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LAMP-OVERFLOW Coupling Approach for 3D Time-Accurate Water-Air Flow in Surface Effect Ship Design

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Revolutionary Research . . . Relevant Results

From Science to Solutions

Overview

- SES (Surface Effect Ship) and ACV (Air Cushion Vehicle) and their dynamics
- CFD simulation technology
- LAMP-OVERFLOW coupling approach for transient water-air two-phase flow around SES
  - LAMP for ship hydrodynamics
  - OVERFLOW for aerodynamics
- Dynamic characteristics of SES system
- Validations over U.S. government T-Craft
- Conclusion

SES and ACV

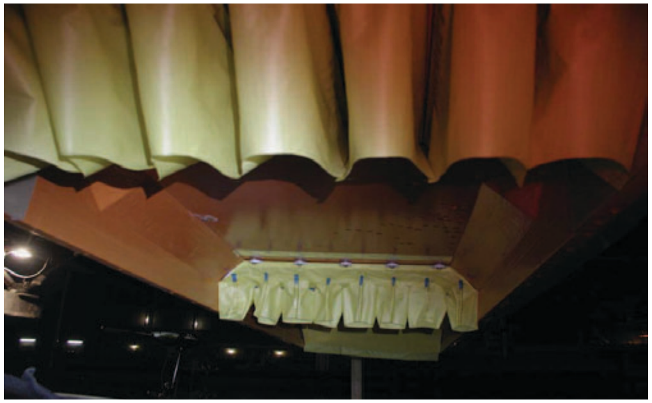
- SES and ACV in common having air chamber (cushion) between hull bottom (wet-deck) and water surface;
- SES encloses the air chamber with twin side hulls, bow and stern seals;
- ACV encloses the air chamber with seal skirts along hull perimeter;
- Pressurized air cushion lift more than 80% of the vehicle weight;
- The low draft reduces both wave and friction drag;
- Challenge is to solve 3D time-accurate water-air two-phase flow for the vehicle in sea environment;

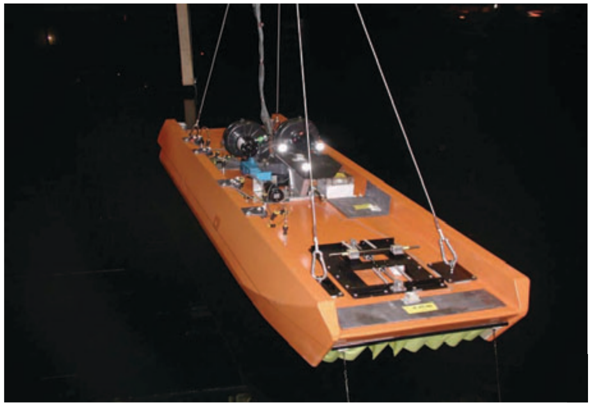
SES in service

ACV serving U.S. Navy

Significant Dynamic Phenomena in SES

- **Ship Hydrodynamics:**
  - Hydrostatic force and moment;
  - Hydrodynamic force and moment due to ship motions in calm water or sea condition;
- **Aerodynamics in the air cushion:**
  - Aerodynamic force and moment on the cushion boundaries;
- **Dynamics of water and air interface:**
  - Contact surface discontinuity
  - Air leakage from the air chamber to the ambient
- **Bow and stern seal dynamics:**
  - Bow and stern seal shape change and motion with respect to the hull;
- **Fan dynamics:**
  - Assuming fan always works on quasi-static fan curve, which determines air pressure and air flow rate.



