Diffraction of Waves on Periodical Structures: acoustic, ultrasonic and acousto-optical diffraction phenomena

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A STRATEGIC LOCATION

**Metz**
- less than 1 hour drive from 3 countries
- 82 minutes from Paris Airport by TGV

**Within 400 miles:**
- over 200 million people
- 6 EU capitals
- 50% of EU GDP
GT-L Mission: Innovative collaborations in research, education, and economic development with European partners

USA

ATLANTA

Georgia Tech Lorraine
European Campus

Industry
Funding agencies

Academia

EU

METZ

Industry
Funding agencies

Academia
Why?

• Core values of the GT-L strategic Plan (2006-2011)

• International collaborations foster the flow of new ideas, create new opportunities, and develop highly valuable qualities of our students

• The quality of the educational experience and research scholarship at GT-Lorraine will carry the mark of excellence that exists on the Atlanta campus
1988  Lorraine/Georgia sister-state agreement
1990  Buildings completed – GTL opens its doors
      ECE Graduate Program with Supélec
1997  ME Graduate Program with ENSAM
1998  GTL-CNRS Telecom
      GTL Summer Program starts
2005  Computer Science Grad Program with Supélec
      Hired “permanent” GTL faculty
      Agreement between Gov. S. Perdue and President Masseret
2006  Creation of GT-CNRS UMI 2958
      Master Pro GT/ENSAM/SUPELEC
      Undergraduate Program (Int. Plan) starts at GT-L
2007  Inauguration of the UMI laboratories
      Externally funded research (industry, ANR, etc…)
Activities

- Graduate Programs ECE, ME, CS
- EU partner schools in France, Germany, Italy, Russia
- Undergraduate Summer Programs (all colleges)
- Academic Research (ECE/ME/CS)
- GT-CNRS UMI2958 Laboratory
- Economic Development
Enrollment

• Summer Program 2007
  – 125 US students, 28 classes, 14 faculty
• Fall 2007: 195 students
  – 160 GTL students: 14 BS + 131 MS + 15 PhD
  – 35 students finishing in Atlanta
  – 15 countries represented (60% French students)
Trends

Nationality of Graduates

- US/Other
- French

Trends

Male/Female Ratio

- Male
- Female
• Unité Mixte Internationale
• UMI GT-CNRS 2958
• Created March 23, 2006 over 80 publications since!
• Inaugurated June 14, 2007
• Director: Prof. Abdallah Ougazzaden
• Only 2 UMIs in engineering in the world
• Only one in France
• Visibility!!!
• “Mirror UMI laboratory on the Atlanta campus”
• UMI: Label of quality that opens doors for French / EU funding - UMI reviewed every 4 years.
Secure Networks includes research on KQD cryptography, Wireless coding and chaos communication. It also includes novel nonlinear functionality in fiber, organic and semiconductor materials.

Smart Materials includes research on fabrication, properties and modeling of semiconductor, dielectric and metallic with projects ranging from Wide-bandgap materials, to phononic crystal to functional materials and acoustic monitoring.
- GT-L new Laboratories (2007)
  - * Optical and Secure Communications
  - * Computing Cluster for Design and Modeling
  - * Materials Characterization and Device Testing
  - * Ultrasonics Characterization and Sensors
Applications

New semiconductors: BGaAlN growth on SiC and AlN (defense, environment, medical...)

Secure wireless communications

Multiscale modeling and design of advanced materials
From desired macroscopic functionalities to Molecular dynamic simulations

Ultrasound C-scans/Polar Wave propagation in complex Media
Reliability of advanced Materials

Smart material on chip for new current sensor (aerospace, transportation industry)

Transduction with novel electroactive porous foams (new sensors for noncontact NDE; reliability of advanced materials)
Welcome to visit us in Metz - France
Declercq’s lab on ultrasonic nondestructive evaluation of materials
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Highlight:

Ultrasonic C-scan system
Research goals:

Understanding ultrasonic diffraction effects on corrugated structures with a focus on physics and nondestructive testing.

