STATIC SPEAKER

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ABSTRACT

Sound is a vibration that propagates as wave of pressure and needs a medium to be transmitted. At first, let's have a look at speakers and see how they work. What we are going to do, is using heat to produce and amplify sound. This approach leads to a phenomenon called "thermoacoustics effect". This effect can be observed in glass blowers, where blowing a hot bulb at the end of a cold narrow bulb produces sound. To investigate the parameters in this phenomenon, our data have been collected and analyzed from several experiments.

Keywords : *Sound Waves, Vibration, Thermoacoustic Effect, amplify Sound*

1. Introduction

Sound is a vibration that propagates as wave of pressure and needs a medium to be transmitted. At first, let's have a look at speakers and see how they work.

As shown in figure (1), it consists of a circular magnet which is the North Pole. Within the cone, there is another magnet which is the South Pole, surrounded by the voice coil. Suspension (spider) supports whatever that is underneath it and allows the cone to move freely up and down.

How does it exactly work?

As we know, there is a magnetic field between the magnets, so if we put in current in the coil, based on the right-hand rule, we will have a force in a direction (upwards or downwards). Now if we change the direction of our current the force will be in the opposite direction of what it used to be. If we continue changing the direction of the current, the voice coil will keep moving up and down as well as the cone. For having this movement, we have to connect the coil to the AC supply so that it can have a particular frequency.

But how can we hear the sound?

As mentioned before, the cone is attached to the coil, so they have an equal vibration. This movement of the cone, pushes the air and makes what it's called "compression waves", and this is actually the sound waves that we can hear.

What we are going to do, is using heat to produce and amplify sound. This approach leads to a phenomenon called "thermoacoustics effect". This effect can be observed in glass blowers, where blowing a hot bulb at the end of a cold narrow bulb produces sound.

2. Theory

Sound is a wave of pressure, which means periodic change in pressure is needed to produce sound. Since common speakers are used in air and the medium is gas in this case, we focus on propagation of sound wave in air without loss of generality. From thermodynamics we know that pressure of a gas is proportional to its temperature for an ideal gas, and depends on temperature in more general case for real gases according to Van Der Waals equation. This is the point, we instead of changing pressure frequently to produce sound, we can change temperature of air near our device and change in temperature will result in change in pressure, so we can produce sound by changing temperature frequently. Increasing temperature of air requires thermal energy to increase internal energy of medium. According to thermodynamics' first law:

$$\delta U = \delta Q - \delta W \tag{1}$$

$$\delta U = V\delta p + p\delta V \tag{2}$$

Where "U" is internal energy of system, "Q" represents heat transferred to the system and "W" is worked done on system.

Thermoacoustics speaker has no moving parts, so if we assume control volume is volume in semi-sphere of radius "r" on top of our speaker, there shouldn't be any mechanical work on boundary, so there will be no works an also no change in volume.

$$\delta U = \delta Q \tag{3}$$

$$\delta U = V\delta p \ (Eq.4) \tag{4}$$

We found out that we need a heat source which can frequently heat up the system and cool it down. We are going to use electrical power and Joule heating effect as heat source. When the current I is passed through a resistor, it makes the resistor hot and the heat coming off the resistor flows out into the air. The energy used by the resistor is converted entirely to heat. As we told before, we don't need to just increase temperature and also need to cool it down and do it frequently. If we use DC current, it just heats up the device and then air, so we can't produce sound in this way. But what if we apply AC current? An alternative current passes through the resistor and power produced is:

$$P = \frac{1}{2}(RI^2 + RI^2\cos(2\omega t)) = P_{DC} + P_{AC} \tag{5}$$

Where, "ω" is frequency of AC current, "P" is power, "I" is maximum current, and "R" is resistance. As you can see, Power consists of two terms, the first term is called "DC power" and the second one is called "AC Power". DC power just heats up the device and as we mentioned before, this power can't produce sound, but AC power can do it. AC power changes with time and doesn't have constant heat production, which means it depends on time. So during a cycle. Air can be cooled through convection so temperature of air decreases when our device AC power is at its minimum value and increases, when AC power is maximum and near it. So what produces sound is AC power and DC power just increases temperature of our device. We need a resistor which has a high thermal effusivity (a measure which says how fast a material can transfer heat) and also be a perfect electric conductor. This resistor should be as thin as possible, if it's not, heat will be transferred by thermal conductivity between layers of resistors and it reduces speed of heat transfer. Heat is also transferred between layers of resistors through its thickness while our goal is to transfer heat to air, in other words resistor is used as a heat sink which needs. Resistor should transfer heat to air and it occurs through convection so it must have a surface to be able to transfer heat through convection better. We offer to use graphene as resistor. But why graphene? Graphene is an allotrope of carbon and consists of layers, in each layer carbon atoms are bonded to each other with covalent bonds and layers are connected to each other due to van der Waals force. So we expect thermal conductivity not to be isotropic and changes with direction. In fact thermal conductivity K reaches about 3000 W m^{1} K^{-1} in the parallel to planes direction, and 5 W m^{-1} K^{-1} orthogonally. So when number of layers decreases, we can assume that heat transfer in graphene occurs only in parallel to plane and we can neglect it. So if we use thin graphene layer, we can assume that as electric current passes through graphene, it heats up graphene and all heat is in a thin layer of graphene and this heat is transferred to air through convection and heat transferred from the surface which is in contact with air is to other layers is negligible, so efficiency increases. Graphene also has a high thermal effusivity which means it can transfer heat faster in comparison with lots of materials.