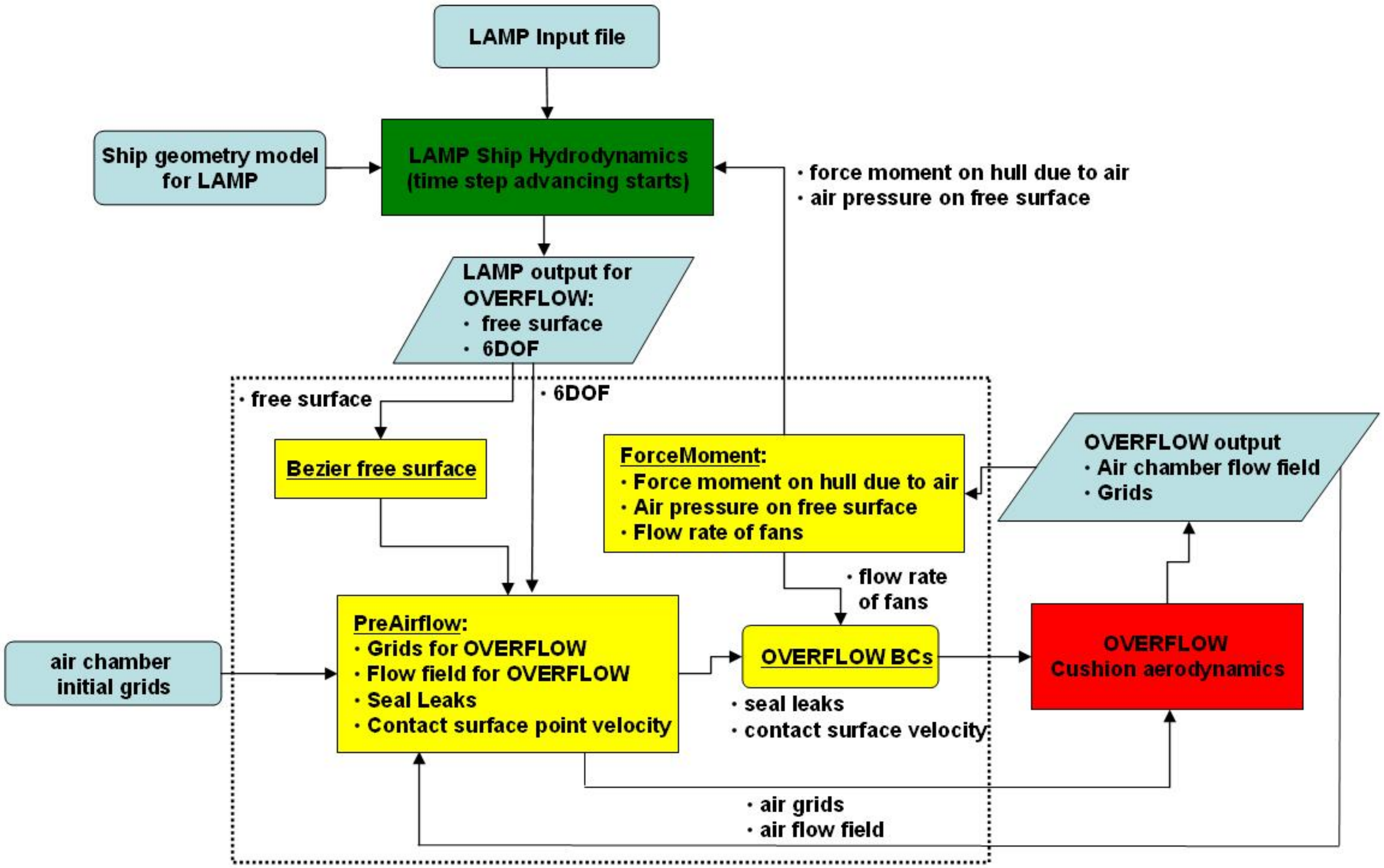


CFD Simulation Technology for SES and ACV

- **Existing ship hydrodynamics code coupled with lumped-parameter aerodynamics model:**
  - General ship hydrodynamics code to simulate ship flows in calm water and sea;
  - Air in air chamber is assumed to be a point mass and its properties are determined by isentropic process for ideal gas and mass conservation;
  - Negligence of non-uniform pressure in air chamber leads to at least two consequences:
    1) Effects of non-uniform pressure in air chamber on ship motions and water-air interface, which is believed to be prominent in full scale ship, can't be evaluated;
    2) Openings and locations of air pumps, which is important in design, become irrelevant.
- **Advanced ship flow codes based on interface capturing approach (level-set, VOF) for water-air two-phase flow:**
  - Technology is promising. There is on-going effort to push for practical applications.
- **Existing ship hydrodynamics code coupled with existing aerodynamics code:**
  - LAMP-OVERFLOW coupling;
  - Like solving any coupling dynamics problems, e.g., FSI, an interfacing code needs to be developed to pass necessary dynamic variables between the two codes and so achieve the coupling simulation.

LAMP-OVERFLOW Coupling Approach

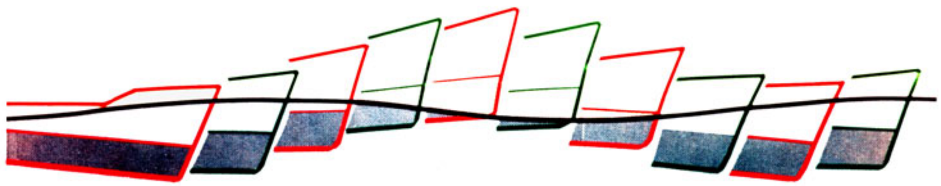
- LAMP to solve ship hydrodynamic flow in ocean waves;
- OVERFLOW to solve pressurized air flow in the air chamber.



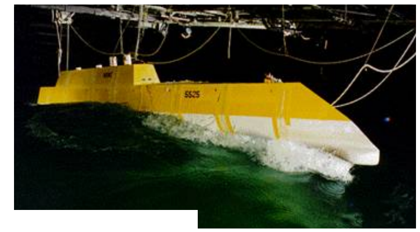
- **The dash-line box encloses the elements of the interfacing code to accomplish LAMP-OVERFLOW coupling**

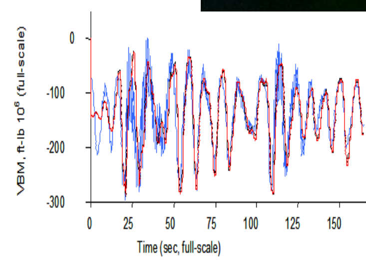
Ship Dynamics: Large Amplitude Motion Program

Time-domain solution of the motions and loads of a ship operating in a seaway

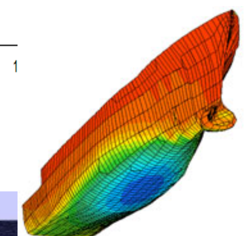


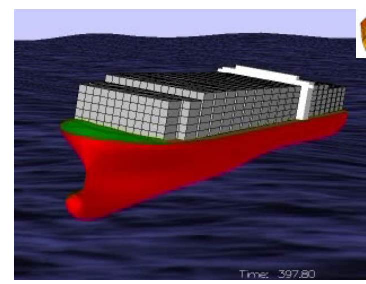
- 3-D solution of wave-body hydrodynamics using a potential flow panel method
- Multi-level: Body-linear or body-nonlinear hydrodynamics and/or hydrostatics / Froude Krylov wave forces
- 6-DOF equations of motions integrated in time-domain
- “Event driven” analysis predicting response to specific series of waves
- Originally developed for ships but general physics-based formulation suitable for a wide variety of marine vehicles
- Integrated models for green-water-on-deck, wetdeck slamming, viscous effects, motion control systems, appendages, and other external forces
- Main girder loads plus pressure interface to finite-element structural analysis
- Models for fenders, mooring lines, air cushion, etc.



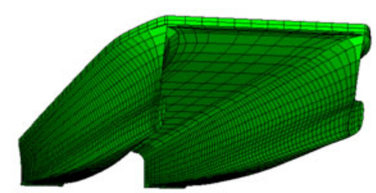


VBM for 5525 in Hurricane Seas





FE Load for CG-47



Mathematical Models to Achieve LAMP-OVERLFOW Coupling (1)

(1) Free surface representation using Bezier surface:

$$x(s,t) = \sum_{k=0}^{m}\sum_{l=0}^{n} B_k^m(s)\cdot B_l^n(t)\cdot \hat{X}_{k,l}$$

$$y(s,t) = \sum_{k=0}^{m}\sum_{l=0}^{n} B_k^m(s)\cdot B_l^n(t)\cdot \hat{Y}_{k,l}$$

$$z(s,t) = \sum_{k=0}^{m}\sum_{l=0}^{n} B_k^m(s)\cdot B_l^n(t)\cdot \hat{Z}_{k,l}$$

Bernstain polynomial:

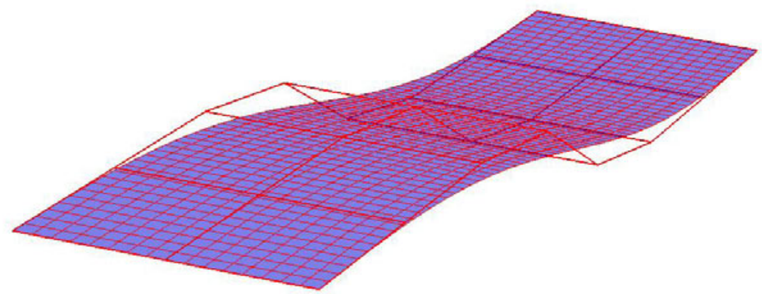
$$B_k^m(s) = \frac{m!}{k!(m-k)!}s^k(1-s)^{m-k}$$

- Mapping x(i,j) and y(i,j) into a unit square s(i,j) and t(i,j) by solving:

$$f_1(s,t) = \sum_{k=0}^{m}\sum_{l=0}^{n} B_k^m[s(i,j)]\cdot B_l^n[t(i,j)]\cdot \hat{X}_{k,l} - x(i,j) = 0$$

$$f_2(s,t) = \sum_{k=0}^{m}\sum_{l=0}^{n} B_k^m[s(i,j)]\cdot B_l^n[t(i,j)]\cdot \hat{Y}_{k,l} - y(i,j) = 0$$

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial s} & \frac{\partial f_1}{\partial t} \\ \frac{\partial f_2}{\partial s} & \frac{\partial f_2}{\partial t} \end{bmatrix} \qquad \begin{pmatrix} s \\ t \end{pmatrix}^{n+1} = \begin{pmatrix} s \\ t \end{pmatrix}^{n} - (A^{-1})^n \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}^{n}$$

