Wave Impact & Air Bubbles

Yin Lu (Julie) Young
Wen Feng Xie
Princeton University
FEM: Modal Frequencies

In air

In water

Blade frequency in air (Hz)

mode number

ABAQUS, C3D20R
- 20x10
- 20x20
- 20x40
- 30x40
- 40x10
- Experiment

2nd mode

1st mode

measured
predicted

blade angle (degrees)
NEESR-SG: Development of Performance Based Tsunami Engineering (PBTE)
Typical Analysis Procedure

- Time scale of slamming: \( \sim 10^{-3} \) to \( 10^{-2} \) sec
- Wave period: \( \sim 10^2-10^3 \) sec for tsunamis
- Natural period of structure: \( \sim 10^0-10^1 \) sec
  - Assume incompressible water
  - Ignore viscosity and vorticity
  - Ignore air-water interaction
  - Ignore water-structure interaction
  - Reasonable for low speed wave impact, or for impact of pointed bodies
  - Not reasonable for the initial stage of high speed impact where the compressibility of air and fluid mixture is important, and where \( \frac{dv}{dt} \gg g \)
High-Speed Wave Impact

• Air cushion may be created due to plunging wave, bottom impact with large deceleration of the flow, local geometry of the impact, etc

• Reduce initial peak pressure, increase load duration, and introduce pressure oscillation following initial peak.

• Incompressible assumption and Froude scaling of model test results become unsustainable.
  - At Patm, 1% air => \( c = 120 \) m/s, 20% air => \( c = 30 \) m/s (compressible air-fluid mixture)
  - \( Fr = \frac{\text{inertial force}}{\text{gravitational force}} \) => length & time scales are modified by accounting for gravity => only for incompressible flows.

Faltinsen, Landrini, & Greco (2004)
Impact Pressure and Aeration

- ~2.5m above MWL, $H_{si}$~4m
- $P_{\text{max}}$=745kPa ($P_{\text{hydrostatic}}$~10kPa)
- $t_d$~3ms, vertical extent~7cm
- Ave. velocity of wave ~20m/s
Physics are poorly understood b/c most designs are based on small scale freshwater model tests scaled w.r.t. Froude number

- Aeration level of seawater > freshwater
- Typical modal size of bubbles in salt water (<1 mm), in fresh water (~5 mm) => bubbles persist much longer in saltwater
- More air crushion effect (lower impact pressure but longer load duration, more oscillations)
- More susceptible to fluid cavitation (highly localized pressure pulses due to cavitation collapses, especially in cracks or joints due to reflections from closed ends)
- Bullock et al (2005) reported that many instances of sub-atmospheric pressure has been record along the crack units at Admiralty Breakwater
- Numerical compressible computations by Peregrine et al (2005) also reported sub-atmospheric pressure in the air pocket, and longer-period pressure oscillations due to pulsation of the air pocket.
Fluid Cavitation

- High frequency & high amplitude pressure pulses
- Material fatigue, pits, erosion
- Cavitation number

\[ \sigma = \frac{P_{atm} - P_{vapor}}{\rho U^2} \]
Damages Caused by Cavitation

Karum Dam, Iran

corrosion-doctors.org

Different mound heights

Different void ratio

Cavitation
Previous Work - Wave Impact

- **Incompressible without elasticity & cavitation**
  - Bagnold (1939) - experiment + 1D water piston compressing on an air cushion (water hammer)
  - Cooker & Peregrine (1990, 1992, 1996) - flip-through motion without trapped air, pressure impulse function
  - Peregrine & Kalliadasis (1996) - used filling flow model to model flip-through with trapped air

- **Compressible without elasticity & cavitation**
  - Topliss et al (1992) - use linearized model of a semicircular air pocket to find modes of acoustic oscillation
  - Peregrine & Thais (1996) - used filling flow model to model flip-through with trapped air where the filling fluid is a air-water mixture. Impact with significant compressibility effects do not fit the simple pressure-impulse model.
  - Zhang et al. (1996) - used 2D irrotational flow model to simulate trapping of an air pocket.
Previous Work - Slamming

