Sound Absorption Properties of Thermally Bonded Nonwovens Based on Composing Fibers and Production Parameters

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Received 3 February 2003; accepted 8 December 2003

ABSTRACT: This article reviews the noise absorption capacity of thermally bonded nonwovens in the range of audible frequencies (125–2500 Hz). First, we focus on the effects of the properties of the fibers, which constitute nonwovens, on the sound absorption properties, and then we consider the web orientation angle of nonwovens. We also investigate a composite model of the sound absorption properties of nonwovens, including the surface roughness and panel vibration. We have used an impedance tube interferometer, which provides the normal incidence sound absorption coefficient of materials, for the determination of the noise absorption properties of nonwovens produced under different conditions. The noise absorption capacity of nonwovens depends primarily on the thickness and surface characteristics of specimens, but the effects of the fiber contents are only marginal. Interestingly, when there is a panel in front of nonwovens, the noise absorption capacity increases significantly at low and medium frequencies (250–1000 Hz). © 2004 Wiley Periodicals, Inc. J Appl Polym Sci 92: 2295–2302, 2004

Key words: polyesters; barrier

INTRODUCTION

Undesirable and potentially hazardous noises are a side effect of modern life and technology. The environmental impact of noise is a matter of increasing concern with the continuing development of new technologies, such as the trend toward faster, more powerful machinery, and there have been innumerable attempts to find effective means of noise abatement. The problem of noise generated within a closed space can be particularly acute, but several practical solutions do exist.[1,2]

This work is based on previous studies on the use of textiles as noise control elements; they indicated the feasibility of applying textiles to noise abatement technology. The use of nonwovens for noise reduction is based on inherent advantages, such as the economical price of the raw materials and efficient thermoprocessing. Previous studies of noise absorption in nonwovens have shown that the noise absorption coefficients (NACs) of these media in the high-frequency range ($f > 2000$ Hz) are comparable to NACs of conventional noise absorption materials such as rock wool and glass fibers. There are several studies on the sound properties of nonwovens, but none so far have addressed how the physical details of the surface and structure influence the behavior.[3–6]

In this study, we measured NACs for different acoustic absorption parameters, such as porous, resonance, and panel parameters, and we examined the relationship with nonwoven web characteristics, including the fiber contents. Acoustic barriers made of thermally bonded nonwovens can have several interesting applications, such as fillings inside walls separating neighboring apartments in wooden houses, noise shelters in the transfer industry, and acoustic enclosures for noise equipment in factories and workshops.[7–11]

SOUND ABSORPTION MECHANISM

Porous type

Nichols expressed the porous-type absorption mechanism as follows:

$$\frac{R_1 d^2}{\rho^{1+x}} \approx \text{Constant} \tag{1}$$

where R_1 is the flow resistance, d is the nonwoven thickness, ρ is the nonwoven density, and x is the orientation constant (0.3–1.0).[12]

Resonator type

The sound absorption coefficient of the resonator type has a maximum value at the specific frequency, which

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Journal of Applied Polymer Science, Vol. 92, 2295–2302 (2004)

TABLE I
Nonwoven Processing Conditions for Sound Absorption Properties Depending on the Fiber Content

Sample	LMP (6 den, 42 mm)	Ultrafine fiber (0.05 den, 42 mm)	Regular PET (2 den, 42 mm)
ULT1	40	0	60
ULT2		20	40
ULT3		40	20
ULT4		60	0

TABLE II
Nonwoven Processing Conditions for Sound Absorption Properties Depending on the Midweb Orientation Angle

Sample	LMP (6 den, 42 mm)	Ultrafine fiber (0.05 den, 42 mm)	Orientation angle (°)
LAY1	40	60	0
LAY2			35
LAY3			45
LAY4			90

is called the resonant frequency (f_o). This is caused by the resonance of the system composed of the air mass in the perforation and air spring at the air space. f_o is expressed as follows:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{P}{L(t + 0.8d)}} \tag{2}$$

where c represents the sound velocity, P is the open area, L is the thickness of the air space, t is the plate thickness, and d is the perforation diameter.[1,12]

Panel type

The resonant frequency of a panel absorber is determined as follows:

$$f_0 = \frac{60}{\sqrt{mt}} \tag{3}$$

where m is the mass per unit area and t is depth of the partitioned air space.[1,12]

EXPERIMENTAL

Sample preparation

We prepared recycling poly(ethylene terephthalate) (PET) fibers for sound absorption properties that varied with the manufacturing conditions. According to the fiber contents, five different types of PET fibers were used. Low-melting-point PET fiber (LMP; 6 den and 42 mm) for binding, ultrafine PET fiber (0.05 den and 42 mm), and three different PET fibers (2, 3, or 7 den and 42 mm) with the same length but different levels of fineness were used. Table I shows the sample identifications for measuring the sound absorption properties according to the fiber contents.

