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Title	Multiple-frequency perfect absorption by hybrid membrane resonators
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Source	Applied Physics Letters, v. 116, (16), April 2020, article number 161902
Version	Published Version
DOI	10.1063/5.0002974
Publisher	AIP Publishing
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Submitted: 29 January 2020 . Accepted: 07 April 2020 . Published Online: 22 April 2020

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ABSTRACT

Besides generating their own perfect absorption bands, the primary hybrid resonances of a hybrid membrane resonator (HMR) consisting of a decorated membrane resonator (DMR) backed by a cavity can also provide strong assistance for weak resonances to create secondary hybrid resonances and multiple-frequency perfect absorption by forming a low impedance region between the primary hybrid resonances. The weak resonances can be introduced by placing another DMR in front of a HMR or by using a DMR with an off-centered platelet in an HMR. In one such sample, five perfect absorption bands within the range of 200–1000 Hz are experimentally observed with minimum reflection values ranging from 1.2% to 7%.

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Acoustic metasurfaces with perfect absorption are highly desired for many applications.¹ Hybrid membrane resonators (HMRs) consisting of a decorated membrane resonator (DMR)² backed by a sealed gas cavity,³ along with several other types of functional structures,^{4–18} are termed “perfect absorbers” in the literature if their absorption coefficient reaches 0.99 or above (reflection $\leq 10\%$). In the original HMR, the hybrid resonance between the DMR and the cavity leads to the critical coupling and the perfect absorption of the incident waves. A modified version of the HMR, where the membrane is replaced by a rigid platelet, achieved perfect absorption when a porous plate is added.⁴ Critical couplings can also be realized by various forms of Helmholtz resonators (HRs), such as the HRs coupled via a narrow channel,⁵ the HRs with embedded apertures which operate in virtually the same mechanism as the coupled HRs,⁶ the HRs coupled to the narrow slits where the strong interaction between them result in the impedance match to air,⁷ or the HRs with small holes to enhance the thermal acoustic effect for dual-frequency perfect absorption.⁸ Besides DMRs, resonators such as HRs or a viscoelastic porous plate backed by a cavity can also achieve perfect absorption.⁹ Coiling schemes or coplanar spiral tubes are often used to reduce the thickness of the devices made by the HRs^{10–13} or the HMR.¹⁴ A planar array of 16 Fabry-Pérot resonators with thickness close to the limit of the causality constraint exhibits a near-perfect flat absorption spectrum starting from 400 Hz.¹⁵ Using an elastic HR cavity, high absorption around two frequencies has been observed.¹⁶ Broadband quasi perfect absorption (above 0.9) is achieved by multiple-unit-cell structures¹⁷

and by the coherent absorption of a series of weak absorbers.¹⁸ Devices with tunable absorption frequencies by an external voltage^{19,20} have also been reported. So far, multiple-frequency (three or more frequency bands) perfect absorption (above 0.99) can only be realized by structures with more than one sealed cavity.

In this paper, we introduce the mechanism of hitchhiker hybrid resonances riding on the wake of the primary hybrid resonances of HMRs for perfect absorption. The impedance spectra show that relatively weak resonances can generate secondary (hitchhiker) hybrid resonances and perfect absorption in the frequency region of small impedance formed by the strong HMR primary hybrid resonances. One approach of introducing secondary resonances is to place another DMR in front of a HMR. The other approach utilizes the secondary resonances of the DMR on the HMR. Using a DMR with an off-centered platelet, five perfect absorption bands within the range of 200–1000 Hz are experimentally observed from the corresponding HMR, with minimum reflection values ranging from 1.2% to 7%.

The structure parameters of the DMRs are summarized in Table I. All the membranes are 0.2 mm thick. The membrane of DMR-1 is made of transparent polyvinyl chloride (PVC). The membranes of the remaining DMRs are made of latex rubber. The decorating platelet is either one or two stacked steel washers 6 mm in diameter. DMR-2 and DMR-3 each consists of a DMR surrounded by large side orifices. The transmission of a DMR was measured first, with the purpose of identifying its resonances and anti-resonances.² The side orifices were sealed off when measuring the transmission spectra of DMR-2 and DMR-3.

TABLE I. List of the samples and their structural parameters.

