or pressure) is minimum. If the gap is triggered or overvolted in phase with the density minima then we could reasonably expect that multiple arc channels will form at these minima provided that the density modulation is strong enough. The question, "How strong is strong enough ?, is best answered by experiment. A conventional multichannel rail gap is driven with a very rapidly rising trigger such that the streamer sites on the cathode will be well formed by the time the A–K voltage collapses. The streamer sites in a conventional gap depend upon random irregularities which cause local field enhancements. These enhancments are only near the irregularity and do not extend across the width of the A–K gap. This is in contrast to the acoustically induced density rarefaction which consists of a low density channel across the entire A–K gap. Thus we expect that the same result in terms of arc channel formation will occur at a much lower value of field to density enhancement for the acoustic case as compared to the conventional case.

EXPERIMENTAL RESULTS

An experimental two electrode rail gap was constructed as shown in Fig.3. A pair of Altec–Lansing Type 908–8B compression drivers are located at each end. The drivers are powered by an Altec–Lansing dual channel type 1270B amplifier rated at 200 watts per channel. The experimental apparatus was acoustically characterized using one of the drivers at a constant excitation of one watt and the other 908–8B driver as a receiving transducer. The measured characteristics over the frequency range from 1 kHz to 4 kHz is shown in Fig.4. The highest Q resonance was observed at 1600 Hz which coresponds to two and one half wavelengths (51.7 cm) between the 908–8B diaphragms. With one watt of drive the peak sound level at 1600 Hz was about 157 dB which corresponds to a molecular density modulation of 1.4% peak or 2.8% peak to peak. The standard zero dB sound reference level of 20 micronewtons per square meter is used throughout this paper. The rapid fall off in sound level with frequency shown in Fig.4 was not expected and is attributed to the acoustic resistance of the screen and baffle in the 908–8B drivers. Operation at 1600 Hz (20.7 cm wavelength) provides three nodes on the 25 cm long electrodes. With the drivers operating at 25 watts a density modulation of more than 10% peak to peak is obtained.

The first experiments were done using a d.c. discharge current limited by a 1.0 Megohm resistor. The gap between the 25mm diameter electrodes was set to 2 mm and had a d.c. breakdown threshold of about 4 kV. With the frequency near 1600 Hz the position of the d.c. arc channel could be moved about 2 cm by changing the frequency from 1450 Hz to 1600 Hz.

