Numerical Experiments of Fluid-Structure Interaction with CFX

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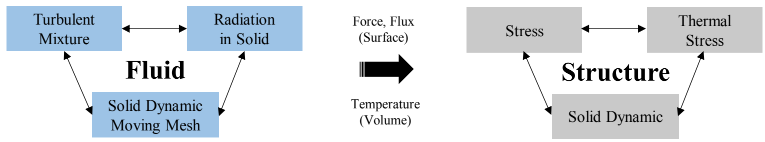
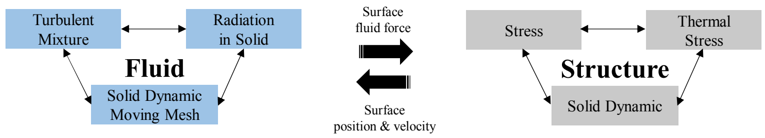
Contents

Introduction

- Fluid-Structure Interaction(FSI)
  - One-way: Conventional method, **Sequentially**



  - Two-way: Improved method, **Simultaneously**

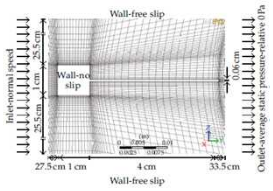


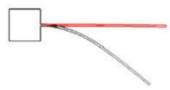
By ANSYS

Introduction

- Comparison between One-way and Two-way

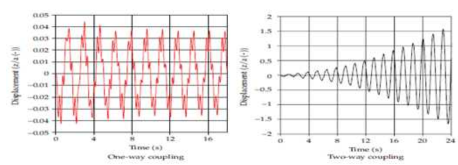
Red: One-way
Black: Two-way



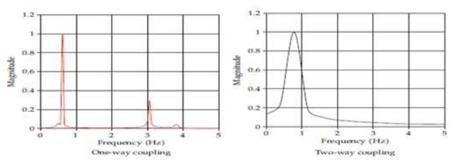


Natural frequency: 0.78 Hz

· Displacement

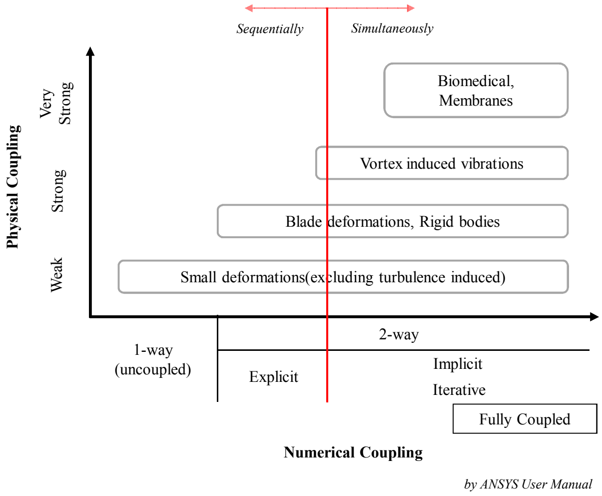


· Frequency spectrum



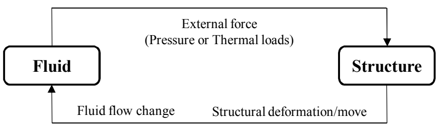
(FK Benra et al., 2011)

FSI Modeling Approaches



FSI: Two-way

- FSI describes the couple dynamics of fluid and structure mechanics.



- Types of FSI
  - Aerodynamics
    : Computational Fluid Dynamics(CFD)
  - Bio-engineering
    : Understanding of the flow of blood in vessels or heart.
  - Civil-engineering
    : Vibration of structure, Turbulent flow

Governing Equations: Fluid

- Computational Fluid Dynamics(CFD)
  - Navier-Stokes equation

$$\rho\left(\frac{\partial \boldsymbol{v}}{\partial t}+\boldsymbol{v}\cdot\nabla\boldsymbol{v}\right)=-\nabla p+\nabla\cdot\boldsymbol{\tau}+\boldsymbol{f}$$

$\boldsymbol{v}$: flow velocity
ρ: fluid density
p: pressure
$\boldsymbol{\tau}$: component of total stress tensor
$\boldsymbol{f}$: body forces on the fluid per unit volume

  - Conservation of Mass

$$\underbrace{\frac{\partial}{\partial t}\int_v \rho dv}_{\text{Rate of change of mass}} = \underbrace{-\oint_s \rho\boldsymbol{u}\cdot\boldsymbol{n}ds}_{\text{Net inflow of mass}}$$