We also prepared samples for the investigation of the nonwoven properties, especially web properties. The sample specification for this purpose is provided in Tables II and III. Table II shows the effect of the web orientation angle on the sound absorption properties, and Table III shows the fiber contents for the sound absorption properties depending on the web thickness. The nonwoven multiangle layering method is illustrated in Figure 1.

For the surface roughness test, the samples were classified by the embossed area percentage on the specimen surface area. Sample identifications of the surface roughness test are presented in Table IV. Sample WD had 5 mm × 5 mm (width × depth) etching, NE had 2.5 mm × 5 mm etching, and NED had 2.5 mm × 10 mm etching.

The panels, which were used for resonance tests, were polypropylene (PP) films with two different thicknesses and aluminum foil. Each had a 0.03-mm PP film, a 0.08-mm PP film, and 0.03-mm aluminum foil. The processing conditions for the resonance tests are given Table V.

We performed a carding process three times for better evenness and better orientation for all prepared webs, and a hot-air-through bonding machine, which was specially designed for providing optimum bonding conditions for a given low-melting-point polyester, was used for binding. The hot-air-through bonding machine was set to an air temperature of 130°C, a feeding speed of 0.6 m/min, and a 30 cm × 30 cm bonding area.

Sound absorption measurements

The equipment used in this experiment, manufactured by Bruel and Kjaer, consisted of a cylindrical steel tube. The sample was fastened to the tube wall, and a

TABLE III
Nonwoven Processing Conditions for Sound Absorption Properties Depending on the Web Thickness

Sample	LMP (6 den, 42 mm)	Regular PET (2 den, 42 mm)	Thickness (mm)
THI1	40	60	15
THI2			30
THI3			40
THI4			50

