Frequency filtering with multiple scattering in resonators cluster

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1 Executive summary

There has been evidence that metamaterial cloaking is an effective method in blurring the scattered fields from coated targets in response to probing waves. In this work, we investigate the possibility of creating an object that cannot be detected by radar-like detection techniques. Our goal is to make the object unrecognizable, before attempting to make it appear as if it were a completely different object in future works. To achieve this, we design a metamaterial cloaking which contains a layer of resonators. These resonators are not aligned and we show that their random orientation along with their number and type can influence significantly the behaviour of the cloaking. The interesting properties of such metamaterials are highlighted in numerical simulations carried out in a simplified 2D acoustic framework. Early findings show that cloaking prevents from empirical learning of the cloaking behaviour from coated engines, since each coated engine would use a specific set of parameters and have a unique signature. At the same time, the more diverse the possible behaviours, the more feasible it is to choose parameters mimicking the signature of some other object. Finally, we demonstrate the advantage of using resonators rather than square-shaped components and we discuss the possibility of replacing resonators with simpler components.

2 Introduction

In noise canceling, cavity resonators are useful as they can stop incoming signals, such as acoustic and electromagnetic waves. The technique is rather simple: a protected area is surrounded by particles that resonate at a given frequency k in order to trap incoming waves of the same frequency. Based on this idea, one can imagine using a mix of different types of particles, each one resonating at a different frequency, in order to filter specific frequencies. A natural framework to investigate the behavior of such materials is multiple scattering theory. This field studies the average properties of materials made of many particles, whose locations are not exactly known, but described with a probability distribution instead. In an industrial perspective, the advantage of this approach is that the particulate material does not need a specific structure, simplifying its manufacturing process.

The goal of this internship is to design metamaterial surfaces that prevent radar/sonar tracking from identifying a target. By including resonators in the cloaking, we are able to trap waves with specific frequencies and orientations. More specifically, we are interested in distorting the signal with cloaks using a random component so that each cloaked device has a different signature, making them harder to catalogue. We carry our investigations in a 2D acoustic setting. Our simulation results rely on the Foldy-Lax self consistent method [1], a technique describing the interaction of waves with several obstacles. This technique requires to know the behavior of each isolated scatterer with respect to the incoming waves. All of this information is contained in the so-called T-matrix which only depends on the properties of the scatterer (shape, material, etc.). Work on the derivation of the T-matrix for the case of a Helmholtz resonator has been carried out in the papers [5, 4]. Multiple scattering problems can be numerically solved with the MultipleScattering.jl library written in the Julia language [6], which we have used throughout this work.

3 Methodology

3.1 A simplified model in 2D

We investigate the effectiveness of resonator barriers in cloaking larger objects in a simple 2D setting. For these tests we will use a large disk to represent the target, for instance the cockpit of a helicopter. To validate our results, we illuminate the target and measure the resulting scattered fields on sensors placed on a screen located behind the source (cf Figure 1). We then compare the results of a cloaked and uncloaked target in this setting.

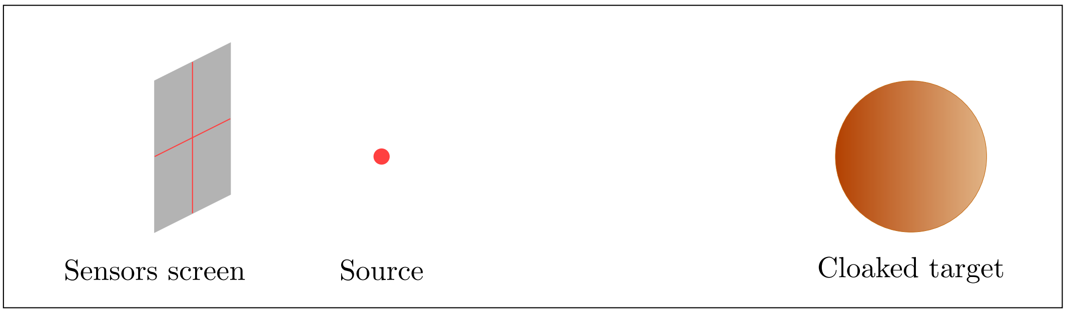

Figure 1: Target detection using waves.

