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The Application of Acoustic Radiation Modes to Engine Oil Pan Design

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THE APPLICATION OF ACOUSTIC RADIATION MODES TO ENGINE OIL PAN DESIGN

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General workflow of numerical optimization

Optimization Techniques

- Sizing Optimization
- Topometry Optimization
- Topography Optimization
- Freeform Optimization

—————> Reduce sound pressure

- Current optimization approaches do not directly use sound power as the optimization goal.
- If the transfer function used in optimization is directly related to radiated sound power, radiated sound power could be targeted.

Acoustic radiation modes!

- ✓ Radiate sound power independently
- ✓ Can be obtained numerically

Acoustic Radiation Modes

- ARM is only a function of frequency and the shape of the radiating surface.
- ARM is a set of velocity distribution
- Each of the ARMs radiates sound power independently, i.e. the overall radiated sound power can be obtained by simply summing up the sound power from each radiation mode

- It has been demonstrated that acoustic radiation modes can be used as basis functions in acoustic holography.

- Sound power of each radiation mode can be ranked, revealing the most effective radiators

Our Goal

- Find the structural vibration pattern, which radiates the most sound power, and disrupt it by modifying the structure, to reduce radiated sound power.
- There is a huge potential to apply the acoustic radiation modes for structural optimization in the design stage with the help of multibody simulation to reduce radiated sound power.

Formulation of Acoustic Radiation Modes

Apply BEM on the source surface,

$$c(x)p(x) = \int_s \left(p(y) \frac{\partial G(x, y)}{\partial \vec{n}} + i\rho\omega v_n(y)G(x, y) \right) dS$$

We can obtain the following relation

$$\mathbf{C} \mathbf{p}_s = \mathbf{A}_s \mathbf{p}_s + \mathbf{B}_s \mathbf{v}_s$$

Combine and rearrange the terms

$$[A] \{ \tilde{p}_n \} = [B] \{ \tilde{v}_n \}$$

Radiated sound power is then

$$\bar{P}(\omega) = \frac{1}{2} \text{Re} \left\{ \{ \tilde{v}_n \}^H [G] [A]^{-1} [B] \{ \tilde{v}_n \} \right\}$$

where

$$[G] = \sum_m \int_{S_m} [I]_m^H \{N\}^* \{N\}^T [I]_m J_m dS$$

Formulation of Acoustic Radiation Modes (2)

- The radiation resistance matrix is defined by

$$[Z] = [G][A]^{-1}[B]$$

- And then the sound pressure and particle velocity can be related by

$$\{\tilde{p}\} = [\tilde{Z}]\{\tilde{v}\}$$

- Apply singular value decomposition to the real part of $[\tilde{Z}]$

$$\text{Re}([\tilde{Z}]) = [Q]^T [\lambda] [Q]$$

- The columns in $[Q]$ are the acoustic radiation modes, and the corresponding terms in $[\lambda]$ is the radiation efficiency.
- ARM currently is widely used in the field of active noise control.

Calculate Sound Power using Acoustic Radiation Modes

- Overall sound power can be calculated when the surface velocity is given by

$$\bar{P}(\omega) = \frac{1}{2} \text{Re} \left\{ \{\tilde{v}_n\}^H [G][A]^{-1} [B] \{\tilde{v}_n\} \right\}$$

- Simply replace $\{\tilde{v}_n\}$ with a scaled acoustic radiation mode, the individual sound power of the acoustic radiation mode is obtained by

$$\bar{P}_i(\omega) = \frac{1}{2} \text{Re} \left\{ \{q\}_{i, \text{scaled}}^H [G][A]^{-1} [B] \{q\}_{i, \text{scaled}} \right\}$$