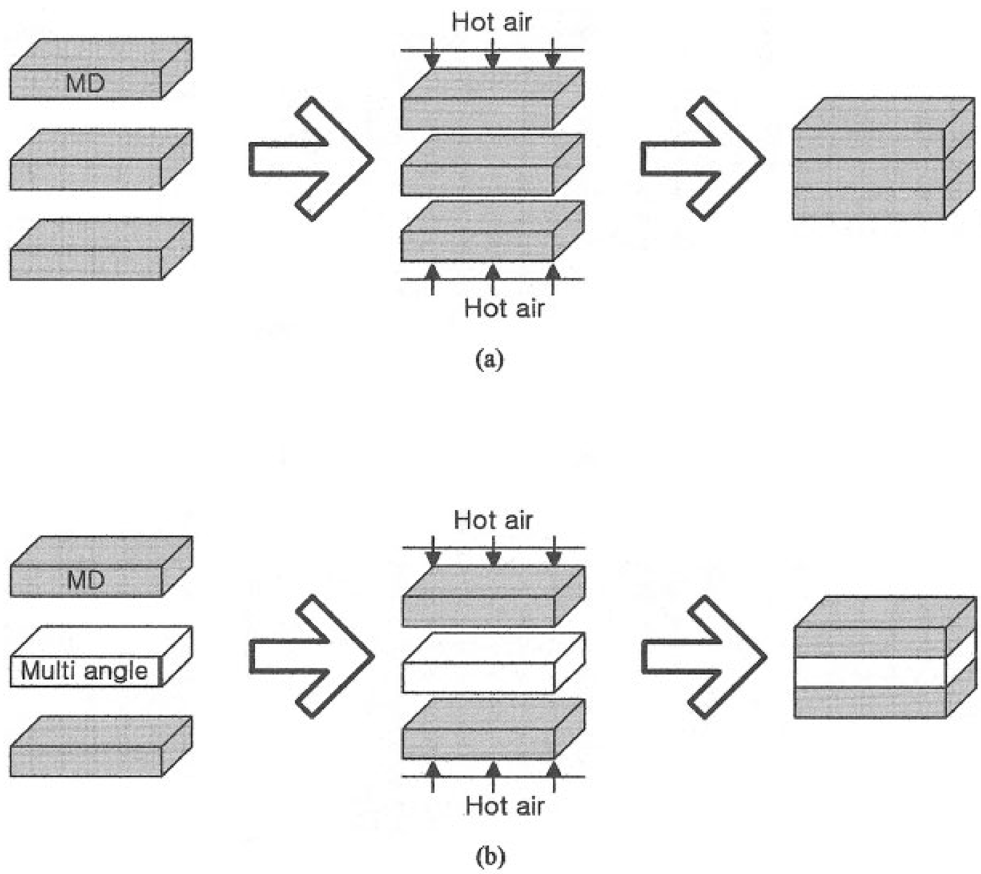

Figure 1 Nonwoven multiangle manufacturing methods for sound absorption materials: (a) nonwoven composed of a fully oriented web and (b) nonwoven composed of a partially oriented web.

loudspeaker that could emit sound waves of well-defined frequencies was attached to its rigid wall. The nodes and antinodes of the standing waves emitted by the loudspeaker and those reflected from the sample were detected by a small microphone that could slide along the axis of the tube. The diameter of the tube (d) was smaller than the wavelength of the emitted sound wave (typically, $d = 10$ cm for $f < 1600$ Hz and $d = 3$ cm for $f > 1600$ Hz), so the wave could be considered a plane wave propagating along the axis of the tube. A schematic diagram for measuring the normal incidence sound absorption is given in Figure 2.

RESULTS AND DISCUSSION

We measured the NAC values at each of the octave band frequencies. In the following figures and tables, NACs are designated by α. We also determined the noise reduction coefficient (NRC); it is the average of NACs at 250, 500, 1000, and 2000 Hz, and it is often used as an objective method for estimating the practical sound absorption ability at an audible frequency.[2]

Contents of the ultrafine fibers

Several fiber contents were previously studied to determine the effect of the fiber fineness on sound ab-

TABLE IV
Nonwoven Processing Conditions for Sound Absorption Properties Depending on the Surface Roughness

	Fiber content			Embossing		
		Regular PET (42 mm)				
Sample	LMP (6 den, 42 mm)	3 den	7 den	Type	Area percentage on specimen surface area	Depth (mm)
				WE	51	5
EMB	30	50	20	NE	36	5
				NED	36	10

TABLE V
Nonwoven Processing Conditions for Sound Absorption Properties Depending on the Panel Vibration

Sample	LMP (6 den, 42 mm)	Regular PET (42 mm)		Layer type
		3 den	7 den	
COM1	30	50	20	PP film, 0.03 mm
COM2				PP film, 0.08 mm
COM3				A1 foil, 0.03 mm

sorption properties.[7,8] In this study, we used ultrafine fibers (ca. 0.05 den); the content of the ultrafine fibers increased in the following order: ULT1, ULT2, ULT3, and ULT4. All of the ULTs contained 40% LMP, and the portion of the ultrafine fibers increased from 0 to 60% against regular PET. The relationship between the sound absorption and ultrafine fiber contents is illustrated on Figure 3. NAC of the sample is proportional to the increase in the ultrafine fiber contents. The difference in NACs between ULT1 and ULT4 increased with the ultrafine fiber contents from the low-frequency region; especially at the middle frequency (f = 750 Hz), the variation between ULT1 and ULT4 reached almost 0.25. The differences in the NAC curves between samples decreased with increasing frequency. When the concentration of ultrafine fibers was lower than 50%, there was little effect on NAC of the nonwoven in the high-frequency region. Despite the small difference in NACs in low- and high-frequency regions, an average increasing rate of NRC with the ultrafine fiber contents was significant.

