COMSOL Multiphysics Simulation of Ultrasonic Energy in Cleaning Tanks

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Outline

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• Motivation for the Study
• Model Descriptions
• Results and Discussion
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Background of Ultrasonic Cleaning

- Ultrasonic based cleaning technique, widely used in various industries

- Transducers convert the input high frequency electronic oscillation from the ultrasonic generator to mechanical vibrations with ultrasonic frequency (generally 15kHz to 400kHz)

- Once generated, the transducer vibrations propagate through the fluid medium in the cleaning tank and form time-varying pressure field

Schematic drawing of a typical ultrasonic cleaning tank with **plate type transducers**, showing array of transducers bonded to the bottom

Small volume table top unit

Large scale, multi tank unit
Main effect to achieve contamination removal in ultrasonic cleaning: **ultrasonic energy driven cavitation**

Within the fluid medium, each point along the wave oscillates with pressure ranging between a maximum and a minimum, where cavitation bubbles grow.

- In almost all cleaning applications, it is important to control the cavitation energy.
- For a given set of ultrasonic tank parameters, the cavitation effect is largely impacted by the amount of ultrasonic energy.
Motivation for the Study

To study the ultrasonic energy as impacted by tank volume and/or shape by evaluating the propagation of ultrasonic waves in cleaning tank containing cleaning fluid.

- Determining optimal ultrasonic energy level often becomes the key to the success of ultrasonic based cleaning.
- Ultrasonic energy requirement, usually represented by watts per gallon, developed in one ultrasonic cleaning tank often cannot be used as a base to design another one with different volume and/or shape for the same process performance.
Model Geometry

A quarter of ultrasonic cleaning tank with water as cleaning medium

- Define a cleaning zone where parts to be cleaned typically located.
  - 1 inch from the tank wall and 2 inch from the top/bottom

Symmetrical Planes

Each circle representing the radiation area of one transducer
Boundary Conditions

Tank Wall: **External Shell**

- Symmetrical planes
- Bottom (non transducer area): hard wall

Transducer radiation area: **pressure**
Governing Equations

Pressure acoustic model for water domain

\[ \nabla \cdot - \frac{1}{\rho_c} (\nabla p_t - q_d) - \frac{k_{eq}^2 p_t}{\rho_c} = Q_m \]

\[ p_t = p + p_b \]

\[ k_{eq}^2 = \left( \frac{\omega}{c_c} \right)^2 \]

Linear elastic shell for stainless steel tank wall

\[ - n \cdot \left( - \frac{1}{\rho_c} (\nabla p_t - q_d) \right) = a_n \]

\[ - \rho \omega^2 u - \nabla \cdot \sigma = - \frac{p_t n}{d} \]

Maximal mesh elements size: 1/5 of wavelength
Describing Ultrasonic Transducer Operation

During ultrasonic cleaning, it is common practice to sweep around a frequency range near the center frequencies of ultrasonic transducers.

- Compensate variation of transducer center frequency
- Avoid acoustic wave transmission dead spot (nodes) in the tank

During each sweep cycle, the transducer output power peaks at the center frequency and reduces away from center frequency.
Describing Ultrasonic Transducer Operation

While sweeping transducer arrays around a center frequency, peak power for each transducer occurs randomly around the nominal center due to manufacturing variation.

Boundary pressure for transducer area

\[ p_0 = \left( \frac{2 \cdot \rho_c \cdot C_c \cdot P_e}{A} \right)^{1/2} \]

\( \rho_c \): density of water, 1000kg/m\(^3\)
\( C_c \): speed of sound, 1418m/s
\( P_e \): transducer operation power
\( A \): radiation area of transducer

Nominal center frequency
Results and Discussion

Frequency domain simulation scanned from 39kHz to 41 kHz at a step of 0.01 kHz and solved for

- Pressure,
- Displacement field
- Displacement of shell normals

From the pressure field distribution, ultrasonic intensity (W/in^2) distribution is calculated based on following equation

\[ P_{ac} = \frac{p^2}{2 \cdot \rho_c \cdot C_c} \]

\( \rho_c \): density of water, 1000kg/m^3
\( C_c \): speed of sound, 1418m/s
Results and Discussion-Continue

Average power density within the cleaning zone over frequency range is determined
- To estimate the effective ultrasonic density transmitted to the cleaning zone for different tank volume with same power input.

![Graph showing the relationship between volume and average power density in the cleaning zone.]

Higher effective power density in the cleaning zone is observed at larger volume despite the lower power input/volume.

- Suggesting the ultrasonic energy input that required by cleaning task for a given cleaning system may not be a simple derivative of input ultrasonic energy per unit tank volume.
Conclusions

- Ultrasonic energy transmission within the tank is impacted by the tank geometry/volume.
- The ultrasonic energy input that required by cleaning task for a given cleaning system may not be simply described by input energy per unit tank volume.
- The model can be applied to match ultrasonic power density input for cleaning tanks of different geometries.
- Further study can include cleaning objects in the tank.
THANK YOU!