MODELING OF HETEROGENEOUS PERFORATED PANELS

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ABSTRACT

Heterogeneous perforated panels are of great interest as sound absorbers, while achieving a smart high-end decoration in meeting rooms, showrooms, conference halls... However, their uneven nature may pose a difficulty when trying to predict their acoustic performance using traditional impedance models. This work explores the use of different analytical methodologies to estimate the acoustic properties of heterogeneous perforated panels. The proposed approaches are compared to finite element simulations that reproduce an impedance tube setup for different absorber configurations. Preliminary results show that these methodologies may be useful in the design stage of such devices.

RESUMEN

Los paneles perforados heterogéneos resultan de gran interés como absorbentes sonoros, a la vez que consiguen un acabado elegante en salas de reuniones, salas de exposiciones, salas de conferencias... Sin embargo, su naturaleza irregular puede plantear dificultades al intentar predecir su rendimiento acústico usando modelos de impedancia tradicionales. Este trabajo explora el uso de diferentes metodologías analíticas para estimar las propiedades acústicas de paneles perforados heterogéneos. Los enfoques propuestos se comparan con simulaciones en elementos finitos que reproducen una configuración de tubo de impedancia para diferentes configuraciones de absorbente. Los resultados preliminares muestran que estas metodologías pueden ser útiles en la etapa de diseño de tales dispositivos.

1. INTRODUCTION

Heterogeneous perforated panels may be considered periodically heterogeneous structures with surface regions of different perforation rate or whose perforations differ in size. Because of their positive visual impact, these materials are preferably chosen for indoors in which a smart high-end decoration is pursued (e.g. in meeting rooms, showrooms, conference halls…). In this context, perforated panels backed by an air cavity and a rigid wall work as resonant sound absorbers [1, 2], the sound attenuation being produced by viscothermal losses in their holes. Miasa et al. [3] investigated experimentally the performance of perforated panels with holes of multiple sizes compared to uniform size. Their results showed that a multi-size perforated panel

absorber may enhance and widen the effective absorption frequency band of the resonator. Therefore, it is of great interest the development of predictive models to study the acoustic properties of these systems.

Generally, flat rigid perforated panels containing periodically arranged circular perforations are modeled using a simple theoretical approach (e.g. Zwikker and Kosten [4], Maa [5]…). For perforations with other cross-sectional shapes, the models by Stinson and Champoux [6] or Atalla [7] can be used instead. In brief, once the geometrical characteristics of the panel are known, the acoustic properties of the absorber under normal plane wave incidence can be easily predicted using any of these approaches. Nevertheless, these models are limited to homogeneous perforated panels, and do not account for the uneven nature of the heterogeneous panels, which may result in notable differences when predicting their absorption performance. Moreover, these discrepancies may become even more significant for the case of multi-size perforated panels if there is a high contrast between the diameters of the holes. For this reason, the need for alternative methodologies that overcome these limitations and serve as an accurate predictive tool is justified.

One of the most general and widespread methods used to determine the acoustic behaviour of heterogeneous perforated panel absorbers is the Finite Element Method (FEM). Wang and Huang [8] studied a configuration consisting on a waveguide coupled to the panel-cavity system to be analyzed, the latter being described following the Maa model [5]. In doing so, its sound absorption performance when impinged by a normal incidence plane wave was estimated. A more simplified approach for this same analysis is the Admittance Sum Method (ASM), which obtains the global surface admittance of the resonator and thus its sound absorption from the sum of the surface admittances of the different perforated regions in the panel. Sakagami et al. [9, 10] analyzed the excess attenuation of two perforated panel absorbers with different perforation ratios arranged periodically and alternately in parallel using this method. In these latter works, the specific model for perforated panels proposed by Maa [5] was used. Another extended methodology, frequently used to determine the acoustic properties of multiple layer systems, is the Transfer Matrix Method (TMM) [11]. This method uses a matrix representation to model the plane wave propagation in a serial arrangement of any number of layers of porous materials and predict the absorption performance of the whole system. Each of these porous layers is typically modeled following the classical Johnson-Champoux-Allard (JCA) equivalent fluid model [12, 13]. Verdière et al. [14] extended this method to deal with heterogeneous sound absorbing materials such as patchworks, acoustic mosaics, and other acoustic elements assembled in parallel. Since these materials resemble in some way the case of a panel with differentiated perforated regions, this method may be interesting to the study of its acoustic properties. In fact, according to [14], this so-called Parallel Transfer Matrix Method (PTMM) can be applied to predict the absorption properties of any parallel assembly of finite size materials. More recently, Pieren and Heutschi [15] shown that the same universality is offered by the Equivalent Circuit Method (ECM). They demonstrated that a large variety of backing termination conditions can be handled using this method.