Nonwovens of multiangle layered webs and different thicknesses

The web orientation effects were analyzed through nonwovens that had the same fiber contents but different orientation angles (0, 35, 45, and 90°), which were controlled during the carding process. NAC of a multiangle layered web is shown in Figure 4. LAY4 showed the highest NRC; this means that the higher orientation angle variation produced smaller pores. Both

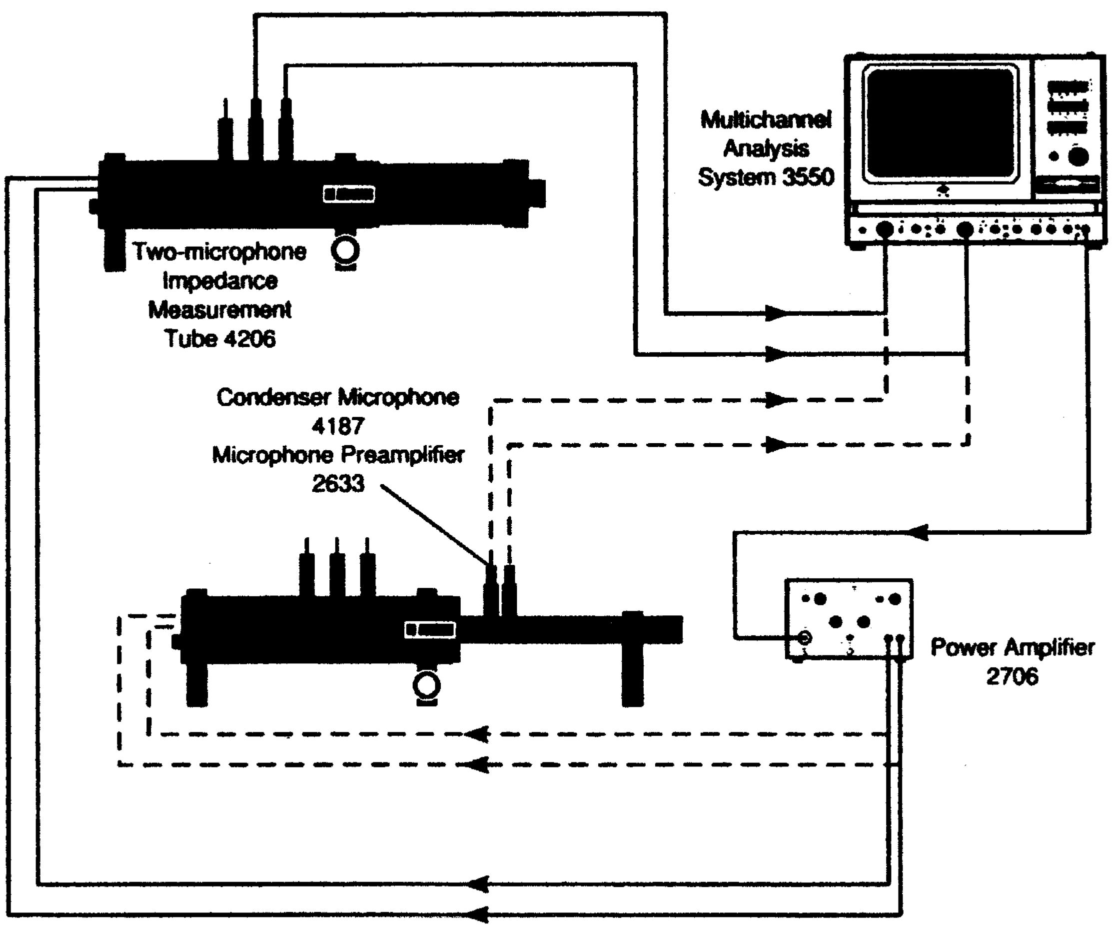

Figure 2 Schematic diagram for measuring the normal incidence sound absorption.