3.2 Design of a cloaking

The cloak consists of a layer of resonators covered with an extra protective layer (cf Figure 2). This arrangement is supposed to mimic how these resonators might attach to an object that needs to be cloaked with glue or paint. The orientations of the resonators are voluntarily chosen to be random for two main reasons. First, the manufacturing process of the cloaking is rather simple since they only need to be glued together in a matrix, without any precautions on their orientations. Second, each cloak will be unique, making it difficult to catalogue the cloaked targets. In our numerical experiments, we use simulated Helmholtz resonators made of a cavity and a mouth. Their different sizes and properties are given in Table 1.

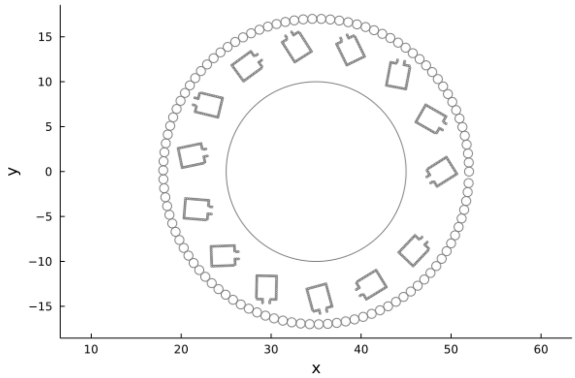

Figure 2: Target cloaked with a layer of resonators and an external protective layer.

cavity radius	1
cavity length	2.5
mouth radius	0.3
mouth length	0.5
1^{st} resonant frequency	$\omega_0 = 1.99$
2^{st} resonant frequency	$\omega_1 = 3.99$

Table 1: Parameters of an isolated resonator.

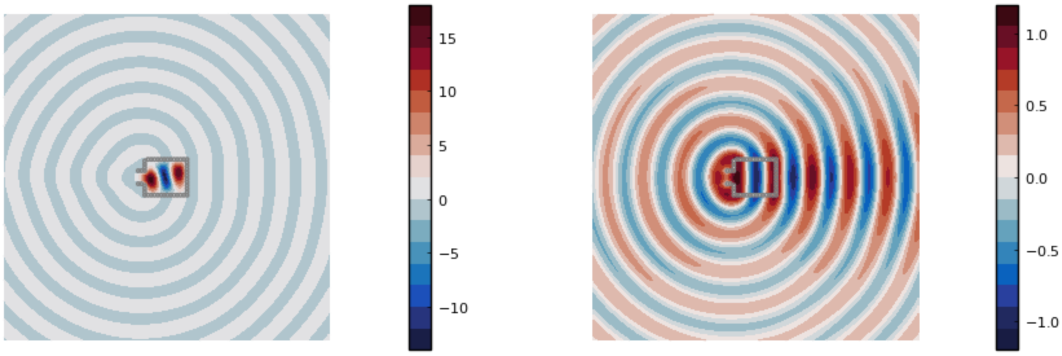

Figure 3: Response of a simulated resonator at a resonating frequency $\omega_1 = 3.99$ (left) and a non resonating frequency $\omega = 2.77$ (right).

3.3 Efficiency of the cloaking

Response distortion

To measure the efficiency of the cloaking, we will qualitatively compare the simulated data from a cloaked and an uncloaked target. To visualise the effect of the cloak, we computed the scattered field near the boundary of the cloaked and uncloaked target (cf Figure 4). We see that the presence of the resonators significantly distorts the fields. Indeed, while most of the energy released by the uncloaked target is confined in cones, it is spread in all directions in the case of the cloaked target. We outline the impact of the coat in more details in Figure 5, where the measurements at the sensors are plotted for both the cloaked and uncloaked target. An important observation is that while the profile of the uncloaked target is almost the same for the two different frequencies, especially around the sensors in the middle, the profile of the cloaked target significantly changes.