This work explores the use of the above introduced analytical methods to predict the acoustic properties of heterogeneous perforated panel absorbers. For this purpose, a macroscopic description of the heterogeneous medium is first derived, and then the three sets of analytical methods tested: the Admittance Sum Method (ASM), the PTMM (Parallel Transfer Matrix Method) and the Equivalent Circuit Method (ECM). All of these methods make use of an equivalent fluid description based on the well-known JCA approach to model the different perforated regions of the panel. Calculations in terms of sound absorption were performed for different representative heterogeneous perforated panel absorber configurations. The results were compared to those obtained using Finite Element (FE) simulations that reproduce and impedance tube setup, which served to assess the adequacy of these methods depending on the absorber configuration type.

2. HETEROGENEOUS PERFORATED PANELS

2.1 Macroscopic description

A heterogeneous perforated panel consists of a serie of perforated regions whose perforation rates and/or hole sizes differ from one region to others. One of the main advantages of these panels when compared to homogeneous is that, when being part of a panel-cavity resonator system, they allow broadening its absorption frequency range without necessarily increasing the cavity depth [3, 9, 10]. This potential feature is of great interest in the context of building acoustics, where the space constraints are especially demanding. Further, the combination of different hole sizes or perforations rates not only paves the way for a large variety of aesthetic designs, but also to explore extra capabilities.

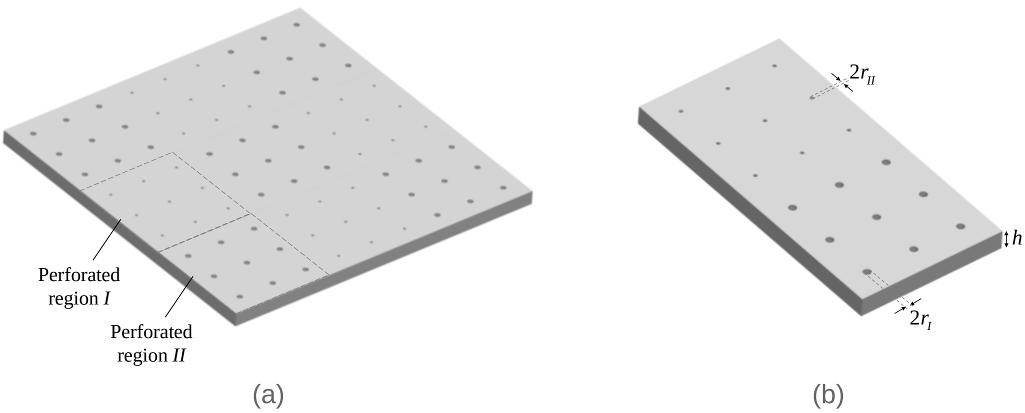


Fig. 1. Schematic of the heterogeneous perforated panel: (a) general view, and (b) elementary cell.

Let us consider the rigid heterogeneous perforated panel of infinite lateral extent shown in Fig. 1.a. For the sake of simplicity, the panel herein described is divided into only two different periodic perforated regions, even though this description could be extended to any multiple region panels. As a rule, a macroscopic acoustic description of a heterogeneous periodic structure can be derived if its periodicity is much smaller that the sound wavelength of interest. Under this assumption, a fluid equivalent to the panel can be defined for normal incidence plane wave propagation by appropriately accounting for each region. The contribution of either region can be described separately from their acoustic properties, namely characteristic impedance, Z_i, and wave number, k_i.

$$Z_i = \sqrt{\rho_{eq,i} K_{eq,i}} \tag{1}$$

$$k_i = \omega \sqrt{\rho_{eq,i} / K_{eq,i}} \tag{2}$$

where $\rho_{eq,i}$ and $K_{eq,i}$ are the complex density and bulk modulus of the equivalent fluid in the ith region, respectively, and ω is the angular frequency. In the perforated regions, these parameters account for the viscothermal dissipative mechanisms, and can be determined by using a classical impedance model as the one described in Subsection 2.2.

