The Chaotic Time Reversal Sensor

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Revolutionary Research … Relevant Results

Overview

Classically chaotic systems display extreme sensitivity to initial conditions … which suggests good sensor applications

Sensors often utilize waves (acoustic, electromagnetic, seismic, etc.) for detection

Wave Chaotic systems show extreme sensitivity to **perturbations**

Time Reversal and *Spatial Reciprocity* are two 'hidden' symmetries of the wave equation that can be exploited to simplify the wave chaotic sensor

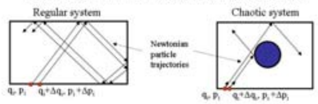
We have developed a novel sensor paradigm that combines the extreme sensitivity of wave chaotic systems with the simplicity of time-reversed and spatially reciprocal waves to create:

The **CHAOTIC TIME-REVERSAL SENSOR**

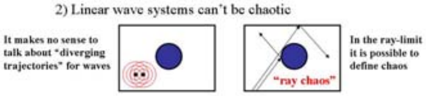
Wave Chaos?

1) Classical chaotic systems have diverging trajectories

2-Dimensional "billiard" tables with hard wall boundaries



2) Linear wave systems can't be chaotic

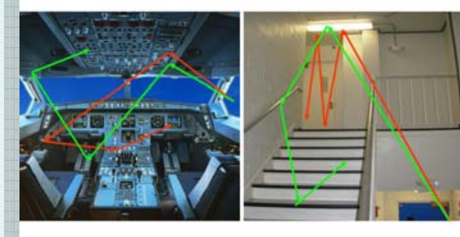


3) However in the semiclassical limit, you can think about rays

Wave Chaos concerns solutions of wave equations which, in the semiclassical limit, can be described by ray trajectories

Ray Chaos

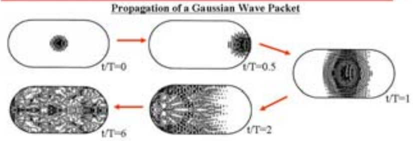
Many enclosed three-dimensional spaces display ray chaos



Now Consider Wave Propagation in Ray-Chaotic Enclosures

The two-dimensional Stadium Billiard shows Ray Chaos, which is illustrated by the spatial **ergodicity** of a ray trajectory.

Propagation of a Gaussian Wave Packet



T = time to propagate along horiz. axis

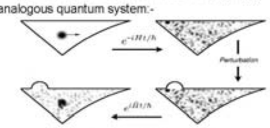
Solve the wave equation (Electromagnetic, Acoustic, Schrödinger equation, etc.) in a ray-chaotic enclosure

Examine the solutions in the semiclassical regime: $0 < \lambda << $ System Size

Tomsovic+Heller PRE 47, 282 (1993)

Quantifying Sensitivity to Perturbation of Wave Chaotic systems using Fidelity or Loschmidt-Echo (M(t))

Consider an analogous quantum system:-



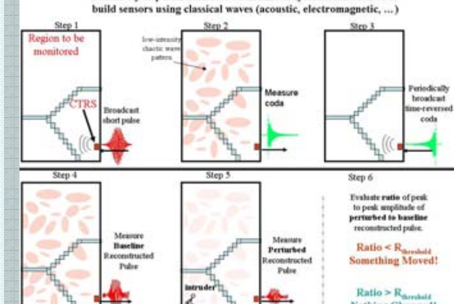
$$M(t) = \left| \langle \Psi_0 | e^{i\tilde{H}t/\hbar} e^{-iHt/\hbar} | \Psi_0 \rangle \right|^2$$

M(t), Loschmidt-Echo, is expected to decay exponentially! (for such perturbations) — Gousev, Richter, Phys. Rev.

The **Loschmidt-Echo** is measured using the **Scattering Fidelity**, which is the Cross Correlation of scattering matrix elements before and after perturbation. — Schafer, Gorin, Seligman, Stockmann, New J. Phys.

