Underwater Bomb Trajectory Prediction for Stand-off Assault Breaching Weapon Fuse Improvement (SOABWFI)

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**Future Assault Breaching System Operational Scenario**

1. **Surveillance.** Satellites, UUV’s and UAV’s identify mines, obstacles, and collect METOC data.

2. **Mission Planning.** MEDAL/JMPS plan routes and incorporate intel data from recon units. Crews rehearse mission.

3. **Breaching Operation.** JABS/CMS precision guided munitions clear mines and obstacles in water and on the beach.

4. **Assault Force Deployment.** EFV/AAV’s launch from well deck and acquire routes to beach.

5. **Inland Objective.** Assault force moves past beach toward inland objective.

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**CoBRA** – Coastal Battlefield Reconnaissance and Analysis  
**JABS** – Joint Direct Attack Munition (JDAM) Assault Breaching System  
**CMS** – Countermine System (darts)  
**MEDAL** – Mine Warfare and Environmental Decision Aids Library  
**JMPS** – Joint Mission Planning System  
**DAGR** – Defense Advanced GPS Receiver  
**BFT** – Blue Force Tracker  
**EPLRS** – Enhanced Position Location Reporting System
Joint Direct Attack Munition (JDAM) Assault Breaching System (JABS)

- Current capability to clear SZ/BZ mines and light obstacles on the beach
- USN and/or USAF Delivered, Signed MOA between USN & USAF for Assault Breaching Munitions Delivery
  - B1, B2, B52, F/A18, JSF
- New mission for an existing weapon system

We know JABS performs well to water depths of 10 ft. Can it go deeper?
Successful breaching in beaches/surf zones by Joint Direct Attack Munition (JDAM) Assault Breaching System (JABS) (from Almqist 2006)
Mission Execution CONOPS

- Transfer Alignment
- Maintain Ready Condition
- Cockpit Displays
  - Launch Acceptable Region
- Load Mission Data
- Load Munition
  - Load Mission Data on Aircraft
- Release
  - Activate Thermal Battery
  - Release/Eject Air Vehicle
  - Safe Separation
- Return
  - UUV to search, classify, and map mine field
- Plan Mission
- Memory Unit

No Change to JDAM Mission Execution
Mine Neutralization by MK84/JDAM

Objective

- Investigate lethality of precision guided bombs against mines in 10-40 ft water depths (VSW).
- Investigate bomb stability after water impact, lethal radius, and optimum detonation depth for fuse design.
Sub-Scale Model Test Objectives

• Use 1/12-scale tests to measure Mk84 bomb trajectory to a shallow water full-scale depth of 160 ft and for a 90 degree water entry angle.

• Evaluate stability performance associated with current USN Ogive, USN MXU-735, and USAF noses and conceptual 25% and 50% blunt nose designs.

• Evaluate trajectory performance for possible tactical water entry angles of 65 and 77 degrees and determine how possible fin or tail section removal during water entry or tail slap within cavity influences trajectory behavior.
Mk84 Bomb Full-Scale Features
(With USN Ogive Nose)
Current Mk84 Bomb Nose Features

- USN Ogive Nose
- USAF Nose
- USN MXU-735 Nose
Conceptual Mk84 Nose Designs

50% Blunt Nose

25% Blunt Nose
Trajectory Scaling

Laminar Flow
- $FS = <0.007 \text{ ft/s}$
- $1/12 = <0.09 \text{ ft/s}$
- Drag coefficient error can be large
- $95\%$ of motion
- Kinematic viscosity is main value that does not scale

Turbulent Flow
- $FS = >2.2 \text{ ft/s}$
- $1/12 = >25.6 \text{ ft/s}$
- Drag coefficient error is small

Flow Around Circular Disk

Drag coefficient, $C_D$

Reynolds number, $\frac{\rho V_d D}{\mu}$
High-Fidelity 1/12-Scale Mk84 Scale Model - 4 Fins

