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Multifrequency ultrasonic transducers with spatially distributed stop band material

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Abstract

Ultrasonic transducers are widely used for surround sensing applications in the automotive industry. A major challenge for today's mobility solutions consists in the development of autonomous driving functions. Highly automated vehicle concepts require a comprehensive surround sensing performance, which leads to an increasing number of sensors. The applied ultrasonic sensors are desired to operate in parallel or in shorter intervals. Hence, transducers with two or more well discriminated operating frequencies are of great interest. Known multifrequency ultrasonic transducers use multiple electromechanical coupling elements resulting in more complex sensor electronics. To overcome this issue, the authors investigate a method for controlling the operational deflection shapes. In finite element simulation, a generic plate-like model for the ultrasonic transducer is employed and different resonator configurations are studied. Spatially distributed stop band material is used to achieve two well-separated operating frequencies with similar and appropriate sound radiation. Furthermore, it is investigated whether the shape modification is caused by the resonant behavior or the added resonator mass. Based on the results, locally distributed resonators are identified as a suitable solution to modify the operational deflection shapes and the corresponding sound radiation of the generic model. Thus, a multifrequency ultrasonic sensor with a single coupling element can be realized.

Keywords: ultrasonic sensor, stop band material, acoustic metamaterial, periodic structure

1 INTRODUCTION

Owing to the recently increased demand for autonomous driving functions, high potential surround sensing applications are required. For decades, ultrasonic sensors provide a reliable environment analysis as part of the driver assistance systems. In order to measure the distance between the sensor and the surrounded objects, the pulse-echo method is used. The sensor, working in its resonant operation point, evaluates the object location by measuring the time difference between emitted sound signal and detected echo [1]. To achieve a detailed resolution of the car's environment, more and more ultrasonic sensors are applied. The time efficient operation of various sensors leads to the desire for multiple operating points. A design with two or more well discriminated operating frequencies and appropriate deflection shapes benefit parallel sensor operation and therefore, shorter operation intervals.

In literature, a few approaches for multifrequency ultrasonic sensors can be found. In [2], a stepped-frequency transducer consisting of loosely coupled magnetostrictive elements is presented. Simultaneous excitation of all elements of a stack leads to a broadband transducer. Although this concept could be used as a multifrequency transducer, it suffers from a lack of efficiency compared to single-frequency equivalents. A split-mode ultrasonic transducer is investigated by [3]. In order to obtain a transducer with multiple acousto-electric resonances, a structure of periodically poled domains in a ferroelectric wafer with free surfaces is used. [4] introduces a piezoelectric micromachined ultrasonic transducer (PMUT). By using multiple electrodes, the device provides high sensitivity at the first, third, and fifth fundamental frequency of the transducer. Further investigations focus on a capacitive micromachined ultrasonic transducer (CMUT) [5]. The authors employ a CMUT array for multiband operation with acoustic elements of different dimensions. For medical applications, especially for interstitial thermal therapy, a transducer with a single electromechanical coupling element but multiple operating points has been designed. [6] introduces this new approach with matching front layers being able to transmit ultrasound at multiple frequencies in the range of several MHz. Another recently developed sensor array for medical purposes works with a zirconate titanate (PCT) transducer in dualfrequency mode (4.1 MHz and 13.3 MHz) [7]. [8] and [9] suggest hybrid solutions for multifrequency sensor usage. By combining different electromechanical coupling mechanisms, e.g. a CMUT and PMUT in one element, multiple resonance frequencies with suitable sound radiation properties can be obtained.

However, the aforementioned approaches show some disadvantages regarding the implementation in driver assistance systems. One lack consists in the usage of multiple electromechanical coupling elements. This leads to more complex electronics and therefore, more expensive sensors. Furthermore, the sound radiation characterized by the directivity pattern should be appropriate, meaning that radiation similar to monopole or dipole behavior without distinctive side lobes is required. The last problem goes with the frequency dependent damping characteristics of air. Operational frequencies in the high ultrasonic range lead to low echo amplitudes due to significant airborne sound damping, while in the lower range various sound sources from the car's environment interact. Thus, the operating frequency has to be in a certain range. For ultrasonic-based parking assistance systems, a operation point between 40 and 50 kHz turned out to be the best compromise [10].