Governing Equations: Fluid

  - Conservation of Momentum

$$\underbrace{\frac{\partial}{\partial t}\int \rho\boldsymbol{u}dv}_{\text{Rate of change of momentum}} = \underbrace{-\oint \rho\boldsymbol{u}\boldsymbol{u}\cdot\boldsymbol{n}ds}_{\text{Net inflow of momentum}} \underbrace{-\oint p\boldsymbol{n}ds}_{\text{Total pressure}} + \underbrace{\oint 2\mu\boldsymbol{D}\cdot\boldsymbol{n}ds}_{\text{Total viscous force}} + \underbrace{\int \rho\boldsymbol{f}dv}_{\text{Total body force}}$$

  - Conservation of Energy

$$\frac{\partial}{\partial t}\int \rho\overbrace{\left(e+\frac{1}{2}u^2\right)}^{\text{Rate of change of kinetic+internal energy}} dv = -\oint \rho\overbrace{\left(e+\frac{1}{2}u^2\right)}^{\text{Net inflow of kinetic+internal energy}}\boldsymbol{u}\cdot\boldsymbol{n}ds$$

$$+\underbrace{\int_v \boldsymbol{u}\cdot\boldsymbol{f}dv}_{\text{Work done by body forces}} + \underbrace{\oint \boldsymbol{n}\cdot(\boldsymbol{u\tau})ds}_{\text{Net work done by the stress tensor}} \underbrace{-\oint \boldsymbol{n}\cdot\boldsymbol{q}ds}_{\text{Net heat flow}}$$

Governing Equations: Structure

- Heat conduction equation

$$\frac{\partial}{\partial t}\rho c_p T = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + S_E$$

ρ: Density
c_p: Specific heat capacity
λ: Thermal conductivity
S_E: Heat generation

- Equation of structural dynamics

$$M\ddot{x} + C\ddot{x} + Kx = F(t)$$

M: Mass
C: Damping coefficient
K: Stiffness
F: External force
$\dot{x} = \partial x/\partial t$
$\ddot{x} = \partial^2 x/\partial t^2$

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F\}$$

Governing Equations: Multiphysics

- The finite element formulation which treats a single phenomenon uses matrix algebra.

$$[\boldsymbol{K}]\{\boldsymbol{X}\} = \{\boldsymbol{F}\}$$

$[\boldsymbol{K}]$: Coefficient matrix
$\{\boldsymbol{X}\}$: Vector of nodal unknowns
$\{\boldsymbol{F}\}$: The known load vector
Subscript 1 is fluid; Subscript 2 is solid

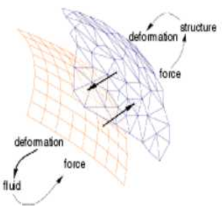
- Matrix Coupling

$$\begin{bmatrix}[\boldsymbol{K}_{11}] & [\boldsymbol{K}_{12}] \\ [\boldsymbol{K}_{21}] & [\boldsymbol{K}_{22}]\end{bmatrix}\begin{Bmatrix}[\boldsymbol{X}_1] \\ [\boldsymbol{X}_2]\end{Bmatrix} = \begin{Bmatrix}[\boldsymbol{F}_1] \\ [\boldsymbol{F}_2]\end{Bmatrix}$$

- Load Vector Coupling

$$\begin{bmatrix}[\boldsymbol{K}_{11}] & [\ 0\ ] \\ [\ 0\ ] & [\boldsymbol{K}_{22}]\end{bmatrix}\begin{Bmatrix}[\boldsymbol{X}_1] \\ [\boldsymbol{X}_2]\end{Bmatrix} = \begin{Bmatrix}[\boldsymbol{F}_1] \\ [\boldsymbol{F}_2]\end{Bmatrix}$$

Red: Coupled effect coefficient
Blue: Iteration for convergence



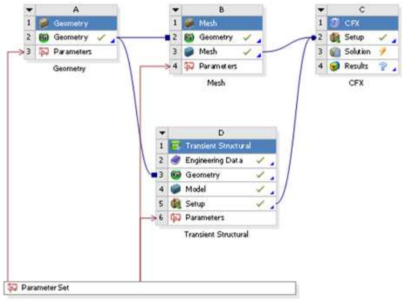
From FLUID side
◦ Conservative Interpolation
- Nodal forces: F_x, F_y, F_z
- Nodal heat rates: Q

◦ Non-Conservative Interpolation
- Nodal force fluxes: F_x”, F_y”, F_z”
- Nodal heat fluxes: Q”

From SOLID side
- Nodal displacements: U_x, U_y, U_z
- Nodal temperatures: TEMP
- Nodal velocities: V_x, V_y, V_z

Numerical Tool

- ANSYS CFX
  Commercial Computational Fluid Dynamics(CFD) program, used to simulate fluid flow in a variety of applications.
  Multiphysics: The ability to combine the effects of two or more different unified simulation environment.