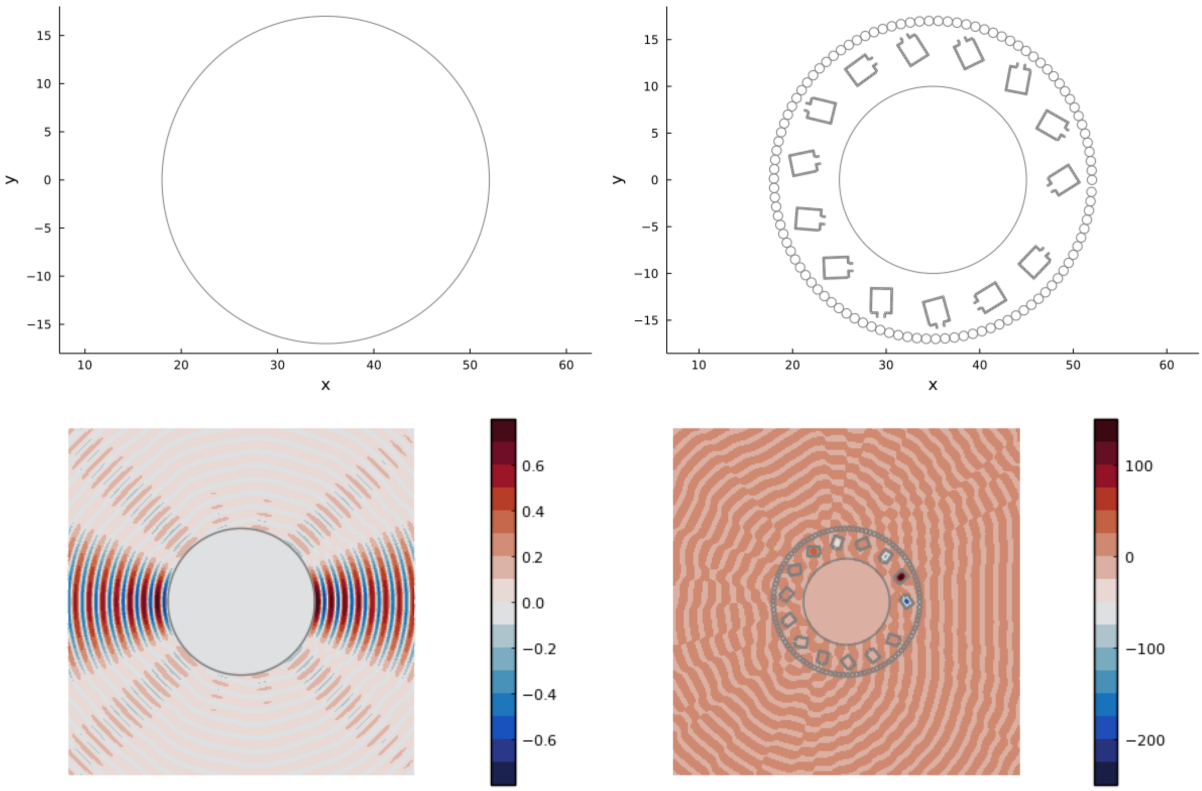

Figure 4: Scattered fields near the uncloaked target (left) and cloaked target (right).