Sample	Membrane diameter and type	Platelet mass (mg)	Side orifices	Eccentricity
DMR-1	60 mm PVC	130	No	No
DMR-2	40 mm latex rubber	260	Yes	No
DMR-3	40 mm latex rubber	130	Yes	No
DMR-4	40 mm latex rubber	130	No	Slightly
DMR-5	40 mm latex rubber	130	No	Yes

The reflection of the corresponding HMR mounted on a hard wall with negligible transmission was then measured. All the measurements were done via the standard 4-microphone impedance tube method.^{2,3,21,22} The absolute error in the reflection was about 0.01.²¹

We begin with HMR-1 as a standard HMR sample to replicate the ones reported earlier,³ made by DMR-1 backed by a cavity of 30 mm in length and 60 mm in diameter. The transmission spectrum of DMR-1 is shown in Fig. 1(a) as the green curve. It exhibits a typical

DMR transmission spectrum² with two resonant peaks near 317 and 825 Hz, respectively, and an anti-resonance dip at 461 Hz. The reflection spectrum of the corresponding HMR-1 (the red curve) exhibits a dip at 368 Hz, which, as expected, is the hybrid resonance between the first resonance and the anti-resonance mediated by the cavity.³ The characteristics of HMR-1 well resemble the HMRS reported earlier.³

The normalized impedance $Z_{Re} \equiv \frac{Z_{HMR}}{Z_0} - 1 = \frac{2R}{1-R}$ ²³ shown in Fig. 1(b), where R is the experimental reflection coefficient, reveals more clearly what happens. The real part of the HMR impedance $\text{Re}(Z_{HMR})$ quickly drops from $\sim 100Z_0$ to below Z_0 in the frequency range between the first resonance and the first anti-resonance as marked by the circle, while $\text{Im}(Z_{HMR})$ crosses the zero line. The details are shown in Fig. 1(c). The reflection dip is not very small (~ 0.3) because the zero-line crossing frequencies of the real and the imaginary parts of Z_{Re} differ by about 3 Hz. Critical coupling could occur if $\text{Re}(Z_{Re})$ is increased by just 0.05 or by increasing the cavity length by 1 cm³ to increase $\text{Im}(Z_{Re})$ by 1.4 as represented fictively by the dashed line.

Realizing multiple-frequency hybrid resonances with a single cavity could significantly broaden the means of noise abatement, in addition to deepening the understanding of the hybrid resonances. At low frequencies, the acoustic impedance of a DMR is much higher than air, simply because the membrane mass density is nearly 1000 times of air. However, when mounted on HMR-1 the hybrid resonance produces a suitable background from 650 Hz to 900 Hz, where the $\text{Re}(Z_{Re})$ remains small such that even a weak resonance bringing only several Z_0 of change to the overall impedance Z_{Re} could bring Z_{Re} to zero in this frequency range, thereby creating a hybrid resonance and perfect absorption. On the other hand, such a weak resonance is not strong enough to bring Z_{Re} from the value of the DMR ($\sim 80 Z_0$) to near zero by its own. In other words, the weak resonance must utilize, or hitchhike on, the response acoustic field of the primary hybrid resonance to achieve its own hybrid resonance. Two general approaches of realizing hitchhiker hybrid resonances are reported below.

Approach-1 is to place another DMR in front of HMR-1 to form a composite HMR. The inset of Fig. 1(d) shows the schematics, where DMR-2 is 12 mm in front of HMR-1. The transmission of DMR-2 [the blue curve in Fig. 1(d)] indicates that its first and second resonances are at 160.7 Hz and 677.8 Hz, respectively, and its anti-resonance is at 237.7 Hz. The reflection spectrum of the composite HMR (the red curve) along with the transmission of DMR-1 (the green curve) is also shown in Fig. 1(d). Due to the large orifices around DMR-2 that significantly reduce its interaction with HMR-1, DMR-2 only slightly perturbs the original impedance of HMR-1, resulting in a small shift in the reflection dip frequency from 368 Hz to 364.4 Hz and a

FIG. 1. (a) The transmission spectrum of DMR-1 (the green curve) and the reflection spectrum (the red curve) of the corresponding HMR-1; (b) the normalized surface impedance of HMR-1. The two up arrows mark the frequencies of the two resonances of DMR-1, while the down arrow marks the anti-resonance frequency of DMR-1. (c) The magnified region of the spectra marked by the circle in (b), where near critical coupling occurs. (d) The transmission spectrum of DMR-2 (the blue curve), the transmission spectrum of DMR-1 (the green curve), and the reflection spectrum of the composite HMR (the red curve). The structure of the composite HMR is schematically shown in the inset; (e) the normalized impedance of the composite HMR in (d). The inset shows a photograph of DMR-2 with large side orifices. (f) The magnified region of the spectra marked by the circle in (e), where near critical coupling occurs.

reduction of its minimum value to 5.2%. Such an improvement is due to the sensitive critical coupling condition subject to the small changes of impedance, as depicted in Fig. 1(c). Another reflection dip appears at 654 Hz. This hybrid resonance is slightly below the second resonance of DMR-2, rather than being between the first resonance and the anti-resonance of DMR-2. Like two passive devices in series in an electric circuit, the total impedance is approximately the sum of the impedance of each device, in this case the impedance of DMR-2 and that of HMR-1. Indeed, compared to the original HMR impedance in Fig. 1(c), the impedance of the composite HMR in Fig. 1(e) contains the hybrid resonance originated from the second resonance of DMR-2 as marked by the blue upper arrow in Fig. 1(e), which brings another near critical coupling with a minimum reflection of 7%.