Within this framework, topics such as backward beam displacement, Chichen Itza and Epidaurus have been studied.
The Framework – by means of example

Ultrasonic (Polar) Scans

Quantitative polar scans of composites:

Practical difficulties !!!

- higher than orthotropic anisotropy
- complicated orientation
- periodic roughness !!!
- finite size
- multi-layered
- piezoelectric
- coated
- incident bounded beams
- ...

extensive study required!
Impressions

Of past research on those ‘difficulties’
Inhomogeneous waves and bounded beams

3D bounded beams

Focal shift for complex harmonic beams

New surface wave

Numerical improvements
The interaction of sound with continuously varying layers

WATER

$z_a$

NAVIGABLE MUD

$z_b$

transition zone

$z_d$

NON-NAVIGABLE MUD

$z_e$

HARD BOTTOM
Sound in Media having discontinuities in more than one dimension

Rayleigh waves propagate ‘around the corner’ on thick aluminum sample. First experimentally observed, later theoretically shown as well.

Lamb waves make edge of (aluminum) plate become acoustic multipole.
Sound in (biased) piezoelectric materials

Lithium Niobate, difference of slowness between piezoelectricity involved and piezoelectricity omitted

Also inhomogeneous waves in such crystals have been studied…
Bulk Acoustic Microscopy

Defects can be visualized in the bulk of a composite.

The internal layered structure can be visualized.
Chichen-Itza (MX) Epidaurus (GR)

Interaction of sound with corrugated surfaces and phononic crystals

Backward displacement
Currently our lab is more and more evolving towards studying the interaction of sound with periodical structures.

Examples outlined here:

- Backward displacement of bounded beams
- Chichen Itza
- Epidaurus
Backward Beam Displacement when ultrasonic bounded beam interacts with a corrugated surface

New theoretical developments and new experiments have revealed what is causing the phenomenon and have revealed better overall insight into the diffraction of ultrasound. *Experiments in Collaboration with Mack Breazeale, Michael McPherson, and others.*

• Quetzal echo at the Mayan pyramid of Kukulkan at Chichen Itza in Mexico
Historical Maya Site of Chichen Itza

El Castillo Pyramid (Kukulkan Pyramid)
Quetzal = Quetzal coatl = Kukulkan = feathered serpent = God of civilization
How can we describe the interaction of the handclap with the staircase?
Common sense and first order approximation:
Bird Chirp is result of Bragg scattering!

??? But is it ???

Bragg scattering time delay can be calculated from grating equation and wave propagation:

\[
t_{m,f} = \frac{|d_z + h_z|}{v \cos \text{Re} \left( \frac{\pi}{2} - \arctan \left( \frac{2\pi f}{v} - \left( m - \frac{\pi}{\sqrt{2q}} \right)^2 \right) \right)}
\]
Bragg-scattering time delay lines
Sonogram calculated from measured echo
(*.wav taken from DAVID LUBMAN)

Acknowledgement: David Lubman was the first to study Chichen Itza seriously.
- New simulation is based on diffraction theory for single ultrasonic plane waves (Claeys and Leroy)
- Which is extended to diffraction of spherical pulses
- Which is applied to audio sound
- and adapted to the physical situation at the pyramid
Numerical result for a mathematical pulse:
simulation OK experiment

NOT really “bragg scattering”
handclap

pattern

“Already present in handclap”
Not unique: in Sri Lanka quacking ducks can be heard...
Chichen Itza = the mouth at the Itzáe's Well
There may be different effects (e.g. caused by hollowness),
But the raindrop effect described here is due to diffraction.