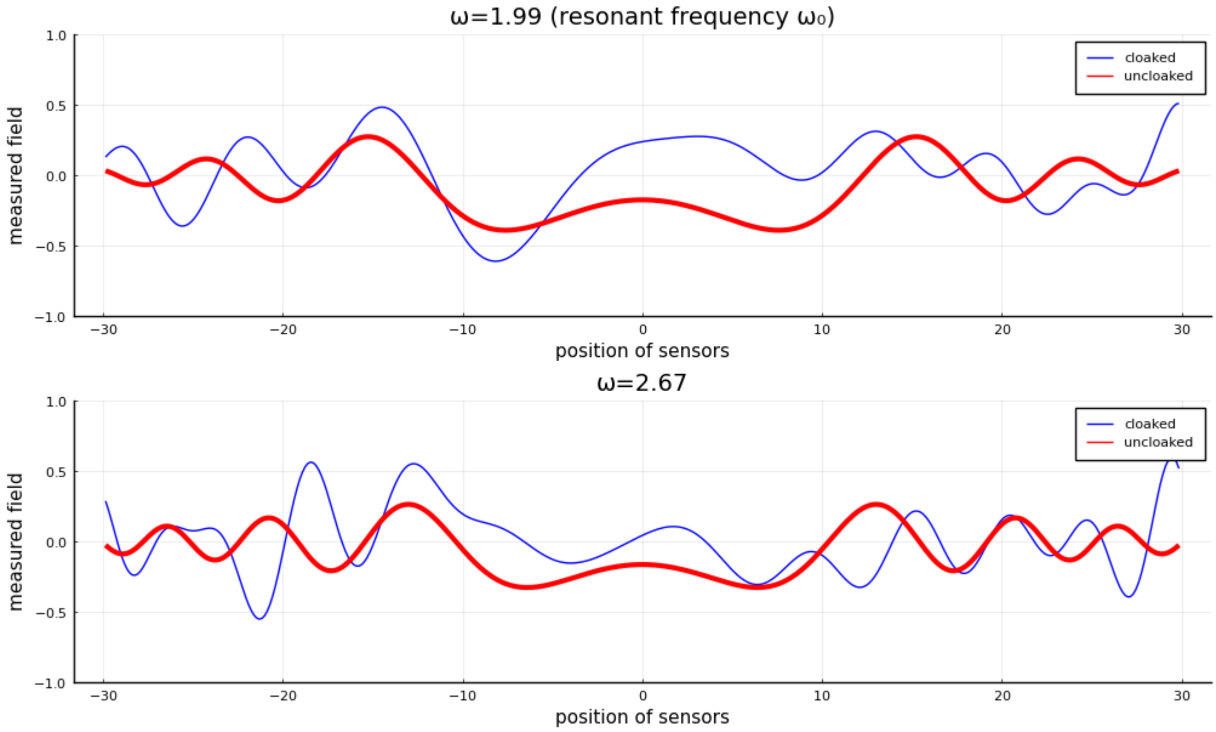

Figure 5: The scattered fields are measured on vertically aligned sensors. Adding the cloak distorts the response of the uncloaked object. The results are displayed for frequencies $\omega = \omega_0 = 1.99$ (top) and $\omega = 2.67$ (bottom).

Unpredictability of the cloaking

The main feature of our cloaking design is that it is configuration-dependant. We, therefore, expect that each cloaked target has a unique signature. For instance, two different possible cloaking are illustrated in Figure 6. In this paragraph, we measure the unpredictability of the cloaking (the difference between the responses from one another). Measurements of the scattered fields at the sensors show that the results depend on the cloak being used. These results are shown in Figure 7 where we compared three different coats. The experiment is carried out for two different frequencies.

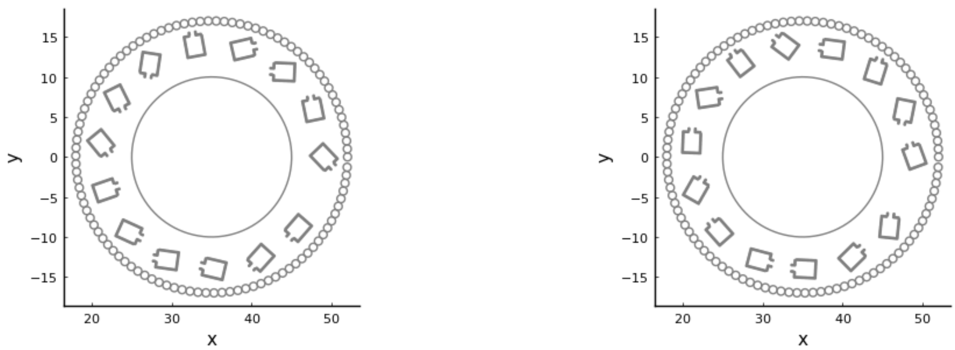

Figure 6: Two different configurations of resonators in the cloaking.

