Design and Evaluation of Electronic Circuit for Plasma Speaker

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Abstract—A plasma speaker produces sound through an electrical arc. It works by heating air, causing it to expand. This releases a pressure wave, which is heard as sound. Few people know of plasma speakers due largely to its limited availability in the market today for use as a consumer product.

Available plasma speakers can be divided into two categories - hobbyist kits and high quality tweeters. Hobbyist kits require assembly and are not designed for high fidelity sound reproduction. High quality plasma tweeters are very expensive, rendering them unsuitable for use in an average household. In this paper we discuss different types of plasma speakers, and present the electronic design and testing of a low cost plasma speaker. The designed product has two AC plasma arcs visible through clear glass domes. Experimental results confirm that the designed plasma speaker can be combined with an electromagnetic bass speaker to achieve a very good frequency response over the audio band.

Index Terms—Plasma speaker, plasma arc, flyback transformer, modulator

I. INTRODUCTION

Conventional speakers are constructed using a magnet and an inductor (coil). The inductor drives a diaphragm back and forth to produce varying pressure waves. These pressure waves are observed as sound. Conventional speakers have difficulty re-producing square waves accurately because the diaphragm has a finite mass and therefore cannot change direction instantaneously.

A plasma arc speaker operates by heating gas by different amounts to produce a continually fluctuating pressure wave [1]. The electrical arc heats up the air surrounding the arc. The phenomenon follows the ideal gas law (Eqn. 1)

$$PV = nRT \tag{1}$$

where,
  P is the pressure
  V is the volume

n is the amount of air molecules (assumed constant)
R is the universal gas constant, and
T is the absolute temperature.

If the temperature increases, the volume or pressure must also increase. As the arc length is fixed, the volume of the gas surrounding the arc cannot increase. This means that the pressure P must increase. This pressure wave then radiates out from the arc and is observed as sound. At low frequencies the assumption of a fixed number of air molecules is not valid; this leads to a poor low frequency response.

The primary advantage of a plasma speaker for sound reproduction is that there is no diaphragm and therefore no mechanical mass. This means a plasma speaker has the potential to reproduce sound with high fidelity up to 150 kHz [2]. The frequency limitation of a plasma speaker is due to the thermal mass of the gas that is being heated; however this is much lower than the mechanical mass of a paper diaphragm.

There are three types of electrically sustained plasma speakers; these are the DC arc plasma speaker, AC arc and an ion wind speaker [3]. Both the DC arc and AC arc plasma speakers use a high voltage to breakdown the gas between the two electrodes. Once the gas has broken down into a conductive state the current is modulated to release varying amounts of heat to produce pressure waves [4]. The ion wind speaker operates via a different principal. For the ion wind speaker there are two charged electrodes, between them is a strong electric field. Particles that come in contact with the cathode become negatively charged and flow towards the anode. The flow of charged particles can be controlled by varying the strength of the electric field [5].
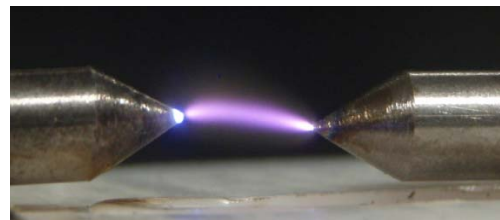

Fig. 1. Fixed arc

The type of speaker designed and investigated in this paper is the AC arc plasma speaker. There are two sub-

types of AC plasma speakers - fixed arcs and Tesla type arcs. Plasma speakers with fixed arcs have two electrodes at a set distance apart and the arc forms between these two electrodes as shown in figure 1. Tesla type arcs operate in a similar way to a Tesla coil, with the arc branching out to the surrounding air as shown in figure 2. For this research project a fixed arc was chosen.
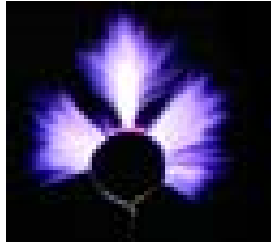

Fig. 2. Tesla style arc [6]

The aim of this research project is to investigate into the design of a plasma arc loudspeaker to produce good quality sound. Additionally, the completed system will have a safe and clearly visible arc.