To overcome this disadvantages, the authors investigate a novel approach employing locally distributed resonators in order to obtain a multifrequency transducer with a single electromechanical coupling element and suitable sound radiation at two distinctive resonance frequencies. By adding structures of resonators to a geometry, it is possible to prevent free wave propagation in certain frequency ranges. Thus, so called stop band materials can be formed [11, 12]. Recent publications in this research area demonstrate that depending on the frequency range, stop band material can decrease both, the acoustical [13] and the vibrational [14] response of dynamic structures. [13] presents a promising outlook for periodic resonant structures causing desired band gaps for low frequencies. Moreover, the periodic resonators represent an easy tuning possibility for the band gap behavior. Another research work by [15] investigates the influence of the resonator spacing. It is shown that random arrangement can also lead to appropriate band gaps but the distance in between the resonators is required to be at a sub scale of the corresponding wave-length. Due to their ability to generate frequency ranges without free wave propagation, stop band materials are predestined to increase sound transmission loss of structures [14]. For this purpose, [16] considers rubber coated lead spheres, which are embedded in epoxy, in order to create a stop band material. In [17], the authors use stop band material to reduce mechanical cross-coupling in phased-array transducers.

In this study, stop band material is applied to modify the operational deflection shape (ODS) of a generic transducer model. As stop band material is only effective within a certain frequency range while outside this range there is only marginal influence on the dynamic behavior, certain operating frequencies can be tuned mainly independently of each other. These characteristics open up the possibility for a multifrequency transducer design. The recently published work of [18] provides a more detailed insight into the topic of this paper. While in the present paper, numerical studies are carried out to investigate the influence of the particular dynamic behavior of the resonators, [18] extends the frequency range to ultrasound and further includes experimental results. Moreover, different boundary conditions are considered and the sound radiation behavior of the transducer test cases is investigated.

2 MODEL DESCRIPTION

In this section, the investigated models are presented. First, a simplified model representing the ultrasonic transducer is discussed. Thereafter, the according finite element models of all test cases are presented.

2.1 Test cases

To analyze the potential of stop band material for multifrequency approaches, a generic model is employed. The ultrasonic transducer is reduced to a rectangular plate with fixed boundary conditions on all sides. Assuming the transducer to be in sound emission mode, the electromechanical coupling element can be substituted by a centric dynamic load. The top of the plate, made of epoxy, represents the sound radiating surface. The described model forms the reference case for further modifications. One design variation consists in adding spatially distributed resonators to the plate. The resonators are attached to the downside of the model and are distributed as shown in Figure 1. A middle section without any resonators (I) and two border sections with each containing 72 resonators (II) are formed.

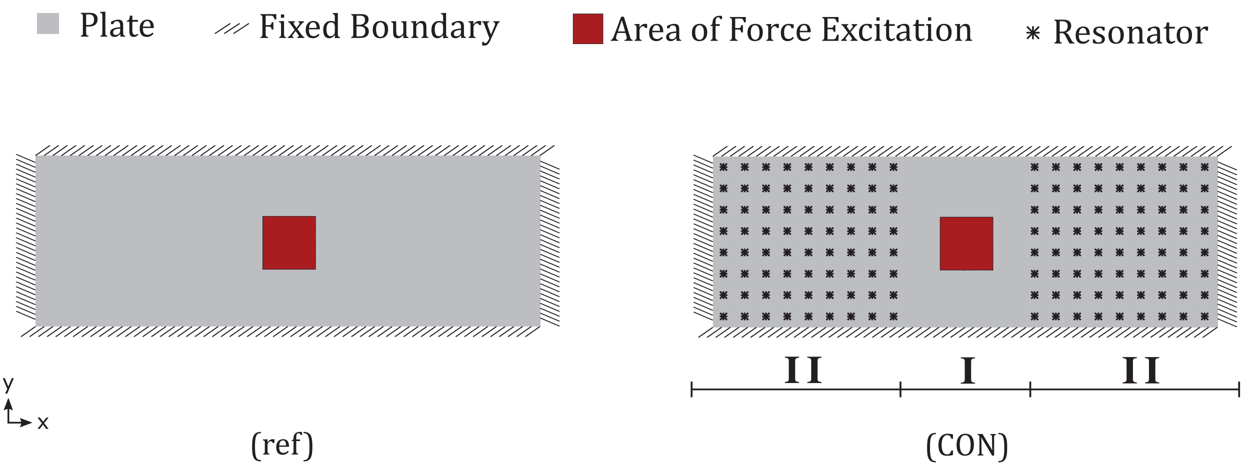

Figure 1. Generic model of the ultrasonic transducer. Plane epoxy plate as reference case (ref) and modification with spatially distributed resonators (CON). Excitation is realized through a dynamic load.