- **Incompressible without elasticity**
  - Von Karman (1929) - 2D wedge, linear theory
  - Wagner (1932), Watanabe (1986), Howinson et al (1991) - included pressure due to jet spray

- **Compressible without elasticity**
  - Ogilvie (1963) and Skalak & Feit (1966)
    - Supersonic flow theory, F.S. beyond contact surface will not be disturbed
    - Pressure $\sim V$, predicted magnitude $> \text{experiment}$.
    - Air cushion decelerates flow $\Rightarrow$ reduces max pressure
    - Impact pressure increases when air could escape
  - Vehagan (1967), Johnson (1968), Lewison & Maclean (1968)
    - Lighter body decreases impact pressure due to faster deceleration

- **Compressible with elasticity**
  - Carcaterra & Ciappi (2000): acoustic model (no air pockets)
    - Hydroelastic effect plays important role in max. elastic force & wave-induced vibration (critical condition)
Previous Work - Slamming

- **Incompressible with elasticity**
  - Faltinsen (1999), Korobkin & Khabakhpasheva (1999), Kvaalsvold & Faltinsen (1995), Faltinsen (1997): used beam or mass-spring models
    - Hydroelasticity effects should be considered for deadrise angle < 5°.
  - Haugen (1999): used multiple beam model
    - Air-cushion effects may be important when there are several dominant natural periods of structural vibration.
  - Korobkin & Khabakhpasheva (2006): potential flow+beam model+normal mode method (Fourier decomposition of sinusoidal wave form)
    - Central impact, edge impact, impact with attached cavity
    - Blockage or added-mass effect due to elastic deflection of the beam is important b/c it leads to higher hydrodynamic loads than equivalent rigid beam
    - Duration of edge impact > duration of central impact => double increase of beam deflection & stresses for edge impact.
    - Cavity attached to the plate may be formed just before the hydrodynamic loads, and the resulting secondary reload on the structure can be comparable to the initial impact.
Wave Edge Impact

Central Impact

Attached Cavity

Korobkin & Khabakhpasheva (2006)
Green water and slamming (Faltinsen et al. 2004)

Water shipping on a FPSO (floating production storage and offloading) unit

Observed water evolution during bottom slamming - cavity deforms, moves, detaches, and collapses
Numerical Methodology

1. Multiphase Eulerian Fluid Solver

\[
\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} + \frac{\partial G(U)}{\partial y} = 0
\]

\[p = p(e, \rho)\]

\[\rho = \alpha \rho_g + (1 - \alpha) \rho_l\]

**EOS for Gas, Water and Solid**

\[\rho e = \frac{p}{\gamma_g - 1} \quad \rightarrow \text{Gas}\]

\[p = p_0 + (\rho - \rho_0)c_f^2\]

\[\rho e = \frac{p}{\gamma_l - 1} + \frac{\gamma_l(B - A)}{\gamma_l - 1} \quad \rightarrow \text{Weakly compressible Liquid}\]

\[\rho e = \frac{p}{\gamma_s - 1} + \frac{\gamma_s(B_s - A_s)}{\gamma_s - 1} \quad \rightarrow \text{Tait EOS for Solid}\]
Numerical Methodology

One-fluid cavitation model

\[
a = \left[ \alpha \rho_g + (1 - \alpha) \rho_l \right] \left[ \frac{\alpha}{\rho_g a_g^2} + \frac{(1 - \alpha)}{\rho_l a_l^2} \right]^{-1/2}
\]

\[
dp/d\rho = a^2
\]

1. **Isentropic model**

\[
\frac{\alpha}{1 - \alpha} = \frac{K}{1} \left( \frac{p}{p_{cav}} \right)^{1/\gamma_i} \left( \frac{p}{p_{cav}} \right)^{1/\gamma_g}
\]

\[
\rho = K \rho_g^{cav} + \rho_l^{cav}
\]

- Isentropic model considers the cavitation mixture is fully compressible and is derived based on gas EOS and fully compressible flow EOS.