II. REVIEW OF PLASMA SPEAKERS

A plasma arc speaker is not a new concept, with various products being in commercial production since 1957 [7]. In all of these commercial products the plasma speaker has been used as a tweeter. The plasma arc speakers available today can be classed into two categories; high cost, high fidelity tweeters and hobbyist kit sets.

a) The Hill Type-1 Plasma Speaker [8] that was brought to the market in 1978 used helium as a cover gas in a way similar to a MIG (metal inert gas) welder using argon gas to improve the quality of the electrical arc. Because the product required a periodic refilling of the helium tank, the product never became a commercial success.

b) The Acapella Tweeter [9], shown in figure 3, is a tweeter that is still available today for 18,000 USD. It is stated to have a frequency response of 5 kHz-50 kHz and a max sound pressure level of 110 dB at 1 m [10]. For this tweeter the plasma arc is not a strong aesthetic attraction.

Fig. 3. The Acapella tweeter [10]

c) There are several plasma speaker kit sets available in the market. These kits cost from 80 USD upwards [11].

III. OVERVIEW OF ELECTRONIC CIRCUIT

The functional block diagram of the electronic circuit is shown in figure 4. The circuit has been designed to operate from a wide range of supply voltages, and is be able to operate off the mains voltage with minor alterations to the circuit. Running off the mains voltage would eliminate the need for a large (250W) external power supply. Due to safety requirements the circuit was only tested from supplies up to 48V.
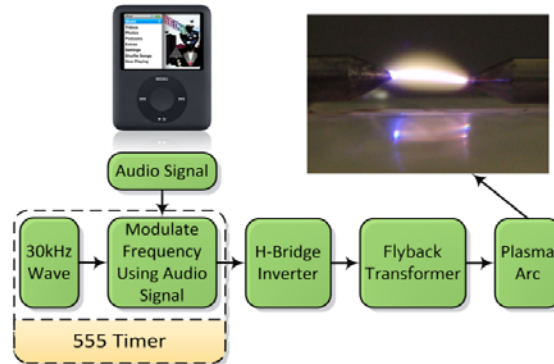

Fig. 4. Block diagram of the circuit operation

The principal of operation is relatively simple. A base frequency of 30 kHz is modulated using an analogue audio input which varies both the duty cycle and the frequency as shown in figure 5. The modulated square wave is used to control the H-bridge driver at 48V. The output of the H-bridge is a square wave which is feed into a flyback transformer to generate a high voltage. A flyback transformer can, in simple terms, be modelled as an inductor - if a voltage is applied to it, the current through it will slowly build up. The time this current is allowed to build up for depends on the modulation of the square wave. After the current has built up, the voltage is switched in direction by the H-bridge which causes a very large rate of change of current through the inductor. As the voltage across an inductor is proportional to the rate of change of current, a very large voltage is produced at the switching point. This large voltage is used to produce a spark.
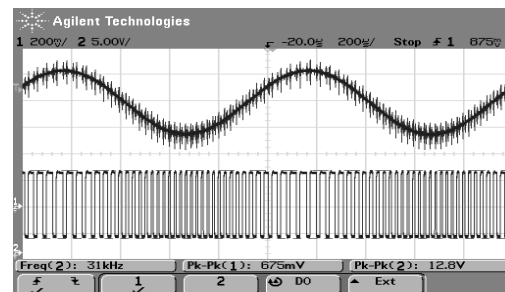

Fig. 5. - Audio input wave (upper) and modulated square wave (lower)

IV. CIRCUIT DESIGN

In this section we present the details of the main components of the circuit.

A. Audio Input

The first stage of the circuit is to control the amplitude of the input. This design has been setup to have an audio input from an MP3 player; this input typically ranges from 0 to 2.5 V and is varied on a logarithmic scale. For modulation of the frequency in the next stage, the audio amplitude needs to range up to approximately 12 V peak-to-peak. The operational amplifier used in the circuit was only capable of generating a positive output voltage from 0 to15 V since a voltage supply of +15 V was used. This means that output should be 7.5 V when the input is 0 V. To achieve this, the ground of the audio input is lifted up using a simple voltage divider bias circuit.

