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Computational Simulation of a Pulsating Supercavity
Introduction

Ventilated Supercavities

• Supercavity achieved when a body travelling underwater is enveloped in a pocket of gas
  - Cavity fully envelopes the body

• Ventilated supercavity achieved by ventilating gas into the separated flow region downstream of a cavitator

*Supercavitating Body Photographs from the University of Minnesota* *http://cav.safl.umn.edu/gallery.htm*
Introduction

Three Cavity Closure Regimes

Re-entrant Jet

Twin Vortex

Pulsation
Ventilated Supercavity Pulsation

- Pulsation is a self excited resonance phenomenon of the gas/water system
  - Characterized by traveling waves on cavity walls that cause volume to change periodically (monopole noise source)

- Song (1962) modeled ventilated supercavity as mass/spring system and accurately predicted its resonance/pulsation frequency
• Rearward facing truncated cone cavitator with embedded static and dynamic pressure sensor
  - Senses cavity pressure

• Experiments performed in ARL Penn State 0.305 m water tunnel
  - Hydrophone mounted on water tunnel window
• Cavity interior pressure and noise vary sinusoidally and in-phase with time

• Spectrum level of cavity interior press. is 20 dB greater than that measured by window hydrophone

> Due to spherical spreading of sound waves from cavity interface

Pulsation Tone: 36.6 Hz

20 dB
• Acoustic pressure, \( p(r,t) \), from fluctuating volume or monopole source is given by

\[
p(r,t) = \frac{\rho}{4\pi r} \frac{d\xi(t - r/c)}{dt}
\]  

(1)

• Assuming time harmonic motion of the interface we get

\[
p(r,t) = \frac{2\pi f \rho a^2}{r} \hat{u}_r e^{j2\pi f(t-r/c)}
\]  

(2)

• Substituting measured values of \( f \), \( a \), \( r \) and \( \hat{u}_r \) into (2) gives

\[
20 \log\left(\frac{p_{pk}(r,t)}{\sqrt{2}}\right) = 171.1
\]

171.5 dB Measured with Window Hydrophone
• Lump $2\pi j \rho a^2 \hat{u}_r$ from Eq. 2 together to form complex pressure amplitude

$$p(r, t) = \frac{\hat{A}}{r} e^{j2\pi f (t-r/c)} \quad (3)$$

• Evaluate $\hat{A}$ on interface to obtain expression for radiated sound pressure

• Given/assuming pressure inside cavity is uniform and constant across interface

The radiated sound pressure from pulsating supercavity can be obtained simply from a pressure sensor inside the cavity and accounting for spherical spreading from the interface!
• When the spectrum level of the cavity interior pressure was varied up to 20 dB during experiments aimed at suppressing pulsation noise, the spectrum level of the radiated noise varied commensurately.

We have shown conclusively that the cavity interior pressure can be used as a measure of the radiated noise from a pulsating supercavity!
Finite Volume CFD

- Finite volume CFD properly resolved the three dynamic closure modes
  - Incompressible physics for re-entrant jet and twin vortex
  - Compressible in the gas phase required to capture pulsation
Finite Volume CFD

• Pulsating supercavity in 0.305 m water tunnel captured well with CFD
  - Cavity generated at Fr = 4.5
  - Second order cavity

• CFD accurately captured cavity internal pressure amplitude, frequency (38 Hz) and phase
Finite Volume CFD

- CFD predicted cavity interior pressure spectrum level of 177.3 dB is in good agreement with the measured spectrum level of 176.1 dB
- Radiated sound pressure spectrum level at the hydrophone location is in good agreement with the CFD prediction
  - Spherical spreading from interface with CFD cavity interior pressure
  - Monopole source with CFD cavity volume velocity
Pulsation Control

- Pulsation is a resonance phenomenon where the interface waves force the gas/water system at its natural freq. - Analogous to forcing an oscillator at its natural freq.
- An oscillator’s response can be much diminished when forced away from its natural frequency

Transient response to an applied force for identical undamped oscillators with natural frequency $f_0$

Animation courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State
Pulsation Control

- Alter the supercavity resonance frequency from its constant ventilation rate value by modulating the ventilation rate
  - Inhibits resonance freq. excitation from interface waves whose frequencies remain largely unchanged
  - Approach has its roots in parametric oscillators

- Approach was investigated by solving modified Hill’s equation (in keeping with Song’s analysis)

\[
\frac{d^2 s}{dt^2} + \frac{b}{2\pi f_0} \frac{ds}{dt} + 4\pi^2 f_0^2 \left[1 + h \sin(2\pi f_{mod}(t + \tau))\right]s = S_0 \sin 2\pi f_0 t
\]

- Damping
- Modulation strength, frequency, and phase
- Shear layer instability induced pressure
Pulsation Control

Cavity Growl

Modulation Frequency, $f_{mod}$ (Hz)

Resonance Frequency, $f_0$ (Hz)

Area (m$^2$)

Time (s)

Exponential Growth Rate $\alpha$

$h=0$ contour
Pulsation Control

- $V_\infty = 2.7 \text{ m/s}$
- $f_o = 39.2 \text{ Hz (185.8 dB)}$
- $f_{mod} = 40.0 \text{ Hz (161.1 dB)}$
- 45.3 dB reduction at pulsation freq
Pulsation Control

1/133.3 real time

1/1.64 real time
Tonal Noise

- Proper Orthogonal Decomposition is being applied to cavity images in order to relate interface structures to features in pressure spectra.
• The radiated noise spectrum appears almost identical to the cavity interior pressure spectrum but is offset in level correspondingly to spherical spreading
  - Suggests the cavity is a broadband source of monopole sound
  - Coherence >0.5 between interior cavity pressure sensor and window hydrophone when SNR >10 dB
  - Cross spectrum phase indicates broadband sound propagation from cavity to window hydrophone
Ventilation Gas

- Ventilating with different gases allows us to change the effective stiffness of the cavity.
  - The denser the gas, the stiffer the cavity and the higher the pulsation frequency.
- Ventilating with SF$_6$ allows us to maintain the cavity at 1/5 the air ventilation velocity, which may reduce broadband noise.
  - Since cavity pressure/size appears to be mass flow rate controlled.

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]

Added mass of water surrounding cavity.
Summary

- Pulsating supercavities are monopole sources of sound that are dominated by the noise at the pulsation frequency.

- All ventilated supercavities radiate broadband noise, including pulsating supercavities.
  - The broadband radiated noise levels are much lower than the levels associated with cavity pulsation.

- The cavity interface perturbations are related to/induce the interior pressure fluctuations and these pressure fluctuations are radiated through the interface as sound.

- It is possible to model the physics of ventilated supercavities with CFD.

- Pulsating supercavities can be transitioned into either twin vortex or re-entrant jet supercavities by modulating the ventilation rate.
  - Detune its natural frequency from the interface wave forcing frequency.
  - Also verified with CFD.
• Ventilating the cavity with SF₆ maintains the cavity with a ventilation velocity 20% that of air which reduces noise

• The greater the density of the gas, the stiffer the cavity and the higher its natural frequency