The 6th OpenFOAM Korea Users' Community Conference

해양플랜트를 위한 플랫폼거동-계류계 연성해석 솔버 개발

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INDEX

1. 서론

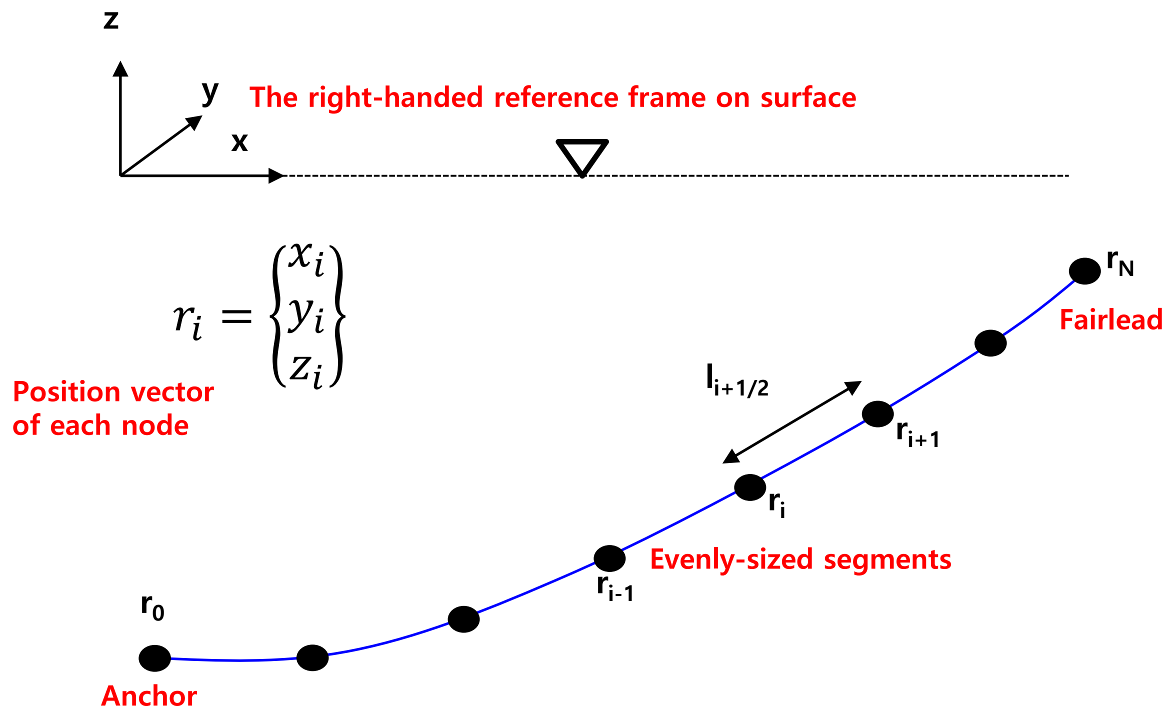
□ 연구배경

- 대부분의 상용 계류계해석 코드는 플랫폼거동에 대해서 potential 이론을 적용하고 있음
- 플랫폼의 거동을 계산하는데 있어서 플랫폼 주변의 점성효과에 대해서 고려할 수 없음