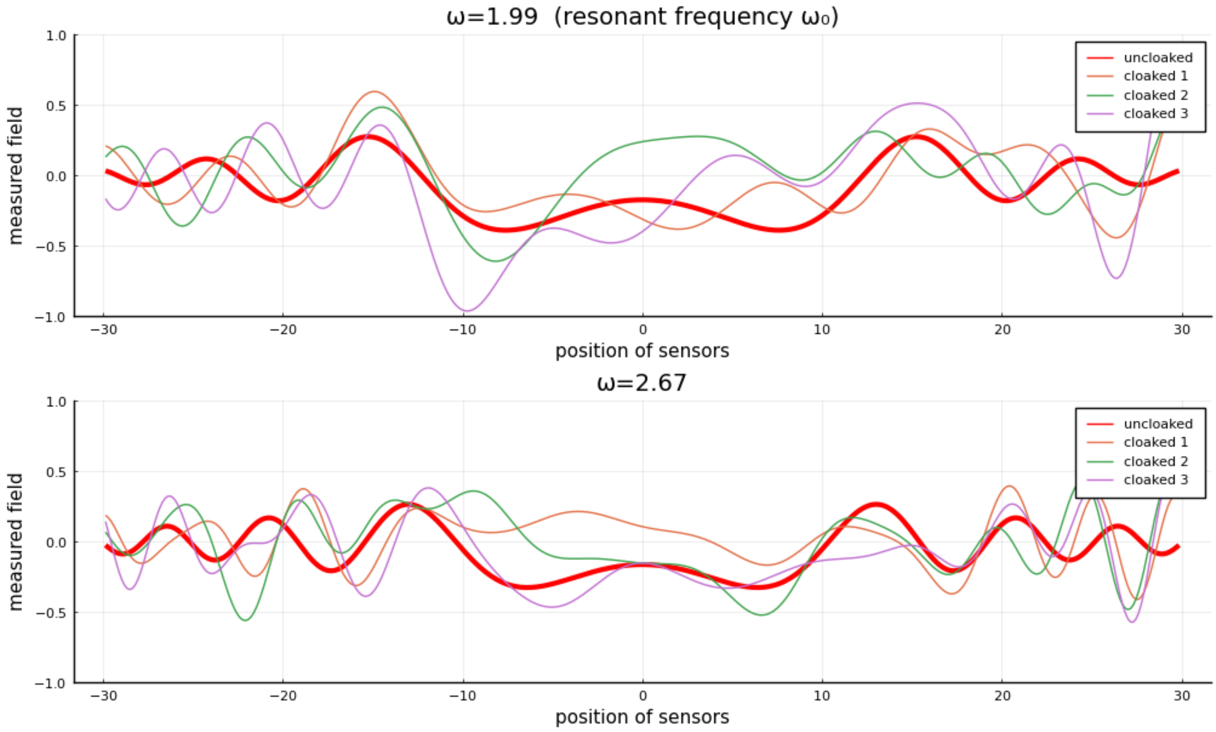

Figure 7: Response of different cloakings.

A natural question that arises is how correlated (or uncorrelated) are the measured data from a cloaking to another. To answer this question, we computed the average response of all possible coats along with the standard deviations of the responses (cf Figure 8-9). On these figures, the larger the band (that corresponds to the standard deviation), the more unpredictable is the cloaking.

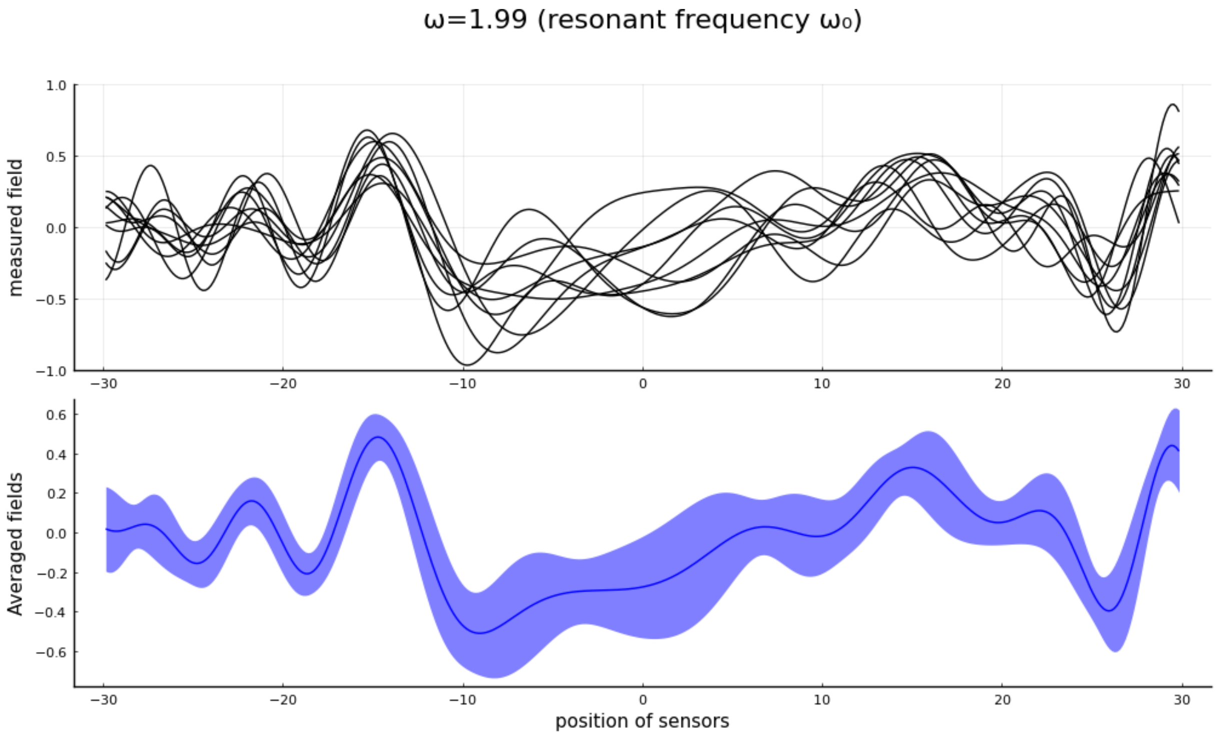

Figure 8: Averaged data from different cloakings for $\omega = 1.99$.