<table>
<thead>
<tr>
<th>Mk84 Bomb</th>
<th>Length (in.)</th>
<th>Weight (lb)</th>
<th>Center of Gravity (in.)</th>
<th>Radius of Gyration (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CGx</td>
<td>CGy</td>
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<tr>
<td>Full Scale</td>
<td>150.51</td>
<td>2076.64</td>
<td>63.12</td>
<td>0.130</td>
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<tr>
<td>True 1/12 Scale</td>
<td>12.54</td>
<td>1.202</td>
<td>5.260</td>
<td>0.010</td>
</tr>
<tr>
<td>As-Built 1/12 Scale</td>
<td>12.54</td>
<td>1.201</td>
<td>5.362</td>
<td>0.000</td>
</tr>
<tr>
<td>% Error</td>
<td>0.0</td>
<td>-0.1</td>
<td>0.2</td>
<td>–</td>
</tr>
</tbody>
</table>

Due to neglecting casing lugs and strakes

Neglected because the bomb does not rotate about x-axis
High-Fidelity 1/12-Scale Mk84 Scale Model - 4 Fins

- Al 7075-T6 Body and Tail
- Copper Weight
- Epoxy Filler

12.54" long

Ø1.50"
Tests With Simulated Fin or Tail Removal

Models represent possible different damage scenarios due to excessive loads during water entry or tail slap within cavitaded region.
Sabot Design

Low-Density Foam

Aluminum Crushable Sabot
**SRI Test Arrangement**

- 4” dia. Gas Gun
- 2 Phantom 7 Cameras (10,000 fps) in Periscope
- 30-ft-dia. by 20-ft-deep Water Shock Pool
- Underwater Lights
1/12th Scaled Model Test Results

- Tail With Four Fins
- Tail With Two Fins
- Tail With No Fins
- No Tail

VSWZ Depth
6-FOF Bomb Trajectory Model

- Dynamic Fluid Model
- Dynamic Bubble Model
- Core Physics Bomb Trajectory Model
- Drag & Lift Forces/Torques

$C_d, C_l, C_m$
There is no existing formulae for calculating $C_d \ C_l \ C_m$ for MK-84 Bomb.
Dynamical Determination of Drag/Lift Coefficients

\[ \beta \gamma = - \frac{e}{2} \]

\[ \beta \rightarrow \text{bomb elevation angle} \]
\[ \gamma \rightarrow \text{bomb velocity angle} \]
\[ \alpha \rightarrow \text{attack angle} \]
Definitions of \((C_d\ C_l\ C_m)\)

\[f_{\text{drag}} = \frac{1}{2} C_d \rho A_w V^2\]
\[f_{\text{lift}} = \frac{1}{2} C_l \rho A_w V^2\]
\[M_{\text{trav}} = \frac{1}{2} C_m \rho \Pi_w V^2\]

\(\Pi_w \rightarrow \text{Underwater volume}\)

\(A_w \rightarrow \text{Underwater area}\)
Theoretical Base

\[ m \frac{d\mathbf{V}}{dt} = \left( \rho \Pi - m \right) g \mathbf{k} + f_{\text{drag}} \mathbf{e}_d + f_{\text{lift}} \mathbf{e}_l \]

\[ \mathbf{I} \cdot \frac{d\Omega}{dt} = \mathbf{r}_v \times \mathbf{f}_b + \mathbf{r}_f \times \left( f_{\text{drag}} + f_{\text{lift}} \right) + \mathbf{M}_r \]

Here, \( \mathbf{V} \) is the translation velocity of COM, \( \Omega \) is the angular velocity.
Determination of $C_d$, $C_l$, $C_m$ from Experimental Data

\[ C_d = \frac{(\rho \Pi - m) \mathbf{g} \cdot \mathbf{e}_d - m \mathbf{v} \cdot \mathbf{e}_d}{\frac{1}{2} \rho DLV^2} \]

\[ C_l = \frac{(\rho \Pi - m) \mathbf{g} \cdot \mathbf{e}_l - m \mathbf{v} \cdot \mathbf{e}_l}{\frac{1}{2} \rho DLV^2} \]

\[ C_m = \frac{\mathbf{J} \cdot \frac{d\Omega}{dt} \cdot \mathbf{e}_m^h + \sigma \rho \Pi g (\mathbf{e} \times \mathbf{k}) \cdot \mathbf{e}_m^h - \frac{n}{2} \sigma_f (\mathbf{e} \times \mathbf{F}_r^f) \cdot \mathbf{e}_m^h}{\frac{1}{2} \rho A_w L_w \mathbf{v}^2} \]

\[ + \frac{\sigma}{L_w} \left( C_d (\mathbf{e} \times \mathbf{e}_m^h) \cdot \mathbf{e}_m^h + C_l (\mathbf{e} \times \mathbf{e}_l) \cdot \mathbf{e}_m^h \right) \]
Separation of SRI Bomb Trajectory Data

