Carbon Nano-Tube Speakers

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Abstract—This review paper examines the rapidly evolving field of carbon nanotube (CNT) speakers, with emphasis on enclosed coaxial designs for automotive exhaust noise control. We present a comprehensive analysis of CNT speaker technology, covering fundamental principles, design considerations, and performance characteristics. The paper explores multi-physics modeling techniques, integrating electrical, thermal, and acoustic phenomena to accurately simulate CNT speaker behavior. Experimental validation methods, including acoustic modal analysis and flow-based studies, are discussed. We compare open and enclosed CNT speaker configurations, highlighting the advantages of coaxial designs. The review also addresses current challenges, such as power efficiency and durability, and outlines promising future research directions. By synthesizing recent advancements, this paper provides a valuable resource for researchers and engineers working on next-generation acoustic devices.

I. Introduction

Traditional loudspeakers, which dominate current audio technology, operate through a mechanical principle involving permanent magnets and voice coils attached to cone-shaped diaphragms. When current flows through the voice coil, the resulting movement produces pressure waves that propagate through the medium.These traditional speakers are effective but they face limitations in specialized applications due to their moving parts and structural complexity.

Carbon nanotube (CNT) speakers represent an innovative approach to generate sound, as they operate on the thermoacoustic principle rather than mechanical vibration. These non-moving, ultra-lightweight, and flexible thin-film loudspeakers generate sound through a unique mechanism: alternating current passes through electrodes to a low heat capacity CNT thin film causes rapid surface temperature changes, leading to expansion and contraction of adjacent air to produce pressure waves. The structure is remarkably simple, consisting of only two electrodes and a CNT thin film with a mass per unit area of 1.5 μg/cm^2. [5]

The development of CNT speakers traces back to early thermoacoustic studies by Crandall in 1917, though suitable materials for human-audible sound generation were not available at that time. A breakthrough came in 2006 when Yu et al. demonstrated sound production using CNT thin films at audio frequencies. These speakers exhibit several characteristics which include pure resistance up to 10 kHz, frequency response from zero to 100 kHz, high temperature tolerance, and flexible form factor adaptability.

These properties make CNT speakers particularly valuable for applications in automotive and aerospace industries, where lightweight, heat-resistant acoustic solutions are crucial. For instance, in active exhaust noise cancellation, CNT speakers offer advantages over conventional external speakers due to their ability to withstand high temperatures and conform to space constraints within exhaust tubes. Recent research has expanded our understanding of CNT speaker performance through various experimental studies, with particular focus on frequency-dependent sound pressure levels (SPL).

This technology promises to open up new opportunities in acoustic applications where traditional speakers face some basic constraints.

II. Working Principle

Chemical vapor deposition (CVD) is a technique that allows carbon nanotubes (CNTs) to grow dense structures on silicon wafers. Known as ”forests,” these formations can be single or multiple. Thin CNT films are created when the nanotubes tangle together when pulled from one side. All CNT speakers are built on these films.

CNT films are extremely lightweight, flexible, incredibly thin, and stick easily to any surface. These characteristics make them perfect for designing and making CNT speakers. The way CNT speakers work is based on the thermoacoustic effect.The thermoacoustic effect is a phenomenon in which sound waves are generated due to temperature differences in a gas or fluid. When a gas is heated, it expands and contracts as it warms and cools,respectively, creating pressure waves that produce sound.The sound generation process in a CNT can be started by passing an alternating current to a thin film of carbon nanotubes. The current flow induces Joule heating in the nanotubes. Due to the low heat capacity and high thermal conductivity of CNTs, the temperature of the nanotubes oscillates rapidly in response to the alternating current. The air nearby the CNT film undergoes rapid expansion and contraction due to these temperature oscillations, which creates pressure waves. These pressure waves propagate through the medium as sound waves.

To generate sound using the thermoacoustic effect, there are two main requirements for the conductor material. First, it must be very thin, and CNT films fit this perfectly because of their nanoscale thickness. Secondly, the material needs to transfer the heat generated by the alternating current very quickly which is possible if the material has a low heat capacity. CNT’s have a much lower heat capacity compared to regular metal conductors.

