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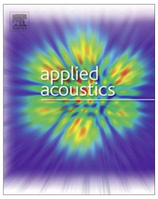

Technical note

Optimizing the manufacturing parameters of carbon nanotubes stiffened speaker diaphragm using Taguchi method

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ABSTRACT

This study developed a thermal transfer printing (TTP) technique to fabricate a carbon nanotubes (CNTs) stiffened speaker diaphragm. The self-developed TTP stiffening technique does not require a high curing temperature that decreases the mechanical property of CNTs. Therefore, the inherent strength of CNTs was preserved. In addition to increasing the stiffness of diaphragm substrate, this technique alleviates the middle and high frequency attenuation associated with the sound pressure curve of a speaker, thereby smoothing the sound pressure curve and achieving a full sound range as well as reducing bass distortion and enhancing treble clarity. Furthermore, the TTP technique can stiffen a localized area on a diaphragm substrate, thus increasing diaphragm stiffness without markedly raising diaphragm weight. The Taguchi quality engineering method was applied to identify the optimal process parameters (i.e., transfer area, stiffening pattern, coating layers, and transfer temperature). Finally, the optimal process parameters were employed to fabricate a stiffened diaphragm, which was then assembled onto a speaker. The result indicated that the stiffened diaphragm improved the smoothness of the sound pressure curve for the speaker, which produced a mid-frequency dip difference (ΔdB) of 1.9 dB and an attenuation peak frequency (f_{peak}) of 4220 Hz.

1. Introduction

Current technological products, including speakers, are mostly lightweight. Speakers have become an integral part of people's everyday life and are prevalently applied in a variety of products such as television, computers, tablet computers, and mobile phones. To fulfill market demands and customer needs for thinner panel speakers with excellent sound quality, problems concerning middle and high frequency attenuation in thin panel speakers must be resolved. The diaphragm in thin panel speaker is the key component of a speaker. The mechanical property of a diaphragm directly influences crucial acoustic characteristics of the speaker (including the sound pressure level (SPL) and frequency range).

Typically, the major material of the diaphragm is coarse paper. However, the lack of stiffness produces unclear sound at middle and high frequency. Therefore, Al foil or polyethylene naphthalate (PEN) pasted on coarse paper or form materials have been studied to enhance the stiffness. However, poor adhesion and over-weight problem occur and limit their application. It is reported that using CNTs as an additive can enhance the mechanical property of resin [1–3]. Compared with regular polymer, CNTs have lower expansion coefficient, which reduces the residual stress in laminated polymer composites. Previous studies have reported that the magnitude and distribution of thermal residual stress can be adjusted by selecting the appropriate material combination and controlling the compositional gradient [4,5]. In addition, CNTs have favorable strength and stiffness and is capable of changing material properties such as electrical and thermal conductivity. However, past studies also have observed that mixing high-concentration CNTs with epoxy lowers the mechanical strength of the epoxy, which is primarily attributable to the aggregation of the CNTs and the formation of hollow pores in the epoxy [6,7]. Regardless, the composite coating containing CNTs and epoxy has not been studied for using as the diaphragm in thin panel speaker.

In this study, we self-developed a thermal transfer printing (TTP) technique to prepare the diaphragm in thin panel speaker. TTP is a process through which coatings are bonded to the surface of a transfer material at temperature from 80 °C to 120 °C [8]. The composite paste of CNTs and epoxy was first roller-pressed onto a polyethylene naphthalate (PEN) substrate to reinforce the PEN, after which the backside of the PEN was coated with hot melt adhesive (HMA). The fabricated TTP paper (CNTs + epoxy/PEN/HMA) was cut into adequate size and shape. Next, a TTP machine

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was used to locally or fully press TTP paper onto a coarse paper to manufacture a stiffened speaker diaphragm. Although Bian and Zhao reported that the Young's moduli of CNTs decrease when the temperature of the environment exceeds 200 °C [9]. In our study, the proposed TTP stiffening technique does not require a high curing temperature that decreases the mechanical property of CNTs; hence, the inherent strength of CNTs was preserved. The resulting stiffened diaphragm exhibited increased stiffness, which improved the bandwidth and sound quality of the speaker, thereby markedly improving the overall smoothness of the sound curve. Simultaneously, the weight was reduced and the adhesion was also improved while using the stiffened diaphragm. Besides, in this study, the Taguchi quality engineering method was used to minimize the number of experimental trials. The relationship among the process parameters including stiffening pattern, coating direction, transfer area, and transfer temperature of stiffened diaphragm have also been therefore investigated.

2. Methodology

In this study, a PEN membrane was used as the substrate for fabricating TTP paper. The front and back of the PEN were respectively coated with CNTs/epoxy and HMA to form the TTP paper. The fabricated TTP paper which was thermally transferred and printed onto a coarse paper to form a diaphragm. Subsequently, the effect of diaphragm fabrication on smoothness of the sound pressure curve was investigated, and Taguchi quality engineering method was applied to identify the optimal process parameters.

