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

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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
The vapor pressure of many common explosives increases significantly with increasing temperature

- 2°C increase (25°C to 27°C)
  - 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%
Possible Solution: Inhomogeneous waves

- Waves that decay spatially in a direction perpendicular to their propagation—complex wavevector

Controlled by the decay parameter $\beta$

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
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

\[
\tilde{H} = \frac{1}{i\omega} \tilde{Z} \quad \tilde{a} = i\omega \tilde{Q}
\]

- Find the least-squares source accelerations

\[
\tilde{a} = \left(\tilde{H}^* \tilde{H}\right)^{-1} \tilde{H}^* \tilde{P}
\]

- Calculate the acoustic source power and relative phase

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

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
Results

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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

- 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%) (1 Pa)
  - RMS Error: 2.2 mPa
  - Total Acoustic Power: 3.5 mW
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
- Inhomogeneity can be varied
- Standoff distance is kept at 50 cm
- Source spacing is varied from 6 to 10 cm
- Decay parameter $\beta$ 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.
Fitting an exponential curve to the bounds of the deviation, a range of $\beta$ values can be determined.

For stainless steel at its optimal incidence angle $6.853^\circ$, the optimal inhomogeneity is $\beta = 5.12 \times 10^{-5} \text{ rad/m}$.

With power and phase errors, $\beta$ can vary up to $0.1926 \text{ rad/m}$, 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.
Future Work

- 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
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Questions?