2. **Isothermal model**

\[
\frac{\alpha}{1 - \alpha} = \frac{K}{1} \left( \frac{p}{p_{cav}} \right)^{1/\gamma_g}
\]

\[
\rho = K \rho_g^{cav} + \rho_l^{cav}
\]

- Isothermal model considers the cavitation mixture is weakly compressible and is derived based on gas EOS and weakly compressible flow EOS.
Numerical Methodology

2. Lagrangian Solid Solver

General continuum solid model

\[ \rho \ddot{\delta}_i = \sigma_{ij,j} + f_i \]

\[ \sigma_{ij} = c_{ijkl} \varepsilon_{kl} \]

\[ \varepsilon_{kl} \equiv \frac{\delta_{i,j} + \delta_{j,i}}{2} \]

3. Fully FSI Coupling

(1) Eulerian-Eulerian Approach

\[ \frac{dp_I}{dt} + \rho_{IL} c_{IL} \frac{du_I}{dt} = 0 \]

along \[ \frac{dx}{dt} = u_I + c_{IL} \]

\[ \frac{dp_I}{dt} - \rho_{IR} c_{IR} \frac{du_I}{dt} = 0 \]

along \[ \frac{dx}{dt} = u_I - c_{IR} \]

(2) Eulerian-Lagrangian Approach

\[ \frac{dp_I}{dt} + \rho_{IL} c_{IL} \frac{du_I}{dt} = 0 \]

along \[ \frac{dx}{dt} = u_I + c_{IL} \]

\[ \rho \ddot{\delta} = \sigma_{,x} + f \]

\[ \sigma = E \delta_{,x} \]

\[ \delta_i = p_I - p_{atm} \]
1D Validations

Case 1: Water-hammer
Case 1a: Upstream cavitating flow

\[ L = 200 \text{m} \quad p_{us} = 5.49164 \text{ bar} \]
\[ u = 1.5 \text{ m/s} \quad p_{ds} = 0.98165 \text{ bar} \]

Experiment from Sanada (1990)

Fig. 2 The pressure histories for upstream cavitating flow.
1D Validations

Case 1b Midstream cavitating flow

\[ L = 200m \]
\[ u = 1.5 \text{m/s} \]
\[ p_{ds} = 0.98165 \text{bar} \]
\[ p_{us} = 5.49164 \text{ bar} \]

Experiment from Sanada (1990)
(b) Midstream type

Fig. 3 The pressure histories for midstream cavitating flow.
1D Validations

Case 1c Downstream cavitating flow

\[ L = 200 \text{m} \]
\[ u = 1.5 \text{m/s} \]
\[ p_{us} = 4.90235 \text{ bar} \]
\[ p_{ds} = 0.98165 \text{bar} \]

Experiment by Sanada (1990)

(c) Downstream type

Fig. 4 The pressure histories for downstream cavitating flow.
1D Validations

High-velocity fluid impact

\[ u_0 = 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 \text{(m/s)} \]

\[ L = 10 \text{m} \]

The pressure pulse caused by cavitation collapse drops when the fluid velocity is high due to the high local pressure.

\[ \frac{p_c - p_{ic}}{p_c} = 2.0\% \quad \text{for} \quad u_0 = 5 \text{(m/s)} \]

\[ \frac{p_c - p_{ic}}{p_c} = 6.6\% \quad \text{for} \quad u_0 = 50 \text{(m/s)} \]

where subscripts “c” “ic” mean compressible and incompressible.

Fig. 5 The maximum pressure at solid boundary caused by high-speed fluid impact and cavitation collapse.
2D Applications

- Toroidal collapse of cavitation bubble
- Two tiny bubbles are created

QuickTime™ and a BMP decompressor are needed to see this picture.

