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Investigation on micro-perforated panel absorber with ultra-micro perforations

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ABSTRACT

Micro-perforated panel (MPP) absorber has been widely used in noise reduction and is regarded as a promising alternative to the traditional porous materials. However, the absorption bandwidth of a single MPP is always insufficient to compete with the porous materials. Thus its practical application such as interior finish of room walls which has strict restrictions on space is prevented. According to Maa's theory, a possible approach to obtain high sound absorption over broad frequency band is to reduce the perforation diameter and increase the density of the perforation properly. And the absorption limits of a single MPP even can be obtained by reducing the perforation diameter to less than 100 μm. However, it's difficult for traditional processing technology such as machining punching to fabricate such small perforations, thus MPPs with ultra-micro perforations have seldom been reported yet. In this paper, trial production of MPPs with ultra-micro perforations based on MEMS technology and measurement of their normal absorption coefficients were carried out. Results show that better absorption capability can be given with MPPs by using a ultra-micro perforation. Maa's conclusion that MPP absorbers can satisfy high sound absorption in broad frequency range by reducing the perforation diameter is therefore validated experimentally.

1. Introduction

Micro-perforated panel (MPP) absorber is promising as a basis for the next generation of sound absorbing constructions [1–4]. This absorber has notable advantages in practice since it is lightweight, inexpensive, resistant to wind and humidity, and fiber-free, due to this, there is no health concern. The basic construction of a MPP absorber consists of a thin flat panel perforated with a large number of sub-millimeter perforations fitted in front of a rigid backing wall with an air space between them, as illustrated in Fig. 1a. Simple construction is one of its significant advantages, too. It is seen in Fig. 1a that the acoustic performance of such a device can be completely determined by the perforation diameter *d*, the panel thickness *t*, the distance between centers of adjacent perforations *b* and the depth of the air gap *D*. The basic theory of MPP absorber was first put forward by Maa [1]. According to Maa's theory, the sound absorbing characteristics of MPP absorbers can be precisely predicted with the maximum error being no more than 6%. And since Maa's pioneering works, as an innovative fiber-free solution to the noise control problem, MPP absorber is finding more and more applications in areas such as room acoustics [5,6], environmental noise abatement [7], duct silencing systems [8] and acoustic window systems [9].

Although MPP absorber offers an outstanding alternative to the traditional porous materials, its sound absorption capability is usually not quite enough for a practical applications especially in constrained space. Many studies have been conducted on improving the sound absorption performance of MPP absorbers. A compound absorber is used to broaden the absorption bandwidth by adding a second MPP to the primary one in tandem, the double-layer design can extend the absorption bandwidth to lower frequencies, but at the cost of occupying more space due to the extra layer construction [2]. Another approach is to arrange multiple MPP absorbers of different frequency characteristics in parallel [10–12], hence an MPP absorber array. However, the excess cost associated with the extra honeycomb construction should be installed between MPP and the rigid wall in order to make various MPP absorbers play different role. Theoretically [3,4], aiming at broadband absorption, a more straightforward and space-saving approach is to reduce the perforation diameter and increase the perforation ratio properly, and Maa pointed out that this method can even reach

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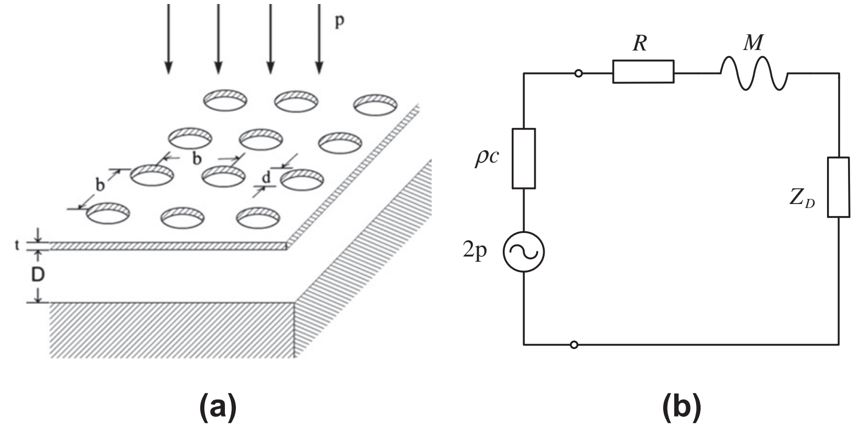