The next stage is the volume control part of circuit. This part of the circuit could be excluded from the design depending on the application. A pull down resistor on the input would still be advisable if no volume control was desired. The volume control implemented on this design was a simple voltage divider as shown in figure 6. The potentiometer had a logarithmic scale as this was more suited to the human hearing response.
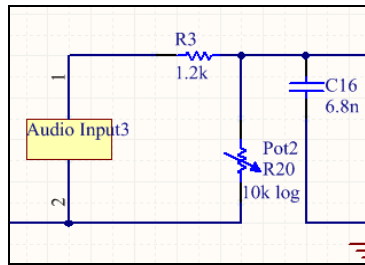

Fig. 6. The volume control on the audio input

B. Amplifier

An operational amplifier is used to amplify the audio signal to the desired level. Volume control cannot be done with this device due to the voltage offset on the audio input. When selecting the gain for the op-amp the audio input offset must be adjusted so that at 0V input the output is approximately 7.5 V (half the supply voltage).
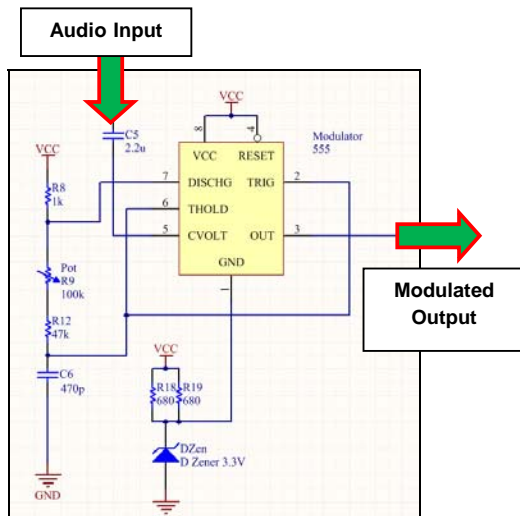

Fig. 7. The Modulator

C. Modulator

The modulator control circuit is one of the most important parts of the circuit; it generates the 30 kHz square wave and modulates it with the audio input. This setup, shown in figure 7, alters the high time of the H-bridge inverter; the low time remains constant. Therefore both the duty cycle and the frequency are affected.

The IC used is a simple 555 timer. If the input to the control voltage is ignored, the circuit can more easily be analysed. C6 is the timing capacitor (470 pF) which is charged from V_{CC} through R8, R9 and R12. C6 discharges through R9 and R12. Since R8 is significantly smaller than R9+R12 the duty cycle is kept very close to 50%. The control voltage input of the 555 timer controls the level at which the capacitor C6 is considered charged (the capacitor on the audio input removes the DC offset). A high control voltage input will mean that C6 is required to reach a higher level before the output is switched low. To reach this higher level the capacitor takes longer to charge thus increasing the high time. If the control voltage is above the supply voltage of the IC the capacitor will never reach this level and the output will remain high. The low voltage level, at which the output is switched high, remains at a constant level regardless of the control voltage input. The low time is increased due to the larger amount of charge stored on the capacitor; the effect on the low time is small compared to the effect on the high time. The result of this is when the control voltage is increased the duty cycle increases, this increase in duty cycle can be calculated using Eqn. 2.

$$Control\ Voltage\ level = V_{cc}\left(1 - e^{-t/RC}\right) \quad (2)$$

where,
  t is the capacitor charging time
  R is R9+R12
  C is the capacitance of C6 and
  V_{cc} is the supply voltage

If the control voltage was to approach the supply voltage, t would approach ∞ and the duty cycle would approach 100%.