- To obtain the scaled acoustic radiation modes, simply project velocity to each radiation mode by

$$\{q\}_{i, \text{scaled}} = \{q\}_i^T \{v_n\} \{q\}_i$$

- Overall sound power can be also calculated by summing up the sound power from each radiation mode

$$\bar{P}(\omega) = \sum \bar{P}_i(\omega)$$

Proposed Workflow

- **Engine Oil Pan**
 - 1.5 mm thick stainless steel
- **Excitation**
 - Displacement boundary condition obtained from multibody simulation 0 to 500 Hz
 - Excitation applied at the bolt holes
- **Structural solution**
 - Modal Superposition

Obtain Acoustic Radiation Modes of the Oil Pan

Step 1: The oil pan is discretized into acoustic mesh

Step 2: Influence matrices $[A]$ and $[B]$ are obtained using BEM solver (OpenBEM in this case)

Step 3: Obtain power radiation resistance matrix

$$[Z] = [G][A]^{-1}[B]$$
$$\text{Re}(\tilde{Z}) = [Q]^T [\lambda] [Q]$$

Columns are radiation modes

Calculate Radiated Sound Power

Step 4: Calculate sound power radiation

$$\bar{P}(\omega) = \frac{1}{2} \text{Re} \left\{ \{\tilde{v}_n\}^H [G][A]^{-1} [B] \{\tilde{v}_n\} \right\}$$

Obtain Vibration Velocity Response

Step 4: Calculate velocity response using boundary condition supplied by multibody dynamic simulation

197.4 Hz

247.8 Hz

264.6 Hz

331.8 Hz

428.4 Hz

466.2 Hz

Obtain scaled radiation modes and calculate sound power

Step 5: Calculate scaled radiation mode

$$\{q\}_{i,\text{scaled}} = \{q\}_i^T \{v_n\} \{q\}_i$$

Step 6: Calculate sound power of each scaled radiation mode

$$\bar{P}_i(\omega) = \frac{1}{2} \text{Re} \left\{ \{q\}_{i,\text{scaled}}^H [G][A]^{-1} [B] \{q\}_{i,\text{scaled}} \right\}$$

Make modification targeting specific vibration pattern

Step 7: Select radiation mode to disrupt and make structural modification

Velocity Response at 197.4 Pre-Modification

Velocity Response at 197.4 Post-Modification

Re-evaluate Radiated Sound Power

These steps can be repeated until a satisfying result is obtained.

Observations

- The shape of the radiation modes along with the sound power from each of the radiation modes assisted in the determination of the target vibration pattern which has to be disrupted.
- The modification is precise and effective. More than 7 dB reduction was achieved at the target frequency.
- In the first iteration, the target frequency is clear and the vibration pattern is simple. Engineer can probably make the same decision without knowing the sound power from each of the radiation modes.

Second Iteration (1)

1: Calculate radiated sound power

2: Evaluate sound power from each radiation mode

3: Visualize selected radiation modes

4: Visualize vibration pattern

Side moving outward in-phase

Second Iteration (2)

5: Modify the structure such that the coupling between the structural vibration and the 2nd radiation mode is disrupted.

260.4 Hz Pre-Modification

260.4 Hz Post-Modification

Step 6: Evaluate the effectiveness of the modification.

Observations:

- Acoustic radiation mode helped pinpoint the vibration patten which corresponds to high sound power radiation.
- Sound power at 260.4 Hz was suppressed by more than 6 dB.
- In this case, the modification also helped bring sound power down in some adjacent frequencies.
- Unfortunately, the sound power around 330 Hz went up due to this modification, so further modification might be required.

Conclusion

- A procedure of structural optimization based on acoustic radiation mode is proposed.
- Unequivocal reduction of radiated sound power by decreasing the degree of coupling between the structure's surface vibration and the radiation modes has been achieved.
- The proposed procedure allows the engineer to make smart and effective decisions without necessarily requiring expensive and time consuming optimization procedures.

A 3D rendering of a red ballpoint pen with a silver tip, positioned diagonally. The pen has just finished writing the words "Thank you" in a black, cursive script on a white surface. The pen's shadow is cast to the right.