Furthermore, two configurations of the resonators are investigated. As shown in Figure 2, each resonator consists of a beam like shaft and a tip mass. While the first configuration (CON1) is entirely made of epoxy material, similar to the plate, configuration 2 (CON2) has an additional middle section where another type of material is assigned. In here, an artificial epoxy equivalent with the same density and Poisson's ratio but only a tenth of the Young's modulus is used. However, introducing this more flexible material offers the possibility to separate the effects caused by the dynamic behavior of the stop band material from additional mass effects. With regard to automotive applications, smaller and more complex transducer geometries are relevant. The authors presented a study with such geometries in [19]. But once proved on the generic model, the principle of spatially distributed stop band material can be transferred without difficulty.

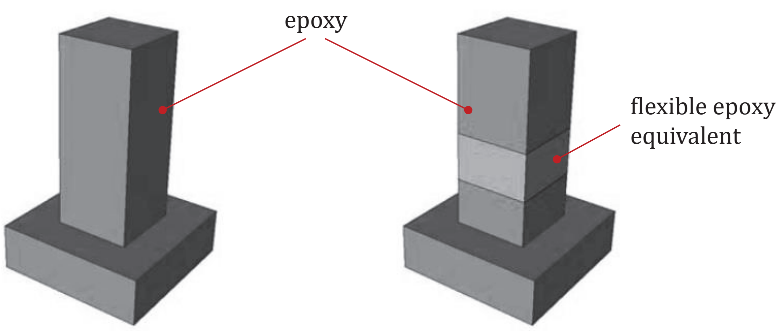

Figure 2. Two different test cases of the resonator design. CON1: Resonator entirely made of epoxy. CON2: Resonator made of epoxy and a more flexible epoxy equivalent in the middle shaft section.

2.2 Finite element model

The dynamic behavior of the above shown test cases is investigated in a finite element (FE) simulation. The simulations are carried out with the commercial software Simulia Abaqus 2017. The employed FE model is set up of 20 quadratic node-brick elements (element type C3D20) [20]. In order to avoid mesh dependencies, a mesh convergence study following the guidelines of [21] is carried out. All applied materials are considered to be linear elastic, therefore, fulfilling Hooke's law. The contact between the resonators and the plate is modeled as a tie constraint with a surface-to-surface formulation. In a harmonic analysis, the forced response function and the ODS is analyzed in the frequency range from 3 kHz to 25 kHz with a step size of 55 Hz.

3 RESULTS

The sound radiation behavior of transducers during operation is indicated by the deflection shape in the corresponding operation point (OP). The desired radiation properties for industrial applications, characterized by an homogeneous directivity pattern, is achieved for the first normal mode. Therefore, the new design should show two ODS, which are similar to latter. The first way of realizing this approach is through setting the operating frequency of the system to the first eigenfrequency of the plate-like structure. As shown in Figure 3 (a), the reference test case has three resonance peaks in the analyzed frequency range. The calculated mode shapes are similar to the reference cases from literature, following the rules of Kirchhoff's plate theory [22, 23]. Hence, the first peak at 7.8 kHz provides the desired ODS. Figure 3 (b) shows the frequency response function (FRF) for the modified test cases. In comparison to the reference model, the additional resonator mass causes a frequency drop of 1.4 kHz. On the other hand, the stiffening effect caused by the attached resonators is negligible. However, the stiffening effect on the plate-like structure due to attachement of the resonators is present for both configurations CON1 and CON2 in the same way. Therefore, the first resonance peak occurs at 6.4 kHz for both configurations.