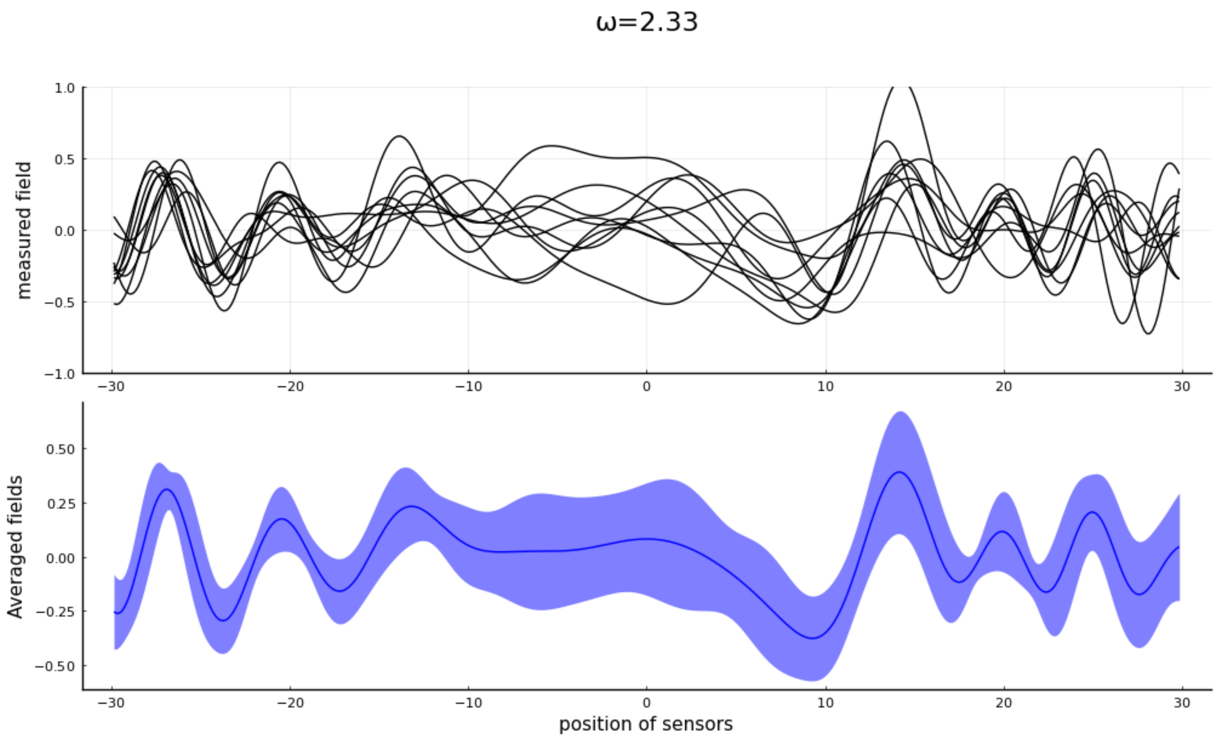

Figure 9: Averaged data from different cloakings for $\omega = 2.33$.

Advantage of using resonators

To conclude our tests, we investigate the advantage of using resonators instead of any other type of scatterer. To this end, we carried out the same experiments as above but replaced the resonators with square shaped sound hard obstacles (cf Figure 10). A sample of data measurements shows that this type of cloaking also distort the signal relatively well (cf Figure 11). However, we notice that the line graphs *"cloaked 1", "cloaked 2"*, and *"cloaked 3"* are very close to each other, even through they are different from line graph *"uncloaked"*. This means that the cloaking with different distributions of square shaped obstacles do not provide a rich variety of cloaking in terms of response to a given incident field. This is confirmed by the plot of the average and standard deviations of the response of a sample of these coats containing squares shaped obstacles instead of resonators (cf Figure 12). Indeed, the bands in Figure 12 corresponding to the standard deviations are much narrower than the ones in Figures 8 and 9.