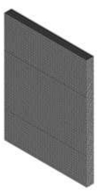
Numerical Tool

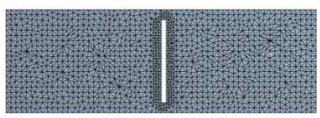
- Advantage
  - Advanced solver technology using coupled algebraic multigrid to achieving reliable and accurate solutions.
  - Uses second order numerics to get the most accurate predictions possible.
  - Analysis of the multyphase flow by coupled solver using a matrix method
- Disadvantage
  - Coupled solver takes a long time of calculation for a given time step because all the variables is solved at the same time.

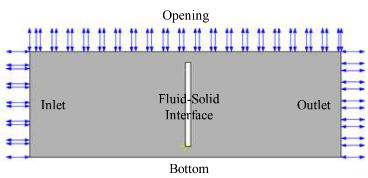
Vibration of Structures Induced by Gate Opening

Example of FSI

- Introduction & Purpose
  It is intended to confirm of vibration of solid and the applicability of the FSI.
- Geometry & Mesh, Initial & Boundary conditions



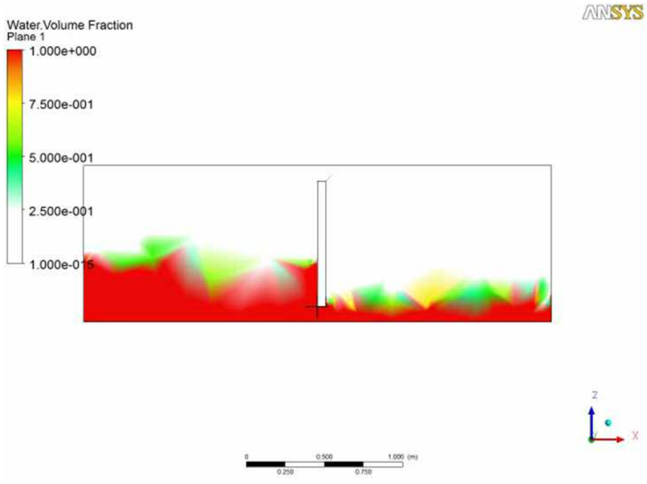




	Gate	Fluid
Mesh size	0.05 m	0.01 m
Total mesh	27703 ea	24000 ea

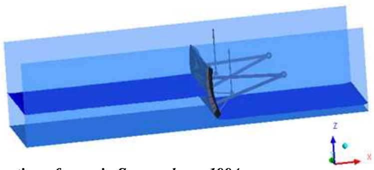
	Inlet	Outlet	Height of gate opening
Variable	h_i	h_o	h
Value(m)	0.40	0.15	0.10

Example of FSI



Radial Sluice Gate

- Introduction
  Sluice gate is commonly a sliding barrier and control water levels and flow rates in rivers. Vibration of sluice gate is generated by the fluid flow.
- Purpose
  Comparison of results from experiment with them from numerical simulation to verify results of fluid-structure interaction.



※ ***Report of hydraulic experiments and observation of wave in Saemankum, 1994.***

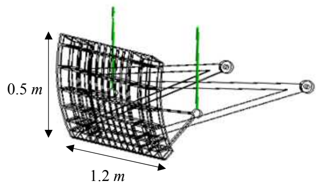
- Experiment conditions
  - Straight open channel with width 1.2 m, length 30 m, height 0.5 m
  - Constant upstream height: 0.32 m
  - Constant downstream height: 0.11 m

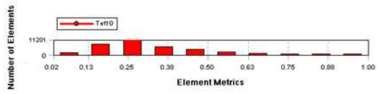
Geometry & Mesh

- Gate
  - Gate and gate arm - Acryl
  - Lifting lug - Steel

	Value
Mesh size	0.03 m
Total mesh	34259 ea

	Prototype	Model	
		Required value	Apply value
Scale	1	1/25	
Unit weight	7.85	7.85	Acryl: 1.20 Steel: 7.85
Mass	320 ton	20.48 kg	20.90 kg
Elastic modulus	2.01×10^{9}	8.04×10^{7}	Acryl: 2.80×10^{7} Steel: 2.01×10^{9}