D. H-bridge driver

The driver uses 4 MOSFETs in an H-Bridge configuration to provide a high power output at 48 V. The H-bridge is controlled by the modulator circuit. The MOSFETs are driven by an IRFP450 MOSFET driver, which is capable of driving MOSFETs at up to 600 V, i.e. the supply voltage can be up to 600 V. The 48 V square wave is feed into a flyback transformer to step up the voltage. 100nF capacitors are placed in parallel with each MOSFET to protect it from voltage spikes from the flyback transformer. These capacitors caused oscillations with the flyback transformer as shown in figure 8. This however did not appear to have any effect on the audio quality.
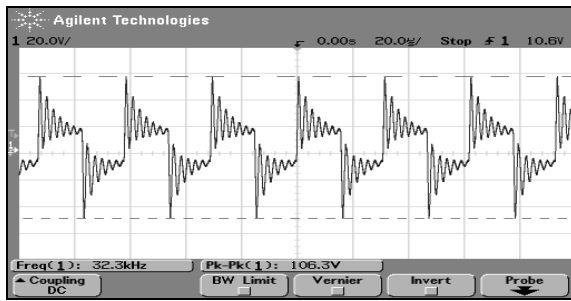
Fig. 8. The voltage waveform across the flyback transformer

E. Flyback transformer

In the design two flyback transformers have been used to produce two plasma arcs, although using only works equally well. A flyback transformer is a loosely coupled transformer with a large ratio of turns.
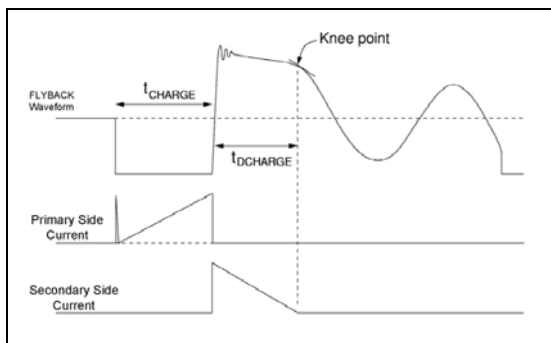

Fig. 9. Flyback transformer waveform [12]

Figure 9 shows how the primary current builds up approximately linearly over time. As this current builds up, the amount of energy stored in the transformer increases. This means that lower the frequency more is the energy stored in the flyback transformer, and more is the energy that is released in the arc. These properties enable the heat output of the plasma arc to be controlled by varying the frequency (or high time) of the input wave. The output wave is rectified and smoothened with a high voltage capacitor (see figure 10).
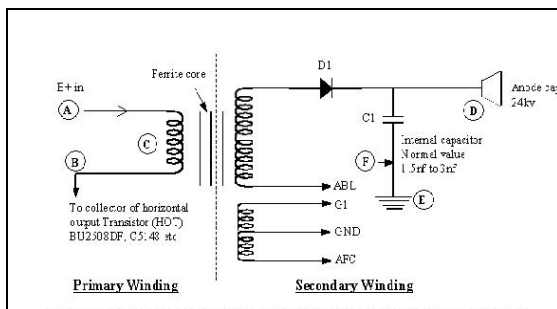

Fig. 10. Internal schematic of a flyback transformer

V.   DESIGN OF ENCLOSURE

As plasma speakers perform better at higher frequencies and poorly at low frequencies, a conventional electromagnetic speaker was used to fill in the lower frequencies. This conventional speaker was located in the lower mid section of the unit.

Fig. 11. The complete product

The two plasma arcs were housed within two glass domes in the top of the unit; the sound was then channelled out through the amplifying horns. (Figure 12) Unfortunately this design was unsuccessful due to the destructive interference caused from the reflection of the sound waves off the inner surface of the dome. There was also a build up of nitrogen dioxide within the glass dome which increased the energy required to ionise the air.
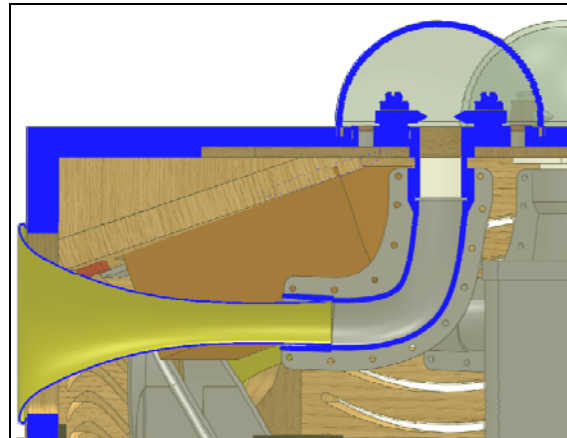