Fig. 1. Schematic diagrams of the MPP absorber and its equivalent circuit.

the absorption limits of a single MPP absorber by using a ultra-micro perforation of diameter less than 100 μm. Thus study on MPP absorber with ultra-micro perforations has great significance. However, due to the limitation of traditional processing technology, MPP absorber with ultra-micro perforations has seldom been reported yet and so the conclusion mentioned above by Maa has not been experimentally validated. In this study, as an attempt to wideband sound absorbers that can be used in constrained space, a trial production of MPPs with ultra-micro perforations were fabricated based on MEMS technology, and their normal sound absorption characteristics were experimentally investigated. Results show that the half-absorption (i.e., the sound absorption coefficients $\alpha \geqslant 0.5$) bandwidth of MPP absorbers with ultra-micro perforations is greatly improved, indicating the tremendous potential of a single MPP for noise reduction.

2. Maa's theory of MPP absorber

Maa's theoretical analysis of MPP absorber is based on electro-acoustical equivalent circuit under a simplified condition, as modeled in Fig. 1b. In Fig. 1b is shown the equivalent circuit of a single layer of MPP mounted at distance D from a rigid wall, where R and M are the specific acoustic resistance and reactance of the perforations. The sound wave impinging on the structure is equivalent to a source of sound pressure 2p as produced on the rigid wall with the time factor exp $(-j\omega t)$ suppressed throughout (analogous to the open-circuit voltage) and internal resistance ρc as that of air [1], with ρ the air density and c the sound speed. Z_D is the impedance of the air space between MPP and the rigid wall, Z_D can be expressed as:

$$Z_D = -j\rho c \cdot \cot(\omega D/c) \tag{1}$$

where $\omega = 2\pi f$, is the angular frequency of incident acoustic wave. The basic idea of Maa's theory is to regard a MPP as a parallel connection of the perforations. An perforation can be regarded as a short tube. The propagation of sound waves in narrow tubes was first discussed by Rayleigh [13], and a simplified version was given by Crandall [14] for very short tubes in comparison with wavelengths. For the equation of aerial motion inside the tube, by assuming sinusoidal functions of time and zero velocity on the tube wall, an exact solution for the acoustic impedance of the tube was derived:

$$Z_1 = \frac{\Delta P}{\bar{u}} = j\omega\rho t\left[1 - \frac{2}{k\sqrt{-j}}\frac{J_1\left(k\sqrt{-j}\right)}{J_0(k\sqrt{-j})}\right]^{-1} \tag{2}$$

with

$$k = \sqrt{\frac{\rho\varpi}{\eta}}\frac{d}{2} = \sqrt{\frac{\varpi}{\mu}}\frac{d}{2} \tag{3}$$

where Δp is sound pressure difference between the two ends of the tube, $\bar{u}$ is the average velocity of air inside the tube, t is the panel thickness, η is dynamic viscosity constant of air, $\mu = \eta/\rho$ is kinematic viscosity constant of air, d is diameter of the tube, J_1 is Bessel's function of the first kind and first order, J_0 is Bessel's function of the first kind and zeroth order. Because the calculation was rather complicated, Crandall proposed two approximation formula for very narrow ($k < 1$) and relatively wide ($k > 10$) tubes:

$$\begin{aligned} &Z_1 \xrightarrow[k<1]{} \frac{4}{3}j\omega\rho t + \frac{32\rho\mu}{d^2} \\ &Z_1 \xrightarrow[k<10]{} j\omega\rho t + \frac{4\rho\mu}{d}\sqrt{\frac{\varpi}{2\mu}}(1+j) \end{aligned} \tag{4}$$