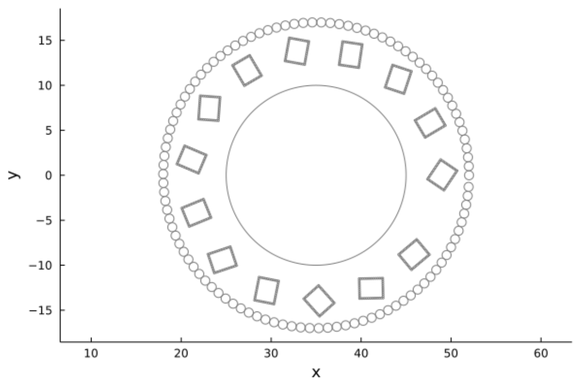

Figure 10: Resonators replaced with square-shaped obstacles.

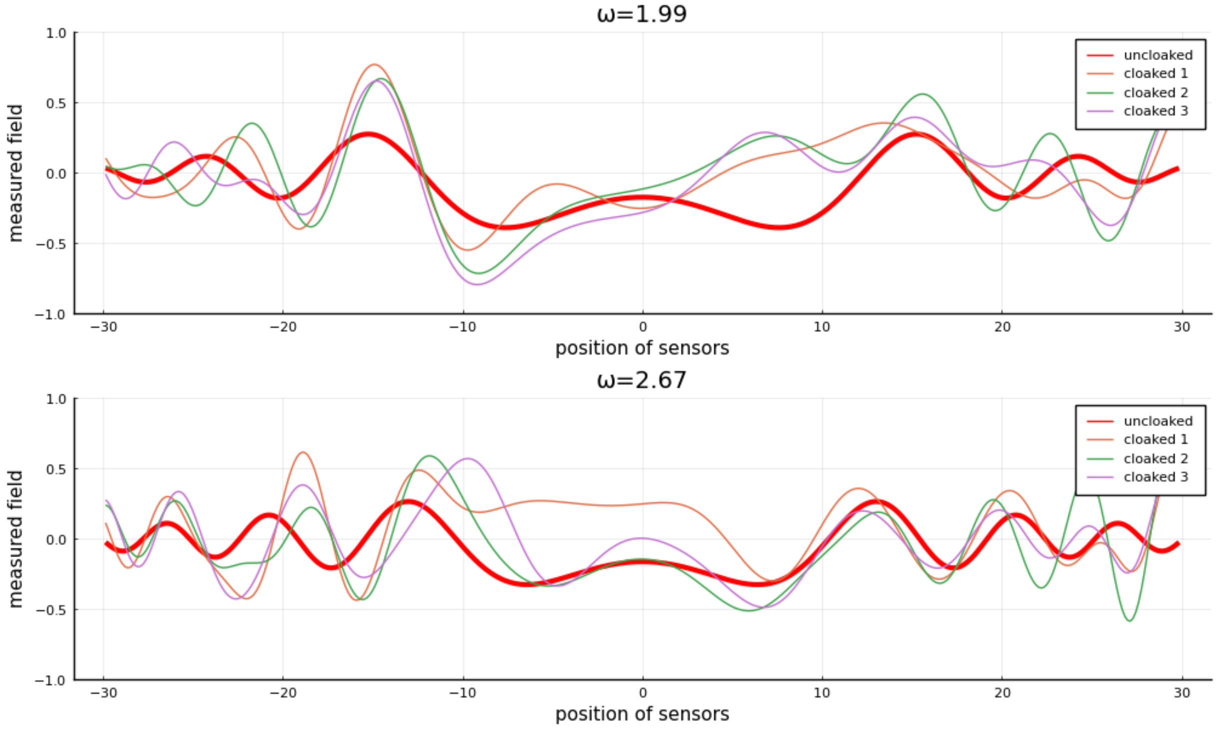

Figure 11: Responses of different coats with resonators replaced with square-shaped obstacles.