Heat transferred to the system is summation of heat transferred to graphene and air:

$$\delta Q = \delta Q_a + \delta Q_g \tag{6}$$

also we know that:

$$\delta Q_a = \frac{C_a}{C_a + C_g}\delta Q \tag{7}$$

$$\delta Q_g = \frac{C_g}{C_a + C_g}\delta Q \tag{8}$$

$$C_g = m_g c_{p,g} = \rho_g S d_g c_{p,g} \tag{9}$$

$$C_a = m_a c_{p,a} = \rho_a S d_a c_{p,a} \tag{10}$$

Where C is thermal conductivity in constant pressure, S is surface, d is thickness, c is specific heat capacity and ρ is density and index "a" is for air and g is for graphene. Since surface of air which is in contact with graphene is equals to graphene surface, so we didn't use index for S." d_a" is skin depth of the thermal boundary layer of air and defined as a distance where if temperature of heat source changes, after $\frac{1}{f}$ seconds , air is affected by change in temperature and f is frequency .

$$d_a = \sqrt{\frac{k_a}{\rho_a c_{p,a}}} \tag{11}$$

If we use this in Eq.7 we will have:

$$C_a = e_a . S . \omega^{-\frac{1}{2}} \tag{12}$$

Where "e" is thermal effusivity. We can define effusivity for graphene as:

$$e_g = \rho_g d_g c_{p,g} \sqrt{\omega} \tag{13}$$

Which has same dimension with e_a.

So we have:

$$\delta Q_a = \frac{e_a}{e_a + e_g}\delta Q = \frac{e_a}{e_a + e_g} . \frac{P_{AC}}{f} \tag{14}$$

Using Eq.3, Eq.4 and Eq.14 at the same time will give us:

$$\delta p = \frac{e_a}{e_a + e_g} . \frac{P_{AC}}{f} . \frac{1}{V} \tag{15}$$

"V" is volume of control volume which we defined before as a hemisphere, so:

$$V = \frac{2}{3}\pi r^3 \tag{16}$$

Since wave is sonic, it travels at speed of sound. We want to assume our speaker to be a point source. This requires dimensions of graphene be much smaller than wavelength. So if we want to produce a sound of frequency 100 Hz, speed of sound in room temperature and 1 atmosphere pressure is approximately 300 m/s, so wavelength will be 3 meters and that will be surely much greater than dimensions of graphene we will use. So this can be a reasonable assumption to think of our speaker as a point source. If we assume speed of sound as "Va", then after 1/f seconds, wave will reach the distance "r":

$$r = \frac{Va}{f} \tag{17}$$

$$V = \frac{2}{3}\pi(\frac{Va}{f})^3 \tag{18}$$

$$\delta p = \frac{e_a}{e_a + e_g} . \frac{3 P_{AC} f^2}{2 \pi V a^3} \tag{19}$$

Eq.19 gives us a relation between change in pressure and input power. But it needs correction. As sound wave travels through a medium, its energy attenuates due to viscosity and amplitudes of wave decreases exponentially with distance from point source due to formula:

$$A = A_0 e^{-\alpha z} \tag{20}$$

A" is reduced amplitude, A_0 is unattenuated amplitude of the propagating wave at some location, "z" is the distance which sound traveled and α is attenuation coefficient which probably depends on Prandtl number and viscosity of medium. The Eq.19 says that pressure is proportional to AC power and since AC power is a cosine wave, there will be an extreme point for AC power (and also pressure) when:

$$t = T = \frac{1}{2f} \ (here\ frequency\ of\ AC\ power\ is\ 2f)$$

After this time, wave reaches r_0 and has a maximum pressure and:

$$r_0 = \frac{Va}{2f} \tag{21}$$

So A_0 must have its maximum value ($A_0 = 1$) at this distance and must decrease as wave propagates in air. So we can assume that: $A_0 = r_0 . F(r)$ and $r_0 F(r_0) = 1$. So we can correct Eq.20:

$$\delta p = \frac{e_a}{e_a + e_g} \cdot \frac{3P_{AC}f^2}{2\pi V a^3} A_0 e^{-\alpha z} = \frac{e_a}{e_a + e_g} \cdot \frac{3P_{AC}f}{4\pi V a^2} r_0 F(r) e^{-\alpha z} \quad (22)$$

We used AC current of frequency ω and AC power is 2ω. Since pressure is proportional to AC power, sound wave will have frequency 2 times of input frequency. Since oscillator can produce AC current of frequency 0 to even more than 20 KHz, this device can produce sound of any frequency. This Thermoacoustic device doesn't have any moving parts and can produce sound of all frequency and is limited just by frequency of oscillator. In Eq.19 we didn't consider dissipation of energy. Here we have heat transfer and air moves as its temperature and density changes, so energy dissipation may depends on Prandtl number. Since sound propagates through a fluid, it may also depends on viscosity of fluid. But Eq.22 includes energy attenuation and as we mentioned before, α probably depends on Prandtl and viscosity of medium.

Future Work:

1- Using analogy between Stokes' second problem to derive energy dissipation and skin depth thermal boundary layer.
2- Simulating device in Comsol to discuss about heat transfer in graphene and air.
3- Doing experiments on experimented results.
4- Amplifying sound

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