After the relevant acoustic properties are obtained, the normal incidence sound absorption coefficient, α, of the heterogeneous perforated panel absorber can be calculated from

$$\alpha = 1 - \left| \frac{Z_S - Z_0}{Z_S + Z_0} \right|^2 \tag{3}$$

where Z_0 is the characteristic impedance of air, and Z_S is the surface impedance of the absorber, to be determined from the analytical methods described later in Section 3.

2.2 Johnson-Champoux-Allard (JCA) model

The Johnson-Champoux-Allard (JCA) model [12, 13] was chosen to study the acoustic properties of each perforated region of the elementary cell of the panel depicted in Fig. 1.b. Even though other approaches exist in the literature [4, 5], the JCA model is more generic aside from ease the description of the panel in terms of transfer matrices. This model describes the acoustic wave propagation in this porous medium from five parameters: perforation rate (or porosity), ϕ, tortuosity, α_∞, static flow resistivity, σ, viscous characteristic length, Λ, and thermal characteristic length, Λ'. Given that the panel is supposed to be motionless (i.e. rigid skeleton), an equivalent fluid description of each perforated region can be derived with the following complex density and bulk modulus expressions

$$\rho_{eq} = \frac{\alpha_\infty \rho_0}{\phi} \left(1 + \frac{\sigma \phi}{j\omega \rho_0 \alpha_\infty} \sqrt{1 + \frac{4j\omega \alpha_\infty^2 \mu \rho_0}{\sigma^2 \Lambda^2 \phi^2}} \right) \tag{4}$$

$$K_{eq} = \frac{\gamma P_0}{\phi} \left(\gamma - (\gamma - 1) \left(1 + \frac{8\mu}{j\omega \Lambda'^2 N_P \rho_0} \sqrt{1 + \frac{j\omega \Lambda'^2 N_P \rho_0}{16\mu}} \right)^{-1} \right)^{-1} \tag{5}$$

where ρ_0 is the air density, μ is the dynamic viscosity of air, γ is the ratio of specific heats, P_0 is the atmospheric pressure, and N_P is the Prandtl number. Assuming circular cross-section perforations, the static flow resistivity may be defined as $\sigma = 8\mu/(\phi r^2)$, r being the hydraulic radius of the perforations; and the viscous and thermal characteristic lengths are equal to that hydraulic radius, that is $\Lambda = \Lambda' = r$. It should be noted that an equivalent tortuosity, $\alpha_\infty = 1 + 2\varepsilon_e/h$, must be used so as to account for the effective thickness of the panel and the interaction between the perforations, $\varepsilon_e = 0.48(\pi r^2)^{1/2}(1\text{-}1.14\phi^{1/2})$ representing the correction length [7], and h the actual thickness.

3. ANALYTICAL METHODS

3.1 Admittance Sum Method (ASM)

The Admittance Sum Method (ASM) allows obtaining the acoustic properties of the heterogeneous perforated panel absorber considering this as a parallel assembly of acoustic elements. Total surface impedance is found by adding the admittances of each perforated region of the elementary cell shown in Fig. 1.b in series with an associated air cavity as

$$Z_S = \left(\sum r_i Y_i \right)^{-1} \tag{6}$$

where r_i is the surface ratio of the ith region to the total surface of the elementary cell (which should not be mistaken with the hole size, r), and Y_i is the admittance of each of these regions, which can be calculated as the inverse of the surface impedance $Z_{S,i}$ of the respective panel ith region, this latter being related to its respective characteristic impedance, Z_i, and wave number, k_i, as follows

$$Z_{S,i}=Z_i\frac{-jZ_{ac}\cot(k_ih)+Z_i}{Z_{ac}-jZ_i\cot(k_ih)} \tag{7}$$

where $Z_{ac,i}$ = -$jZ_0\cot(k_0h_{ac,i})$ is the acoustic impedance of the corresponding backing air cavity, $h_{ac,i}$ and h being the thickness of the cavity and the panel, respectively, and k_0 the wave number of air.