Fig. 12. The plasma arc enclosure system

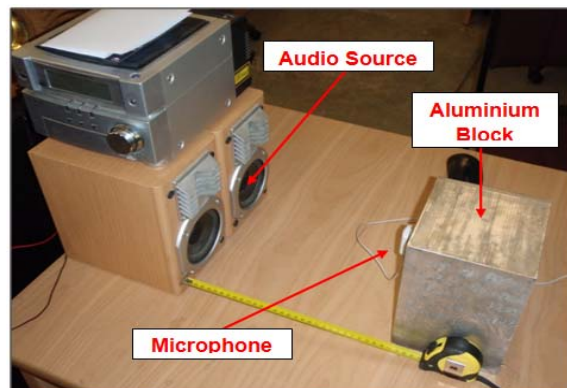## VI.   TESTING

A. Test Setup

Fig. 13. Test setup

Testing was performed on the plasma speaker and a mid-range home stereo system (Panasonic SA-PM03) so that the performance of the plasma speaker can be evaluated against a common consumer audio product.

The tests were done in a quiet room. The plasma speaker unit had two plasma arc speakers and a single electromagnetic speaker to fill in the lower frequencies.

Audio testing was performed using a notebook computer and a microphone. A tone was generated by the computer; this tone was fed into the audio unit. A microphone was connected back to the laptop to analyse the received signal. The tone generated swept through 20 Hz to 20 kHz to analyse the audio reproduction at all audible frequencies. The microphone was placed in front of the unit, 300mm from the front edge (Figure 13). A distance of 300mm was close enough so background noise had a minimal effect, while being far enough so the sound wave was received equally from each of the speakers. All testing was performed using a single channel input.

B. Test Results

Frequency level response and THD (Total Harmonic Distortion) tests were performed. These are standard measurements done to evaluate audio circuits. Figures 14 and 15 show the frequency level response and THD respectively for the Panasonic home audio system while figures 16 and 17 show the frequency level response and THD respectively for the plasma speakers. These tests were repeated for the plasma speaker when combined with the electromagnetic bass speaker and these are shown in figures 18 and 19.
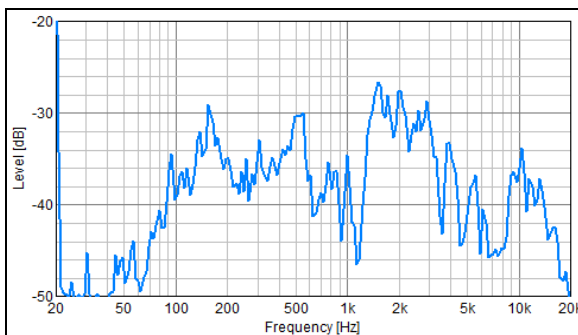

Fig. 16. Frequency level response of the plasma speaker
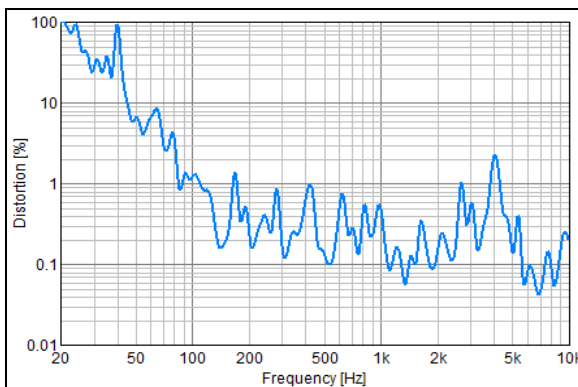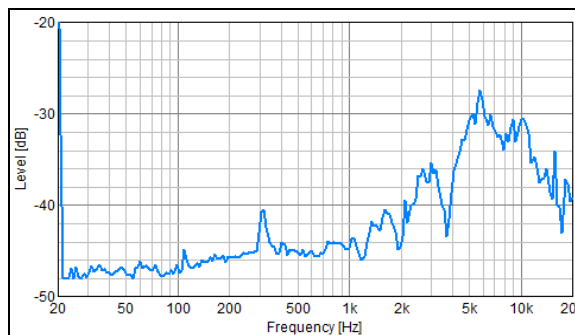