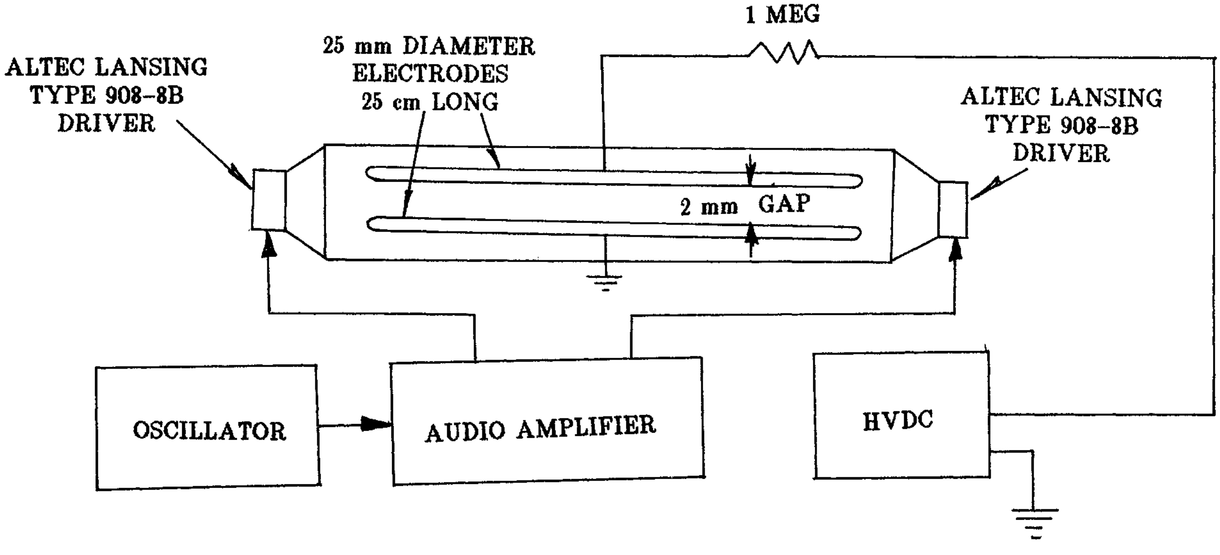

Fig.3
DIAGRAM OF ACOUSTIC EXPERIMENT
using
HIGH VOLTAGE DC CURRENT LIMITED ARC

The percentage position change in wavelengths is about equal to the percentage change in frequency as expected. The control of the arc was very definite with the acoustic drive above 14 watts. The 14 watt drive level is about a density modulation of only 1 % peak to peak. With the voltage slightly above threshold and acoustic drive above 25 watts it was observed that the width of the arc channel could be affected by adjusting the frequency. At about 1650 Hz the arc channel spread to about a 5 cm wide discharge. This same arc spreading was observed at several other frequencies. If then the d.c. source voltage was increased the widened arc channel decreased to about 1 mm; this behavior is not yet understood.

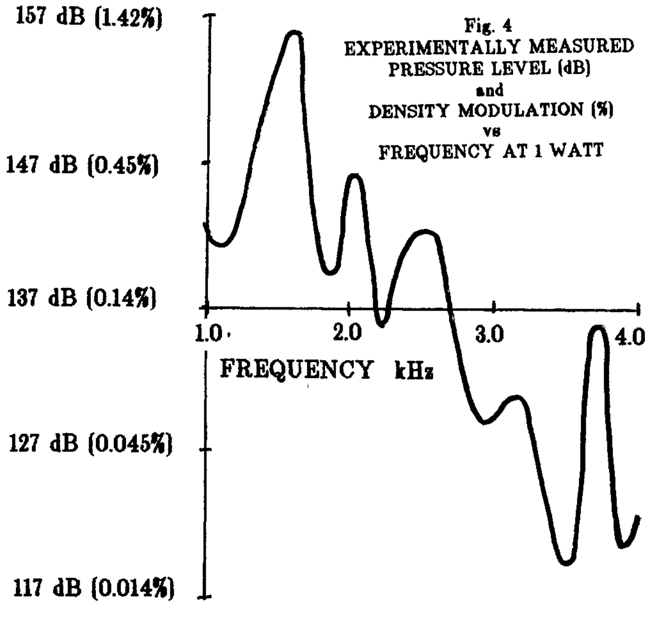

Fig. 4
EXPERIMENTALLY MEASURED
PRESSURE LEVEL (dB)
and
DENSITY MODULATION (%)
vs
FREQUENCY AT 1 WATT

The circuit diagram in Fig.5 was used for pulse experiments. The audio oscillator frequency is counted down by a factor of 1000 and then sent thru a variable delay unit before being used to trigger the thyratron high voltage pulser. Operation at the maximum resonance frequency of 1600 Hz provides for only three nodes on the electrodes. Since adjacent nodes alternate in density maxima and minima, only every other pulse will produce two density minima along the electrodes. The alternate pulses will have only one. Thus when operation was observed at 1600 Hz, two arc channels were not observed with a high degree of consistency but were located at about the expected location of the density minima. Operation at higher frequencies to obtain more nodes on the electrodes produced inconsistent multichanneling and a somewhat random behavior. Since the pressure and density modulation falls rapidly above 3 kHz as shown by Fig.4 and the d.c. experiments indicated a density modulation of about 1.0% (p-p) is required to maintain arc channel control, solid multichanneling is not to be expected with the experimental equipment used.