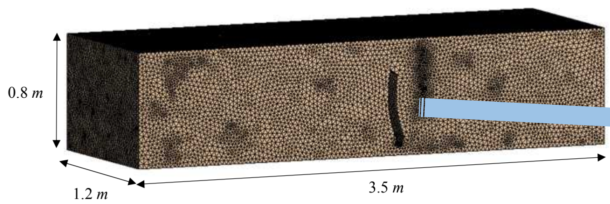


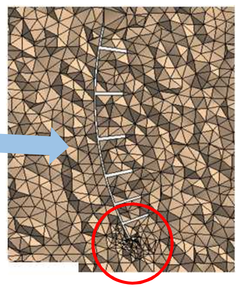


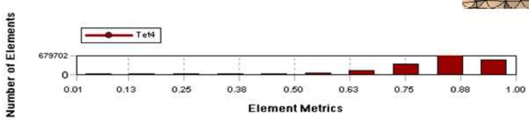
Geometry & Mesh

- Fluid

	Value
Mesh size	0.03 m
Total mesh	1699860 ea







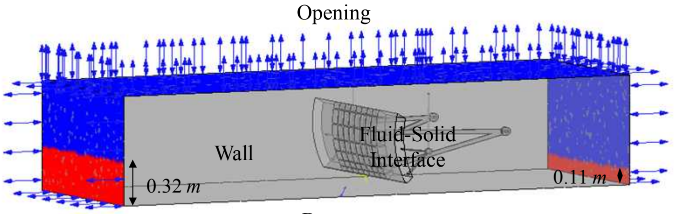
Initial & Boundary Conditions

- Initial conditions

	Inlet	Outlet	Height of gate opening
Variable	h_i	h_o	h
Value(m)	0.32	0.11	0.01, 0.04, 0.08

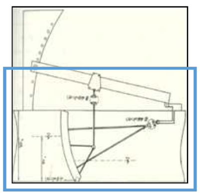
- Boundary conditions

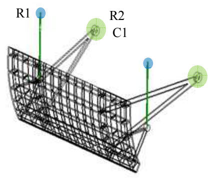
	Type	Condition
Inlet	Opening	Hydraulic Pressure
Outlet	Opening	Hydraulic Pressure
Top	Opening	Atmospheric pressure
Bottom	Wall	No-slip
Wall	Wall	No-slip
Gate	Wall	No-slip(Multifield)



Initial & Boundary Conditions

- Restriction conditions





	Displacement		
	X Component	Y Component	Z Component
R1	Free	Constant	Constant
R2	Constant	Constant	Free

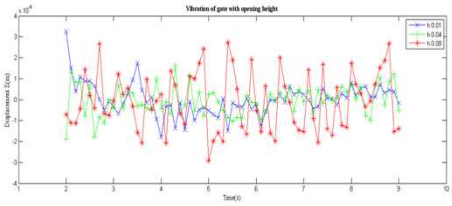
	Cylindrical Support		
	Radial	Axial	Tangential
C1	Fixed	Fixed	Free

- Simulation cases

Height of gate opening (m)	Discharge(m^3/s)	Simulation times(s)
0.01	$\bar{Q} = 0.0261$	10
0.04	$\bar{Q} = 0.0939$	
0.08	$\bar{Q} = 0.1669$	

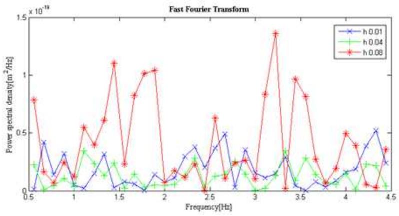
Results

- Vibration of gate



Dispalcement	Height of opening gate, *h*		
	0.01	**0.04**	**0.08**
Max(m)	0.81×10^{9}	0.68×10^{9}	2.67×10^{9}
Min(m)	-1.26×10^{9}	-0.94×10^{9}	2.04×10^{9}
Value(m)	2.06×10^{9}	1.62×10^{9}	4.71×10^{9}

Fast Fouier Transform

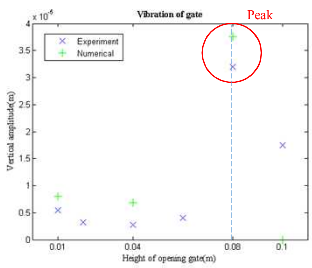


Distribution of frequency has the same tendency with experimental results. When height of opening gate is 0.08 m, vibration is the max value.

Results

- Analysis of amplitude

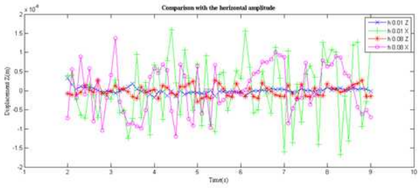
Height of opening gate(m)	Experiment	Numerical	
	Vertical amplitude(m)	Vertical amplitude(m)	Horizontal amplitude(m)
0.01	5.4×10^{-6}	7.96×10^{-6}	2.44×10^{-4}
0.04	2.7×10^{-6}	6.81×10^{-6}	0.79×10^{-4}
0.08	32×10^{-6}	37.66×10^{-6}	2.47×10^{-4}



Results of vibration analysis in numerical experiment have the same tendency with the experimental results. At the height of opening gate is 0.08 m, max value of amplitude occurs.