As CNT films meet both these key requirements, which is being thin and having low heat capacity, it makes them

Fig. 1. Image of a Planar CNT Speaker. Adapted from [4]

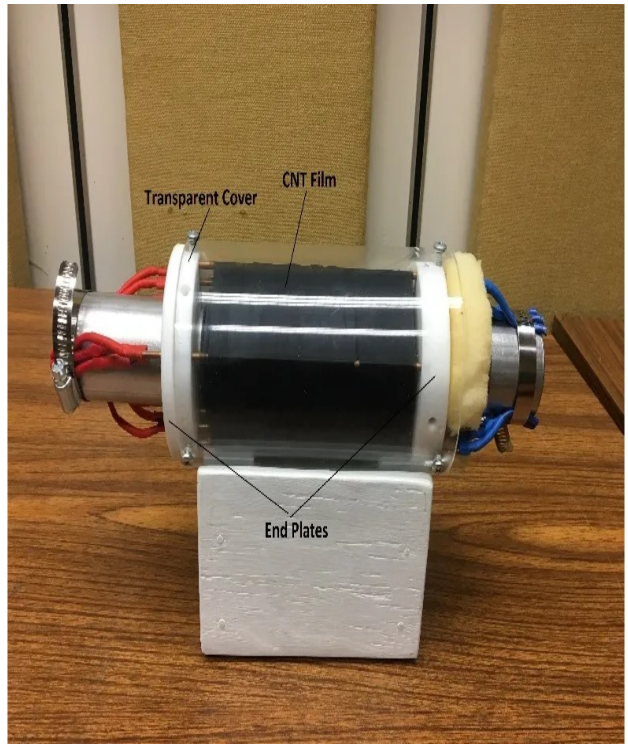

Fig. 2. Image of a Coaxial CNT Speaker (type of a Cylindrical CNT Speaker). Adapted from [4]

ideal for making thermoacoustic transducers, which convert electrical signals into sound.

III. Types of CNT Speakers

There are primarily two types of carbon nanotube (CNT) speakers:

A. *Planar CNT Speakers*

A planar CNT (carbon nanotube) speaker is one of the simplest kinds of CNT speakers. In this type, a thin sheet of CNT material is stretched between two copper strips that are set up parallel to each other. The copper strips act as electrodes, carrying electrical current to the CNT sheet. To keep everything safe and stable, these copper strips are embedded in an insulating material, which stops the current from flowing where it shouldn't and gives the speaker structure.

When an alternating electric current flows through the CNT sheet, it heats up quickly and cools down just as fast, with these temperature changes matching the rhythm of the current. This rapid heating and cooling affects the air around the sheet, causing tiny changes in air pressure that produce sound waves.

Building a planar CNT speaker is straightforward, with most of its weight coming from the copper strips, insulation, and the wiring. The CNT sheet itself is incredibly lightweight—almost ”massless” in comparison to the other parts—so it doesn't add much to the total weight.

B. *Cylindrical CNT Speakers*

Let's take a look at the cylindrical CNT speaker. Imagine a speaker shaped like a tube or cylinder. Inside this tube, thin metal strips (electrodes) are arranged in a circle and run parallel to each other, lining the inside wall of the cylinder. A CNT film (the special sound-producing material) is wrapped around these electrodes, covering them in a continuous spiral.

Each electrode alternates between positive and negative, which means the electric current flows in a way that balances out across the entire structure. When an electric current is applied, the whole wrapped CNT film heats up and cools down together, which changes the surrounding air pressure evenly in every direction. This setup creates a sound field that spreads consistently all around the speaker, giving a more immersive listening experience.

In short, while a flat (planar) CNT speaker directs sound in a particular direction, the cylindrical CNT speaker distributes sound evenly all around it due to its shape and the way the CNT film is wrapped.