3.2 Parallel Transfer Matrix Method (PTMM)

Similarly to ASM, the Parallel Transfer Matrix Method (PTMM) predicts the sound absorption performance of the whole heterogeneous perforated panel absorber seeing this as a collection of acoustic elements in parallel, backed by an additional region that works as the air cavity of the resonant system. For this purpose, transfer matrices were developed for each region of the elementary cell described in Section 2.1, and coupled together following the procedure described in [14]. Assuming each region as being locally reacting and normal incidence plane wave propagation, the acoustic fields at the upstream (M) and downstream (M') of each region i, defined by the sound pressure, p, and longitudinal particle velocity, u, are linked by

$$\begin{bmatrix}p(M)\\u(M)\end{bmatrix}=[T]_i\begin{bmatrix}p(M')\\u(M')\end{bmatrix}=\begin{bmatrix}t_{i,11} & t_{i,12}\\t_{i,21} & t_{i,22}\end{bmatrix}\begin{bmatrix}p(M')\\u(M')\end{bmatrix} \tag{8}$$

where the 2x2 transfer matrix $[T]_i$, when an equivalent fluid description is adopted, is given by [11]

$$[T]_i=\begin{bmatrix}\cos(k_ih) & jZ_i\sin(k_ih)\\ \frac{j}{Z_i}\sin(k_ih) & \cos(k_ih)\end{bmatrix} \tag{9}$$

the acoustic properties to be used in these matrix elements, Z_i and k_i, being derived from the JCA model described above for the perforated regions, and being Z_0 and k_0 for the air cavity region.

Inasmuch as the perforated regions are in parallel, admittance matrices must be defined for such regions as

$$[Y]_i=\begin{bmatrix}y_{i,11} & y_{i,12}\\y_{i,21} & y_{i,22}\end{bmatrix}=\frac{1}{t_{i,12}}\begin{bmatrix}t_{i,22} & t_{i,21}t_{i,12}-t_{i,22}t_{i,11}\\1 & -t_{i,11}\end{bmatrix} \tag{10}$$

Thereby, the transfer matrix of an elementary cell of the heterogeneous perforated panel can obtained from the combination in parallel of every region as

$$[T]_{hpp}=-\frac{1}{\Sigma r_iy_{i,21}}\begin{bmatrix}\Sigma r_iy_{i,22} & -1\\ \Sigma r_iy_{i,22}\,\Sigma r_iy_{i,11}-\Sigma r_iy_{i,12}\,\Sigma r_iy_{i,21} & -\Sigma r_iy_{i,11}\end{bmatrix} \tag{11}$$

By multiplying $[T]_{hpp}$ by the transfer matrix of the air cavity, $[T]_{ac}$, the global transfer matrix of the absorber is

$$[T]_g = \begin{bmatrix} t_{g,11} & t_{g,12} \\ t_{g,21} & t_{g,22} \end{bmatrix} = [T]_{hpp}[T]_{ac} \quad (12)$$

Once the overall transfer matrix has been derived, it is straightforward to obtain the normal incidence surface impedance of the whole resonator system from $Z_S = t_{g,11}/t_{g,21}$.

3.3 Equivalent Circuit Method (ECM)

The Equivalent Circuit Method (ECM) is very useful to analyze the acoustic wave propagation throughout a series and/or parallel assembly of acoustic elements [15]. In the case of the heterogeneous perforated panel, each of the perforated regions can be represented using the Π-type two-port network depicted in Fig. 2.a, that relates the acoustic pressure, $p(M)$ and $p(M')$, and volume flow, $U(M)$ and $U(M')$, at the input and output ports, respectively, from the following generalized impedance expressions

$$Z_{\alpha,i} = \frac{Z_i}{r_i}\sinh(jk_i h) \quad (13)$$

$$Z_{\beta,i} = \frac{Z_i \sinh(jk_i h)}{r_i \cosh(jk_i h) - 1} \quad (14)$$

The parallel arrangement of these perforated regions can be described from the equivalent network shown in Fig. 2.b. Thus, using basic circuit analysis theory, the whole panel can then be connected in series to any termination impedance (e.g. a backing air cavity), and hence the sound absorption of the absorber assessed.