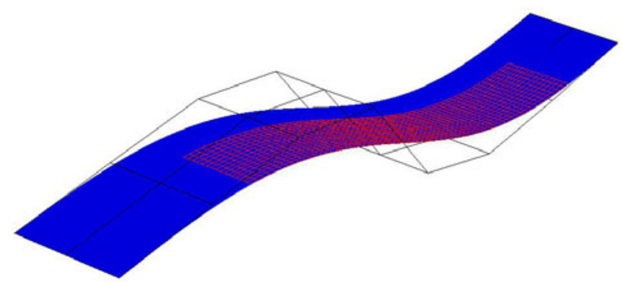


- Using least square method to find control points of $\hat{Z}_{k,l}$

$$\min: I = \sum_{i=1}^{i_{\max}}\sum_{j=1}^{j_{\max}}\left[\sum_{k=0}^{m}\sum_{l=0}^{n} B_k^m[s(i,j)]\cdot B_l^n[t(i,j)]\cdot \hat{Z}_{k,l} - z(i,j)\right]^2$$

$$\frac{\partial I}{\partial \hat{Z}_{k,l}} = 2\sum_{i=1}^{i_{\max}}\sum_{j=1}^{j_{\max}}\left\{\left[\sum_{k=0}^{m}\sum_{l=0}^{n} B_k^m[s(i,j)]\cdot B_l^n[t(i,j)]\cdot \hat{Z}_{k,l} - z(i,j)\right] B_k^m[s(i,j)]\cdot B_l^n[t(i,j)]\right\}$$

Let: $\frac{\partial I}{\partial \hat{Z}_{k,l}} = 0$ and solve for $\hat{Z}_{k,l}$



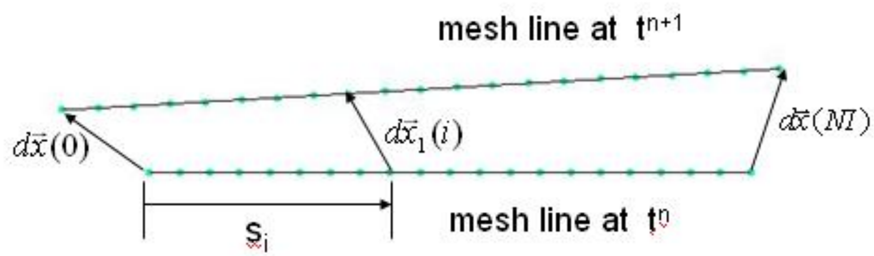
Revolutionary Research . . . Relevant Results

From Science to Solutions

Mathematical Models to Achieve LAMP-OVERLFOW Coupling (2)

(2) Dynamic grid generation using TFI :

$$s_{i,j,k} = \frac{\sum_{m=1}^{i} \left\| \vec{x}_{m,j,k} - \vec{x}_{m-1,j,k} \right\|}{\sum_{m=1}^{NI} \left\| \vec{x}_{m,j,k} - \vec{x}_{m-1,j,k} \right\|} \qquad t_{i,j,k} = \frac{\sum_{m=1}^{j} \left\| \vec{x}_{i,m,k} - \vec{x}_{i,m-1,k} \right\|}{\sum_{m=1}^{NJ} \left\| x_{i,m,k} - \vec{x}_{i,m-1,k} \right\|} \qquad w_{i,j,k} = \frac{\sum_{m=1}^{k} \left\| \vec{x}_{i,j,k} - \vec{x}_{i,j,m-1} \right\|}{\sum_{m=1}^{NK} \left\| x_{i,j,m} - \vec{x}_{i,j,k-1} \right\|}$$



$$d\vec{x}_1(i,j) = (1 - s_{i,j}) d\vec{x}(0,j) + s_{i,j} d\vec{x}(NI,j)$$

$$d\vec{x}_2(i,j) = d\vec{x}_1(i,j) + (1 - t_{i,j})[d\vec{x}(i,0) - d\vec{x}_1(i,0)] + t_{i,j} d\vec{x}(NI,j)[d\vec{x}(i,NJ) - d\vec{x}_1(i,NJ)]$$

$$d\vec{x}_3(i,j,k) - d\vec{x}_2(i,j,k) = (1 - w_{i,j,k})[d\vec{x}(i,j,0) - d\vec{x}_2(i,j,0)] + w_{i,j,k}[d\vec{x}(i,j,NK) - d\vec{x}_2(i,j,NK)]$$

Mathematical Models to Achieve LAMP-OVERLFOW Coupling (3)

(3) Flow field update :

$$q_{new}(\xi,\eta,\zeta) = q_{old}(\xi,\eta,\zeta) + d\vec{x}(\xi,\eta,\zeta)\cdot\nabla q_{old}(\xi,\eta,\zeta)$$

$$\nabla q = \begin{pmatrix} \dfrac{\partial q}{\partial x} \\ \dfrac{\partial q}{\partial y} \\ \dfrac{\partial q}{\partial z} \end{pmatrix} = \frac{1}{J}\begin{bmatrix} \dfrac{\partial x}{\partial \xi} & \dfrac{\partial x}{\partial \eta} & \dfrac{\partial x}{\partial \zeta} \\ \dfrac{\partial y}{\partial \xi} & \dfrac{\partial y}{\partial \eta} & \dfrac{\partial y}{\partial \zeta} \\ \dfrac{\partial z}{\partial \xi} & \dfrac{\partial z}{\partial \eta} & \dfrac{\partial z}{\partial \zeta} \end{bmatrix}\begin{pmatrix} \dfrac{\partial q}{\partial \xi} \\ \dfrac{\partial q}{\partial \eta} \\ \dfrac{\partial q}{\partial \zeta} \end{pmatrix}$$

Mathematical Models to Achieve LAMP-OVERLFOW Coupling (4)

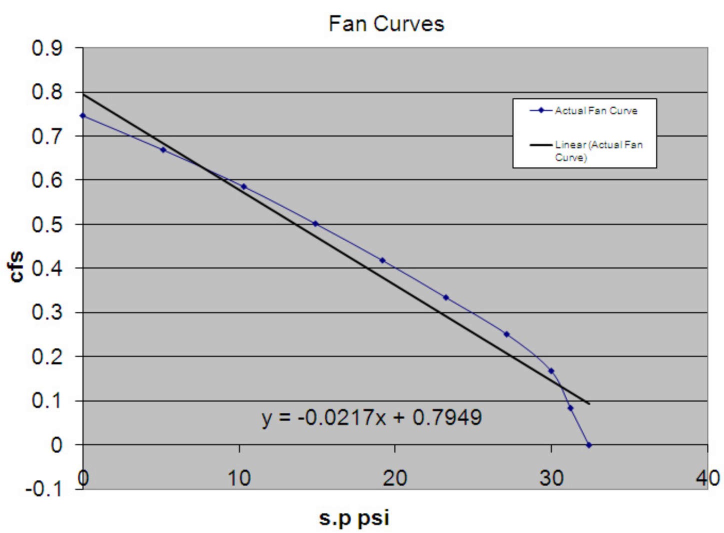
(4) Moving boundary velocity and contact surface discontinuity:

Impose $$v_n = \frac{d\vec{x}_{boundry}}{dt} \cdot \vec{n}$$ on wall and free surface for OVERFLOW

Free surface contact discontinuity is captured:

$$[v_n] = 0 \quad [p] = 0 \quad \text{but} \quad [\rho] \neq 0 \quad [v_t] \neq 0$$

(5) Fan dynamics:



Validations over U.S. Government T-Craft

T-Craft:

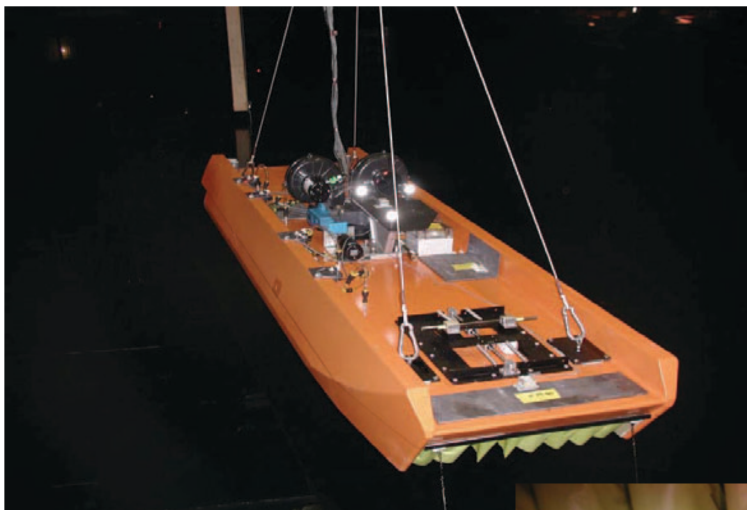
- L_m=99.5 inches
- Disp=121.2 lbs
- Speed > 7.3 knots

λ=30.209

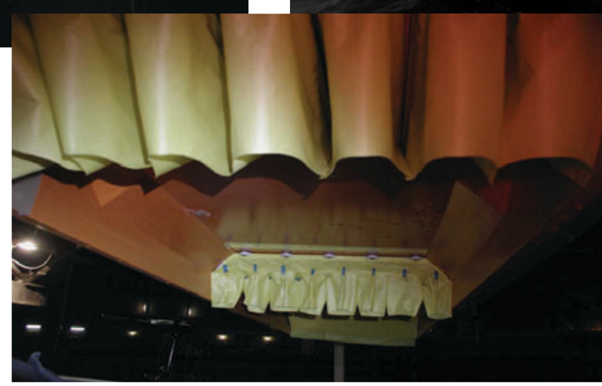
Full size Surface Effect Ship:

- L_s=250.5 feet
- Disp= 1,533.67 LT
- Speed > 40 knots

T-Craft model

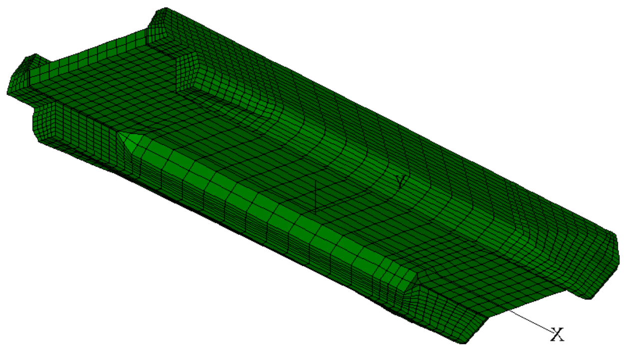


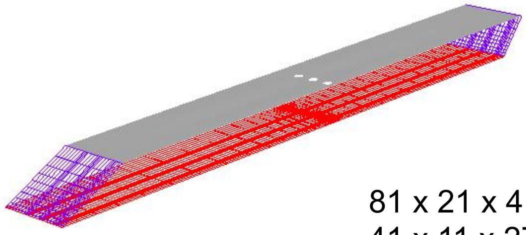
An Operational SES



T-Craft Hull and Air Chamber Combined Model for LAMP-OVERFLOW Coupling

stern

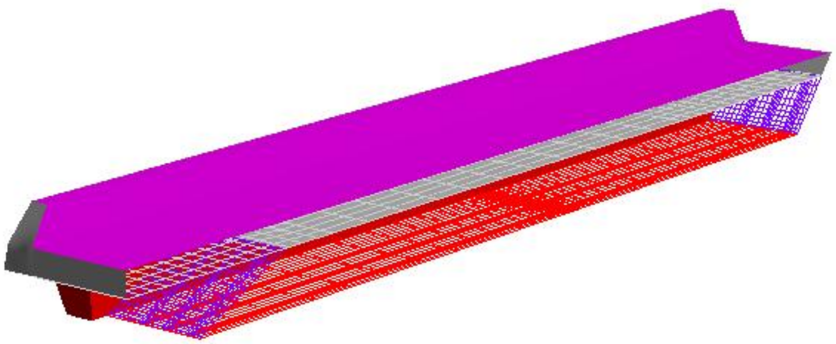




81 x 21 x 41 and
41 x 11 x 27

• T-Craft hull model for LAMP

• Air cushion model for OVERFLOW



bow

stern

• a combined model for LAMP-OVERFLOW coupling simulation

Revolutionary Research . . . Relevant Results

From Science to Solutions

Dynamic Characteristics of SES System

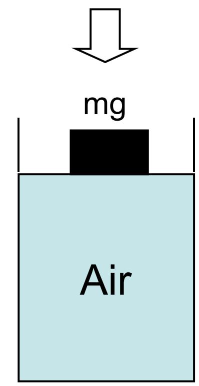
from Aerodynamics Perspective:

- Dynamic compression by hull weight on air cushion assuming no leakage

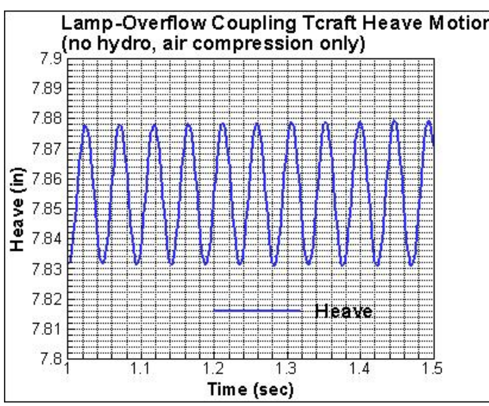
$$\frac{d(\rho\Lambda)}{dt}=0 \qquad \Lambda^{\gamma} p = c \qquad m\ddot{z} = F_{air} - mg$$

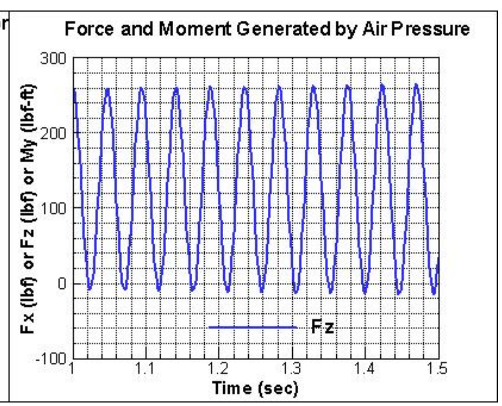
$$f_{n,air} = \frac{1}{2\pi}\sqrt{\gamma g\left(\frac{p_a}{p_{c,g}}+1\right)\frac{1}{z_c}} \qquad \Delta z = z_{initial}\left[1-\left(\frac{p_a}{p_{c,a}}\right)^{1/\gamma}\right]$$

- LAMP-OVERFLOW coupling accurately simulated the hull heave oscillations due to air pressure wave;
- simulation revealed pitch response to air pressure wave is not stable.