IV. Advantages over Traditional speakers

Carbon Nanotube speakers are remarkably efficient, especially when compared to standard speakers. Unlike traditional speakers, which generate sound by mechanical components such as voice coils, diaphragms, and magnets, CNT speakers use the thermoacoustic effect. By eliminating moving parts, CNT speakers reduce energy losses caused by friction, inertia, and mechanical resistance by getting rid of the moving parts and thus resulting in efficient sound reception. This efficiency is especially noticeable at higher frequencies, where traditional speakers suffer performance issues due to the energy demands of vibrating mechanical parts in the speaker. Furthermore, the thermoacoustic effect of CNT speakers requires less power input to reach comparable sound levels, resulting in decreased power consumption—a significant benefit for portable devices and battery-powered applications.

The unique features of carbon nanotube films contribute to the lightweight nature of CNT speakers. These speakers produce sound using an incredibly thin and flexible CNT film, which is just a few micrometres thick. This lightweight design stands apart from standard speakers, which require heavy components such as magnets, coils, support frames etc. CNT speakers are substantially lighter without these heavy elements, making them reliable for applications requiring minimal weight. CNT speakers are flexible, which makes them perfect for new inventions like foldable electronics, wearable gadgets, and super-portable music systems. Regular speakers, on the other hand, are too rigid or heavy for these kinds of designs.

Particularly at high frequencies, CNT speakers are notable for their crystal-clear sound quality. Carbon nanotubes' rapid heating and cooling allows them to generate high-frequency sounds with minimal distortion and great detail, which makes them ideal for applications requiring distinct treble. CNT speakers naturally cover a wide range of sounds without the need for complex setup. Traditional speakers require many components to handle various sound ranges ,such as tweeters for high notes and woofers for low ones. his makes the sound clearer and the design simpler. As CNT speakers don't have moving parts, they cut down on distortion and deliver sound more precisely, especially for high-pitched sounds that regular speakers struggle with.

V. Design concept

To fully understand the design of the CNT speakers, two key parameters that are crucial to consider are resistance and power density.

A. *Understanding Parameters*

1) *Resistance*

The design of the CNT speaker is significantly influenced by its resistance. CNT films have a resistance of 750 Ω per square, making them thin conductors. This means that the resistance of each square of the CNT film is 750 Ω. The resistance (750 Ω) of a 1 cm² square of CNT film is equal to that of a 0.25 cm² square.

CNT speakers are typically made from several layers of CNT film that have been rolled together. When there are five layers, they are connected in parallel, which reduces the speaker's overall resistance.

The overall resistance of the five-layer film is 150 Ω if the resistance of each layer is 750 Ω. The arrangement of the CNT film wrap between the electrodes determines the CNT speaker's net resistance. The length of the CNT film is divided by the electrode spacing to determine how many squares it contains. The parallel resistance formula is used to get the total resistance, which is influenced by each square in the CNT film wrap.

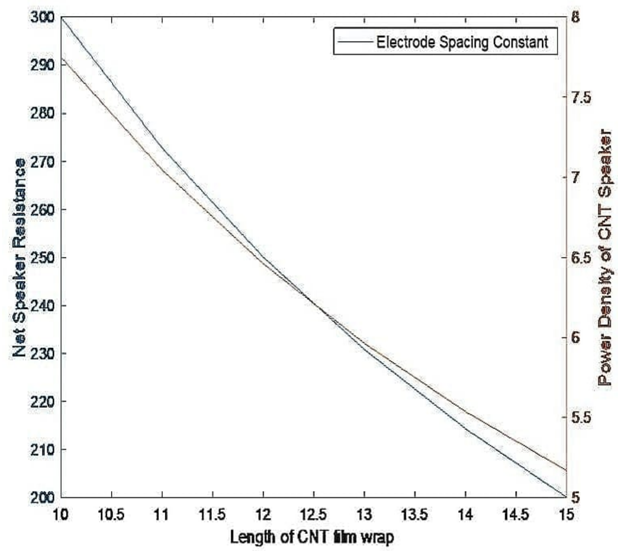

Fig. 3. Graph depicting the relationship between net speaker resistance and power density with respect to the length of the CNT film wrap. The plot illustrates how increaseing CNT wrap length, decreases resistance as well as the power density of the CNT speaker. Adapted from [3]

The number of squares between electrodes depends on the length of the CNT film. Longer films have more squares, which improves the electrical conductivity of the speaker and lowers the net resistance in Figure 3.

