# Hydrodynamic Performance and Structure Response Prediction of Submarine via CFD/FEM

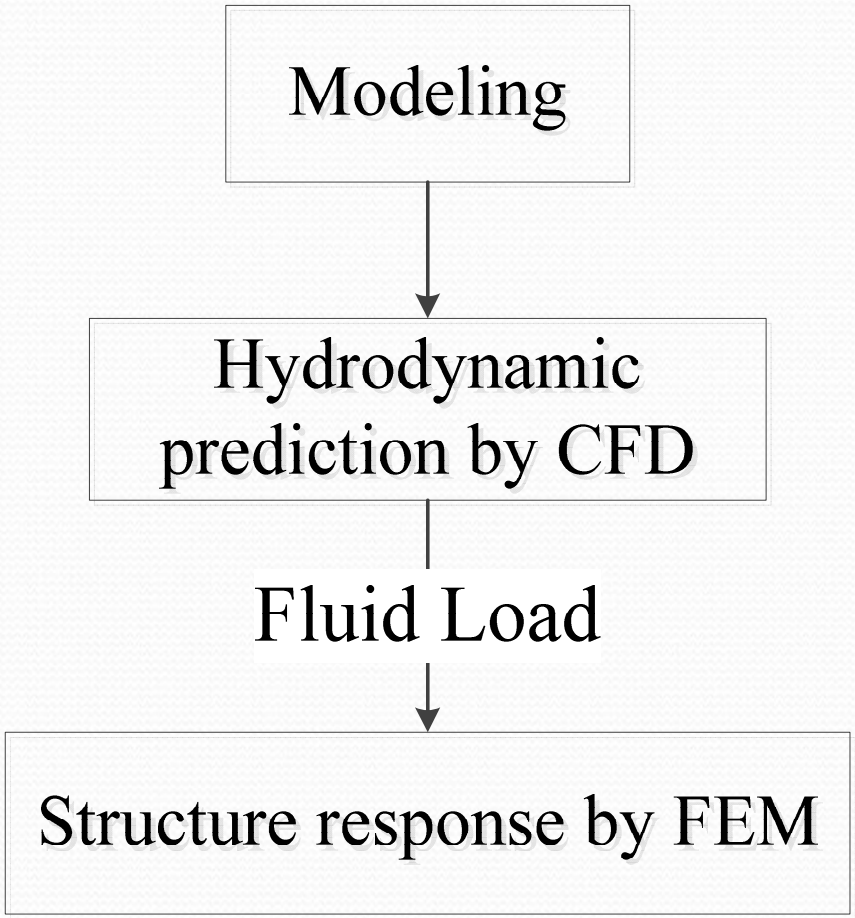
***Jing-wei Jiang***

(Naval Academy of Armament, Beijing, China)

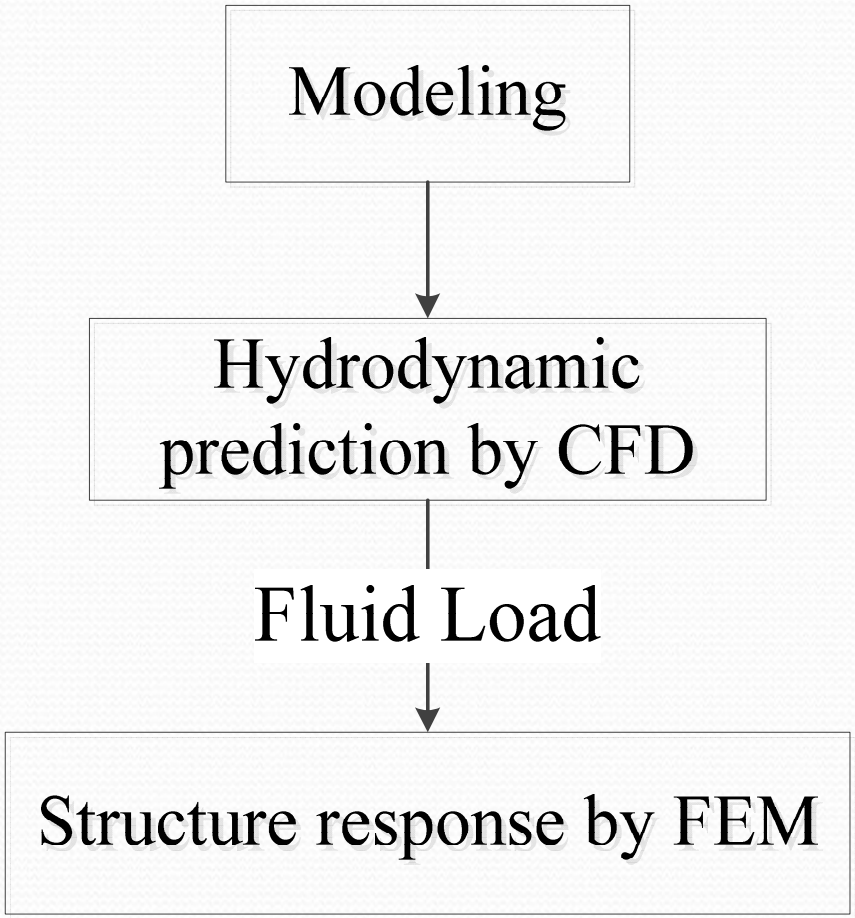
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- Introduction
- Theoretical Formulas
  - Computational Fluid Dynamic: Turbulence Model
  - Finite Element Method: Governing Equation
- Case study — SUBOFF
  - Pressure coefficient
  - Structure response
- Conclusion
- Further discussion