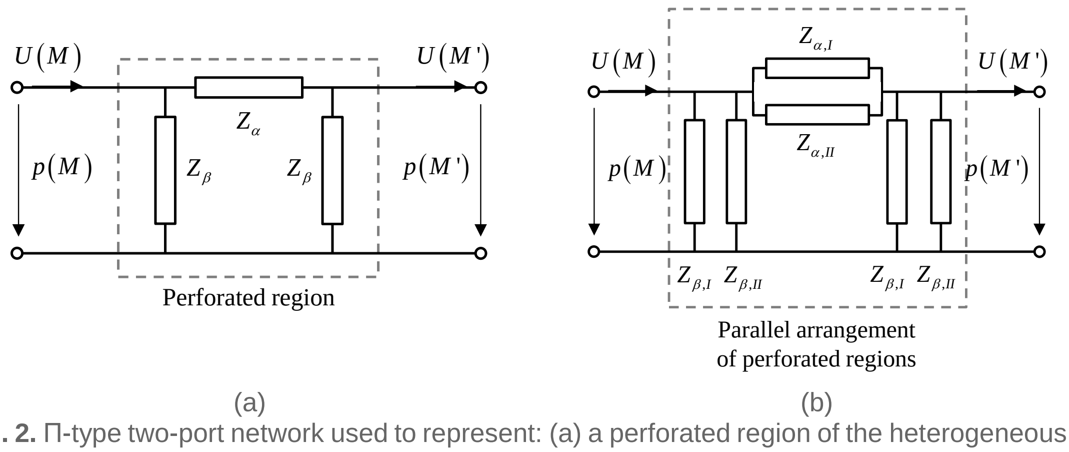


Fig. 2. Π-type two-port network used to represent: (a) a perforated region of the heterogeneous perforated panel, and (b) a parallel arrangement of perforated regions.

4. RESULTS

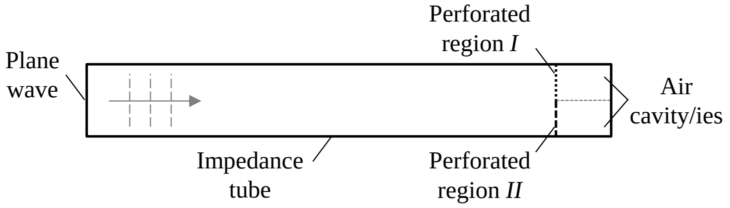
4.1 Assessment of the adequacy of the methods

In order to assess the adequacy of the methods, predictions of the sound absorption performance of two simple heterogeneous perforated panel configurations are compared to those obtained with FE simulations. One of them is composed of two different perforated regions whose backing cavities are independent (isolated case), whereas in the other, these regions share the same backing cavity (non-isolated case). In both cases, the panel is backed by an air cavity with h_{ac} = 10 mm, each perforated region representing half of the total surface of the panel, $r_I = r_{II} = 0.5$. The geometrical characteristics of the panel, necessary to calculate the JCA parameters of its respective perforated regions, are summarized in Table 1.

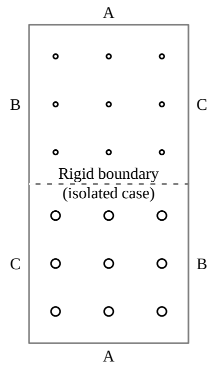
Table 1. Geometrical characteristics of the heterogeneous perforated panel.

Perforated region	*h* (mm)	*r* (mm)	*Φ* (%)
I	2	0.2	0.44
II	2	0.4	1.77

For the numerical simulations, an impedance tube setup that reproduces the ISO 10534-2:1998 standard [16] was implemented using the Acoustics module of the FE software COMSOL Multiphysics®. Fig. 3a shows the numerical scheme developed. The fluid in the impedance tube and air cavity regions were modeled as air, whereas the fluid in the tubes of the perforated regions was modeled using the JCA equivalent fluid model. Continuity conditions were imposed in the identity pair boundaries of the impedance tube and air cavity denoted as A, B and C (see Fig. 3b) so as to account for the periodic nature of the panel. In the configuration for which the air cavities are isolated, an acoustically rigid boundary condition was imposed in the virtual plane separating them.