Maa [1], observing the discontinuity between the two cases, developed an approximation solution for perforation of sub-millimeter size which made k lie between 1 and 10, namely for micro-perforated panel (MPP):

$$Z_1 = \frac{32\rho\mu t}{d^2}\sqrt{1+\frac{k^2}{32}} + j\omega\rho t\left(1 + 1\Big/\sqrt{3^2+\frac{k^2}{2}}\right) \tag{5}$$

In comparison with conventional formula for perforated panel absorbers, however, an outstanding feature of Maa's theory is that acoustic resistance of the perforations, which becomes significant when the perforations are very small, is taken into account and without additional porous materials. Maa points that comparing with the exact values, they agree well, with the error being no more than 6% [1].

End corrections must be added, the end correction of the acoustic mass comes from the sound radiation from the ends of tube, and makes the effective length of the tube increased by 0.85 d if radiation from both ends are counted. End correction of the acoustic resistance is produced by the friction loss due to a part of the air moves along the panel when the air flows into and out of the tube, the additional part of the acoustic resistance is $2\sqrt{2\omega\rho\eta}$, if both sides of the tube are ended in infinite panels. According to Maa's theory, the specific impedance of a MPP is equal to the specific acoustic impedance of a single tube (plus end corrections) divided by the perforation ratio (total area of the perforation on a unit area of panel), thus the specific acoustic impedance of MPP normalized by ρc (the characteristic impedance of air) can be calculated by

$$z_{\mathrm{MPP}} = \frac{Z_1}{\sigma \rho c} = r + j\omega m \tag{6}$$

with

$$r = \frac{32\mu}{\sigma c}\frac{t}{d^2}\left(\sqrt{1+\frac{k^2}{32}}+\frac{\sqrt{2}k}{8}\frac{d}{t}\right) \tag{7}$$

$$m = \frac{t}{\sigma c}\left(1 + 1\bigg/\sqrt{3^2+\frac{k^2}{2}}+0.85\frac{d}{t}\right) \tag{8}$$

where σ is the perforation ratio, $\sigma = 78.5d^2/b^2$ if the perforation is arranged in square lattices, b is the distance between centers of adjacent perforations, c is the sound velocity in air, r is the normalized specific acoustic resistance of MPP, m is the normalized acoustic mass of MPP. The normal specific acoustic impedance of the cavity behind the MPP, again normalized by ρc, is

$$Z_D = -j\cot(\omega D/c) \tag{9}$$

According to the equivalent circuit in Fig. 1b, the normalized specific acoustic impedance of the whole structure can be calculated by

$$z = r + j\omega m - jcot(\omega D/c) \tag{10}$$

For normal incidence, the absorption coefficient is derived by

$$\alpha = \frac{4r}{(1+r)^2 + (\omega m - \cot(\omega D/c))^2} \tag{11}$$

The maximum absorption coefficient is

$$\alpha_{\max} = \frac{4r}{(1+r)^2} \tag{12}$$

According to Maa's theory, it is suggested that the lower limit 0.5 of absorption coefficient should be taken for useful absorption range. Replace α in Eq. (11) for 0.5, and for the lower and higher limit frequency can be calculated respectively by

$$\frac{\omega_1 D}{c} = \frac{\cot^{-1}[8r-(1-r)^2]^{1/2}}{1+\frac{g}{1+8r-(1-r)^2}} \tag{13}$$

$$\frac{\omega_2 D}{c} = \frac{\pi - \cot^{-1}[8r-(1-r)^2]^{1/2}}{1+\frac{g}{1+8r-(1-r)^2}} \tag{14}$$

with

$$g = \omega m/(\omega D/c) \tag{15}$$

The half-absorption bandwidth can be calculated by

$$n = \sqrt{\omega_2/\omega_1} \tag{16}$$

Table 1
The material and structural parameters of MPP absorbers.

Material	Specimen	d (μm)	t (μm)	b (μm)	D (mm)	σ (%)
Silicon	1	27	200	55	20	18.92
Silicon	2	44	200	106	20	13.53
Silicon	3	54	200	156	20	9.41
Silicon	4	68	200	216	20	7.78
Silicon	5	80	200	277	20	6.55

$\alpha_{\max}$ and n are the basic performance parameters of MPP absorbers.