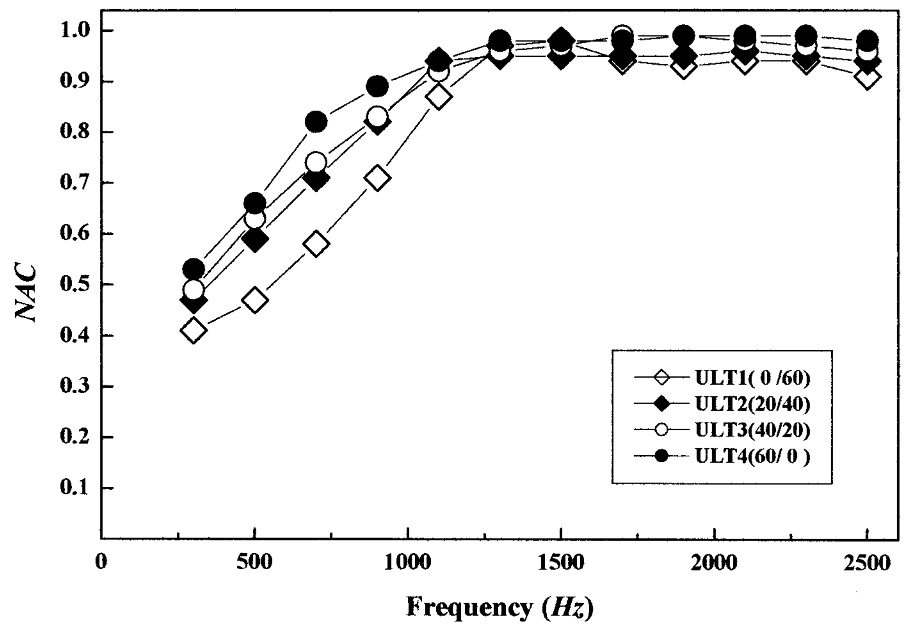

Figure 3 Effect of the ultrafine fiber contents on the sound absorption properties.

the pore size and the air were resistance affected by the web layering properties, although the difference in NAC was marginal at the low and high frequencies.[7–10]

Figure 5 shows NACs for different web thicknesses; the average absorption coefficient over the frequency range correlated well with the overall thickness. According to basic acoustic principles, NAC and NRC of the samples increased with the frequency and thickness of the nonwovens.

Although NACs of all samples increased with the thickness, THI4 had the highest value at the 250 Hz and increased with frequency. This implies that the sound absorption properties of a sufficiently thick web, around 50 mm, can be competitive with or better than conventional sound-proof materials at audible frequencies.[11]

Fundamentally, the relationship between the thickness and NAC is directly proportional, but it is also

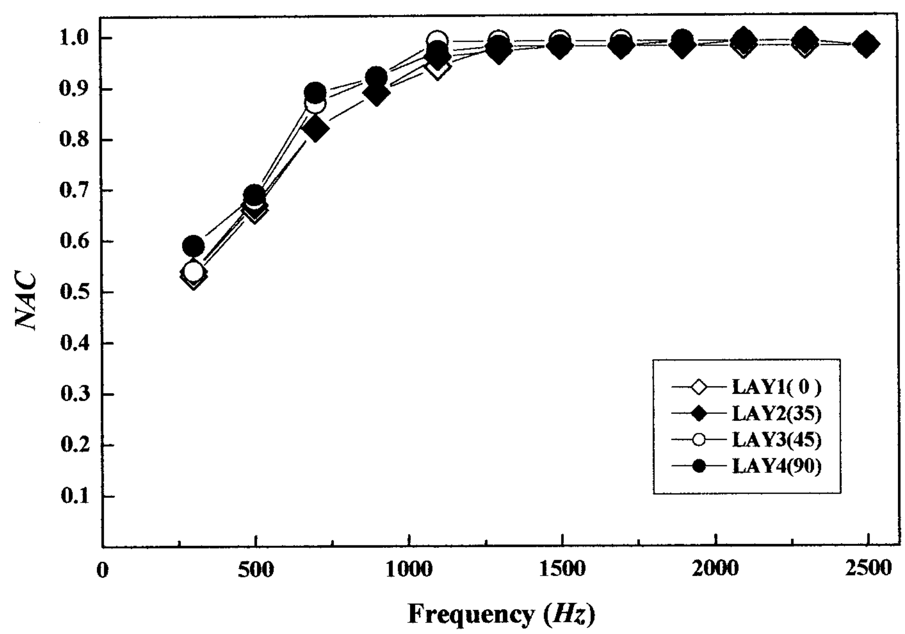

Figure 4 Effect of the modified orientation web angle on the sound absorption properties.