# *Part 1—INTRODUCTION*



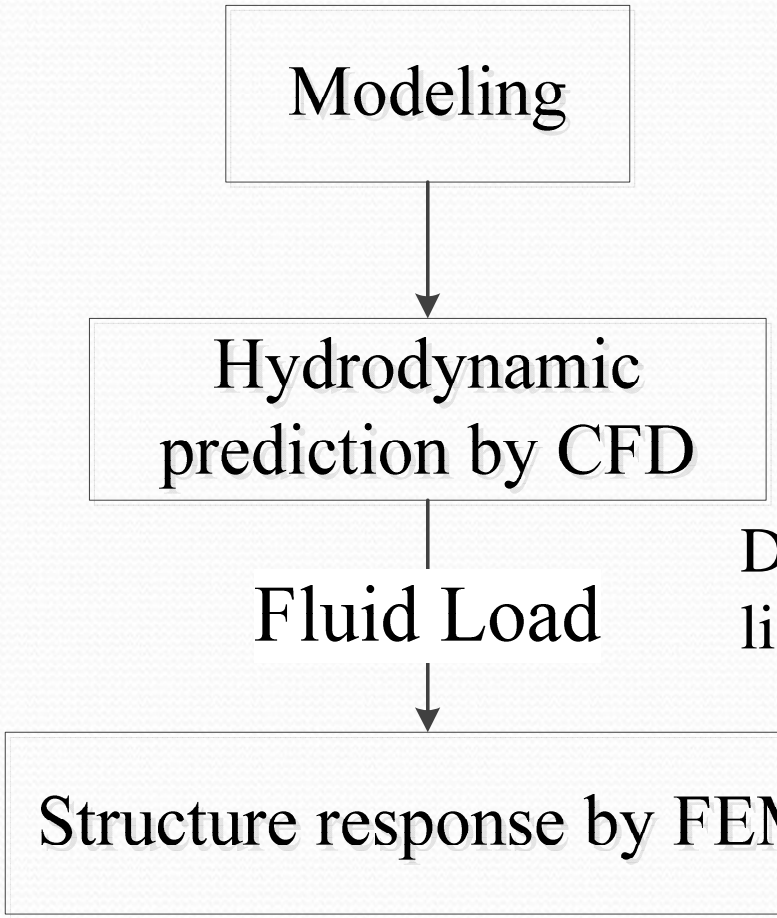
# *Part 1—INTRODUCTION*




***Comparison***

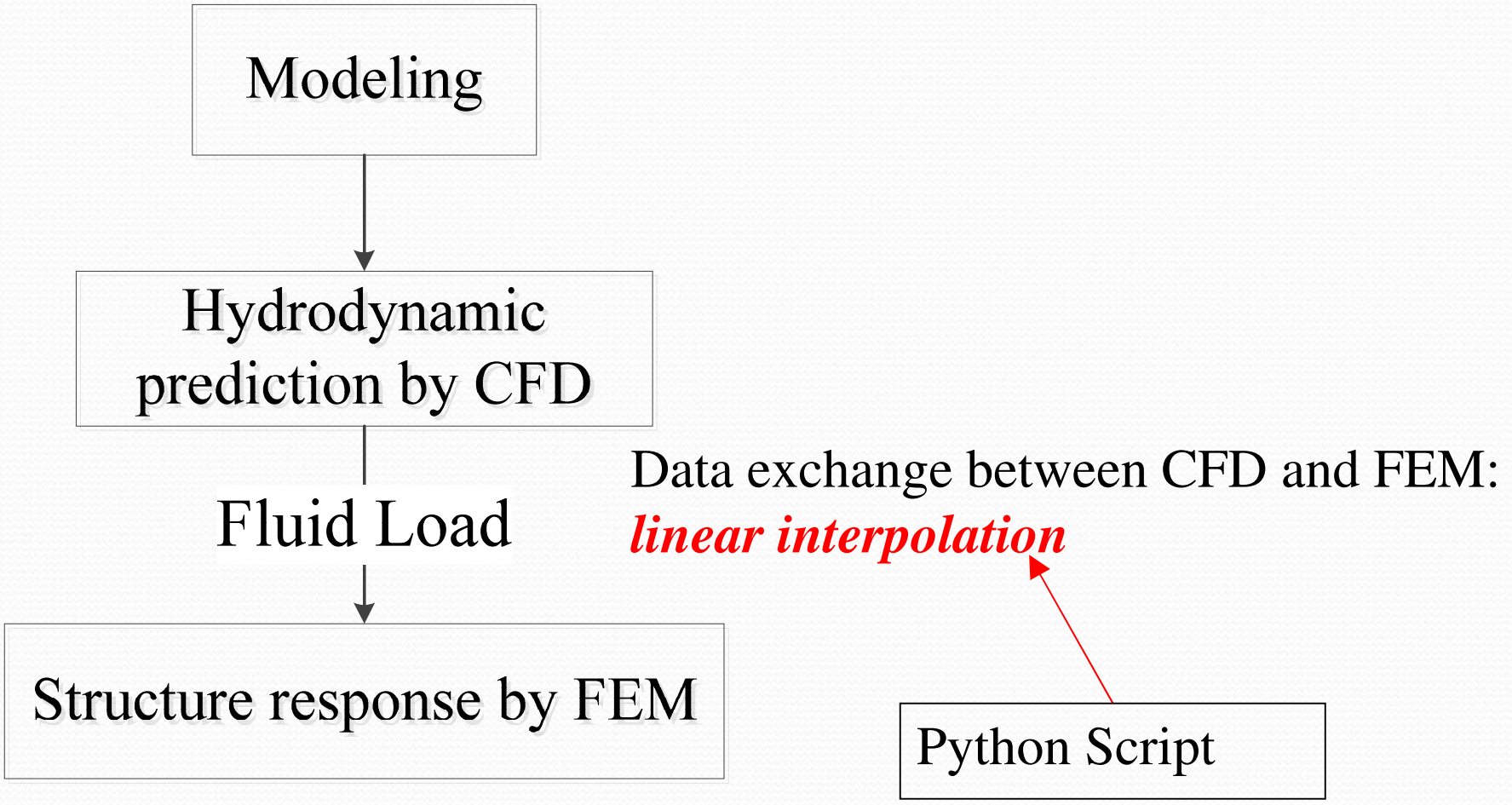
- RNG k-ε
- SST k-ω
- Transition-SST Model

# *Part 1—INTRODUCTION*




Data exchange between CFD and FEM: linear interpolation

# *Part 1—INTRODUCTION*



# Turbulence Model

- RNG k-ε [1]

***Transport equations***

$$\rho\frac{\partial k}{\partial t}+\rho\frac{\partial (ku_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\frac{\partial (ku_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right]+\frac{C_1^*\varepsilon}{k}G_k-C_2\rho\frac{\varepsilon^2}{k}$$

$$\begin{cases}\mu_{eff}=\mu+\mu_t,\ \mu_t=\rho C_\mu\dfrac{k^2}{\varepsilon} & \eta_0=4.377,\ \beta=0.012\\ C_\mu=0.0845, & \alpha_k=\alpha_\varepsilon=1.39\\ C_1^*=C_1-\dfrac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3} & C_1=1.42,\ C_2=1.68\\ \eta=(2E_{ij}E_{ij})^{1/2}\dfrac{k}{\varepsilon} & E_{ij}=\dfrac{1}{2}\left(\dfrac{\partial u_i}{\partial x_j}+\dfrac{\partial u_j}{\partial x_i}\right)\end{cases}$$

[1] S. A. Orszag, V. Yakhot, W. S. Flannery, F. Boysan, D. Choudhury, J. Maruzewski, and B. Patel. *"Renormalization Group Modeling and Turbulence Simulations". In International Conference on Near-Wall Turbulent Flows, Tempe, Arizona*. 1993.

# *Part 2— THEORETICAL FORMULAS*

## Turbulence Model

- SST k-ω[2]

***Transport equations***

$$\rho\frac{\partial k}{\partial t}+\rho\frac{\partial\left(ku_i\right)}{\partial t}=P_k-\frac{\rho k^{3/2}}{l_{k-\omega}}+\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\frac{\partial\left(\varepsilon u_i\right)}{\partial t}=\alpha_2\frac{\omega}{k}P_\omega-\beta_2\rho\omega^2+\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_{\omega^2}}\right)\frac{\partial k}{\partial x_i}\right]+2\rho\left(1-F_1\right)\frac{\sigma_{\omega^2}}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}$$

$$\begin{cases}\sigma_k=2,\alpha_2=0.44\\ \beta_2=0.0828,\sigma_{\omega 2}=0.856\end{cases},\mu_t=\frac{\rho^*\alpha_1 k}{\max\left(\alpha_1\omega,SF_2\right)}$$

[2] F. R. Menter. "Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications". AIAA Journal. 32(8). 1598–1605. August 1994.

# *Part 2— THEORETICAL FORMULAS*

- Turbulence Model
- Transition-SST Model [3,4]

Transport equations

$$\frac{\partial}{\partial t}(\rho\gamma)+\frac{\partial}{\partial x_j}(\rho U_j\gamma)=P_{\gamma 1}-E_{\gamma 1}+P_{\gamma 2}-E_{\gamma 2}+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\gamma}{\partial x_j}\right]$$

$$\frac{\partial}{\partial t}(\rho\tilde{\mathrm{Re}}_{\theta t})+\frac{\partial}{\partial x_j}(\rho U_j\tilde{\mathrm{Re}}_{\theta t})=P_{\theta t}+\frac{\partial}{\partial x_j}\left[\sigma_{\theta t}(\mu+\mu_t)\frac{\partial\tilde{\mathrm{Re}}_{\theta t}}{\partial x_j}\right]$$


[3] F. R. Menter, R. B. Langtry, S. R. Likki, Y. B. Suzen, P. G. Huang, and S. Volker. *"A Correlation Based Transition Model Using Local Variables Part 1 - Model Formulation"*. (ASME-GT2004-53452)2004.