Because there are fewer squares when the electrode spacing is larger, the net resistance increases. As seen in Figure 4, a smaller spacing results in more squares, which reduces resistance and improves efficiency.

2) *Power Density*

CNT speakers generate sound based on input power, as opposed to traditional speakers that use voltage to do so. The safety of CNT speakers is measured by the power density, or the quantity of input power provided per square metre of CNT film. If the power exceeds a certain level, the CNT film could burn out.

The power density is determined by the surface area of the CNT film and the input power.

$$P.D.PowerDensity = \frac{P_{in}}{S}\left(\frac{kW}{m^2}\right)$$

The surface area of a planar CNT speaker is determined by the length of the CNT film and the separation between the electrodes. For cylindrical speakers, it is the sum of the areas between various electrode configurations. The power density is calculated by dividing the input power by the surface area.

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Consequently, the length of the CNT film wrap and the spacing between electrodes have a significant impact on the power density and resistance. Because altering one parameter

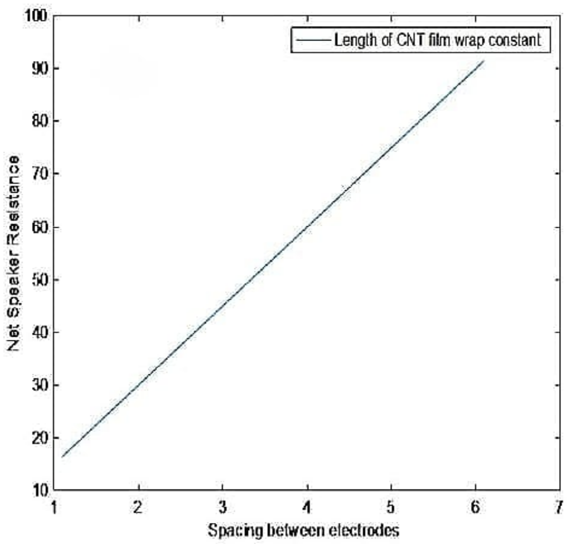

Fig. 4. Graph depicting the relationship between net speaker resistance with respect to the Spacing between electrodes of the CNT film wrap. The plot illustrates how increaseing CNT wrap length, increases resistance of the CNT speaker.Adapted from [3]

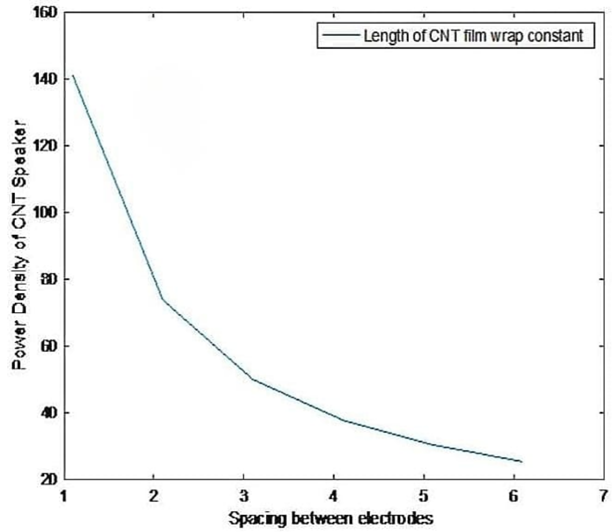

Fig. 5. Graph depicting the relationship between Power Density of CNGT Speaker with respect to the Spacing between electrodes of the CNT film wrap. The plot illustrates how increaseing CNT wrap length, decreases the power density of the CNT speaker.Adapted from [3]

affects the other, striking a balance is essential to ensuring the effectiveness and safety of the CNT speaker design.