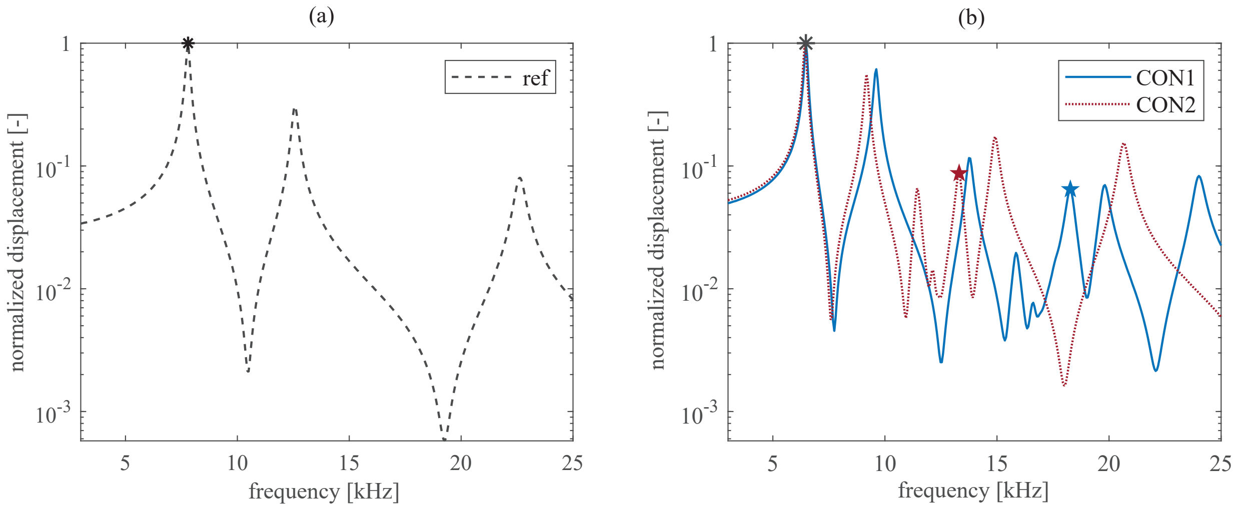

Figure 3. FRF of the sound radiating surface evaluated at the center point. (a) FRF of the reference model. (b) FRF of the configurations with locally distributed resonators. Resonance frequencies with ODS suitable for sound radiation marked with ∗ for 1st operating point and with ★ / ★ for 2nd operating point

Another manner of designing suitable directivity patterns consists in identifying an ODS where one part of the structure behaves similar to the first normal mode while the rest remains in equilibrium position. The FRF plots in Figure 3 (b) depict more resonance peaks in the higher frequency range. At 18.3 kHz and 13.3 kHz in configurations CON1 and CON2, respectively, the middle section II shows free wave propagation with all nodes moving with the same phase. In contrary to that in the outer sections I with added stop band material, the wave propagation is attenuated. As a consequence, the nodes remain almost without displacement. Due to the implementation of a less stiff epoxy equivalent in CON2, the resonance frequency is reduced. As the mass and geometry remain the same for both configurations, the particular ODS is mostly correlated with the dynamic behavior of the spatially distributed stop band material.

In Figure 4, the ODS corresponding to the above discussed operating points are presented. The plots show the normalized profiles along the x-axis of the plate. To evaluate the amplitude and phase both, the real and imaginary part of the displacement is presented. The first graph (a) depicts the ODS of the plain plate for the first resonant operating point. Compared to the reference case, the geometries equipped with stop band material, cf. Figure 4 (b), show a more stretched but for both test cases equal profile at OP1. This can be ascribed to the marginal influence of the resonator dynamics. Moreover, the additional mass plays the more important role for the investigated ODS stretching.