[4] H. Schlichting and K. Gersten. Grenzschicht-Theorie. Springer-Verlag, Berlin, Heidelberg, New York. 1997.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

Assumption ⇒ Material is homogeneous, isotropic, and linear elastic
Small deformation

The dynamic equation of motion with respect to the blade-fixed coordinate system

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

$\{\ddot{u}\}$ nodal acceleration vectors

$\{\dot{u}\}$ nodal velocity vectors

$\{u\}$ nodal displacement vectors

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

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$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

$$[M_s]=\int \rho_s [N]^T [N] dV$$

structural mass matrix

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

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$$[C_s]=\int c[N]^T[N]dV$$

damping matrix

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

Assumption ⇒ Material is homogeneous, isotropic, and linear elastic
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The dynamic equation of motion with respect to the blade-fixed coordinate system

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

$$[K_s]=\int[B]^T[E][B]$$

stiffness matrix

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

Assumption ⇒ Material is homogeneous, isotropic, and linear elastic
Small deformation

The dynamic equation of motion with respect to the blade-fixed coordinate system

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

$$\{F_{ce}\}=\int \rho_s [N]^T \{f_{ce}\} dV$$

$$f_{ce}=-\Omega\times(\Omega\times(x+u))$$

the centrifugal force

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

Assumption ⇒ Material is homogeneous, isotropic, and linear elastic
Small deformation

The dynamic equation of motion with respect to the blade-fixed coordinate system

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

$$\{F_{co}\}=\int \rho_s [N]^T \{f_{co}\} dV$$

$$f_{co}=-2\Omega\times\dot{u}$$

Coriolis force

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

Assumption ⇒ Material is homogeneous, isotropic, and linear elastic
Small deformation

The dynamic equation of motion with respect to the blade-fixed coordinate system

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

$$\{F_h\}=\int[N]^T\{P\}dS$$

hydrodynamic force due to with rigid blade rotating in non-uniform wake

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

Assumption ⇒ Material is homogeneous, isotropic, and linear elastic
Small deformation

The dynamic equation of motion with respect to the blade-fixed coordinate system

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

$$\{f_h\}=\int[N]^T\{P_v\}dS$$

hydrodynamic force due to elastic blade deformation

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 2— THEORETICAL FORMULAS*

## FEM [5]

Assumption ⇒ Material is homogeneous, isotropic, and linear elastic
Small deformation

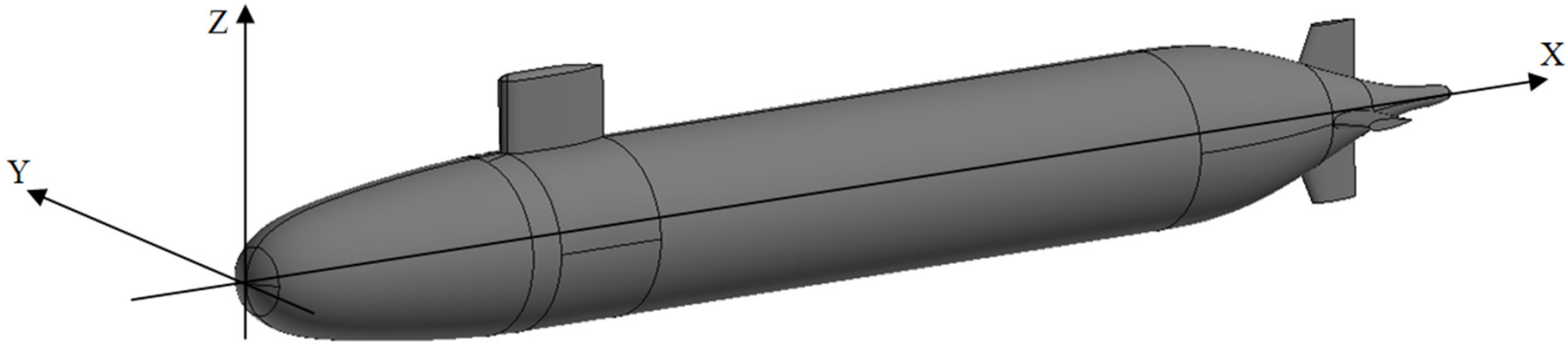
The dynamic equation of motion with respect to the blade-fixed coordinate system

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_{ce}\}+\{F_{co}\}+\{F_h\}+\{f_h\}$$

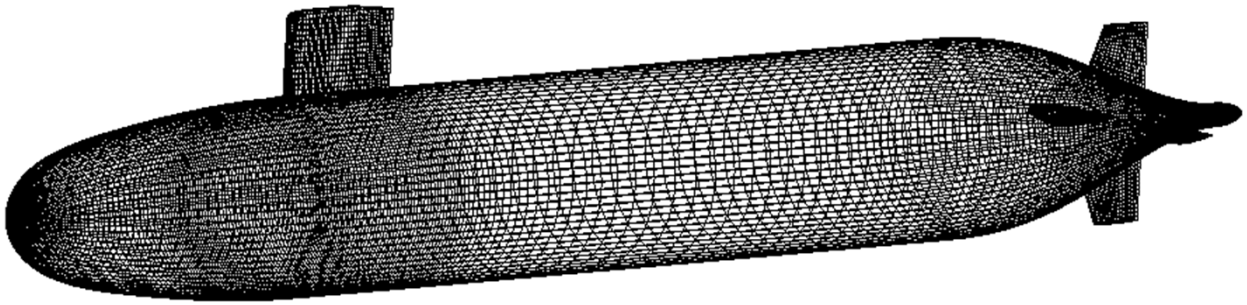
be negligible due to the small deformation.

[5] Wang Xucheng. Finite element method. Tsinghua University Press: Beijing, 2003.

# *Part 3— CASE STUDY*




Coordinate system

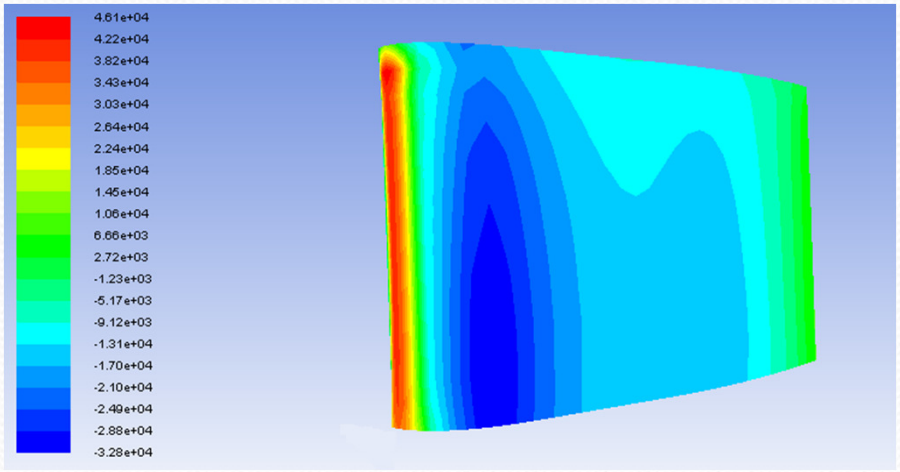


Mesh of Suboff

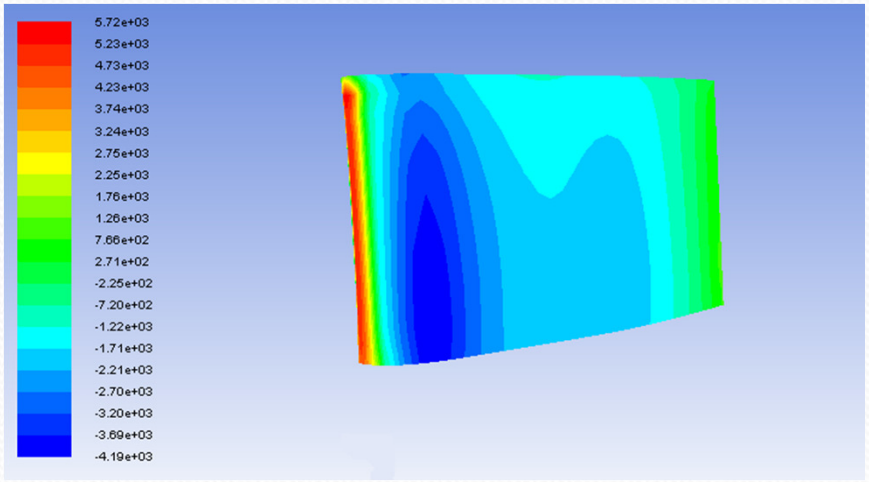
[5] NANCY C G, THOMAS T H. MING S C. GEOMETRIC CHARACTERISTICS OF DARPA SUBPFF MODEL. David Taylor Research Center[R]: 1989.
[6] Nancy C. Groves. GEOMETRIC CHARACTERISTICS OF DARPA SUBOFF MODELS[R]. David Taylor Research Center,1989.