CONCLUSIONS

The experiments with d.c. excitation demonstrated that absolute control of an arc channel position can be established by acoustic modulation and the molecular density modulation of the gas required for this control is on the order of one percent or higher peak to peak. It was discovered that the particular acoustic driver used in the experiments, Altec Lansing type 908-8b, has a screen and baffle which reduces the reflection coefficient of the driver below .99 at frequencies above about 2 kHz.

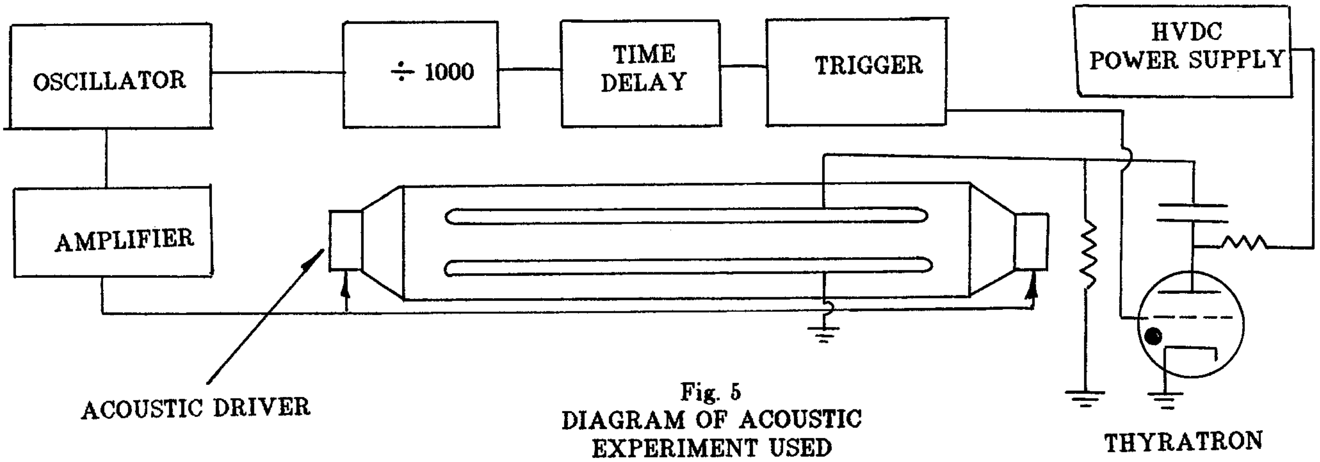

Fig. 5
DIAGRAM OF ACOUSTIC
EXPERIMENT USED
WITH HV PULSE EXCITATION

CONCLUSIONS (CONTINUED)

This reduction in reflection coefficient lowered the acoustic Q of the switch cavity and made it impossible to achieve the required density modulation above 2.5 kHz. The length of the electrode was 25 cm; therefore, for the pulse excitation experiments to have at least two channels on the electrode at all times the frequency must be above 3 kHz. Unfortunatly, it was not possible to demonstrate solid multichannel behavior under pulse conditions with the drivers used. However, it is concluded that the criteria for such pulsed operation has been established as being a density modulation of one percent peak to peak or greater. It is also concluded that this level of modulation is practical and achievable with properly designed drivers. The standard commercial type driver used has acoustic resistance elements which must be eliminated for use in this type of application. Piezoelectric type crystal drivers may also be useful. Implementation of acoustic modulation in future experiments will use specially designed or modified drivers to achieve the density modulation level required at frequencies up to 30 kHz which should provide for multichannel arc spacings of about 10 mm. Future work will also include the use of linear phase modulation between the drivers which will produce a gliding of the density nodes and arc channels. This gliding will reduce the effects of erosion and provide for much longer electrode life. It is also expected that the gliding of the arc channels could improve the voltage recovery time and thus the maximum rep rate capability of the switch.[3]

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[3] J. P. O'Loughlin, "Acoustic Enhancment of Multichannel Spark Gap", Air Force Invention No. 17,986, Weapons Lab Case No. WL 89-137.