To further confirm that the additional reflection dip is due to the second resonance of the additional DMR, we replaced DMR-2 with DMR-3 with half the platelet mass of DMR-2. As is expected,² the first resonance (209.46 Hz) and the anti-resonance (328.16 Hz) of DMR-3 are clearly higher than the corresponding ones of DMR-2, while its second resonance remains at 678 Hz. The reflection dip due to DMR-3 is at 654 Hz, close to that of DMR-2 at 645.2 Hz, with a minimum value of 15%. The spectra are not shown due to space limit.

In principle, one could place more DMRs surrounded by side orifices in front of the HMR to take advantage of the low impedance background of the HMR and realize multiple-frequency perfect absorption at the frequencies determined by the second eigenmode of each individual DMR. The series configuration has the practical advantage that it does not take up the lateral space as the parallel HMR's arrangement does.³

The above cases are examples of hitchhiker hybrid resonances. A hitchhiker resonance is a relatively weak resonance that cannot bring large enough changes in the impedance so as to pull it down from $\sim 80Z_0$ to near zero. However, with the assistance of the primary (and strong) resonances of a host HMR, it can bring the total impedance of the composite HMR to the zero line to create a hybrid resonance. These hitchhiker hybrid resonances do not require the participation of the anti-resonance of the hitchhiking DMR. The primary hybrid resonances of HMR-1 provide the necessary low impedance background in the relevant frequency range, in which resonators like DMR-2 or DMR-3 could produce a hybrid resonance with perfect absorption.

The second approach is to utilize the resonances without a circular symmetry of the DMR on the HMR, such as DMR-4 and the corresponding HMR-4. The optimum cavity length is 67 mm and its cross section is the same as the DMR. The transmission spectrum of DMR-4 [the green curve in Fig. 2(a)] indicates that its first and second primary resonances are at 200 and 670 Hz, respectively. The first anti-resonance is at 306.3 Hz. The second anti-resonance is above 1500 Hz. Besides these prominent features, there are two weak features marked by circles. Their amplitudes indicate that they are due to the small eccentricity of the stress distribution in DMR-4, which is confirmed by simulations. The reflection spectrum of HMR-4 exhibits four dips. The one at 259.7 Hz with a minimum value of 5.0% is the primary hybrid resonance as in HMR-1. The ones at 925 Hz and around 1365 Hz are the hitchhiker hybrid resonances riding on the background of the small impedance region produced by the primary hybrid resonance at 259.7 Hz and the one beyond 1500 Hz. The change of the impedance around 900 Hz, as indicated by the maximum value of $\text{Re}(Z_{\text{Re}})$ arising from the background, is about $30Z_0$ as

FIG. 2. (a) The transmission spectrum of DMR-4 (the green curve) and the reflection spectrum of the corresponding HMR-4 (the red curve). (b) The corresponding normalized impedance of HMR-4. (c)–(e) The magnified views of the frequency regions A1–A3 marked by the circles in (b), where near critical coupling occurs.

compared to about $80Z_0$ for the primary one around 300 Hz. Its hybrid resonance is at 925 Hz with a minimum reflection of 4.5%. The astonishingly weak resonance that brings a change of the impedance of the order of Z_0 at around 1360 Hz produces two reflection dips with minimum values of 6.3% at 1364 Hz and 11% at 1369 Hz.

To further explore the benefit of eccentricity of the DMR, we fabricated DMR-5 with the platelet at 10 mm off the membrane center. The cross section of the cavity for the corresponding HMR-5 is the same as that for HMR-4, and its optimum length is 40 mm. As shown in Fig. 3(a), the first transmission peak and the dip of DMR-5 are

FIG. 3. (a) The transmission spectrum of DMR-5 (the green curve) and the reflection spectrum of the corresponding HMR-5 (the red curve). The inset is a photograph of DMR-5; (b) the normalized impedance of HMR-5. (c) The corresponding transmission and reflection obtained by numerical simulations. (d) The vibration patterns of DMR-5 at its resonant frequencies as indicated by its transmission peak frequencies in the simulations. The small disk on the right side of the membrane center marks the platelet.