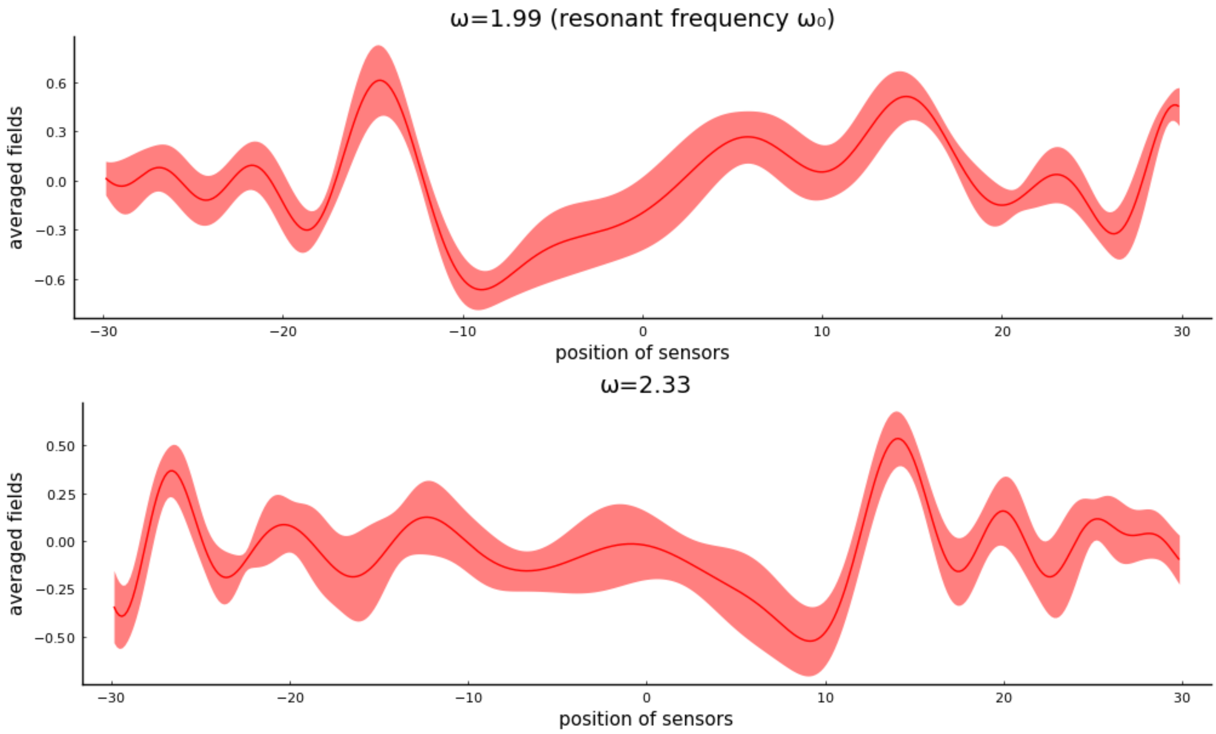

Figure 12: Average response of cloaking with square-shaped obstacles.

4 Results and discussion

These simulations demonstrate the benefits of using layers of randomly oriented resonators to cloak an object. The reflections of the hidden object are strongly distorted, and the random component of the cloaking makes it impossible to be catalogued. We also replaced the resonators with simpler scatterers and we concluded that resonators provide a more unpredictable cloaking mechanism. Using resonators, we obtained good results thanks to the asymmetry of the latter, strongly influencing the scattering profile depending on their orientations. The cloaking, however, had no special behavior at resonating frequencies, raising the question of whether resonators are necessary. For instance, it may be possible to use other particles that have the same features (lack of symmetry, orientation dependant).

Our simulations are also interesting on a theoretical point of view. We showed that the fields scattered from different configurations of resonators varies around an averaged field which corresponds to the scattered field from a hypothetical averaged material. These results confirm the predictions of disordered materials theory. However, the specific case of resonators lying around an object has not been studied in detail and should be investigated thoroughly.

5 Future work

To carry this project further, it would be desirable to study the equivalent electromagnetic problem. In this case, the resonators would be smaller and therefore more realistic for practical applications. It is also crucial to analyse the robustness of the cloaking against radar imaging and check that we are able to dissimulate the position, shape and material of the cloaked target.

More theoretical investigations should also be done to obtain the analytical results on mixtures of resonators that are currently missing. The approach of effective waves [2] is feasible thanks to the existing works on the T-matrix of resonators [5, 4]. These theoretical results will provide the dependency of the average properties of randomly oriented resonator layers with the parameters of the setting (e.g. diameter of the layer, properties of an isolated resonator, distance between the resonators, etc.). On the one hand these would allow us to tune the parameters more accurately (distort the response the most, mimic another object...), on the second hand computing the average properties will require less CPU time.

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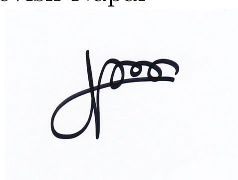

References

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