24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

REDUCING MECHANICAL CROSS-COUPLING IN PHASED ARRAY TRANSDUCERS USING ACOUSTIC METAMATERIAL AS BACKING

Johannes Henneberg and André Gerlach
Robert Bosch GmbH, Corporate Research, Structural Dynamics and Acoustics, Stuttgart, DE
email: johannes.henneberg@de.bosch.com

Holger Cebulla
Chemnitz University of Technology, Professorship Textile Technologies, Chemnitz, DE

Steffen Marburg
Technical University of Munich, Chair of Vibro-Acoustics of Vehicles and Machines, Munich, DE

Phased array transducers are widely used for acoustic imaging and surround sensing applications. A major design challenge is the achievement of low mechanical cross-coupling between the single transducer elements. Cross-coupling induces a loss of imaging resolution. In this work, the mechanical cross-coupling between electro-acoustic transducers is investigated for a basic model. For this issue, the operating frequency is set to a low kHz range which is typical for surround sensing applications. The dimensions of the backing are small with regard to the wavelength which leads to wave reflections on the backing edges. This is different to other researches. It is shown in numerical simulation that a reduction in mechanical cross-coupling can be achieved by using acoustic metamaterial as backing. The effect of using acoustic metamaterial has been validated experimentally. The measurement results show good accordance with the simulation.

Keywords: phased array transducer, cross-coupling, acoustic metamaterial

1. Introduction

Phased array structures of acoustic transducers are used for acoustic imaging in medical applications and for nondestructive testing. Furthermore, there are applications for 3D surround sensing. Depending on the field of use, the typical operating frequency varies in a range from lower kHz for surround sensing [1] up to MHz for nondestructive testing of materials [2] and medical applications [3]. One of the characteristic properties of phased array transducers is the cross-coupling between single transducers. It mainly describes the undesired behavior that array elements are not working entirely independently [4]. In several studies it is shown that cross-coupling influences the performance of a phased array transducer by changing its beam pattern and resulting in loss of resolution [4–7]. In [4], a quantitative theory for cross-coupling in ultrasonic transducer arrays is presented. Surface waves in the backing and load medium are indicated as reason for cross-coupling. Lamb wave A0 mode has been identified as the responsive effect for cross-coupling in a capacitive micromachined ultrasonic transducer array (CMUT) with first order resonance frequency at 2.3 MHz [8]. In this study, we investigate the cross-coupling of a basic array model with a low operating frequency at 5.0 kHz. We focus especially on mechanical cross-coupling caused by the common backing without extra lossy regions. This type of cross-coupling dominates in compact air-coupled phased array transducers with common backing. The dimensions of the backing are small with regard to the wavelength which leads to wave reflections on the edges of the backing. This is different to other researches. The design of the backing is a major challenge in phased array transducers with low operating frequency. To overcome this problem, we show that stop band material can be used to reduce mechanical cross-coupling caused by common backing in phased array transducers. In the last years, stop band materials received a growing attention. In analogy to photonic crystals, in [9] a study with experimental investigation on sonic crystals to design band gap behavior is presented. Stop band materials can decrease acoustical [10] as well as vibrational [11] responses of components in certain frequency bands.

2. Experimental test setup

In analogy to CMUT-arrays, a basic model is set up with two bending elements bonded on a square, common backing. Each bending element forms an electrode of a capacitive transducer. The counter-electrodes are realized on the common backing. To achieve electrical conductivity, the bending elements and the backing are coated with aluminum (5). The cross-section of this basic model is shown in Fig. 1. The two bending elements (1 + 2) are made out of carbon fiber reinforced plastic (CFRP) coated with aluminum. They are bonded with a cyanoacrylate adhesive to epoxy sockets (4) on a common epoxy backing (3). On the bottom side a 5×5 grid of resonators (6) is attached. The acoustic metamaterial is realized with these cylindrical beam resonators. The length of the resonators can be trimmed to achieve different resonance frequencies. Consequently, the frequency range of the stop band changes. Table 1 shows the parameters of the basic model.