Results

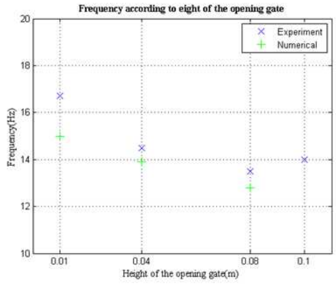
- Vibration in flow direction



Vibration experiment was performed only on the vertical vibration in experiment. However, vibration in flow direction is more important than that in vertical direction.

- Analysis of frequency

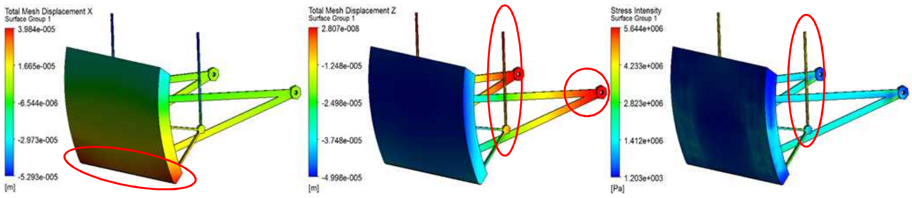
Height of opening gate(m)	Frequency(Hz)	
	Experiment	Numerical
0.01	16.7	15.0
0.04	14.5	13.9
0.08	13.5	12.8



Results

- Sturture Analysis

Max Value	Height of opening gate(m)		
	0.01	0.04	0.08
Total displacement X(m)	4.826×10^{-5}	4.521×10^{-5}	3.984×10^{-5}
Total displacement Z(m)	3.173×10^{-8}	3.014×10^{-8}	2.807×10^{-8}
Stress intensity	5.431×10^{-6}	5.644×10^{-6}	5.644×10^{-6}



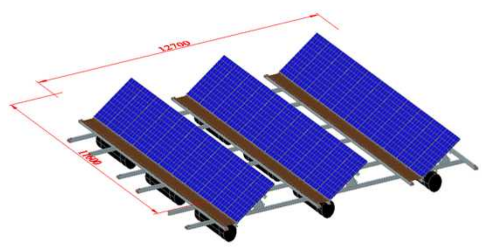
Conclusion and Future works

- Conclusion
  - Techniques of FSI analysis can be applied to vibration analysis.
  - Displacement and amplitude are much affected by the vibration in flow direction rather than that in vertical.
  - In the structure analysis, maximum stress is concentrated at lifting lug.
- Future works
  - Identify the case in according to the frequency change to prevent serious damage caused by the resonance.
  - Vibration analysis using the General Moving Object(GMO) in the operation of the gate in the field.

Floating Type Photovoltaic Composite Structure

Floating Type Photovoltaic Composite Structure

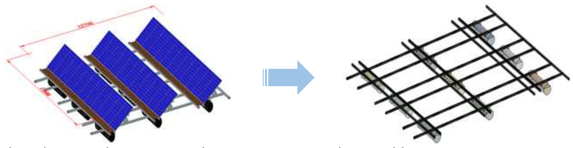
- Introduction
  The floating type photovoltaic composite structure is a structure that enables power generation in reservoir and coast.
- Purpose
  Examine of displacement and stress according to variation of wave height.



※ *Floating type photovoltaic composite structure*

Assumption

- Solar cell module is not stressed.
  Examine the safety of floating structure using only upper frame.



- Wind-induced wave is assumed as linear wave
  - Wave height(η): $\eta = A\cos(kx - \omega t)$
  - X-direction velocity(u): $u = A\omega \frac{\cosh k(x+d)}{\sinh kd} \cos(kx - \omega t)$
  - Z-direction velocity(w): $w = A\omega \frac{\cosh k(x+d)}{\sinh kd} \sin(kx - \omega t)$

  Where, A: amplitude, k: wave number, ω: circular frequency
  x: horizontal displacement, t: time

Geometry

Composed of upper frame, connector and lower floating structure.

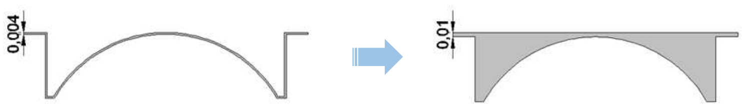
- Upper frame
  - Composed of FRP(The strength of FRP is similar to that of steel but its density is about a quarter of steel.)
  - 2 Unit was connected with 4 connecting hinge.