2.1. Fabrication of TTP paper and stiffened diaphragm

A PEN membrane was used as the substrate for fabricating TTP paper. We first mixed 20 wt.% CNTs (CF182C, Advanced Nanopower Inc.) and epoxy (P859-1, Hong Guan R&D Co.) as the CNTs/epoxy composite paste. As shown in Fig. 1(a), the TTP paper was fabricated by coating the front side of a PEN membrane with CNTs/epoxy paste, then drying it in an oven at 120 °C for 15 min. After the CNT/epoxy coating layer was dried, the backside of PEN was coated with HMA and was dried again in the oven at 70 °C for 10 min to obtain a TTP paper. The CNTs/epoxy coating was used to adjust the thickness of TTP paper; in addition, manually roller-pressing the CNTs/epoxy coating onto the TTP paper enabled evenly spreading the coating onto the material surface.

After the fabrication of TTP paper, a TTP process was used to thermally transfer and print the TTP paper onto coarse paper to form a stiffened diaphragm at an elevated temperature. In this study, as shown in Fig. 1(b), the resulting TTP paper was first stacked onto the coarse paper diaphragm and then subjected to a TTP process in a TTP machine. The following steps of TTP process were illustrated in Fig. 1(b). After pressing to 0.2 kg/cm^2 and heating at 80–120 °C for 10 min, the fabrication of stiffened diaphragm was complete. This study also adopted cold cathode field emission scanning electron microscope (FE-SEM; JEOL JSM-740F, Japan) to observe the cross-sections of the stiffened diaphragm.

2.2. Panel speaker assembly

Fig. 2(a) shows the solid work explosion diagram of the panel speaker. After various speaker components were prepared and ready for assembly, the fabricated stiffened diaphragm was adhered to the speaker surround, which was then assembled to the upper frame as shown in Fig. 2(b). The surround material selected for our panel speaker was 810 polyethylene terephthalate (PET) with the speaker size of which is 30 × 20 × 10 mm. PET surround is attached frame of speaker, PET was placed into a surround mold and heat pressed in an oven to form the speaker surround, which was then attached to the diaphragm and voice coil. Subsequently, the vibration exciter (voice coil) was attached at 90° perpendiculars to the diaphragm. A shown in Fig. 2(a) and (b), the exciter was placed between the magnet and the magnet frame. The magnets were placed above the washer to increase the magnetic flux. The speaker gives sound through the diaphragm vibration that pushed by the voice coil. Most importantly, the vibration exciter (voice coil) must attach to the central area of the diaphragm. Otherwise, sound distortion is easily incurred. Once all the steps have been completed, the adhesives were allowed to solidify for a day, after which the sound pressure curve of the speaker can be measured.

2.3. Sound pressure curve measurement and analysis

As shown in Fig. 3(a) and (b), according to IEC 268-5 [10], speaker set up position from speaker to center point of baffle which is horizontal distance 150 mm and vertical distance 225 mm, and microphone from the speaker 10 cm in an anechoic chamber. The sound test is conducted in an anechoic chamber (at input power of 1 W). The sound pressure signals were then processed by LMS [11] to produce the SPL curves of the plate with or without attached masses.

To avoid influencing the measurement results, sound pressure curve must measure in an anechoic chamber insulated from external sources of noise; acoustical measurement system and CLIO software analysis were employed in measuring the sound pressure curve with pure tone sweep. In the CLIO software, the number of points, bandwidth, and voltage were defined. The measured bandwidth was 20–20 kHz audible to the human ear and was measured at a distance of 10 cm from the self-developed panel speaker. Subsequently, after the input voltage of the speaker was configured, the sound pressure curve and data were measured. In the sound pressure curve, the value difference (ΔdB) between curve valley and average sound pressure level (ASPL) at 2–6 kHz, mid-frequency dip difference value (ΔdB), was used to identify the quality of the sound. A minimum mid-frequency dip difference value (ΔdB) gives a smooth sound pressure curve in the mid-frequency region and a better sound quality. Meanwhile, the attenuation peak frequency (f_{peak}) refers to the first point frequency at which sound pressure curve drops (excluding the first resonant frequency). For the overall curve, if the f_{peak} occurs later, a drop in the sound quality at mid- or high-frequency is also has higher frequency and may even not occur until 20 kHz. Therefore, a large f_{peak} is desirable.

2.4. Taguchi quality engineering

Because stiffening the entire diaphragm may influence the overall sensitivity of the speaker, we attempted to circumvent this problem by performing optimization analysis using the Taguchi method. As shown in Table 1, the Taguchi quality engineering method was used to minimize the number of experimental trials, and the applicable orthogonal array was selected according to the controllable factors and level numbers. Through the Taguchi approach, the optimal product design objective or process can be determined to facilitate mitigating the effects of confounding factors [12,13]. This study was investigated the relationship among the process parameters of stiffened diaphragm (stiffening pattern, coating layers, transfer area, and heat press temperature), and the Taguchi equations representing the larger-the-better (Eq. (1)) and smaller-the-better (Eq. (2)) characteristics are shown below:

$$S/N = -10\log_{10}\frac{\sum_{k=1}^{n} Y^2 i}{n} \tag{1}$$

$$S/N = -10\log_{10}\frac{\sum_{k=1}^{n}\frac{1}{Y^2 i}}{n} \tag{2}$$