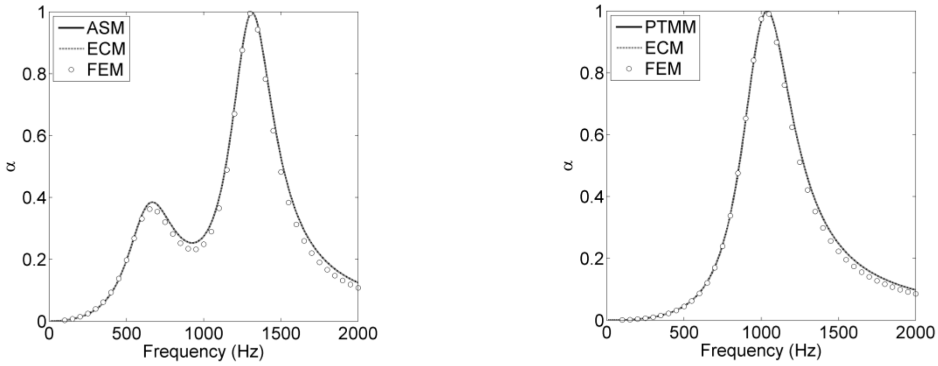
(a)



(b)

Fig. 3. Numerical FE model: (a) schematic of the impedance tube setup, and (b) continuity conditions imposed on the boundaries of the impedance tube and air cavity (frontal view).

A plane incidence pressure wave was imposed at one side of the virtual impedance tube, and the transfer function, necessary to obtain the sound absorption coefficient, was calculated from the pressure field at two separate points in the same. The problem domain was meshed using quadratic tetrahedral elements with a maximum element size of 35 mm (around 5 elements per wavelength for the highest considered frequency), the mesh density being higher near the perforations. Harmonic analysis was carried out in the frequency range between 100 Hz and 2000 Hz. Fig. 4 compares the numerical results and the predictions of the analytical methods for the sound absorption coefficient of both absorber configurations.



(a) (b)

Fig. 4. Comparison of the sound absorption coefficient calculated from the different approaches for the: (a) isolated case and (b) non-isolated case configurations.

In the isolated case (Fig. 4.a), the ASM and the ECM quite accurately predict the sound absorption performance of the resonator system when compared to the FE numerical results. The dual peak in the absorption curve is due to the combination of the two resonant systems. In the non-isolated case (Fig. 4.b), the results are in good agreement with the sound absorption calculated using the PTMM and the ECM. Given that the characteristics of the panel and the air cavity depths were the same in both cases, it was found that the only method that yields correct predictions for both configurations if properly used is the ECM. On the other hand, the ASM can handle the isolated configuration, whereas the PTMM is restricted to the case of non-isolated cavities for each perforated region. Accordingly, these assessments reveal that it is very important to take into account the isolated or non-isolated feature of the backing cavity to properly predict the acoustic behaviour of the absorber.

4.2 Remarks

Some remarks concerning the applicability of the above presented analytical methods to study the acoustic properties of heterogeneous perforated panels are highlighted next. For example, attention must be paid to the fact that a non-periodic distribution of the perforations over the panel surface has a significant effect on the sound absorption prediction [17]. In these cases, the uniform pressure field assumption on the front and rear surfaces of each perforated region is no longer fulfilled, and the predicted results would differ from the correct ones. Consequently, future studies should consider the inclusion of the perforations distribution effect on the prediction of the acoustic behaviour of these resonant systems. Moreover, it would be also important to study the effect of the size of each perforated region with respect to the others, since additional corrections may be necessary if the contrast is too high.

5. CONCLUSIONS

In this work, three analytical methods: ASM, PTMM and ECM, together with the JCA model for porous media, were used to predict the absorption performance of heterogeneous perforated panel absorbers. In order to assess the adequacy of these methods, two different resonant system configurations, one with isolated cavities and one with shared cavities, were examined. The sound absorption coefficient was calculated and compared to FE predictions for these cases following an impedance tube setup. While all of the analytical approaches account for the panel surface heterogeneity, it was shown that only the ECM can capture both the effect of isolates cavities and non-isolated cavities, not so the other analytical methods, which only yield correct results in the isolated case (ASM) or the non-isolated case (PTMM). In summary, these findings suggest that a simple model can be used to predict the acoustic behaviour of such devices provided that special attention is paid the configuration type, being of great interest in the design thereof. All the same, additional research must be carried out to tackle some of the issues stated in the aforementioned remarks, and to extend the study to more complex configurations (e.g. different cavity depths, other perforation shapes…).

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