FRP(Fiber Reinforced Plastics)						Upper Frame	
Density (kg/m^3)	Young's Modulus(GPa)	Allowable Stress(MPa)				Mass (kg)	Volume (m^3)
		Tensile	Compressive	Shear	Bending		
1900.00	33.28	231.76	154.50	26.37	185.40	859.78	0.45252

Geometry

- Connector
  - Shape made by bending a steel plate
  - Convert to 0.01 *m* for minimum material thickness
  - Convert to the solid shape from plate material and the density to be the same weight in order to improve the convergence of calculation

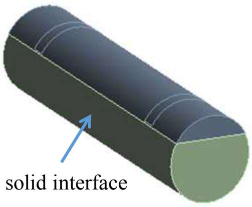
Steel					Unit connector	
Original Density (kg/m^3)	Converted Density (kg/m^3)	Young's Modulus (GPa)	Allowable Stress(MPa)		Mass (kg)	Volume (m^3)
			Tensile	Compressive		
7,850	954.55	200	102.50	80.00	3.2565	0.00341



Geometry

- Lower floating structure
  - Composed of styrofoam
  - Fluid solid interface in FSI simulation

Styrofoam		Lower floating structure	
Density(kg/m^3)	**Young's Modulus**(GPa)	**Mass**(kg)	**Volume**(m^3)
70.00	2.25	34.789	0.497

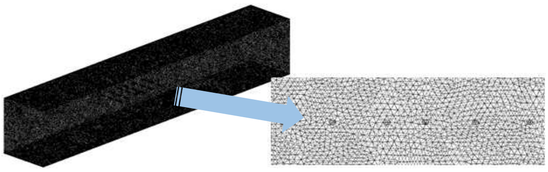


Fluid solid interface

Mesh

Mesh of structure and fluid was composed of tetrahedron mesh(Minimum size = 0.01 m).

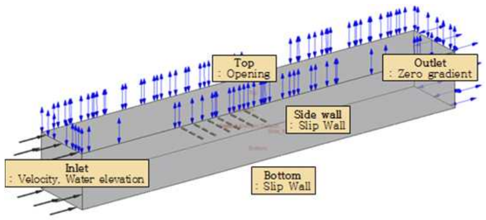
- Fluid



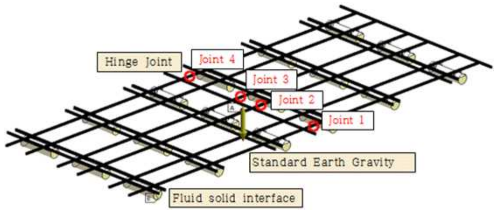
- Structure

Boundary condition

- Fluid



- Structure



Initial condition

- Wind velocity condition : 30 m/s and 45 m/s

  ※ 45 m/s is design wind velocity for dam and reservoir in Korea.

- Wind-induced wave height was calculated by Moliter's equation.

$$h_w = 0.06\sqrt{V/F} + 0.76 - 0.27\sqrt[4]{F}$$

Where, h_w: wave height(m), V: wind velocity(m/s),

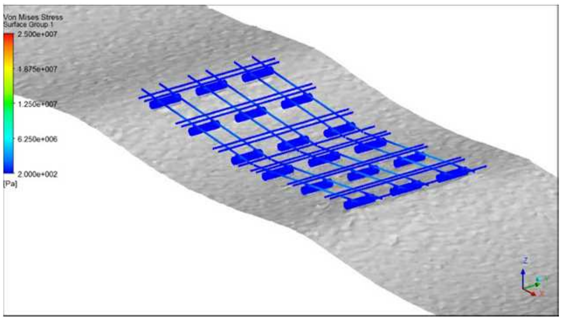
F : fetch(the length of water over which a given wind has blown)

<Table> Inlet condition

Case	Wind velocity(m/s)	Wave height(m)	Period(sec)	Wave length(m)
Case 1	45	1.256	4	24.9724
Case 2	30	1.091	4	24.9724

Results

- Simulation movie (Case 1, Wind velocity = 45 m/s)
  - The floating structure moves up and down by wave propagation.
  - The stress distribution occurred from the movement.