# *Part 3— CASE STUDY*

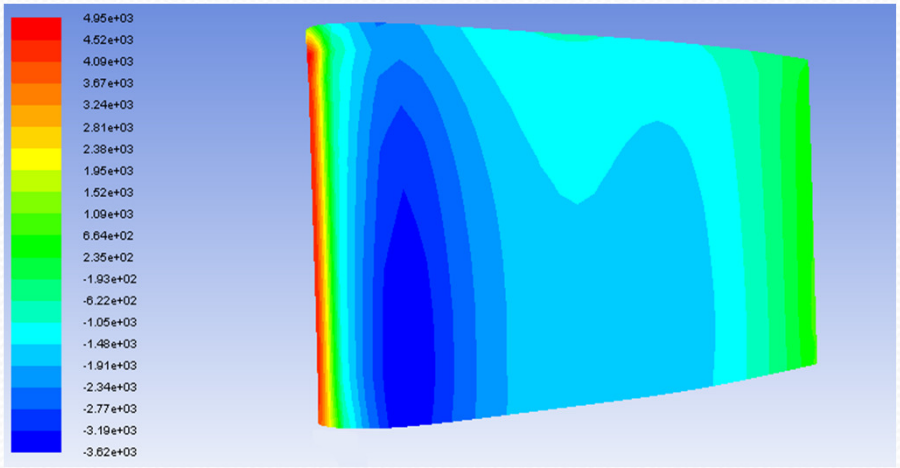
➢ ***Pressure Comparison - pressure distribution of fairwater***