B. Designing

The construction of a simple spool, which is made up of two discs connected by a shaft, was used to model the enclosed, coaxial CNT speaker. The two end discs of the CNT speaker are also composed of insulating material. According to Barnard A. et al., CNT films are acoustically transparent, meaning that sound can pass through them without changing timing or volume. [1]. This is a crucial aspect of the speaker's design.

As previously established, a CNT speaker's resistance and power density are proportional to the total area of the CNT film wrap. A greater film area lowers both resistance and power density. Lower power density is preferable since it increases the speaker's safety buffer. For optimal performance, the CNT speaker's resistance should equal the amplifier's output impedance. In addition, more film area enhances the speaker's sound output.

Since CNT films are acoustically transparent, multiple layers can be stacked to maximize film area without increasing the speaker's length. This is accomplished by using end plates with concentric rings of electrodes, which enable the CNT film to constantly wrap around them. The entire assembly is enclosed to efficiently contain the sound output, and the tubing connecting the end plates is slotted to funnel sound into the tailpipe.

The sound produced by the CNT film is directed into the tailpipe by mounting the two end discs on a pipe with a slit in the middle. An outer cover encloses the entire speaker. This cover has the added benefit of reflecting the sound that the CNT film produces back into the speaker. The reflected sound combines with the original sound because the CNT films let the reflected sound through without changing it. This causes the total sound entering the tailpipe to be 6 dB louder than the sound generated by the speaker alone, because the sounds add up coherently.

Several prototypes have been developed for CNT speakers, but the most commonly used design is described below:

C. Prototype Description

This prototype of the CNT speaker was designed to be more compact, lighter, and durable than most of the prototypes. To withstand hot exhaust gases passing through it, the speaker was fully sealed to prevent the gases from damaging the CNT films. This sealing included an O-ring on one end plate, welded to the pipe, and other adjustments to prevent leaks.

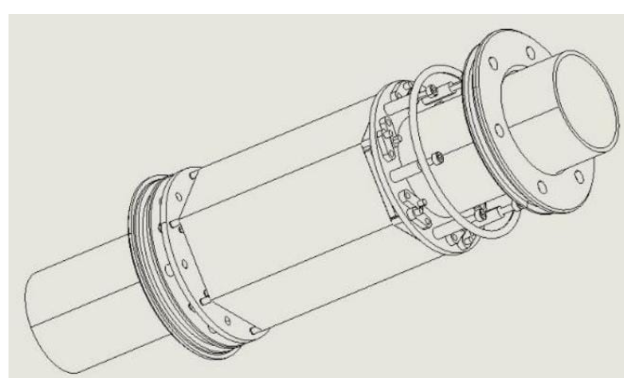

Fig. 6. 3D assembly drawing of second coaxial CNT speaker prototype. Adapted from [3]

The structure featured two concentric electrode rings, each with six electrodes (1/8" in diameter) arranged in rings measuring 2.52" and 3.07". One end of each electrode was brazed to a bracket on the end plate to keep the electrodes stable