Cavitation collapse and associated pressure distributions
2D Applications

Fig. 10. Pressure contours and velocity vectors for bubble collapse near an aluminium boundary:

- Wave propagation within structure
- High-velocity impact on the structure
2D Applications

Fig. 11. Fluid pressure contours (lines) and normalized deviator stress contours (flood) for the aluminium boundary

- Solid experiences yield deformation
- Cavitation bubble firstly prevents wave load, then induces a strong pressure load
Summary & Conclusions

- The effect of gas and vapor bubbles cannot be ignored in the initial stage of impact:
  - Lengthens the duration of load
  - Reduces initial impact load due to air cushion effects
  - Increases pressure loading due to adiabatic compression of air pocket.
  - Introduces multiple reloading and oscillations due to cavitation collapses
  - The problem is particularly severe near corners, cracks, or joints
  - Can lead to local structural failures (yielding, fatigue, cracking, buckling) due to propagation of compressive and tensile shock waves
Summary & Conclusions

• Incompressible assumption and Froude scaling of model test are not valid in the initial stage of impact with entrained air or cavity

• In addition to the shock load and cavitation reload, partial and complete submersion of structure can lead to reduced natural frequency (more susceptible to resonant vibration) and increase in hydrodynamic force due to hydroelastic effects
  – Added mass and hydrodynamic damping
  – Load-dependent frequencies
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Effect of Air Pocket

Bridge Segment Dimensions Robertson et al (2007)

- **Hydrostatic uplift** = buoyancy due to submersion in salt water + compression of air pocket
- **Hydrodynamic uplift** = dynamic compression of air pocket + wave impact
Dynamic Compression of Air Pocket

High speed flow ▶ gas

computational diagram

► When the air pocket is compressed to same length for different fluid velocity, the wall pressure is close, but it takes more time for cases with lower velocity to reach such pressure.

► With higher initial fluid velocity, the air pocket can be compressed to smaller length.

Fig. 7 The wall pressure with time progresses and $u=5 \text{m/s}$ (left); the wall pressure with the length of air pocket and different velocity.
Numerical Methodology

Fig. 1a. Eulerian-Eulerian coupling

- Eulerian-Eulerian coupling defines ghost fluids for two fluids.
- Eulerian-Lagrangian coupling defines ghost fluids for one fluid.

Fig. 1b. Eulerian-Lagrangian coupling
2D Applications

**Shock waves:**

\[ p = p_{\text{max}} \left( \frac{t}{t_{\text{decay}}} \right) \]

\( p_{\text{max}} = 20000 \text{bar}, \quad t_{\text{decay}} = 0.4 \text{ms}; \)

**Gas bubble:**

\( \rho_g = 1.0 \text{kg/m}^3 \quad p_g = 1.0 \text{bar} \quad \gamma_g = 1.4 \)

\( u_g = 0.0 \text{m/s} \quad v_g = 0.0 \text{m/s} \)

**Water:**

\( \rho_l = 1000.0 \text{kg/m}^3 \quad p_l = 1.0 \text{bar} \)

\( u_l = 0.0 \text{m/s} \quad v_l = 0.0 \text{m/s} \quad \gamma_l = 7.0 \)

**Solid:**

\( \rho_s = 2700.0 \text{kg/m}^3 \quad p_s = 1.0 \text{bar} \)

\( u_s = 0.0 \text{m/s} \quad v_s = 0.0 \text{m/s} \)

Fig. 8 Schematic diagram for computations
2D Applications

Fig. 9. Pressure contours and velocity vectors for bubble collapse near a rigid boundary:

- Air cushion effect of the cavitation bubble can be observed
- High pressure pulse created by cavitation collapse
Physical Evidence of Cavitation?

Jantang, Sumatra (Higman)  
Karum Dam, Iran (?)