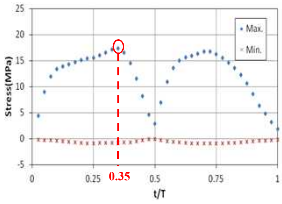
Results

- Case 1(Wind velocity = 45 m/s)
  - Stress

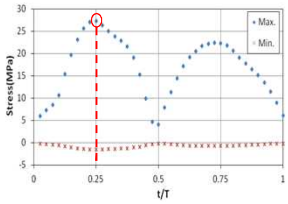
t/T	Principal Stress 1(MPa)		Principal Stress 3(MPa)		Von Mises Stress(MPa)
	Max.	Min.	Max.	Min.	Max.
0.00	5.90	-0.28	8.30	-0.25	8.92
0.10	13.32	-0.40	10.59	-0.61	12.30
0.20	15.08	-0.88	25.53	-1.51	23.60
0.25	15.45	-0.93	27.20	-1.60	25.13
0.30	16.54	-0.87	24.90	-1.51	23.02
0.35	17.30	-0.83	22.84	-1.40	21.12
0.40	14.45	-0.70	19.04	-1.18	17.61
0.50	2.81	-0.19	3.95	-0.24	4.15
0.60	14.96	-0.79	17.04	-0.62	18.60
0.70	16.70	-0.98	22.09	-0.81	23.62
0.75	16.20	-0.96	22.24	-0.81	23.48
0.80	14.52	-0.87	20.59	-0.75	21.58
0.90	8.57	-0.58	15.02	-0.51	16.21
1.00	1.77	-0.21	6.00	-0.27	6.45

Results

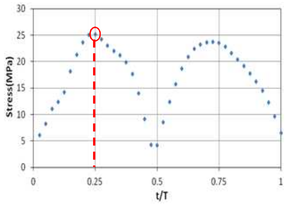
- Case 1
  - Stress(◯ : Maximum value)



Principal Stress 1(Tensile)



Principal Stress 3(Compressive)



Von Mises Stress 1(Equivalent)

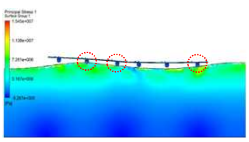
✓Maximum tensile stress occurred at 0.35 T.

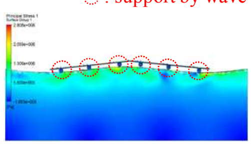
✓Maximum compressive and equivalent stress occurred at 0.25 T.

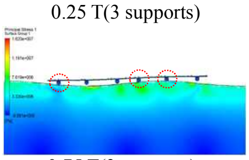
Results

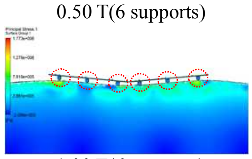
- Case 1
  - Vertical location by variation of phase

◌ : support by wave


0.25 T(3 supports)


0.50 T(6 supports)


0.75 T(3 supports)

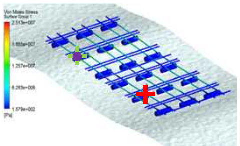

1.00 T(6 supports)

✓Larger stress occurred when the number of supports was smaller(0.25T, 0.75T).

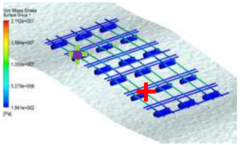
✓Minimum stress occurred when the position of connecting hinge was the highest and lowest(0.50T, 1.00T).

Results

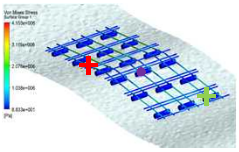
- Case 1
  - Location of maximum Stress by variation of phase



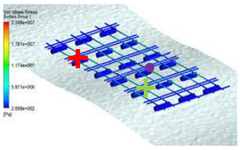
0.25 T



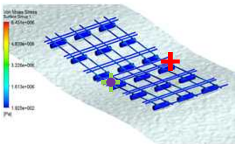
0.35 T



0.50 T



0.75 T



1.00 T

+ : **tensile**
+ : **compressive**
• : **equivalent**

✓Maximum stress position is connecting point between connector and upper frame.

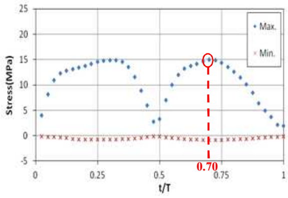
Results

- Case 2(Wind velocity = 30 m/s)
  - Stress

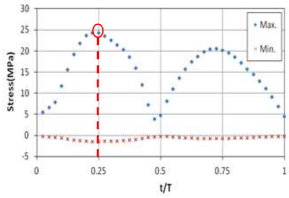
t/T	Principal Stress 1(MPa)		Principal Stress 3(MPa)		Von Mises Stress(MPa)
	Max.	Min.	Max.	Min.	Max.
0.00	4.65	-0.27	7.69	-0.22	8.31
0.10	12.29	-0.39	11.66	-0.65	11.40
0.20	13.73	-0.81	23.59	-1.38	21.81
0.25	14.53	-0.85	24.20	-1.45	22.37
0.30	14.87	-0.80	22.53	-1.37	20.83
0.35	14.53	-0.74	20.22	-1.25	18.70
0.40	11.51	-0.59	15.91	-0.99	14.72
0.50	3.19	-0.22	4.67	-0.24	4.98
0.60	13.17	-0.73	15.71	-0.58	17.15
0.70	14.92	-0.90	20.36	-0.74	21.58
0.75	14.28	-0.87	20.20	-0.73	21.33
0.80	12.54	-0.79	18.49	-0.67	19.40
0.90	6.34	-0.49	12.78	-0.43	13.80
1.00	1.89	-0.17	4.53	-0.31	4.77