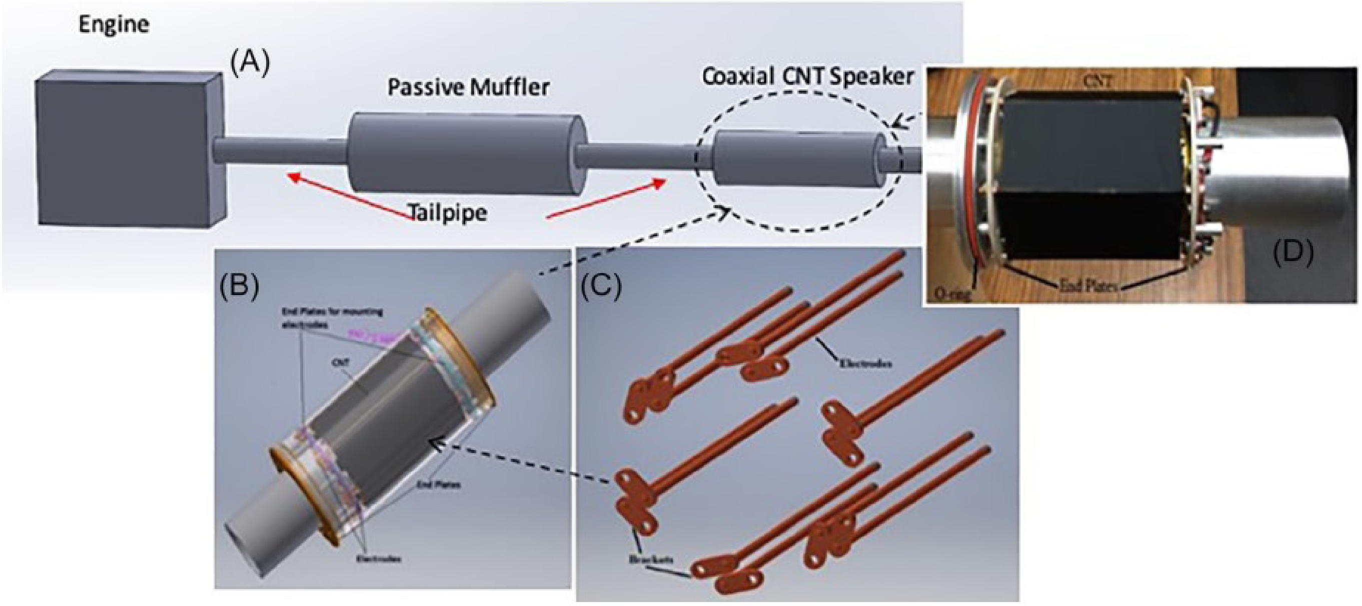

Fig. 7. (A) shows the schematic of the CNT speaker's placement within the exhaust system. (B) illustrates a 3D model of the enclosed coaxial CNT speaker. (C) displays two concentric ring electrode arrangements with rotation-preventing brackets. (D) presents the CNT speaker with the CNT film exposed, without the outer cover.Adapted from [2]

and avoid movement, and the other end was secured with circlips and nuts. The CNT film, measuring 4.84" in length, was wrapped around the rings in five layers to provide a stable surface for sound generation, achieving a speaker resistance of 1.8 Ω, and a power density of 8.4 kW/m² with a 500W input.

For high-temperature resistance, the end plates were made from PEEK plastic, which withstands up to 315°C, unlike Teflon (65°C). A thin, acoustically transparent Kapton film (1 mil thick) was wrapped around a slotted pipe inside the speaker to shield the CNT film from exhaust flow. This prevented the CNT film from being harmed by lateral exhaust flow. A downside of this design was the difficulty of replacing damaged CNT film in the inner ring; replacing it required removing the outer ring film, which was time-consuming and costly.

VI. Acoustic Modal Analysis

In this section, we examine the acoustic modal behavior of a closed coaxial CNT (carbon nanotube) speaker and its effect on sound pressure levels (SPL) across different frequencies. When sound waves travel within any enclosed structure, they can create resonance based on the shape and dimensions of the structure. This phenomenon, known as acoustic resonance, can either increase or decrease sound production based on whether the resonant frequency is in constructive or destructive alignment with the sound produced inside the speaker. By identifying and leveraging these acoustic resonant frequencies, we can strategically increase SPL in enclosed acoustic structures.

The coaxial CNT speaker under study is closed but has unique design features, such as slots covered with a heat-resistant diaphragm. Small changes in internal volume are brought about by this design, which may have an impact on SPL behaviour at various frequencies. Experimental observations suggest that SPL fluctuates within a specific frequency range, increasing at certain frequencies while decreasing at others, likely due to the acoustic resonance created by the speaker's geometry.