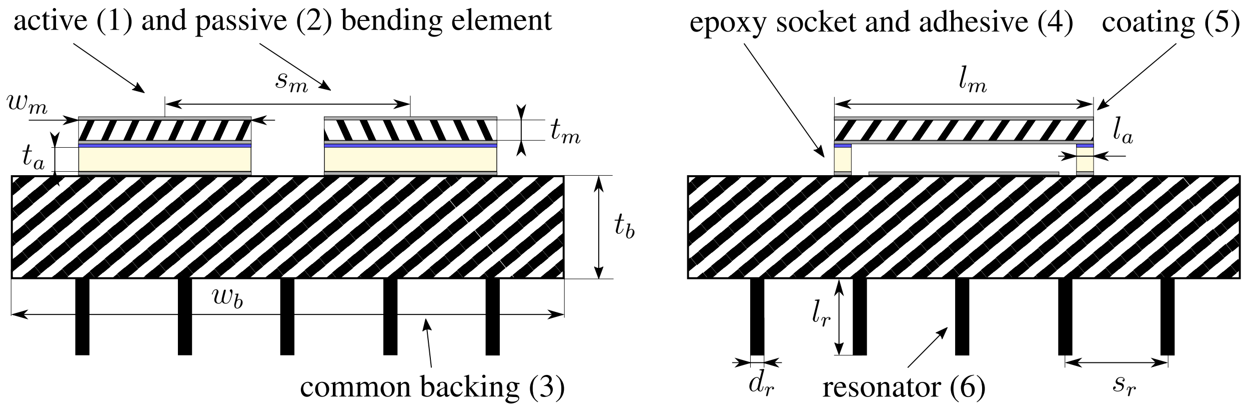

Figure 1: Cross-section of the investigated basic setup. Front view (left) and side view (right). Beam resonators at bottom side form the acoustic metamaterial.

Table 1: Dimensions of the basic setup to investigate the influence of acoustic metamaterial on cross-coupling in phased array transducers.

Parameter		Symbol	Value	Parameter		Symbol	Value
Backing	width	w_b	70.0 mm	Epoxy socket	length	l_a	4.6 mm
	thickness	t_b	3.0 mm		thickness	t_a	30 µm
Bending element	thickness	t_m	0.5 mm	Resonator			
	length	l_m	30.0 mm		length	l_r	0.1 - 12.0 mm
	width	w_m	6.0 mm		diameter	d_r	2.05 mm
	spacing	s_m	24.0 mm		spacing	s_r	10.75 mm

The cross-coupling between the active and passive bending element is calculated by

$$P_n = 10 \lg \left(\frac{\widehat{E}_2}{\widehat{E}_1} \right) \text{dB} . \tag{1}$$

Where E denotes the sum of squared velocity over the whole area each bending element. As we assume uniformly distributed mass for the bending elements, E represents an energy equivalent value. To calculate the cross-coupling between the bending elements, the peak at resonance frequency f_r is used with $\widehat{E} = E(f_r)$. It follows that $\widehat{E}$ appears at different frequencies for each bending element. For simulation, the difference in resonance frequency of the bending elements is small. Thus, there is only small difference whether cross-coupling is calculated at fixed resonance frequency of active bending element or at resonance frequency of each bending element. In the experimental setup, there is more significant difference in resonance frequency between the elements mainly caused by variance in free length of the bending element. By using $\widehat{E}$, an appropriate evaluation of the cross-coupling effect can be calculated. The experimental testing is done by non-contact measurements with scanning laser Doppler vibrometer. The surface velocity is measured at 27 points on each element while the active bending element is excited by an electrical voltage.

3. Results

In finite element method simulation (FEM), the first resonance frequency of the bending elements, which is the operating frequency, is 5.0 kHz. Cross-coupling between the bending elements is calculated from the output of FEM simulation. The influence of the acoustic metamaterial on mechanical cross-coupling caused by the common backing can be shown. At 9.4 mm length, the beams show a resonant behavior at 5.0 kHz. This coincides with the operating frequency of the phased array transducer. For this configuration, the cross-coupling is reduced from -8.4 dB to -19.1 dB. To ensure that the effect is not caused only by the added mass, the resonator length is extended to 12 mm. In this case, the stop band of the metamaterial does not fit the resonance frequency of the bending elements. In this configuration, the cross-coupling is -9.4 dB. Thus, the cross-coupling is reduced by -10.7 dB with resonant metamaterial but only by -1 dB with additional mass. Table 2 shows the results for the different resonator configurations as well as for the simulation and experiment.

Table 2: Influence of different resonator configurations on cross-coupling in the basic setup.

Resonator configuration	Simulation	Experiment
None	-8.4 dB	-10.1 dB
Poorly tuned (12.0 mm)	-9.4 dB	-11.6 dB
Well tuned (9.4 mm)	-19.1 dB	-18.0 dB

The reduction of cross-coupling by attaching acoustic metamaterial, which can be found in the FEM simulation, is confirmed in experimental results. Here, it has been reduced from -10.1 dB to -18.0 dB. The simulation and the experiment show good accordance. The differences can be attributed to variances in specimen setup. Consequently, the resonance frequency of the bending elements varies which leads to differences in cross-coupling. Another reason can be found in the variance of length of resonators in experimental investigation. This is due to the fact that resonators are trimmed by sanding.

4. Conclusion

Weak cross-coupling is one major criteria for high performance phased array transducers. In this study, we show that acoustic metamaterial can reduce mechanical cross-coupling effectively. This provides the possibility to design compact and high performance phased array transducers for acoustic imaging with low operating frequency. In FEM simulation, the cross-coupling has been reduced by more than 10 dB. The results from FEM simulation have been validated experimentally and show quite good accordance. An investigation with different resonator length shows that the effect is caused by resonant behavior of the acoustic metamaterial rather than by added mass.

Acknowledgment

The authors gratefully acknowledge Robert Bosch GmbH for the funding of this research.

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