RNG k-ε



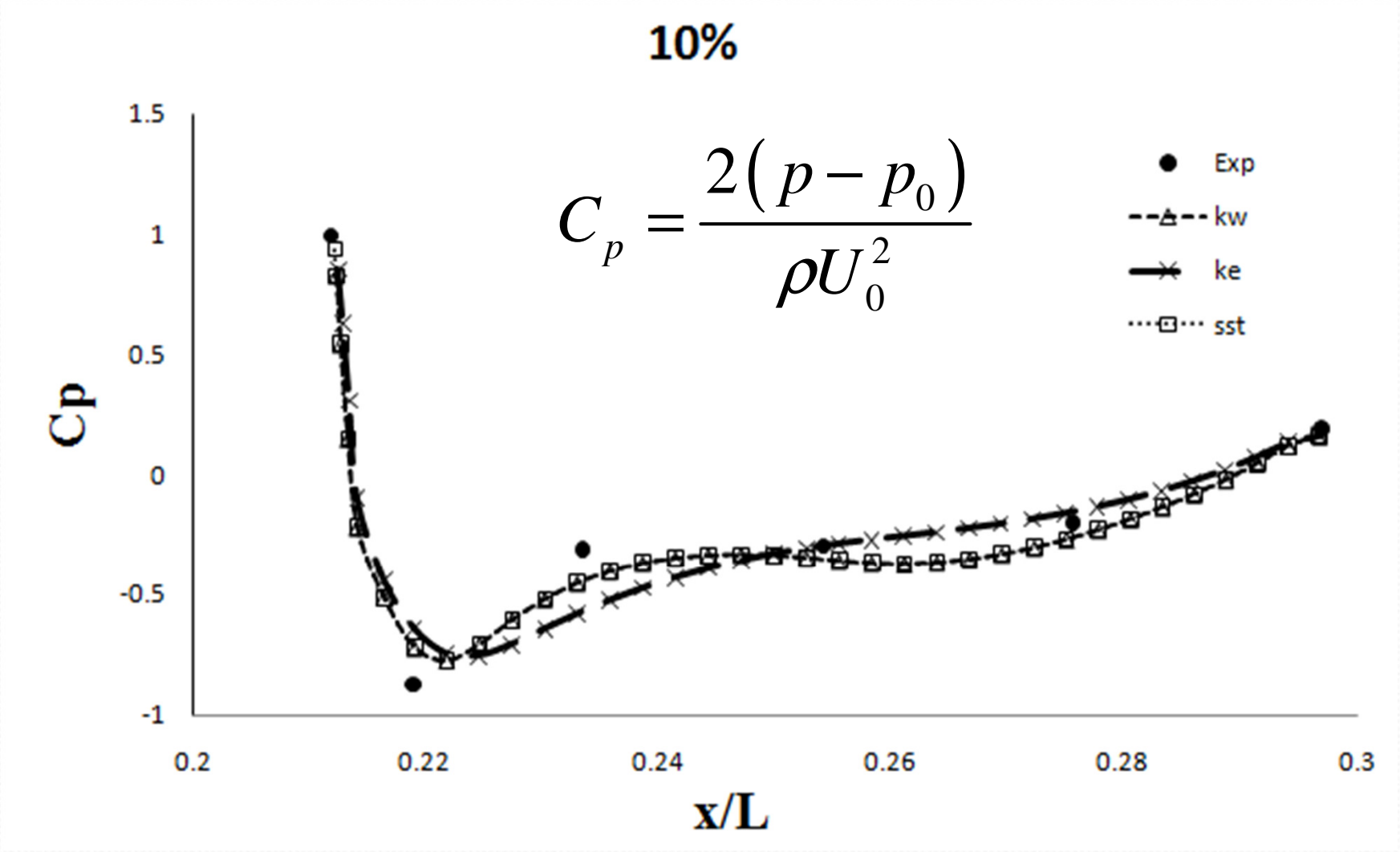

SST k-ω




Transition-SST

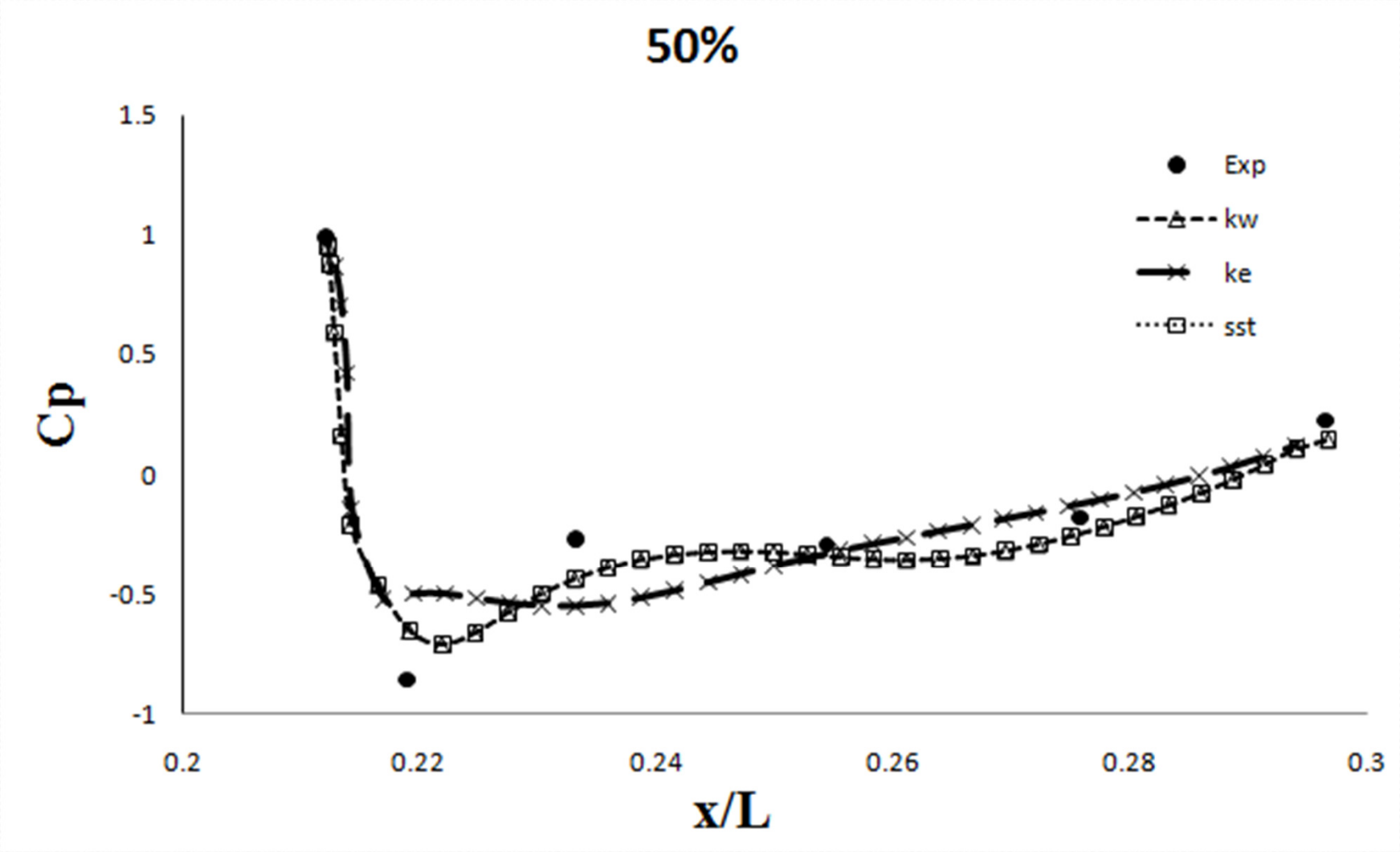
# *Part 3— CASE STUDY*

➢ ***Pressure Comparison -pressure coefficient at different height***



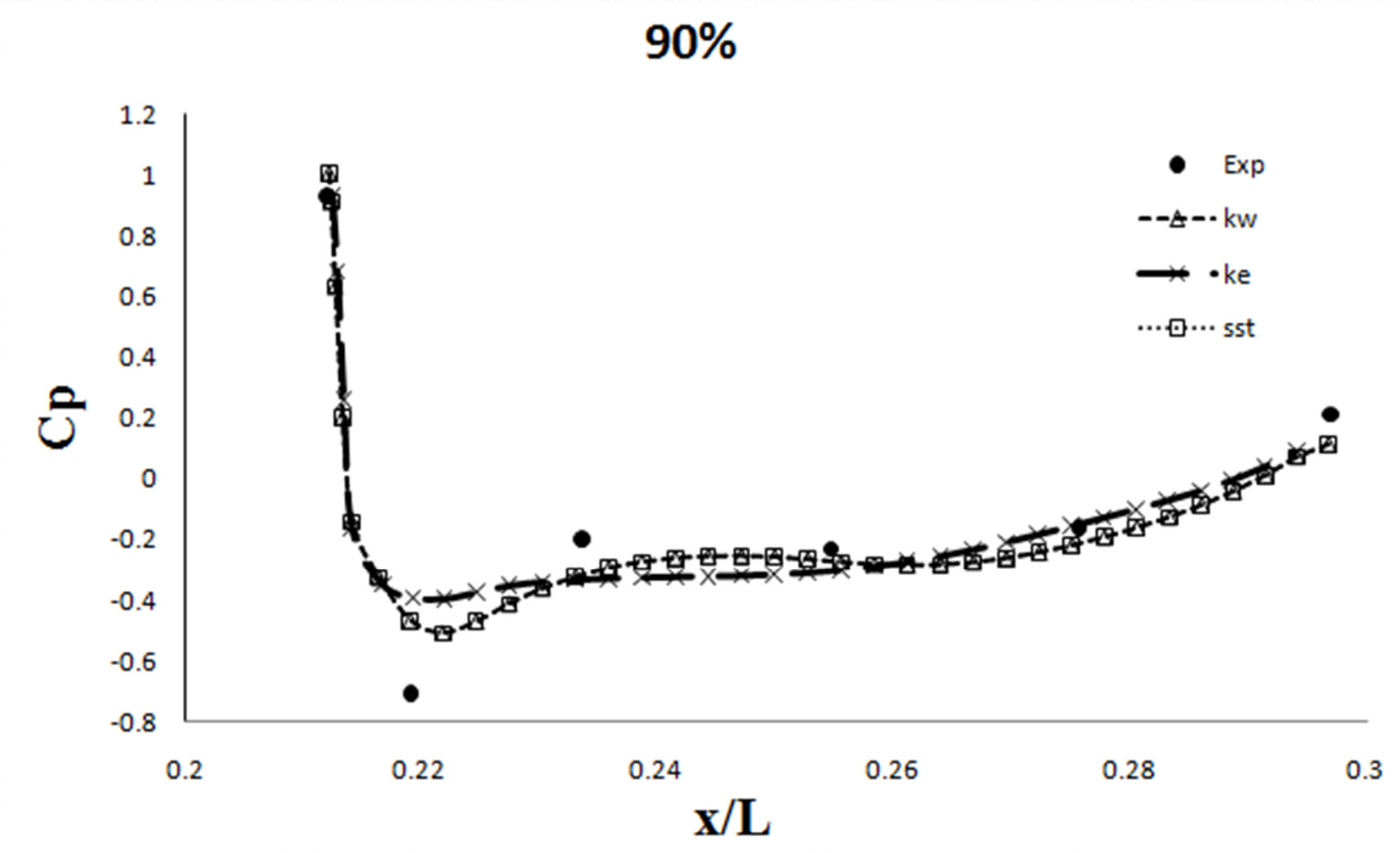
# *Part 3— CASE STUDY*

- ***Pressure Comparison -pressure coefficient at different height***



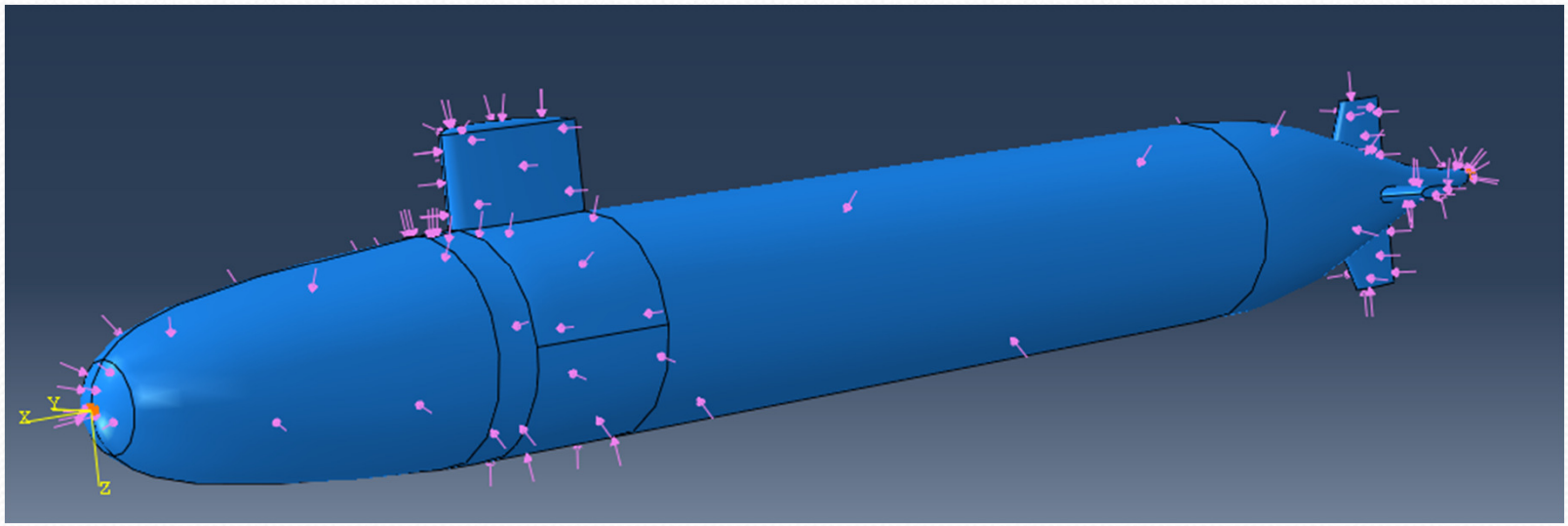
# *Part 3— CASE STUDY*

➢ ***Pressure Comparison -pressure coefficient at different height***