To investigate this, we conducted an acoustic modal analysis using a combination of experimental and simulation approaches. Two condenser microphones were positioned at either end of the coaxial CNT speaker in order to record SPL. A broadband signal covering a wide frequency range (20 Hz to 10 kHz) was initially applied to the speaker, but due to poor coherence between SPL and input signals, we used a sine chirp (a tone that gradually increases in frequency) to measure resonant frequencies more accurately. The sine chirp

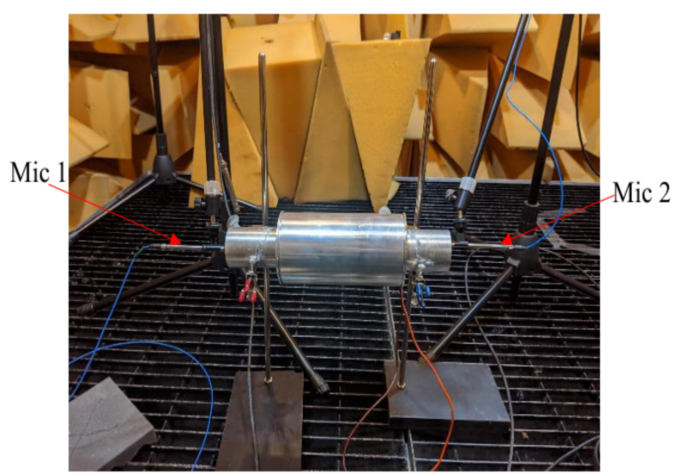

Fig. 8. Experimental setup for acoustic modal test. Two microphones are placed at the two ends of the speaker. A sine chirp signal was used as input to the CNT speaker.Adapted from [3]

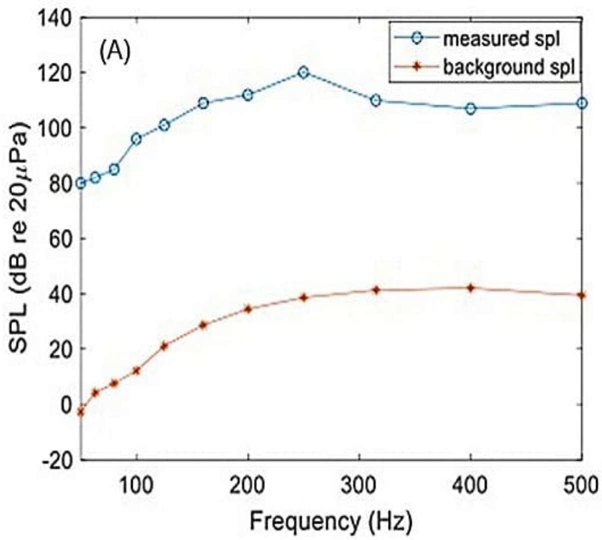

Fig. 9. In-pipe axial SPL of the enclosed coaxial CNT speaker.

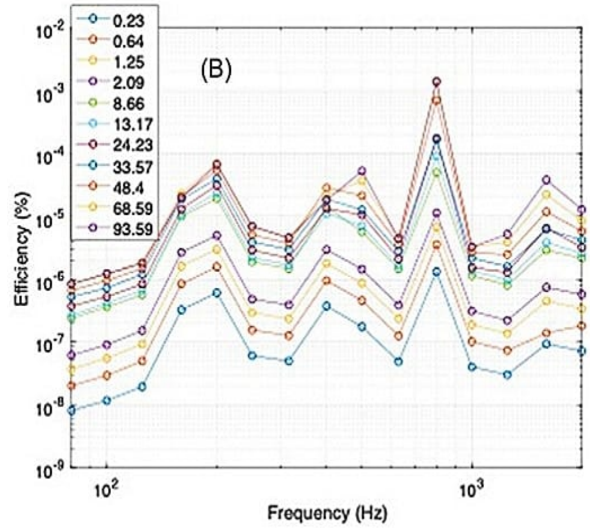

Fig. 10. Coaxial thermophone efficiency for multiple input power levels in the range 0.23 - 93.59 W.

covered a frequency range of 20 Hz to 20 kHz, and testing was conducted at three different power levels to ensure repeatable results across different power settings. The experimentally measured SPL values were then compared with simulated results from a COMSOL model (a physics simulation software) of the coaxial CNT speaker, where we simulated SPL at individual frequencies derived from the experimental data. By verifying that the simulated and real models display comparable SPL responses at the resonant frequencies, this comparison confirmed that the COMSOL model accurately reproduces the speaker's acoustic modal behaviour. Particularly, due to the difficulties in configuring a sine chirp in COMSOL, the simulation was conducted at different frequencies in order to simplify the process instead of using a continuous sine chirp.