about the same as those of DMR-4. The first reflection dip of HMR-5 at 235.5 Hz is comparable to that of HMR-4 at 259.7 Hz. Corresponding to the second transmission peak of DMR-4 are two transmission peaks of DMR-5 and an anti-resonance dip. Between the anti-resonance and the second resonance is the second HMR reflection dip at 483.2 Hz. The small wiggle in the DMR-4 transmission spectrum at around 900 Hz is now strengthened by the large eccentricity of the platelet position, resulting in several fairly strong transmission peaks and dips. Between these peaks and dips are three HMR reflection dips at 763.6 Hz, 936.2 Hz, and 998.9 Hz, with minimum reflections of 1.2%, 7.0%, and 1.8%, respectively. The impedance spectra in Fig. 3(b) show that the $\text{Im}(Z_{\text{Re}})$ crosses the zero line six times and produces five deep and one shallow reflection dips. As the vibration patterns of the resonances of DMR-5 no longer have a clear azimuth symmetry or an anti-symmetry, it is difficult to identify which are primary resonances and which are hitchhikers. Instead, each of them produces hybrid resonances while providing assistance to the others. Collectively, they hitchhike on each other and generate multiple-frequency perfect absorption. The minimum reflection of these hybrid resonances can be tuned by adjusting the cavity volume, so the amount of change of impedance brought by the resonances is not an essential factor in determining the perfection of the critical coupling.

Numerical simulations using the COMSOL Multi-Physics Package were conducted for DMR-5 and HMR-5. The mass density, Poisson's ratio, Young's modulus, and the prestress of the membrane are 980 kg/m^3 , 0.49, 5×10^5 , and 0.4 MPa, respectively. The platelet, the DMR boundary, and the cavity are assumed to be infinitely rigid. The prestress, which determines the elastic property of the membrane, is introduced by stretching the membrane by about 10%. As shown in Fig. 3(c), both the simulation transmission of the DMR and the reflection of the HMR well resemble the characteristics of the experimental ones. In particular, eight reflection dips observed in the experiments are well reproduced by the theory. These experimental (theoretical) reflection dips are at 235.54 Hz (215.8 Hz), 483.21 Hz (484.2 Hz), 546.88 Hz (613.1 Hz), 763.57 Hz (781.4 Hz), 936.23 Hz (941.0 Hz), 998.92 Hz (1004.8 Hz), 1208.8 Hz (1219 Hz), and 1388.6 Hz (1398 Hz). The minimum values of the reflection dips are difficult to reproduce well in the simulations because they are very sensitive to the structure parameters, such as the volume of the cavity.

Figure 3(d) depicts the nine eigenmodes of DMR-5 manifested by the corresponding transmission peaks in Fig. 3(c). The color bar for eigenmodes-1 ranges from 0 to 1, while the remaining ones are from -1 to 1. At eigenmode-1, the entire DMR is vibrating in-phase, so the lower limit of the color bar is 0. The maximum relative error of 4.5% between the simulation and the experimental frequencies occurs at the first eigenmode (207.75 Hz). The relative errors for the remaining ones are around 2%.

The hybrid resonance frequencies of the HMR can be tuned by changing the eigenmodes of its DMR. The vibration patterns of the eigenmodes provide qualitative information about the dependence of the eigenmode frequencies on the structural parameters of the DMR. In eigenmode-1 through eigenmode-3, the platelet vibrates strongly, so their frequencies can be tuned by changing the mass of the platelet. Furthermore, the platelet in eigenmode-3 is in a flapping motion similar to the ones observed earlier,²⁴ so its frequency can be tuned by changing the rotational moment of inertia of the platelet by mass redistribution without changing the

total mass. In eigenmode-4 through eigenmode-9, the vibration field is mostly in the membrane regions, while the platelet remains almost motionless. Only by changing the size of the membrane can we significantly change these frequencies.

In summary, we have experimentally demonstrated another mechanism to realize multiple-frequency perfect absorption using hybrid membrane resonators with a single cavity. Besides generating perfect absorption by themselves alone, the hybrid resonances of a HMR can provide strong assistance to other weaker resonances to create multiple hybrid resonances and perfect absorption. It is conceptually different from the ones using multiple cavities^{5–8,10–18} or the one utilizing a viscoelastic porous plate with intrinsic impedance close to air over a broad frequency range,⁹ leading to perfect absorption at one frequency and high absorption (> 0.93) from 750 to 1500 Hz. Several HMRs similar to HMR-5 but with different sets of perfect absorption peaks could be placed in parallel to form a semi-continuous broadband perfect absorber. The devices reported in Refs. 18 and 19 could provide further tunability by external voltage when incorporated into the HMR devices. The hitchhiker mechanism for hybrid resonances opens up another avenue to realize multiple-frequency perfect absorption meta-surfaces.

This work was supported by AoE/P-02/12 from the Research Grant Council of the Hong Kong SAR government.

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