3. Design and fabrication of MPPs with ultra-micro perforations

Eqs. (7) and (8) show that the normalized acoustic mass of MPP depends mainly on its perforation ratio only, while the normalized specific acoustic resistance of MPP varies also inversely with the perforation diameter. The acoustic resistance and acoustic mass therefore can be varied separately. If the perforation diameter is reduced to a certain extent, sufficient acoustic resistance and lower acoustic mass can be obtained to make a good wideband sound absorber [1]. For the experimental investigation, MEMS technology was applied to fabricate the MPPs with ultra-micro perforations which was difficult to be fulfilled by means of machining. The MPPs made from silicon are rigid enough to satisfy the rigid assumptions of Maa's theory. The specimens were made with various perforation diameters, various arrangements and various perforation ratio. But the panel thickness and the cavity depth are kept constant at 200 μm and 20 mm, respectively. The design parameters are listed in Table 1 and pictures of some of the specimens are shown in Fig. 2. In Table 1, d, t, b, D have the same meaning as those in Fig. 1a, σ is the perforation ratio. Each group of the structural parameters is designed to make the half-absorption bandwidth and the maximum absorption coefficient as large as possible though it may not be optimal.

It can be seen in Table 1 that, as the perforation diameter decreases, for better absorption performance, the perforation ratio should be increased correspondingly. However, the maximum perforation ratio is less than 19.6%, meeting the basic assumptions of Maa's theory [1]. If the perforation ratio is greater than 19.6%, basic assumptions of Maa's theory cannot be fulfilled, the effect of interaction between perforations should be taken into account [15].

4. Experimental results

The experimental normal absorption coefficients were obtained using the impedance tube and standing wave method (see Fig. 3 or [16] for the setup details). Fig. 3 shows the layout of the experiment. A small loudspeaker was placed at one end of the tube with 29.6 mm in diameter. The test material was placed at the other

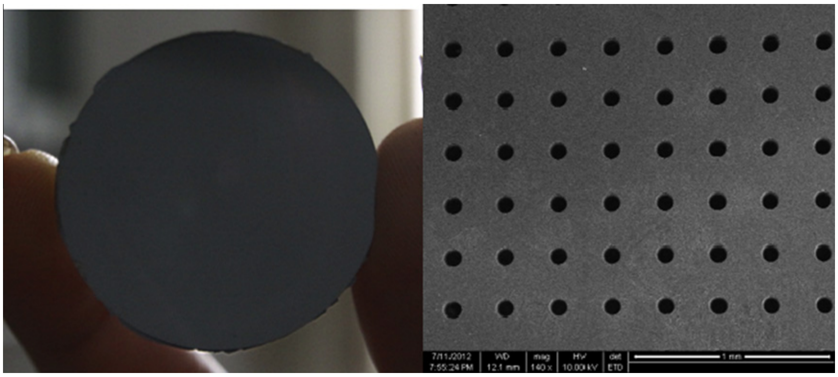

Fig. 2. Photograph and SEM micrograph of No. 3 MPP.

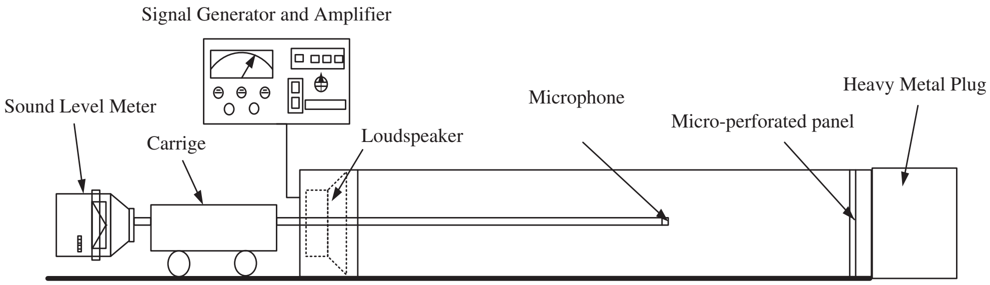

Fig. 3. The layout of the impedance tube.