Modeled as an air spring





$Z_{initial}$=5.79”

	simulation	analytic
$T_{n,air}$ (sec)	0.04	0.04
Δz (inch)	0.023	0.020

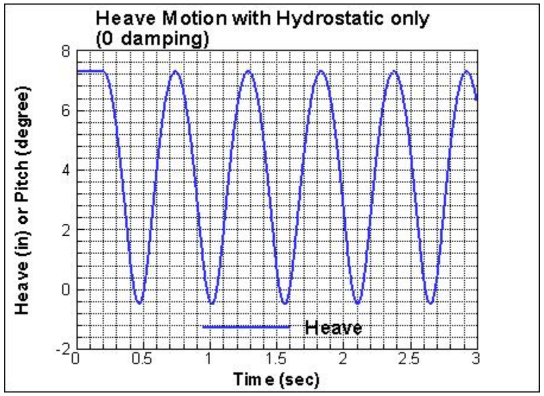
Dynamic Characteristics of SES System

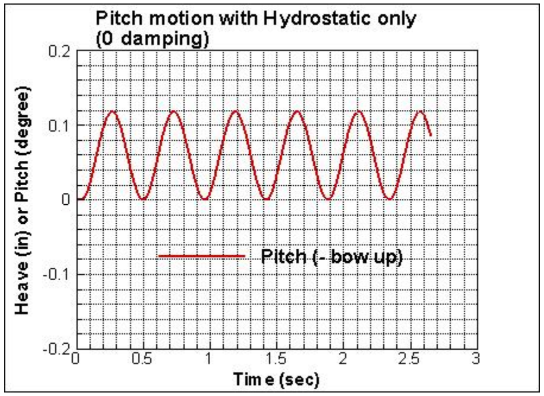
from Hydrodynamics Perspective:

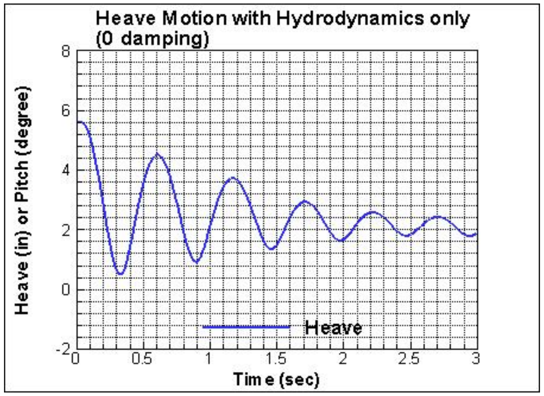
- Hydrodynamics by hull weight

$$f_{n,hydro} = \frac{1}{2\pi}\sqrt{\frac{\rho_w g A_w}{m}}$$

$T_{n,hydro}$=0.5 sec Δz = 3.8”







- Natural period and motion magnitude due to air compressibility is much smaller than those from hydrodynamics for model T-Craft, but they could be comparable for full size vehicle.

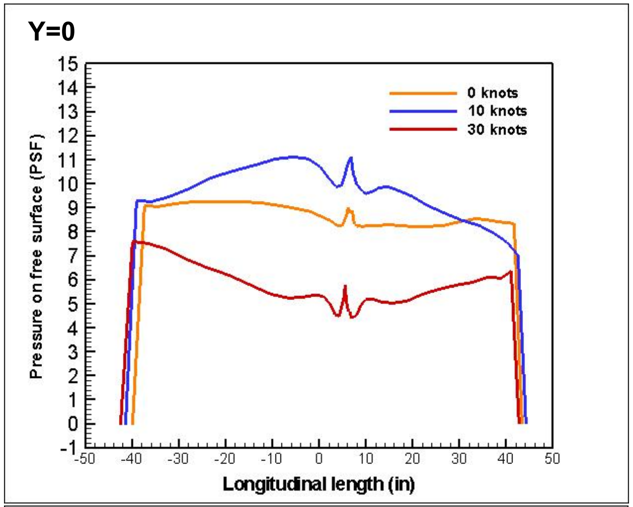
Revolutionary Research . . . Relevant Results

From Science to Solutions

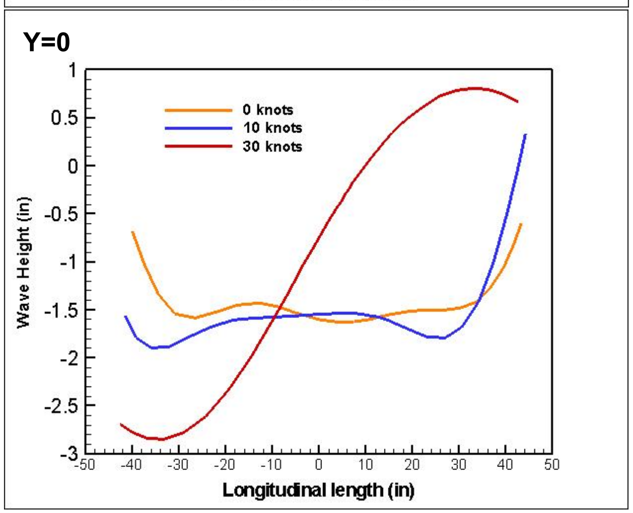
Simulation Results for T-Craft Running in Calm Water at 0, 10 and 30 Knots