In summary, the study confirms that the coaxial CNT speaker's SPL behavior is influenced by acoustic resonance. By examining the resonant frequencies experimentally and validating them through simulation, this analysis provides insights into optimizing sound output in coaxial CNT speaker designs.

VII. Performance Anaysis

The impedance of the CNT speaker was determined by measuring the relationship between voltage and current, using current as the reference. The CNT speaker performs like a pure resistor up to 20 kHz, according to the results, with constant resistance at various input power levels—a perfect characteristic for its operation. Similar findings were observed in other planar CNT speakers.

A key goal for this coaxial speaker was to reach sound pressure levels (SPLs) over 100 dB at low frequencies (0–500 Hz) within the pipe. Tests show that it can produce up to 120 dB at certain frequencies with 105W of power.

According to efficiency measurements, this coaxial thermophone's efficiency fluctuates with frequency, in contrast to ordinary speakers, which have an efficiency of roughly 1%. Although efficiency in open thermophones usually increases steadily with frequency, this speaker's distinctive cylindrical construction results in non-uniform efficiency because of particular acoustic modes.

VIII. Future Applications

A. *Wearable and Flexible Audio Systems*

The flexibility and ultra-thin nature of CNT speakers allow them to be integrated into clothing, headphones, and skin patches, opening up new possibilities for portable and wearable audio devices. With designs that are more comfortable, lightweight, and discreet, this has the potential to completely transform the personal audio experience.

It will have a massive impact on consumer electronics, fitness, and healthcare industries.

B. *Audio Performance Characteristics*

CNT speakers are capable of providing superior sound quality, wide frequency response, and low distortion. Because of this, they are perfect for high-fidelity audio applications such as professional sound equipment, home audio systems, and high-end headphones.

A game-changer in the entertainment and audio technology sectors, offering a new standard for sound quality.

C. *Specialized Environmental Applications*

CNT speakers can operate in high-temperature environments and can be used for industrial exhaust systems, aerospace, and HVAC applications. One of their primary advantages in these sectors may be their capacity to use the thermoacoustic effect to transform heat into sound.

It could significantly improve the efficiency of industrial processes and aerospace systems.

D. *Medical and Research Applications*

CNT speakers can generate non-invasive ultrasound waves, which could be used in medical diagnostics and therapy. They also provide opportunities for materials testing and acoustic monitoring, which spurs innovation in the biomedical domains.

It could lead to new non-invasive diagnostic tools and therapies in healthcare.

E. *Energy and Operational Benefits*

The energy efficiency and lack of moving parts in CNT speakers make them ideal for battery-powered devices and long-term use, such as in portable audio systems, smart devices, and low-energy consumer products.

It will contribute to more sustainable and durable consumer devices, benefiting a wide range of industries from healthcare to consumer electronics.

F. *Advanced Sound Control*

The ability to create directional sound systems, noise cancellation, and focused audio could have significant implications for public announcement systems, museums, and other public spaces, offering new possibilities for personalized audio experiences.

It offers solutions to noise pollution and personalized audio in both public and private spaces.

IX. Conclusion

This review has examined the fundamental aspects and recent advancements in carbon nanotube speaker technology, with particular emphasis on enclosed coaxial designs. Operating on the thermoacoustic principle, carbon nanotube (CNT) speakers have several advantages over conventional speakers, such as superior high-frequency response, high-temperature endurance, and ultra-lightweight design. The enclosed coaxial design, featuring multiple layers of acoustically transparent CNT films, demonstrates optimal performance with sound pressure levels reaching 120 dB at low frequencies. Although there are still challenges with power efficiency, the technology is showing encouraging advancements in a number of applications, such as wearable audio systems and automobile exhaust noise management. As manufacturing processes improve and new applications emerge, CNT speakers represent a significant advancement in audio technology, particularly in environments where traditional speakers face limitations.

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