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Jiajun Zhao

Manipulation of Sound Properties by Acoustic Metasurface and Metastructure

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Supervisor's Foreword

The focus of this thesis is the manipulation of sound properties by artificial materials. Acoustic devices that are engineered to have acoustic properties not yet found in nature are called acoustic metamaterials. Using the mathematical method called transformation acoustics, researchers have demonstrated a host of striking unprecedented acoustic metamaterial devices with unusual sound properties, such as negative density, negative bulk modulus, extraordinary sound transmission, super resolution, etc. In this thesis, the concept of acoustic metamaterials is extended to metasurfaces and metastructures, which are made from assemblies of various elements fashioned from traditional elements such as copper and membrane.

acoustic metasurfaces—different from a bulky acoustic metamaterial which enables interior abnormal sound properties, the proposed metasurface is a subwavelength structure that allows the change of sound properties right at its surface. Thus, instead of a gradual change inside a metamaterial, acoustic waves seem to have an abrupt change after touching a metasurface.

acoustic metastructures—inasmuch as acoustic metamaterials are based on transformation acoustics, the conformal mapping of coordinates inevitably leads to complex material parameters. Realizing these parameters in acoustics is usually challenging. In this thesis, the mechanism of acoustic metastructures does not rely on traditional transformation acoustics. By a unique design, the acoustic metastructure has a much accessible layout instead.

This thesis aims for the fundamental design of acoustic metasurfaces and metastructures, and their functionality in the manipulation of sound properties. Various topics are discussed in this thesis, which include the following: theoretically and simulationally constructing the acoustic metasurface of inhomogeneous acoustic impedance for various applications such as acoustic disguise, acoustic planar lenses, acoustic ipsilateral imaging, and the conversion from propagating to surface acoustic waves; extending the prior proposed structure to be three-dimensional, resulting in the out-of-incident-plane fluid-particle vibration; optimizing acoustic focusing for medical and industrial applications such as focused ultrasound surgery, lithotripsy, and nondestructive testing; and proposing a density-near-zero metastructure to provide an accessible approach for acoustic cloaking.

This thesis gives a broad and comprehensive guideline of designing acoustic metasurfaces and metastructures. It breaks new grounds for acoustic artificial materials, which were usually bulky in size and complicated in structure. By this proposed subwavelength metasurfaces and the metastructures with a simplified layout, multiple potential applications are demonstrated in this thesis.

Singapore
May 2016

Prof. Cheng-Wei Qiu

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3. J. Zhao, H. Ye, K. Huang, Z. Chen, B. Li & C. W. Qiu, “Manipulation of acoustic focusing with an active and configurable planar metasurface transducer”, *Scientific Reports* (2014), DOI: 10.1038/srep06257
4. J. Zhao, B. Li, Z. Chen & C. W. Qiu, “Manipulating acoustic wavefront by inhomogeneous impedance and steerable extraordinary reflection”, *Scientific Reports* (2013), DOI: 10.1038/srep02537
5. T. Han, J. Zhao, T. Yuan, D. Y. Lei, B. Li & C. W. Qiu, “Theoretical realization of an ultra-efficient thermal-energy harvesting cell made of natural materials”, *Energy and Environmental Science* (2013), DOI: 10.1039/c3ee41512k
6. J. Zhao, B. Li, Z. N. Chen & C. W. Qiu, “Redirection of sound waves using acoustic metasurface”, *Applied Physics Letters* (2013), DOI: 10.1063/1.4824758

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Last but not least, PTL!

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Abbreviations

1D	One dimension; one-dimensional
2D	Two dimension; two-dimensional
3D	Three dimension; three-dimensional
B.C.	Boundary condition
BPSO	Binary particle swarm optimization
DNZ	Density near zero
EST	Extraordinary sound transmission
FEM	Finite element method
FWHM	Full width at half maximum
GSL	Generalized Snell's law of reflection
IGSL	Impedance-governed generalized Snell's law of reflection
PAW	Propagating acoustic wave
PT	Piezoelectric transducer
PZT	Lead zirconate titanate
RSI	Acoustic Rayleigh–Sommerfeld diffraction integral
SAI	Specific acoustic impedance
SAW	Surface acoustic wave

Symbols

ω	Angular frequency, rad/s
p	Acoustic pressure, Pa
p_{ro}	p of ordinary reflection, Pa
θ_{ro}	Angle of ordinary reflection, rad
p_{re}	p of extraordinary reflection, Pa
θ_{re}	Angle of extraordinary reflection, rad
p_i	p of incident sound, Pa
θ_i	Angle of incident sound, rad
ρ_w	Density of water, kg/m^3
ρ_a	Density of air, kg/m^3
c_0	Speed of sound, m/s
d	Discretized spacing, m
Z_n	Specific acoustic impedance, Pa s/m
λ	Wavelength, m
k_0	Wave number, rad/m
f	Frequency, Hz
V_0	Amplitude of electric potential, J/C
γ	Damping coefficient, 1/s

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