- **Pressure variation in longitudinal direction is about 15 %**

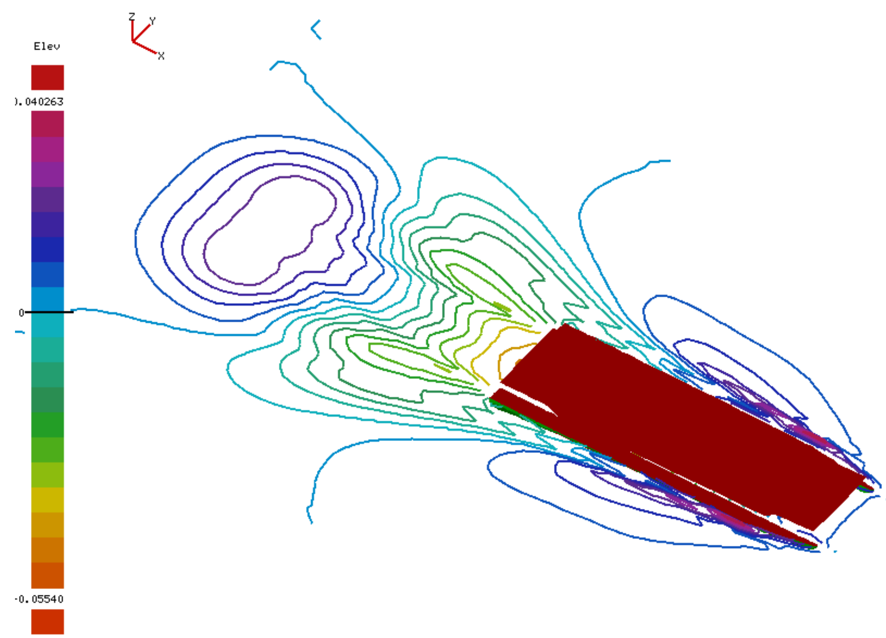
Air cushion pressure distribution on free surface



Free surface profile along air cushion center plane

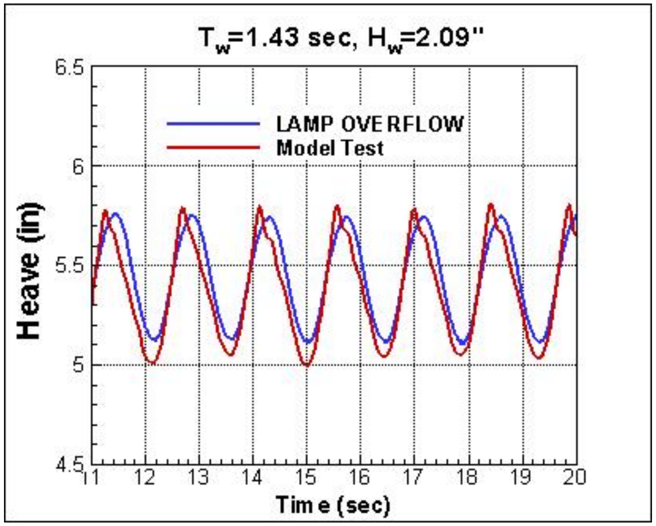


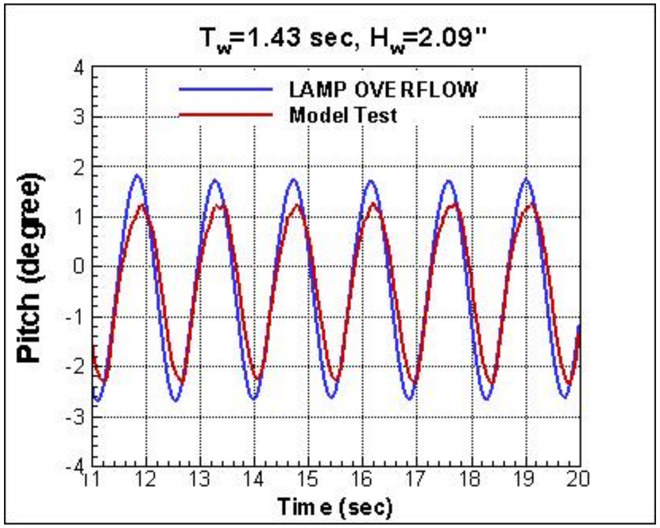
A Kelvin wave pattern of T-Craft at high speed predicted by LAMP:



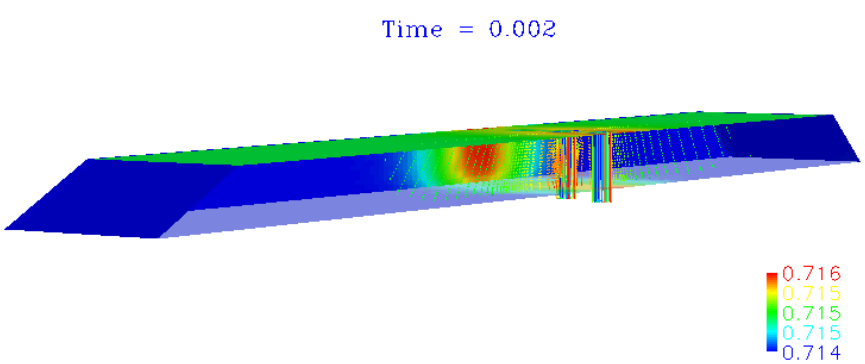
Validations for T-Craft in Regular Waves

CASE 1: run 64 (regular wave, T_w=1.43 sec, H_w=2.09” and 0 knots)



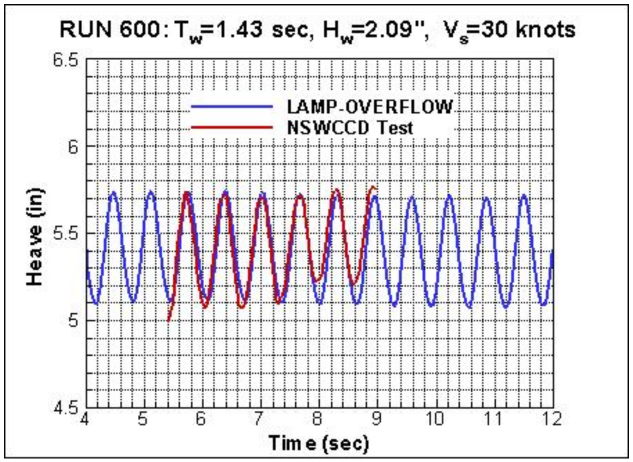


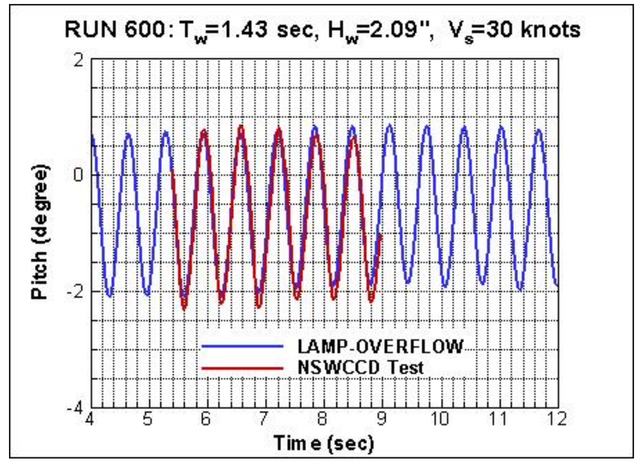
Air flow in cushion:



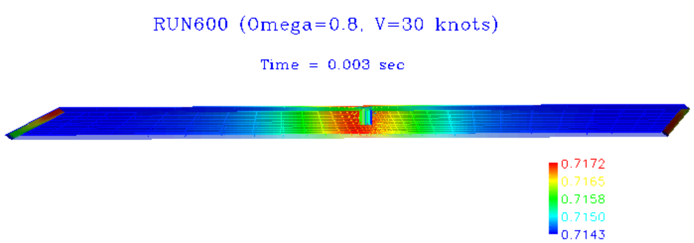
Validations for T-Craft in Regular Waves