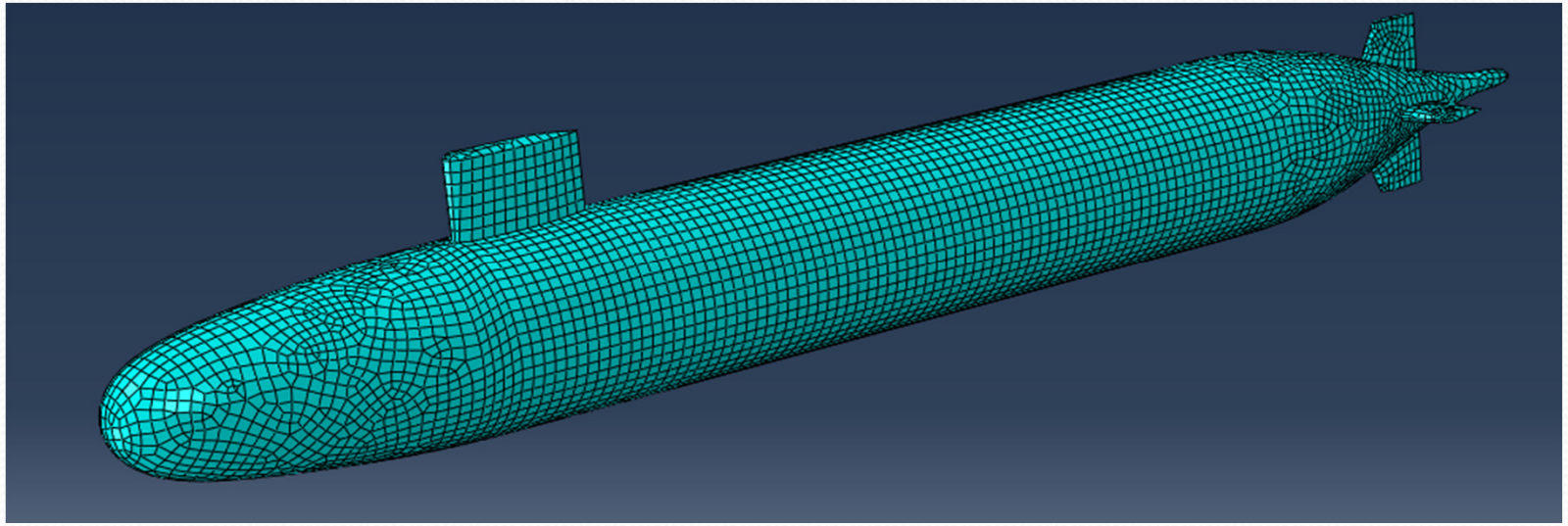


# *Part 3— CASE STUDY*

- ***Structure response***



hydrodynamic load



mesh

# *Part 3— CASE STUDY*

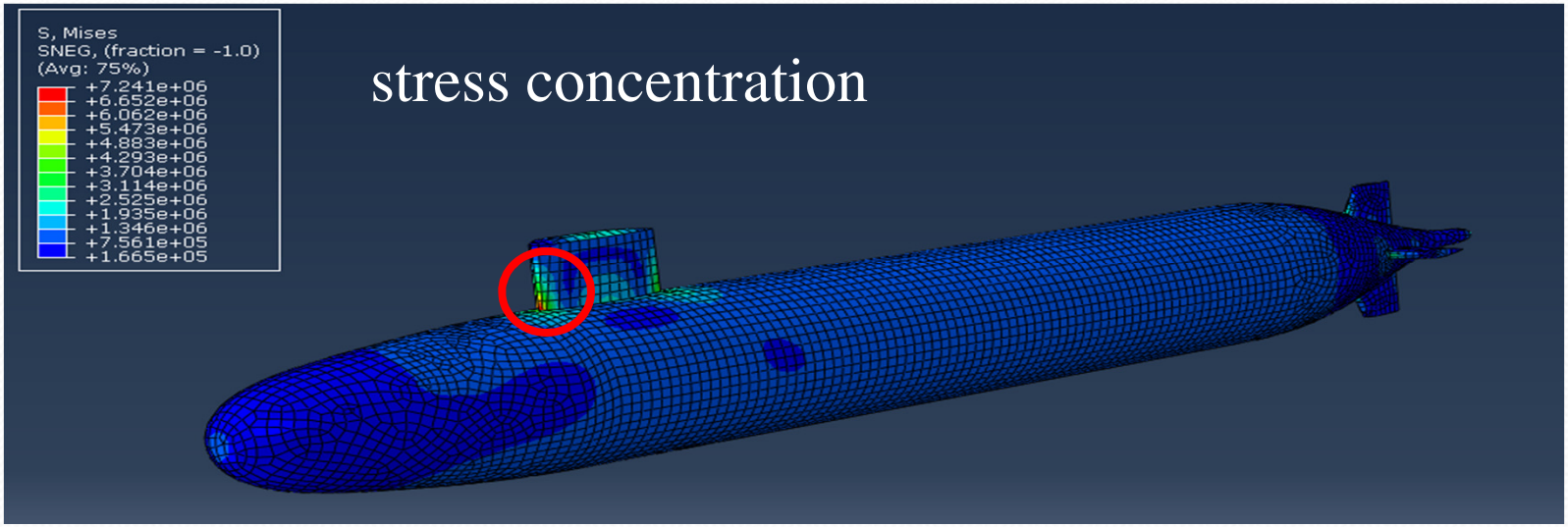
- ***Structure response***

the material and bound condition

| Material | density | Young's modulus | Poisson 's ratio | constraint |
|---|---|---|---|---|
| **structural steel** | 7800 | 120GPa | 0.3 | clamped support at both side |