Fig. 17. THD measurement of the plasma speaker

Fig. 14. Frequency level response of the Panasonic SA-PM03

Fig. 18. Frequency level response of the plasma speaker unit combined with the electromagnetic bass speaker
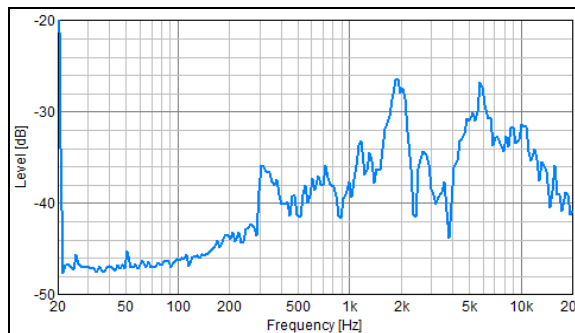

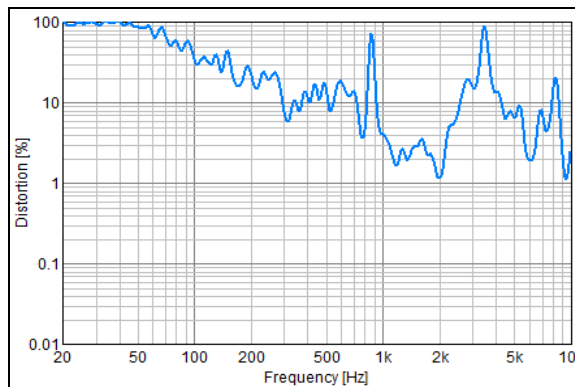Fig. 15. THD measurement of the Panasonic SA-PM03

Fig. 19. THD measurement of the plasma speaker unit combined with the electromagnetic bass speaker

C. Discussions

When the Frequency Level Response is low the THD result is high. This is because the speaker is producing almost no sound and therefore the microphone cannot pick up the tone it expects to hear.

The frequency level response of the plasma speaker (figure 16) shows a strong response in the frequency range upwards of 2 kHz. Above 10 kHz the response decreases, which is attributed to the low pass filter on the amplifier circuit. The low frequency level response is poor. For the THD result of the plasma speaker (figure 17) the THD decreases above 2 kHz but this is still significantly higher than the Panasonic SA-PM03. The plasma speaker reaches 1.2% distortion at best.

The combined system using the plasma speaker and a conventional speaker has a reasonable frequency level response. This shows the combination of the plasma speaker for high frequencies and conventional speaker for low frequencies is a valid concept in terms of frequency level response. However the THD result is high compared to the Panasonic SA-PM03. This is in part due to the electrical interference caused by the plasma speaker to the conventional speakers. The electrical interference with the conventional speaker was observed subjectively. When the plasma arcs were running, a quiet tone was emitted from the conventional speaker, even with no audio input. When the plasma arc was turned off again the tone disappeared. Further research will need to be performed into how much THD is acceptable for this type of system.

VII. CONCLUSIONS AND FUTURE WORK

The plasma speakers were built at approximately 800 USD. This research project has shown the clear opportunity in the market for a plasma speaker at an affordable price. This design however requires further refinement to reduce the THD before it can be considered for commercial production.

A video recording showing the plasma speakers in operation may be obtained by sending a request to g.sengupta@massey.ac.nz.

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