CASE 2: run 600 (regular wave, T_w=1.43 sec, H_w=2.09" and 30 knots)

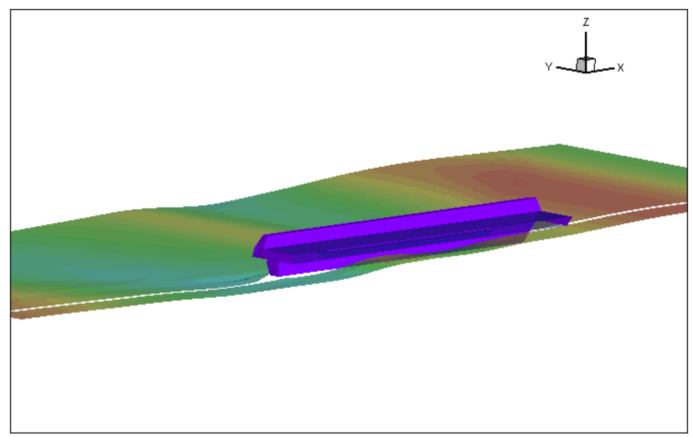




Air flow in cushion:



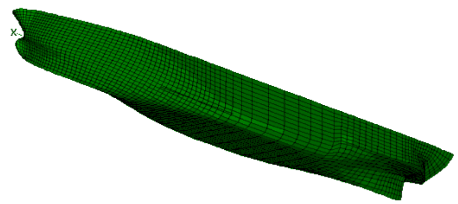
Free surface wave pattern:



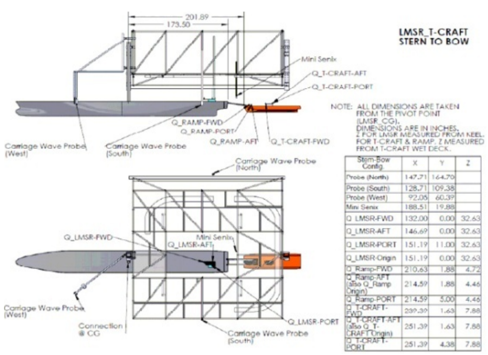
Revolutionary Research . . . Relevant Results

From Science to Solutions

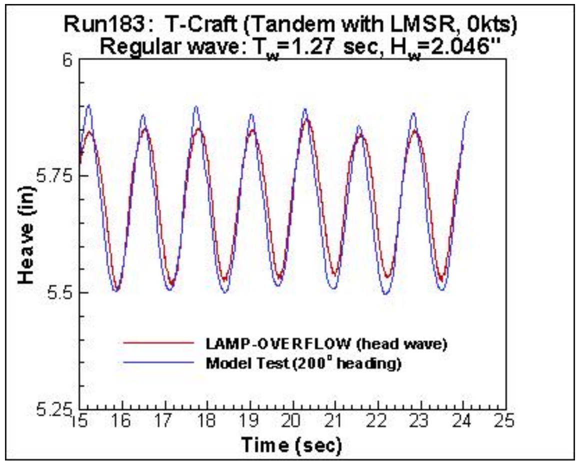
Validations for T-Craft in Tandem with LMSR in Regular Waves