# *Part 3— CASE STUDY*

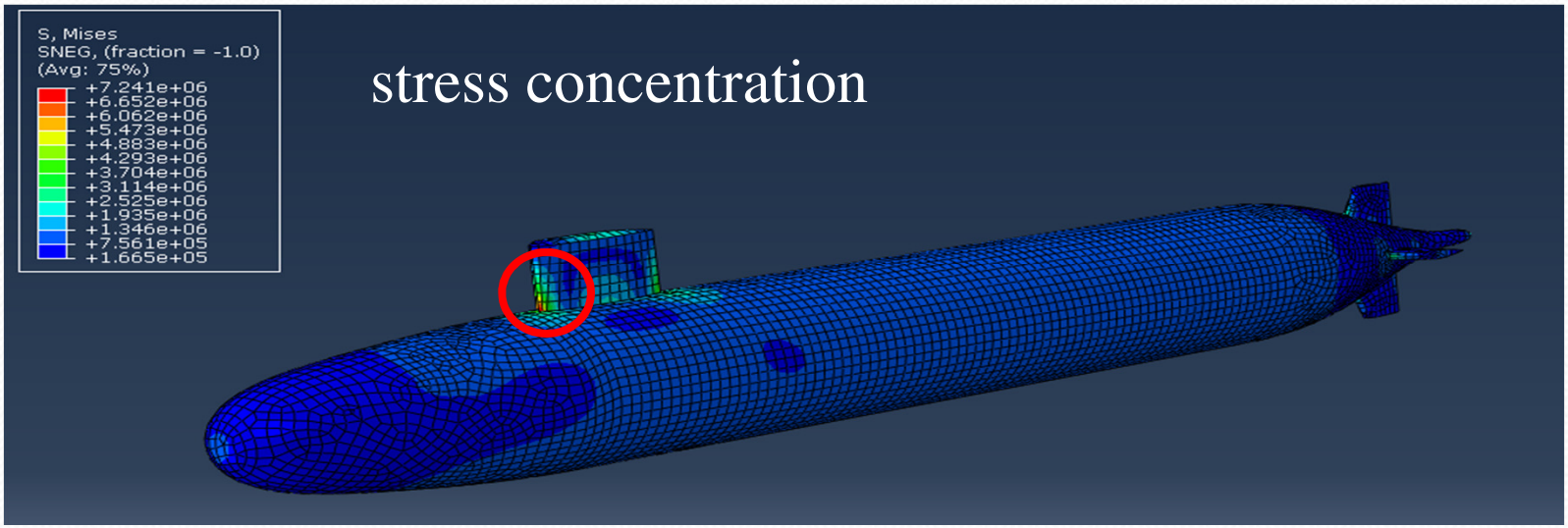
## ➢ *Structure response*




MISES stress distribution

# *Part 3— CASE STUDY*

## ➢ *Structure response*

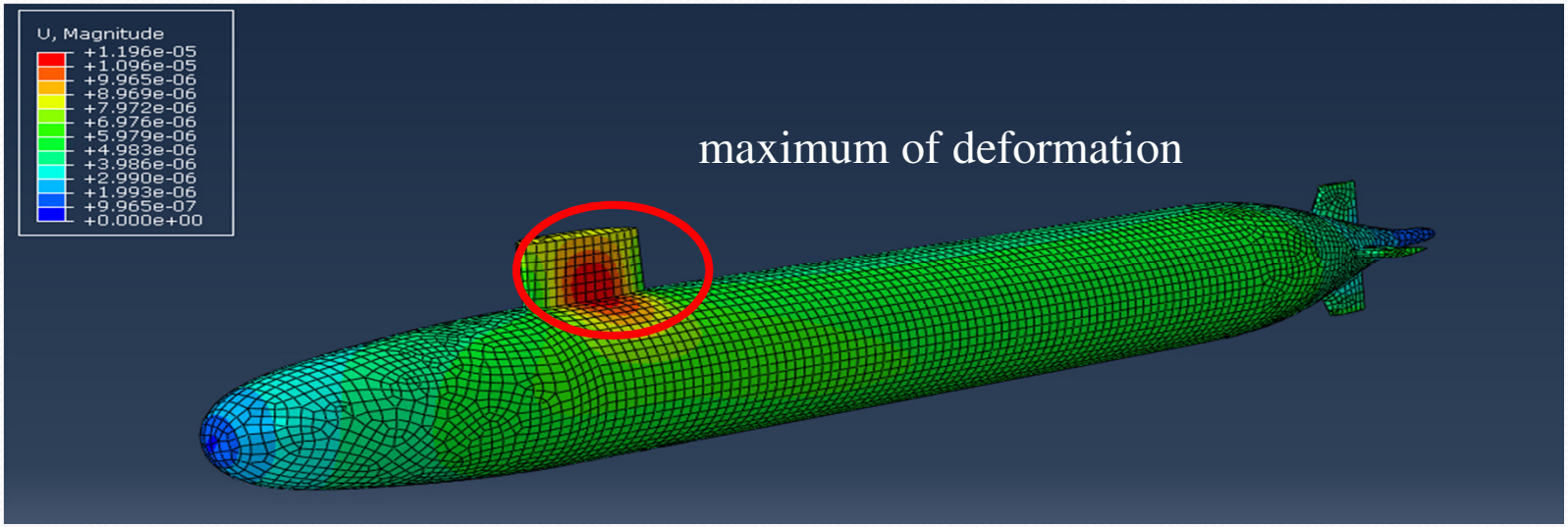



MISES stress distribution

- stress concentration -----forepart of the conning tower

# *Part 3— CASE STUDY*

➢ ***Structure response***




deformation of Suboff

- maximum of deformation ---on both sides of the conning tower

# *Part 4— CONCLUSION*

*This paper:*

- ✓ proposed **an numerical method** to predict hydrodynamics and structure response by CFD/FEM
- ✓ **k-ω model** is the fittest way to predict the hydrodynamics of the SUBOFF considering the computational accuracy and cost
- ✓ The **stress concentration** is **on the forepart** of the conning tower
- ✓ the location of **maximum of deformation** is at **both sides of the conning tower**.

# *Part 4— CONCLUSION*

*This paper:*

✓proposed **an numerical method** to predict hydrodynamics and structure response by CFD/FEM

✓**k-ω model** is the fittest way to predict the hydrodynamics of the SUBOFF considering the computational accuracy and cost

✓The **stress concentration** is **on the forepart** of the conning tower

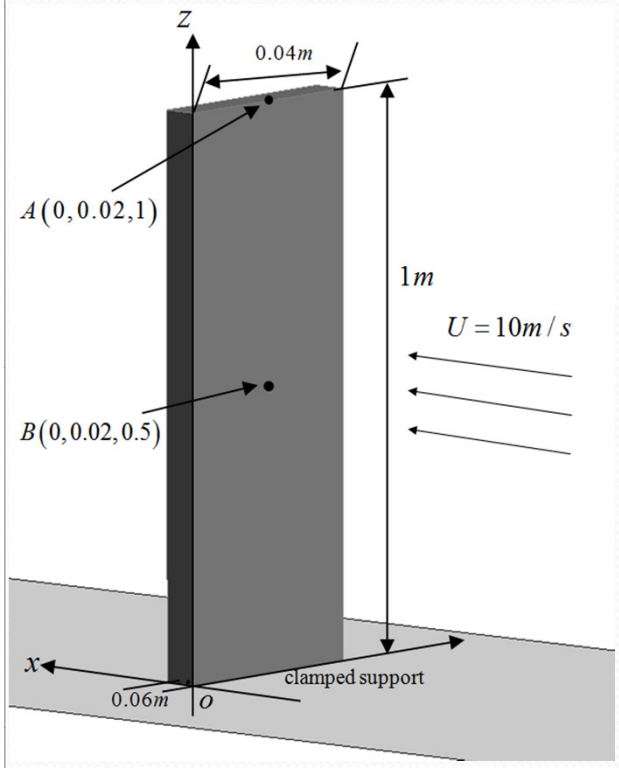
✓ the location of **maximum of deformation** is at **both sides of the conning tower**.