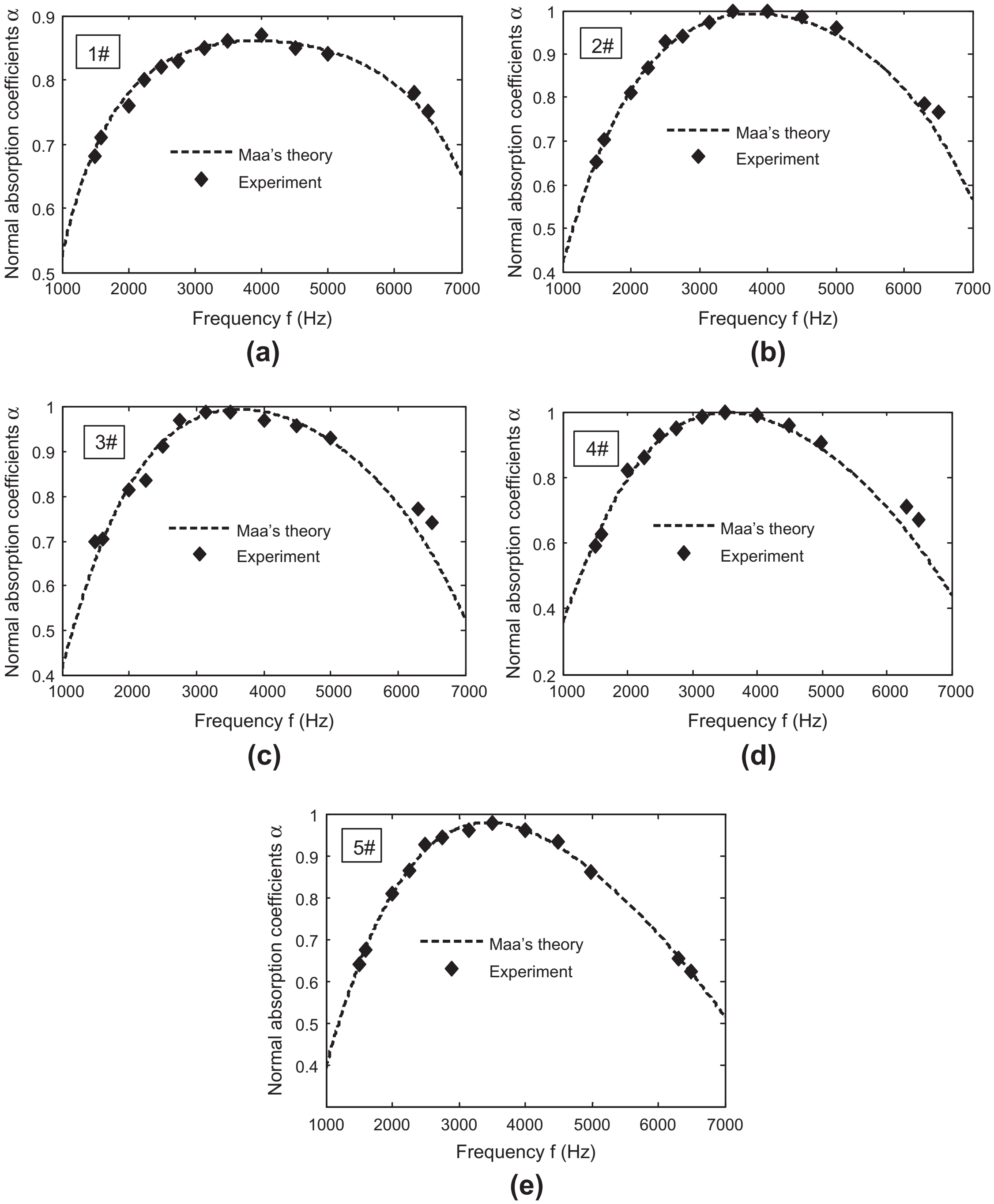

Fig. 4. The predicted and measured absorption coefficients of MPP absorbers with different structural parameters.