• The total 15 trajectories are separated into two groups:

  • (1) 11 trajectories $\to (C_d \ C_l \ C_m)$ semi-empirical formulas

  • (2) 4 trajectories $\to$ model verification
Semi-Empirical Formulas for \((C_d \ C_l)\)

\[
C_d = 0.02 + 0.35 e^{-2(\alpha-\frac{\pi}{2})^2} \left( \frac{Re}{Re^*} \right)^{0.2} + 0.008 \Omega \sin \theta
\]

\[
\theta = \text{sign}(\pi - 2\alpha) \left( \pi^{2.2} - (\pi - |\pi - 2\alpha|)^{2.2} \right)^{\frac{1}{2.2}}
\]

\[
C_l = \begin{cases} 
0.35 \sin(\theta_1) \left( \frac{Re}{Re^*} \right)^{0.2} & \text{if } \alpha \leq \frac{\pi}{2} \\
0.1 \sin(\theta_2) - 0.015 \Omega \left( \frac{Re}{Re^*} \right)^2 \sin(\theta_2^{0.85}) & \text{if } \alpha > \frac{\pi}{2}
\end{cases}
\]

Where \(\theta_1 = \pi \left( \frac{2\alpha}{\pi} \right)^{1.8}\) and \(\theta_2 = 2\pi \left( \frac{2\alpha}{\pi} - 1 \right)^{0.7}\).

\(Re^* = 1.8 \times 10^7\)
Semi-Empirical Formulas for $C_m$

$$C_m = \begin{cases} 
0.07 \sin(2\alpha) \left( \frac{\text{Re}^*}{\text{Re}} \right)^{0.2} & \text{if } \alpha \leq \frac{\pi}{2} \\
0.02 \sin(2\alpha) \sqrt{\left( \frac{\text{Re}}{\text{Re}^*} \right)} & \text{if } \alpha > \frac{\pi}{2}
\end{cases}$$

$\text{Re}^* = 1.8 \times 10^7$
STRIKE35 and SRI Data Inter-Comparison
Test-13

Experiment test 13  time: 0.485s

Model  time: 0.485s
STRIKE35 and SRI Data Inter-Comparison
Test-13
STRIKE35 and SRI Data Inter-Comparison
Speed vs Time (Test-13)
STRIKE35 and SRI Data Inter-Comparison
Speed vs Depth (Test-13)
STRIKE35 and SRI Data Inter-Comparison
Test-14

Experiment test 14  time: 0.406s

Model  time: 0.406s
STRIKE35 and SRI Data Inter-Comparison
Test-14
STRIKE35 and SRI Data Inter-Comparison
Speed vs Time (Test-14)
STRIKE35 and SRI Data Inter-Comparison
Speed vs Depth (Test-14)
STRIKE35 and SRI Data Inter-Comparison
Test-15

Experiment test 15  time:0.233s

Model  time:0.233s
STRIKE35 and SRI Data Inter-Comparison Test-15
STRIKE35 and SRI Data Inter-Comparison
Speed vs Time (Test-15)
STRIKE35 and SRI Data Inter-Comparison
Speed vs Depth (Test-15)
Test pond at China Lake with JDAM near impact (25 ft deep)

Provided by Boeing/ATR Corp
Actual Trajectory

Extrapolated Trajectory

Surface

Bottom

\( \Delta \)
Avg surface impact error = 4.4 ft (4 shots)
Avg bottom impact error = 3.6 ft
Summary

• Small Distance Between Water Entry and Bottom Impact Points → Achieving Objective Requirement to Deliver MK-84 JDAM to a Depth of 40 ft

• 6-DOF Underwater Trajectory Model has been developed, and verified with Test Data, which could be used to facilitate transition to operational capability
Future Work

• Extending SOABWFI to deep water