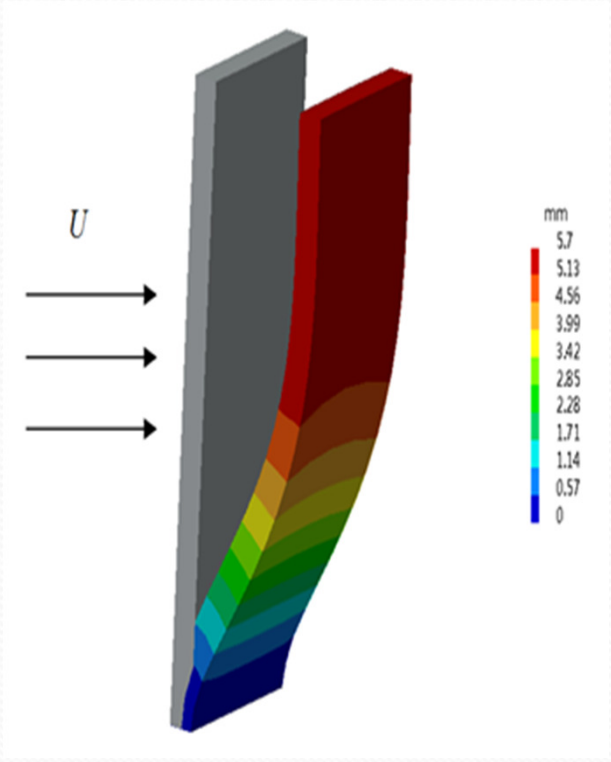
*Unsolved:*

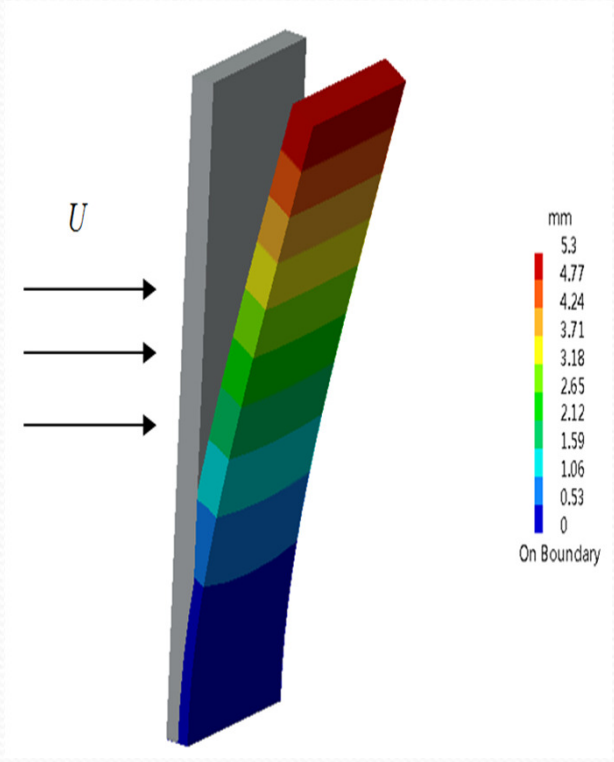
●The iteration of fluid-structure effect is **not** considered.

# *Part 5— FURTHER DISCUSSION*

FSI of a plate: considering iteration



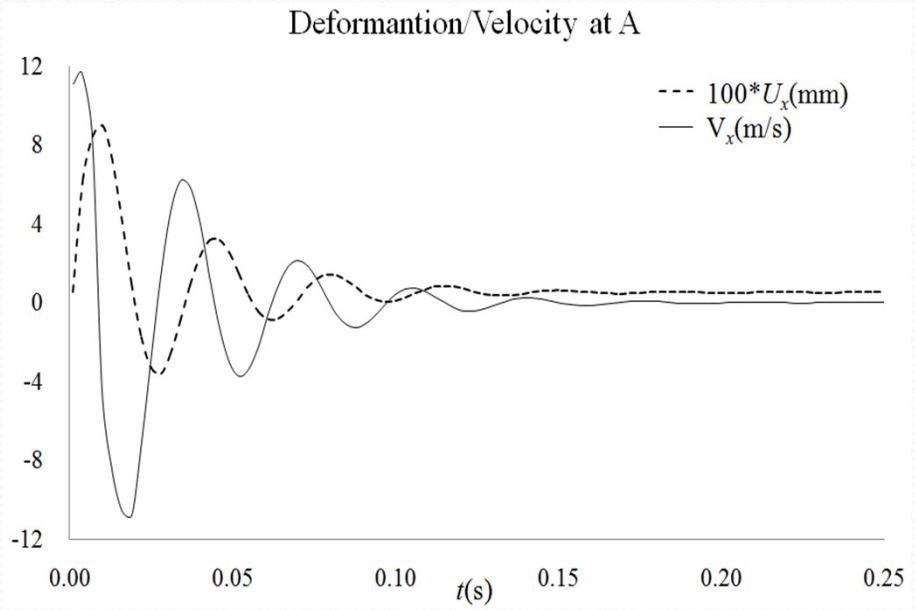



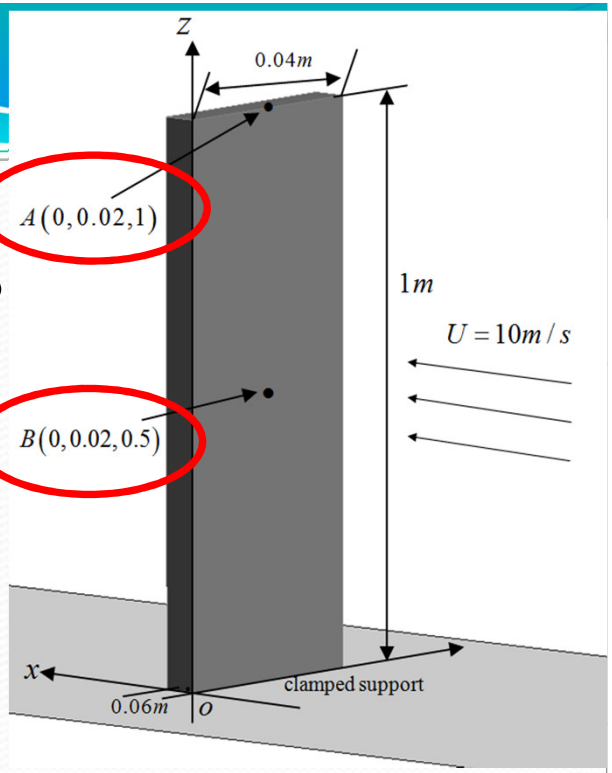

(a) the plate (b) deformation t=0.001s (c) deformation t=0.25s

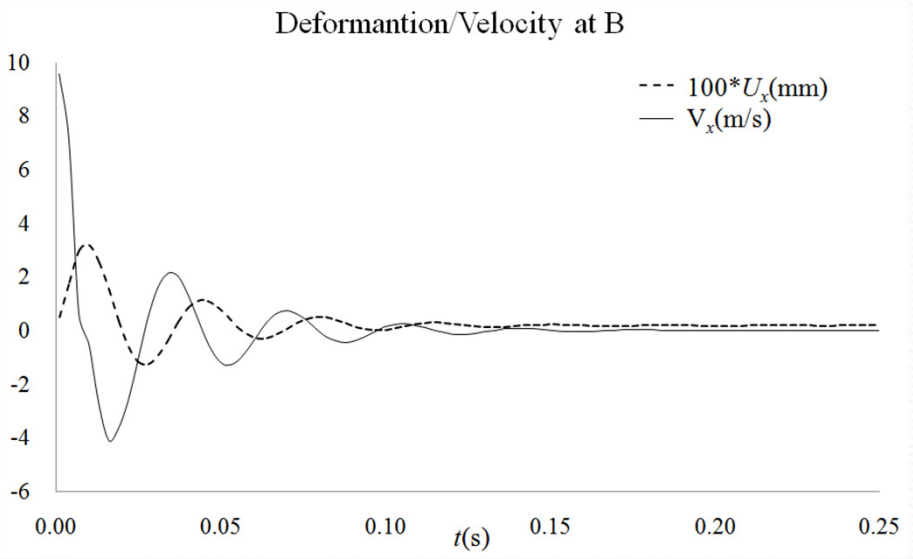
***Jiang Jingwei***, Cai Haopeng, Ma Cheng, Chen Ke. Multi-objective optimal design of ship propeller considering fluid - structure interaction [C], Rhodes: ISOPE, 2016.

# *Part 5— FURTHER DISCUSSION*

## the velocity and deformation of A and B




***Jiang Jingwei***, Cai Haopeng, Ma Cheng, Chen Ke. Multi-objective optimal design of ship propeller considering fluid - structure interaction [C], Rhodes: ISOPE, 2016.

# *Thank you!*

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