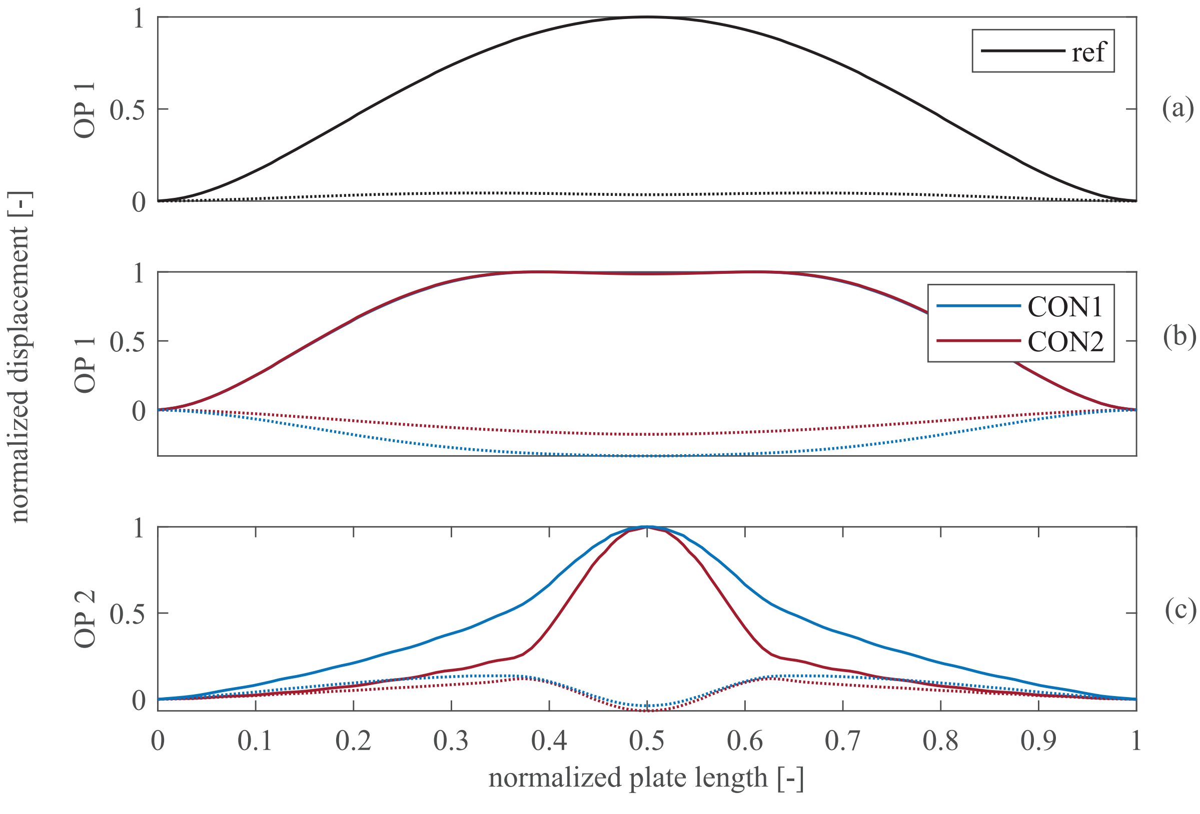

Figure 4. Normalized displacement along the x-axis through the center of the plate for the reference test case at OP1 (a) and the configurations at OP1 (b) and OP2 (c). The solid lines indicate the imaginary amplitude, the dotted lines the real values.

Considering the second operating point, a bigger difference between the two test cases is analyzed. Figure 4 (c) shows the normalized profiles of CON1 and CON2 at 18.3 kHz and 13.3 kHz, respectively. Both ODS have all nodes on one side of the equilibrium position and further only slight changes of the phase. By that, an appropriate sound radiation can be achieved. The resonance frequency and the ODS of this second appropriate operation point is strongly influenced by the particular dynamic behavior and the dimension of the resonator.

4 CONCLUSIONS

The authors present a study on multifrequency ultrasonic transducers with spatially distributed stop band material. Finite element simulation is employed for a generic transducer model. A reference model, consisting of a plain plate-like structure, and two further test cases with different, locally distributed resonators are investigated. Two operating frequencies with suitable ODS are identified within a harmonic analysis. While the first operating frequency is related to the first normal mode of the plain system, the second one strictly depends on the stop band material. By introducing a more flexible epoxy equivalent in the middle section of the resonator, it could be ruled out that the effect is mainly caused by the mass or the inertia of the resonator. Furthermore, the distinctive operating frequencies can be tuned mainly independently from each other. Based on the results, spatially distributed stop band material is identified as a possibility to design multifrequency ultrasonic transducers with only one electromechanical coupling element and appropriate and designable sound radiation.

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