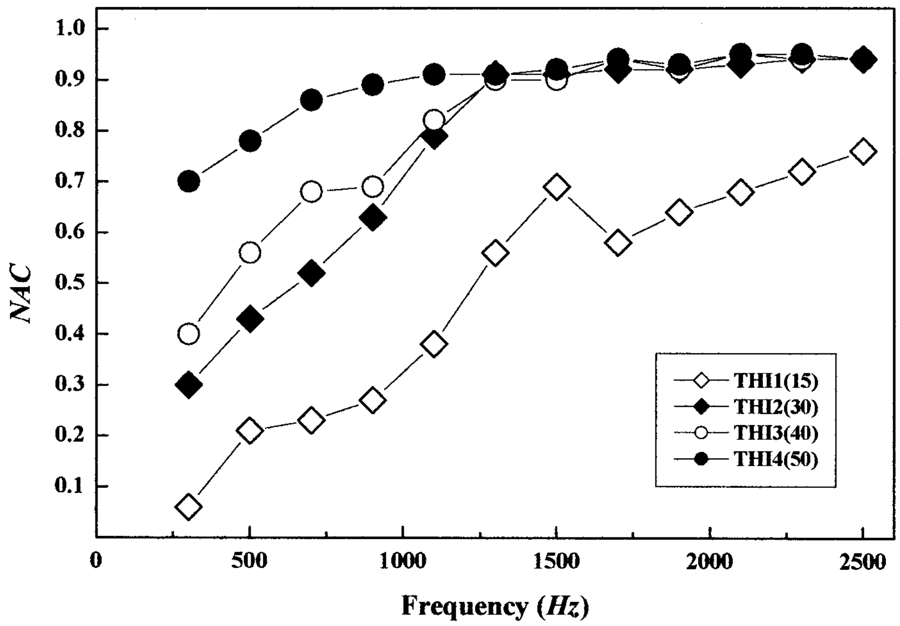

Figure 5 Effect of the nonwoven thickness on the sound absorption properties.

related to the frequency. If the incidence sound wave length over the sound absorber thickness, increasing the thickness is meaningless.

Surface roughness and panel vibration

Sample EMB showed the effect of the surface roughness, WE had the largest embossed area, and NE and NED had almost the same embossed area on the sample surface. Although NE and NED had the same roughness area on the surface, in light of the area contacting the sound wave, NED had a much larger contact area than NE, and it was almost close to WE.

The NAC results for the surface roughness tests are illustrated on Figure 6. All of the samples that had roughness on the surface showed an increase in NAC with respect to the RAW sample, but the tendency of

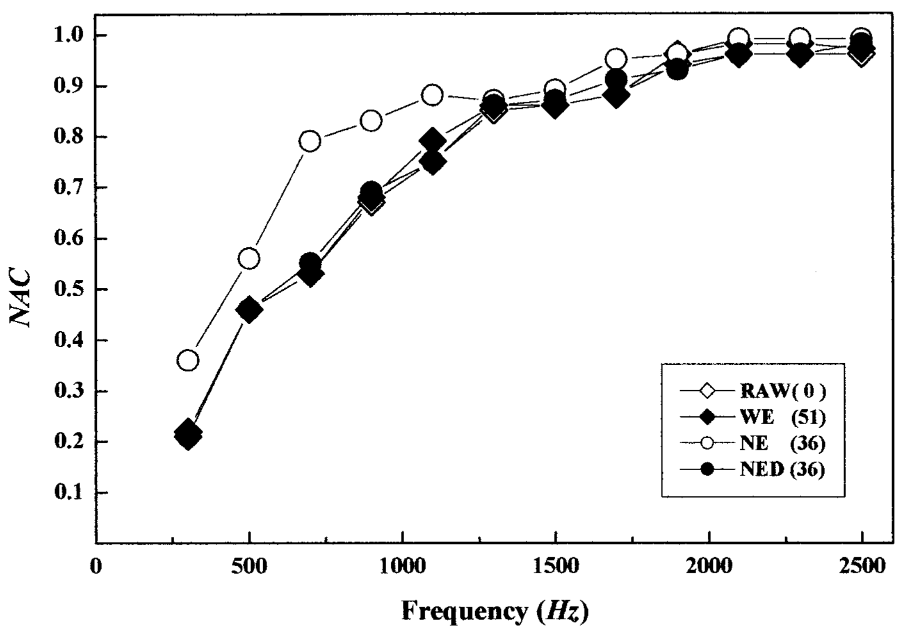

Figure 6 Effect of the surface roughness on the sound absorption properties.