The Rain God ‘Chac’
Analyses of the Chichen Itza raindrop effect record: sonogram

Peak: 304.69 Hz
Analyses of the Chichen Itza raindrop effect record: FFT

Peak: 304.69 Hz
It’s not right to make an analysis based on only one example, therefore additional measurements have been performed on the ‘Moon pyramid’ of Teotihuacan (MX)
Analyses of the Teotihuacan raindrop effect record: sonogram

Peak: 271.86 Hz
Analyses of the Teotihuacan raindrop effect record: FFT

Peak: 271.86 Hz
Numerical analysis (details left out) show the amplitude of first order diffracted evanescent waves propagating along the staircase, caused by sound incident at 85 deg from the normal.

Experimental: 271.86 Hz

Experimental: 304.69 Hz

Estimated frequency for raindrop effect in Chichen Itza and Teotihuacan pyramids
There appears to be a remarkable agreement between experiments and theory. Therefore it is possible to generate a formula that delivers the ‘raindrop frequency’ for any stair periodicity of pyramids (same material, same environmental conditions):

\[ f_{\text{raindrop}} = \frac{81.1881}{q} \]

q is the height (or depth) of the steps of the pyramid: 
0.263 m for Chichen Itza, and 0.298 m for Teotihuacan.
• EPIDAURUS
Overview

- Introduction
- Aim
- Simulation model
- Diffraction and acoustics
- Influence of different parameters
- Conclusions
Introduction

geography:
Introduction

context: ASCLEPIEION
Introduction

theater: constructed in 4\textsuperscript{th} c BC

21 Roman Rows

34 Greek rows
Introduction

theories:

♦ wind

♦ rhythm of Greek poems

♦ masks
Overview

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Aim

- figure out the influence of diffraction on the periodic seat row structure on the acoustics of the theater

cfr. Chichen-Itzá!
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Simulation model

- 2D model
- Diffraction at subsequent positions along the slope
- Consideration of foreground reflections
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Diffraction and acoustics

Epidaurus without seat rows, sound source at 22.63 m from the first row of seats. Reflections on the foreground are neglected.

No diffraction effects

Position in theater 0-50m

Frequency (1-750 Hz)
Diffraction and acoustics

Same situation, but with reflections on foreground

No diffraction effects

Reflections on the foreground result in a better distribution of sound
Diffraction and acoustics

Epidaurus with seat rows, sound source at 22.63 m from the first row of seats. Reflections on the foreground are incorporated.

With diffraction effects
If we subtract the case with diffraction from the case without diffraction, then we highlight the particular influence of diffraction on the seat rows.
Diffraction and acoustics

What if the reflections on the foreground are neglected?

FILTERING EFFECT
but worse distribution

relative damping
relative amplification
Diffraction and acoustics

The diffraction spectrum as a function of frequency and position along the ‘slope’ of the cavea, of the -1 order diffracted sound waves. The raster at approximately 200 Hz indicates the transition between evanescent sound and propagating sound. Note that the amplitudes at frequencies beyond 200 Hz are very small: -15dB and much less.
-2 order diffracted sound. The raster is situated at approximately 450 Hz. The amplitude for frequencies beyond 450 Hz are -10dB or higher. It is this -2 order diffracted sound that is responsible for the filter effect and for favoring frequencies beyond 500 Hz for the audience.
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- Diffraction and acoustics
- influence of different parameters (see paper)
- Conclusions
Overview

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- Conclusions
Conclusions

-the foreground is important for a better distribution of sound throughout the theater

-the seat rows have a filtering effect and pass sound higher than 500Hz at the expense of surrounding acoustic noise

Also:
- season has almost no effect.
- position of source has an effect, but not on the filter threshold
- seat periodicity determines the threshold frequency. The quality of the filter is then determined by the other parameters (material properties, seat shape, …)
questions?

THANKS FOR YOUR ATTENTION

REFERENCES:

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• Nico F. Declercq, Joris Degrieck, Rudy Briers and Oswald Leroy, "Diffraction of homogeneous and inhomogeneous plane waves on a doubly corrugated liquid/solid interface" , Ultrasonics 43(8), 605-618, 2005
• .....
