6-29-2017

Array-based Inhomogeneous Soundwave Generation to Enhance Sound Transmission into Solids

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Kyle, Trevor A.; Woods, Daniel C.; Tiwari, Rahul; Rhoads, Jeffrey F.; and Bolton, J Stuart, "Array-based Inhomogeneous Soundwave Generation to Enhance Sound Transmission into Solids" (2017). *Publications of the Ray W. Herrick Laboratories*. Paper 151.
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Array-based inhomogeneous soundwave generation to enhance sound transmission into solids

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June 29th, 2017*

- Improvised explosive devices (IEDs) pose a great threat to armed forces
- There is not currently an effective way of both detecting and defeating IEDs
- Preliminary research suggests that acoustic excitation of IEDs could lead to an increased thermomechanical response and thus easier detection and defeat
 - Trace vapor detection

Background

- The vapor pressure of many common explosives increases significantly with increasing temperature
 - 2°C increase (25° to 27°)
 - 40% increase in RDX pressure
 - 60% increase in HMX pressure
- It is relatively difficult to transfer acoustic energy from air to a solid due to impedance differences
 - e.g. Normal incidence pressure/power reflection coefficient of a 10 kHz plane wave on stainless steel is essentially 100%

Vapor Pressure of RDX
(from Östmark et al., 2012)

Background

- Possible Solution: Inhomogeneous waves
 - Waves that decay spatially in a direction perpendicular to their propagation—complex wavevector
- Controlled by the decay parameter β
- Allow for greatly enhanced transmission into materials
 - Setting $\beta = 5.12 \times 10^{-5}$ rad/m and at an incident angle of $\sim 6.853^\circ$, stainless steel reflection approaches 0%
- Inhomogeneous plane wave creation requires multiple sources with variable strengths and relative phases

Pressure Reflection Coefficient for Stainless Steel

Least-Squares Solution

- Detailed by Kirkeby & Nelson (1993)
- The sound field at a point is the sum of the sound fields from multiple sources

$$\begin{bmatrix} \tilde{P}_1 \\ \vdots \\ \tilde{P}_R \end{bmatrix} = \begin{bmatrix} \tilde{Z}_{11} & \cdots & \tilde{Z}_{1S} \\ \vdots & \ddots & \vdots \\ \tilde{Z}_{R1} & \cdots & \tilde{Z}_{RS} \end{bmatrix} \begin{bmatrix} \tilde{Q}_1 \\ \vdots \\ \tilde{Q}_S \end{bmatrix}$$

- Impedances $\tilde{Z}_{mn} = i\omega\rho \frac{e^{-ikr_{mn}}}{4\pi r_{mn}}$
- Remove the frequency dependence
- Find the least-squares source accelerations

$$\tilde{\mathbf{H}} = \frac{1}{i\omega} \tilde{\mathbf{Z}} \quad \tilde{\mathbf{a}} = i\omega \tilde{\mathbf{Q}}$$

- Calculate the acoustic source power and relative phase

$$W_n = \frac{|\tilde{Q}_n|^2 \rho v k^2}{8\pi} \quad \phi_n = \arg \left(\frac{\text{Im}[\tilde{Q}_n]}{\text{Re}[\tilde{Q}_n]} \right)$$

Array Design

Are inhomogeneous waves more difficult to reconstruct than homogeneous waves?

Results

- Array simulation:
 - 8 Sound Sources (Monopoles)
 - Spacing of 6 cm
 - Frequency of 10 kHz
 - Standoff Distance of 50 cm
 - 8 Design Points
 - Span of 17.5 cm
 - Room Temperature Air

Results

- 1 Pa homogeneous plane wave
 - Max Error: 9.1 mPa (0.91%)
 - RMS Error: 3.6 mPa
 - Total Acoustic Power: 3.5 mW

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- 1 Pa inhomogeneous plane wave, $\beta = 1 \text{ rad/m}$
 - Max Error: 8.8 mPa (0.96%)
 - RMS Error: 3.4 mPa
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Results

- 1 Pa inhomogeneous plane wave, $\beta = 1$ rad/m
 - Max Error: 8.8 mPa (0.96%)
 - RMS Error: 3.4 mPa
 - Total Acoustic Power: 3.0 mW

Results

- Overdetermined system
 - Unequal number of sources and receivers/design points
- Number of design points increased from 8 to 128
 - RMS Error reduced by 39%
- 1 Pa homogeneous plane wave
 - Max Error: 7.7 mPa (0.77%)
 - RMS Error: 2.2 mPa
 - Total Acoustic Power: 3.5 mW

Results

- Parameters can be modified to reduce errors or power demand
- Source spacing is varied from 6 to 10 cm
- Standoff distance is varied from 15 to 75 cm
- Reducing source spacing and increasing standoff distance reduces errors
- Very minute differences between homogeneous and inhomogeneous cases
- Large source spacing and small standoff distance leads to large pressure errors

Results

- Reducing source spacing reduces power demand
- An optimal standoff distance exists, but it does not correspond to a configuration with low pressure errors
- Large source spacing and small standoff distance leads to large power demands

Results

- Inhomogeneity can be varied
- Standoff distance is kept at 50 cm
- Source spacing is varied from 6 to 10 cm
- Decay parameter β is varied from 10^{-4} to 1 rad/m
- Inhomogeneity is largely inconsequential to pressure or power optimization

Results

- It is possible that small errors in signal generation could cause deviations in the source powers and phases
- Adding Gaussian noise to the Least-Squares source powers and phases gives bounds for the expected reconstructed wave
 - Power Deviation
 - Mean of 0%
 - Standard deviation of 1%
 - Phase Deviation
 - Mean of 0°
 - Standard deviation of 1°
- Standard deviations are simply a baseline
- In this case, noise on initial phase angle is the dominant cause of error

Results

- Fitting an exponential curve to the bounds of the deviation, a range of β values can be determined
- For stainless steel at its optimal incidence angle 6.853° , the optimal inhomogeneity is $\beta = 5.12 \times 10^{-5}$ rad/m
- With power and phase errors, β can vary up to 0.1926 rad/m, taking the reflection coefficient, $|R|$, to unity

- The reconstruction of inhomogeneous plane waves is not appreciably more error-prone or power-demanding than the reconstruction of homogeneous plane waves
- Errors are reduced by increasing standoff distance, increasing the number of design points, and decreasing source spacing
- Power demand is reduced by decreasing source spacing
- Errors in the source powers or relative phases can significantly decrease the reconstructed wave's ability to transmit energy into a target material

- Physically generate inhomogeneous plane waves utilizing an acoustic source array
- Quantify the magnitude of temperature increase in mock energetic materials subjected to inhomogeneous plane waves
- Experimentally tune wave parameters to optimize energy transmission

Experimental Setup

- National Instruments PXIe-8840 Data Acquisition System
 - Generates up to 32 signals for amplification and transmission to sources
 - Reads up to 64 signals from microphone receivers
- Pyle PDBT35 Titanium Super Tweeter
 - 500 W peak power
 - 2,000-22,000 Hz frequency response
- PCB Piezotronics 130F21 ICP Microphone
 - 2-20,000 Hz frequency response

Acknowledgements

- This research is supported by the Office of Naval Research through grant No. N00014-15-R-SN16.

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Questions?