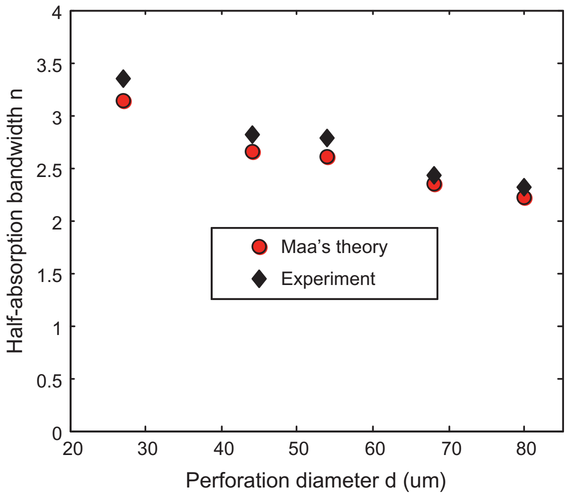

Fig. 5. The predicted and measured half-absorption bandwidth of MPP absorbers with different structural parameters.

end. The sound field in the tube was the standing wave formed by the incident and reflected waves. The standing wave pressure ratio (the ratio of maximum root-mean square pressure to minimum root-mean square pressure) can be obtained by moving the probe microphone connected to a carriage along the tube. The testing frequency ranges from 1500 Hz to 6500 Hz, and the measured frequencies were the center frequencies of 1/3 octave. The absorption coefficients can be calculated by

$$\frac{4P_{\max}P_{\min}}{(P_{\max}+P_{\min})^2} \tag{17}$$

where $P_{\max}$ is the maximum pressure and $P_{\min}$ is the minimum pressure. Fig. 4 shows the comparisons between predicted and measured normal absorption coefficients versus frequency. Fig. 5 shows the comparisons between predicted and measured half-absorption bandwidth as a function of the perforation diameter. The prediction results are generated from Eqs. (11) and (16) respectively. Good agreements are found between predicted and measured results in Figs. 4 and 5. Specimen 1 with 27 μm perforation shows half-absorption bandwidth of 3–4 octaves with the maximum absorption coefficients exceeding 0.85 (see Figs. 4a and 5). This is because of the very high acoustic resistance and lower acoustic mass due to the tiny perforation. Specimen 2 with 44 μm perforation, specimen 3 with 54 μm perforation, specimen 4 with 68 μm perforation and specimen 5 with 80 μm perforation show higher peak absorption with the maximum absorption coefficients exceeding 0.95, but with a relatively narrow half-absorption bandwidth(see Figs. 4b–e and 5). This is due to the fact that large perforations result in large acoustic mass, which makes the absorption frequency band relatively narrow compared with specimen 1. The commonly used MPP absorbers with perforation diameter in the range of 0.2–1 mm is able to achieve a half-absorption bandwidth of 1–2 octaves with the maximum absorption coefficients exceeding 0.85 [17]. In contrast with the traditional MPP absorbers, the absorption performance of MPP absorbers with ultra-micro perforation is greatly improved. And it can also be seen from Fig. 5 that the smaller the perforation diameter, the better the half-absorption bandwidth. Thus Maa's conclusion that reducing perforation diameter can broaden the half-absorption bandwidth of MPP absorber and even reach its absorption limits is validated experimentally. At the same time, the tremendous potential of a single MPP as wideband sound absorber for noise reduction can be inferred from these results.

5. Conclusion

As an attempt to attain wideband sound absorber which are suitable for constrained space, MEMS technology was applied for the trial fabrication of MPPs with ultra-micro perforations which was hard to be realized by the traditional processing technology and their normal absorption coefficients were tested in the impedance tube. Results show that a single MPP absorber can satisfy high absorption in wide frequency range by using a ultra-micro perforation, indicating great potential of MPP absorbers as wideband absorbers for noise control under the condition that there are strict restrictions on space. The measured results have good agreements with the numerical calculations based on Maa's theory, therefore Maa's theory is validated.

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