Results

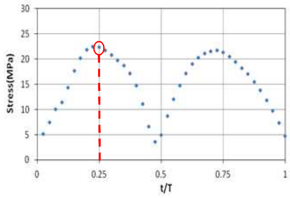
- Case 2
  - Stress(○ : Maximum value)



Principal Stress 1(Tensile)



Principal Stress 3(Compressive)



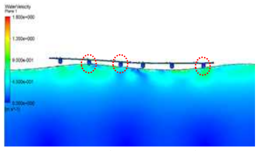
Von Mises Stress 1(Equivalent)

✓Maximum tensile stress occurred at 0.70 T.
✓Maximum compressive and equivalent stress occurred at 0.25 T.
✓Tendency of Case 2 was similar to Case 1.

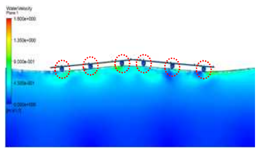
Results

- Case 2
  - Vertical location by variation of phase

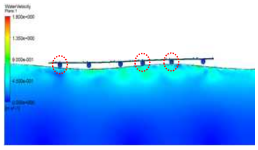
○ : support by wave



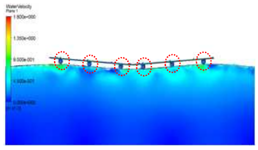
0.25 T(3 supports)



0.50 T(6 supports)



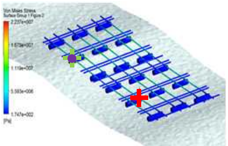
0.75 T(3 supports)



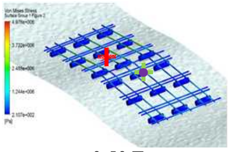
1.00 T(6 supports)

Results

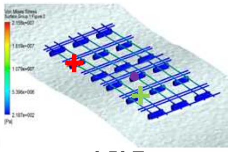
- Case 2
  - Location of maximum Stress by variation of phase



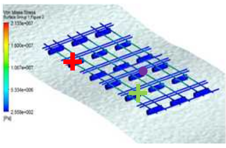
0.25 T



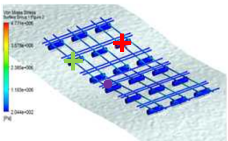
0.50 T



0.70 T



0.75 T



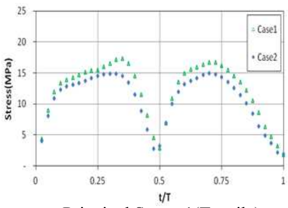
1.00 T

+ : tensile
+ : compressive
• : equivalent

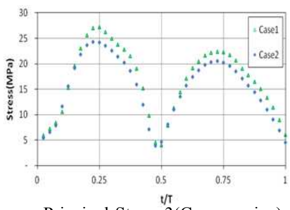
✓Maximum stress position is connecting point between connector and upper frame.

Results

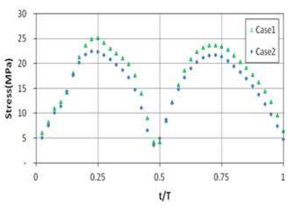
- Comparison between cases
  - Maximum stress



Principal Stress 1(Tensile)



Principal Stress 3(Compressive)



Von Mises Stress 1(Equivalent)

✓ Stresses at Case 1 averagely occurred 7.9~9.5% lager than at Case 2.

Conclusion and Future works

- Conclusion
  - Maximum stress value increases as the wave height is large.
    - Wave height increases from 1.091 m to 1.256 m, Maximum stress increases 7.9~9.5 %.
  - Minimum stress occurred when the position of connecting hinge joint was the highest and lowest.
  - Maximum stress position is connecting point between connector and upper frame.
- Future works
  - Analysis including solar cell
  - Analysis of floating structure in flow
  - Evaluating safety of connecting hinge joint

Conclusion

Conclusion

- In case of the vibration of gate opening, numerical results are similar to them from hydraulic experiments.

  ⇒ The applicability of FSI was confirmed.
- Analysis of Multiphase flow and Dynamical behavior of structures are conducted simultaneously with FSI method. Therefore, the applicability of FSI can be extended overall, however, simulation time excessively increase and higher performance of hardware is needed.

  ⇒ Consideration of efficiency and cost-effectiveness is required.
- Fully coupled analysis may not available with ANSYS-CFD.

⇒ Until now, FSI method is utilized qualitatively in the limited field.

Reference

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Thank you for your attention.
Q & A