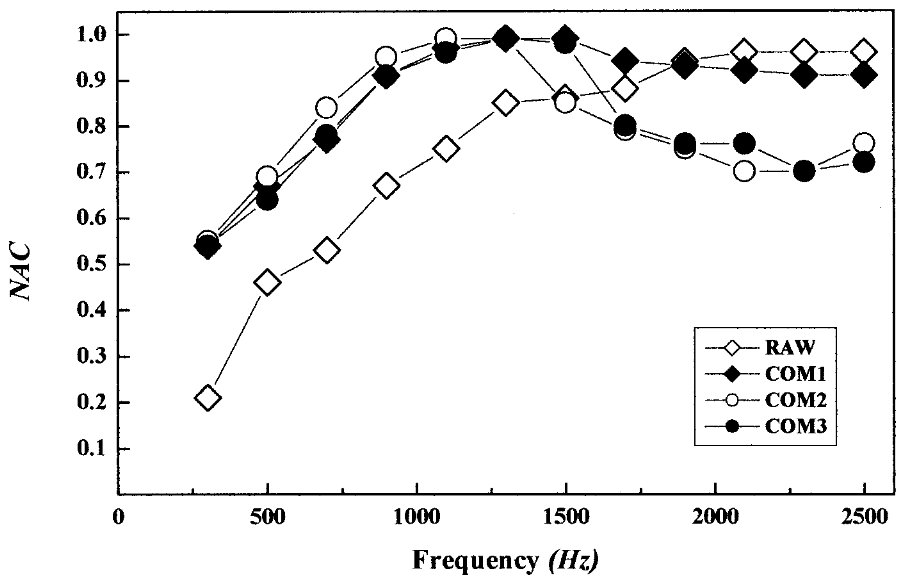

Figure 7 Effect of the panel vibration on the sound absorption properties.

the roughness effect with NE types was much higher NAC and NRC values than for the others. For WE, it could be considered the wide roughness surface of the Helmholtz resonator; however, for NED, it could be considered a reduction of the thickness.[12] Therefore, it was difficult to control sound absorption. Appropriately enhanced surface roughness in the NE sample increased the contact area between the samples and the sound energy, resulting in an increase in NAC. Therefore, reasonable frequencies absorbed by surface roughness can be decided by the inherent sample properties and roughness area.

Three types of panels were examined for panel vibrations. We used thick and thin PP films and aluminum foil, which made vibrations on the surface by sound pressure. The most obvious feature was a tremendous increase in NAC in the low-frequency region, without any exception. Figure 7 shows an increase in NAC in the low- and middle-frequency regions, but in the high-frequency region ($f > 1750$ Hz), a coincidence effect made NAC drop rapidly. The decreasing rate of the 0.03-mm PP film was the lower than that of the aluminum foil and 0.08-mm PP film. The coincidence effect moved to the low-frequency region when the material was thick and rigid and had a low density.

On the basis of the overall results, all of the panel types increased NAC and NRC against the RAW sample, but NAC showed a reduction in the high frequency inverse to that of the RAW sample. These results rigorously matched theoretical equations provided by Hemond.[12] However, the range of optimum absorption frequency regions was broader than the theoretical predictions. Therefore, these studies imply NAC could be improved and controlled in all frequency regions as necessary through the combination of film and fibrous materials.[9–11]

CONCLUSIONS

We have investigated three modes of sound absorption. These materials have different characteristics, not only in their acoustical properties but also in other properties, such as the mechanical strength, chemical stability, fireproofing, and external appearance. It is important to use optimum materials for respective applications. Through a normal incidence impedance tube test, we have determined the following results for improving NAC with different material structures, such as ultrafine fibers, surface roughness, and panel resonance:

1. The contents of ultrafine fibers are directly proportional to NAC and NRC. Ultrafine fibers enhance the mass per unit area, which contributes to an increase in the density and provides more chances for contact with the sound energy in the sound absorption nonwoven. More chances for contact mean more loss of sound energy by the friction and vibration of the internal fibers.
2. The surface roughness of nonwovens is effective for increasing NAC and NRC. Roughness on the surface makes resonance, and so appropriate roughness gives an increase in the sound absorption, but the rate of sound absorption depends on the width and depth. If the sound absorption materials have too much width or depth, the noise will be doubled by the resonance effect and

thickness reduction. The panel resonance effect increases NRC. In the case of NAC, panels promote sound absorption in low- and middle-frequency regions but have the reverse effect in a high-frequency region by the coincidence effect. PP films and foil make vibrations on the surface by sound pressure. Therefore, much sound energy is changed into vibration and friction energy.

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