The **ratio of peak to peak amplitude** of initial and final state of the illustrated (classical) wave evolution is shown to be indicator of perturbation. — Anlage et al. Acta Physica Polonica A

Sensitivity to perturbation of wave chaotic systems can be used to build sensors using classical waves (acoustic, electromagnetic, …)

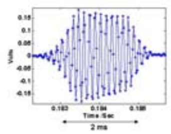


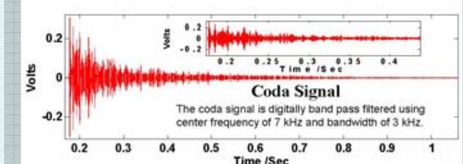
Acoustic CTRS in a Stairwell

Acoustic CTRS in Stairwell:- The incident pulse and Coda signal

Acoustic pulse with a **7 kHz (λ~4cm)** center frequency.

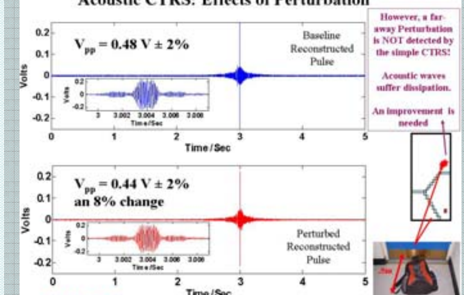
The wavelength controls the size of the intruder that can be detected.



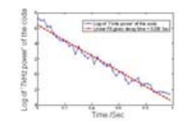


Single-shot data

Acoustic CTRS: Effects of Perturbation



Problem: Dissipation of Acoustic Waves inside the Stairwell



1/e Decay Time τ = 0.2 sec

Consistent with Sabine's Formula:

$$T_{reverberation} = (cV) \Big/ \sum_m (S_m \alpha_m)$$

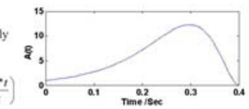
$$T_{reverberation} = 1.3 \text{ sec}$$

(60 dB decay time)

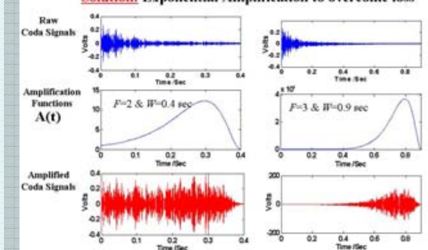
Solution: Exponential Amplification to overcome dissipation

Multiply the coda signal by an exponential $e^{+Ft/\tau}$ that is smoothly terminated after time W

$$A(t) = [1 - 4\left(\frac{t}{W}\right)^3 + 3\left(\frac{t}{W}\right)^4]*\exp\left(\frac{F*t}{\tau}\right)$$



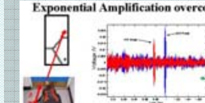
Solution: Exponential Amplification to overcome loss



Both of these amplified coda signals produce excellent detection for non-line-of-sight perturbations

The CTRS is calibrated for a given Enclosure & Type of Perturbation by finding values of parameters which **minimize the ratio of Vp-p of Perturbed Reconstructed Pulse to Vp-p of Baseline Reconstructed Pulse.**

Exponential Amplification overcomes loss limitations enabling distant detection



Description of CTRS operation	V_{p-p} of Baseline Reconstructed Pulse (BRP)	V_{p-p} of Perturbed Reconstructed Pulse (PRP)	Ratio of V_{p-p} of PRP to V_{p-p} of BRP
No Amplification	0.45V (±2%)	0.46V (±2%)	100%→ No Detection!
Amplification with F=3 & W=0.9	0.054V (±2%)	0.037V (±2%)	70%→ Detection!

Conclusions

- A new sensor paradigm has been developed based on the extreme sensitivity of wave chaotic systems to small perturbations
- Time-Reversal Symmetry and Spatial Reciprocity have been exploited to simplify the sensor
- The sensor has been demonstrated with acoustic waves in a cheap and portable manner
- Exponential amplification can be used to dynamically change the range of sensitivity of the sensor

Future Work

- Design a network of CTRS sensors to determine the position and size of the perturbation
- Utilize wavelength diversity to sense perturbations of different sizes
- Study use of Fidelity to quantify the perturbation & to classify it under different universality classes
- Realize the CTRS using low power wave source and receiver controlled by an embedded chip

Some Background Publications:

S. Hemmady, *et al.*, Phys. Rev. Lett. 94, 014102 (2005)
S. M. Anlage, *et al.*, Acta Physica Polonica A 112, 569 (2007)

http://www.csr.umd.edu/anlage/AnlageQChaos.htm

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