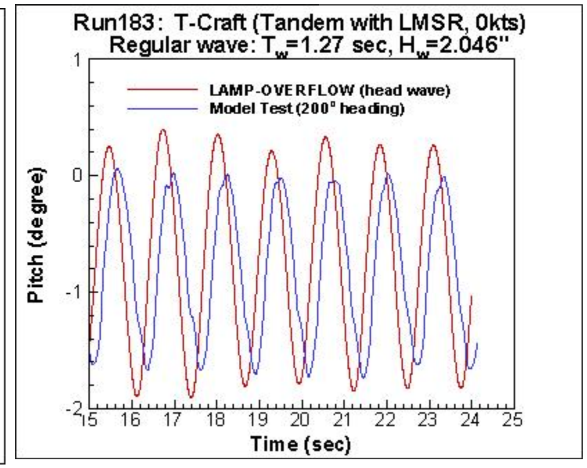


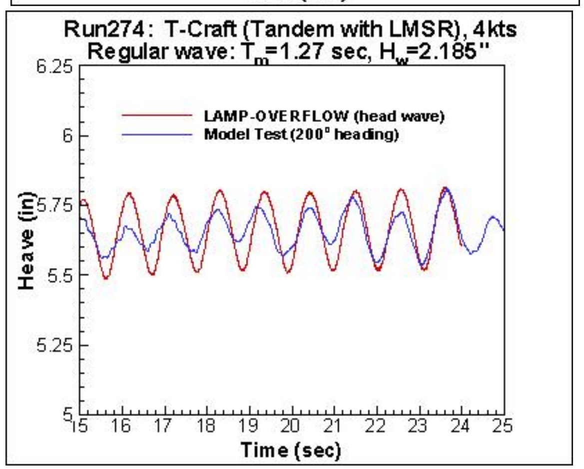
USNS Gordon LMSR model for LAMP

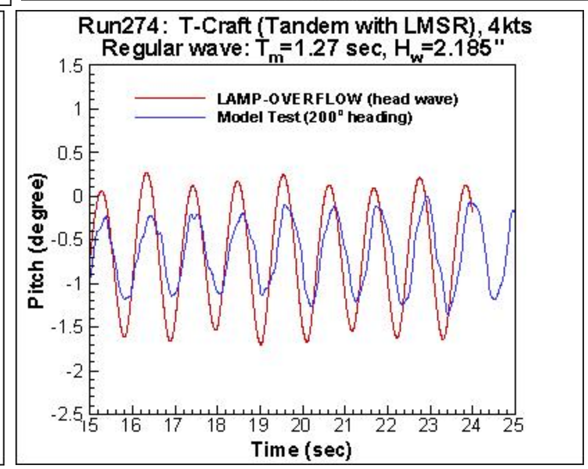


T-Craft in tandem with LMSR



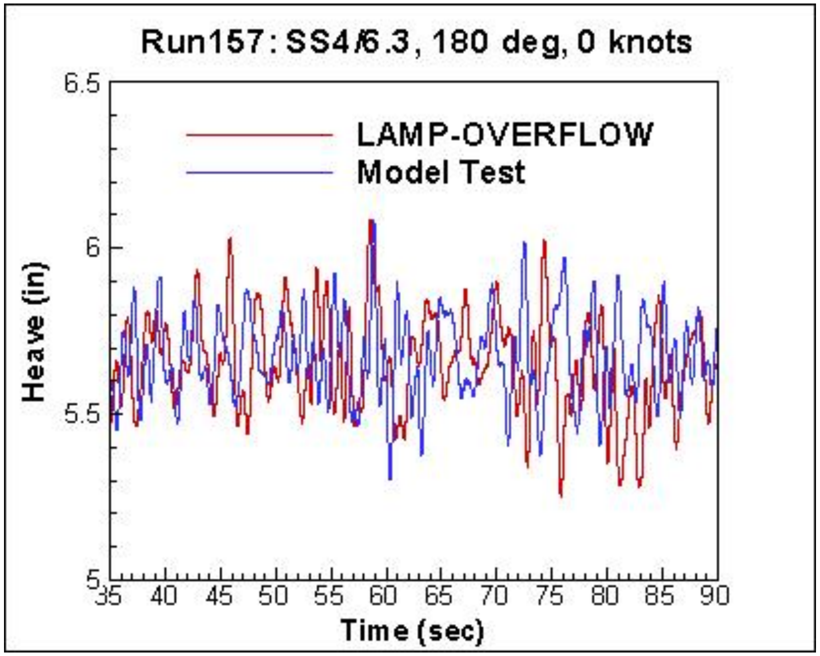


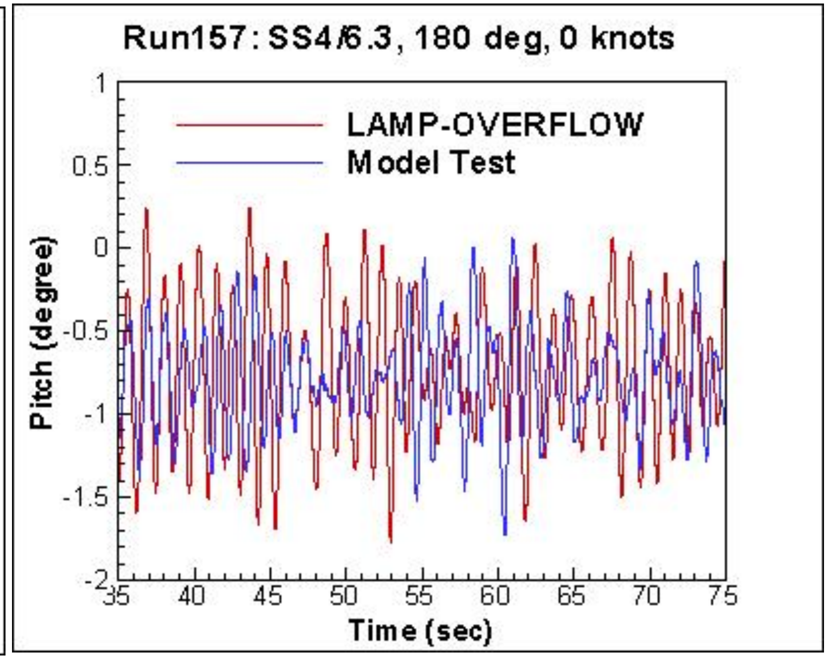




- model test results at wave heading of 200°;
- CFD simulation at wave heading of 180° (head sea).

Validations for T-Craft in Irregular Waves





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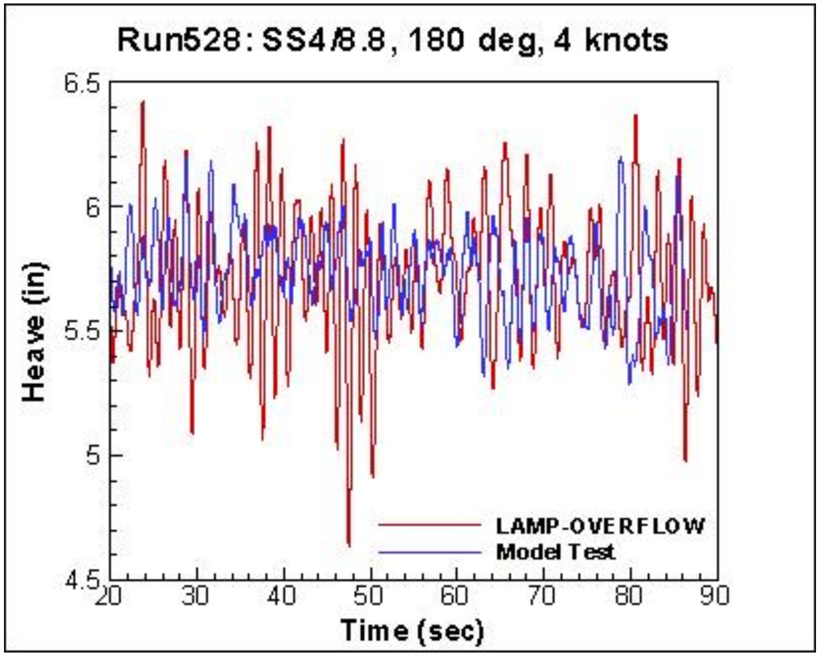

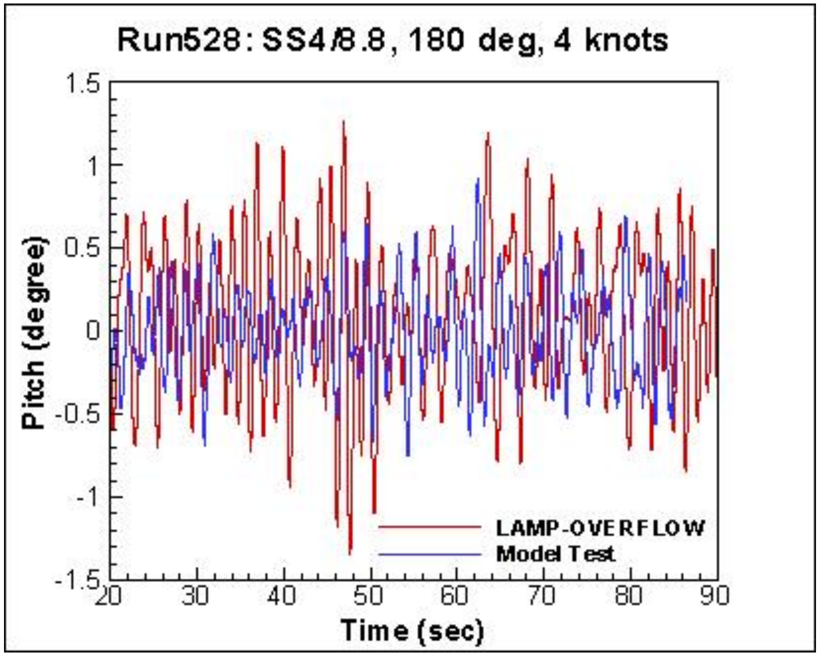

Conclusion

- A program using LAMP-OVERFLOW coupling to simulate water-air transient 3D flows for SES or ACV has been developed;
- The LAMP-OVERFLOW coupling approach enforces the water-air contact surface conditions to be satisfied;
- Preliminary validations showed the approach is very promising in predicting the motions of T-Craft;
- The program is ideal for studying the effects of air cushion compressibility and pressure spatial variations on the dynamic motions of SES or ACV, which is especially important for the full size vehicles;
- With one CPU, the computation time takes about 4 hrs for each simulation (15 sec of physics);
- More validations need to be carried out.

Acknowledgements

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Q&A