□ 연구목적

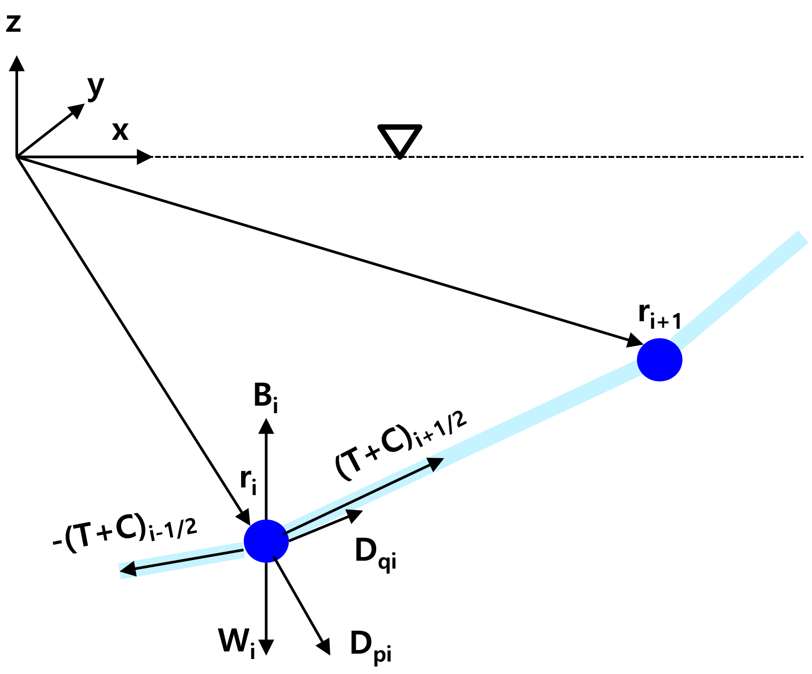
- 계류계해석 라이브러리 개발
- 점성유동에 기초한 플랫폼거동-계류계 양방향 연성해석 솔버 개발

□ 집중질량 모델 (Hall and Goupee, 2015)



- 등간격으로 나뉜 분절(segment)들은 동일한 물성치를 갖음
  - 길이 (l), 직경 (d), 밀도 (ρ), 탄성계수 (E), 내부감쇠계수 (C_{int})

□ 집중질량 모델 (Hall and Goupee, 2015) (계속)



- 내력
  - 내부 인장력 (T)
  - 내부 감쇠력 (C)
  - 집중질량 (W)
  - 부력은 집중질량에 포함하여 계산

- 외력
  - 횡단방향의 항력 (D_p)
  - 접선방향의 항력 (D_q)
  - 횡단방향의 부가질량력 (a_p)
  - 접선방향의 부가질량력 (a_q)
  - 해저면과의 접촉력 (B)

□ 집중질량 모델 - 내력

집중질량 및 부력

$$W_{i+(1/2)} = \frac{\pi}{4} d^2 l(\rho_w - \rho)g$$

$$W_i = \frac{1}{2}\left(W_{i+(1/2)} + W_{i-(1/2)}\right)\hat{e}_z$$

내부 인장력

$$T_{i+(1/2)} = E\frac{\pi}{4}d^2\left(\frac{\|r_{i+1} - r_i\|}{l} - 1\right)\left(\frac{r_{i+1} - r_i}{\|r_{i+1} - r_i\|}\right)$$

내부 감쇠력

$$C_{i+(1/2)} = C_{int}\frac{\pi}{4}d^2\dot{\epsilon}_{i+(1/2)}\left(\frac{r_{i+1} - r_i}{\|r_{i+1} - r_i\|}\right)$$

□ 집중질량 모델 - 외력

횡단방향의 항력

$$D_{p_i} = \frac{1}{2}\rho_w C_{dn} dl \|(\dot{r}_i \cdot \hat{q}_i)\hat{q}_i - \dot{r}_i\| [(\dot{r}_i \cdot \hat{q}_i)\hat{q}_i - \dot{r}_i]$$

접석방향의 항력

$$D_{q_i} = \frac{1}{2}\rho_w C_{dt} \pi dl \|(-\dot{r}_i \cdot \hat{q}_i)\hat{q}_i\| [(-\dot{r}_i \cdot \hat{q}_i)\hat{q}_i]$$

횡단방향의 부가질량력

$$a_{p_i}\ddot{r}_i = \rho_w C_{an} \frac{\pi}{4} d^2 l [(\ddot{r}_i \cdot \hat{q}_i)\hat{q}_i - \ddot{r}_i]$$

접선방향의 부가질량력

$$a_{q_i}\ddot{r}_i = \rho_w C_{at} \frac{\pi}{4} d^2 l [(-\ddot{r}_i \cdot \hat{q}_i)\hat{q}_i]$$

해저면과의 접촉력

$$B_i = dl[(z_{bot} - z_i)k_b - \dot{z}_i c_b]\hat{e}_z$$

□ 집중질량 모델 - 절점의 운동방정식

집중질량 $m_i = \frac{\pi}{4} d^2 l \rho I$

부가질량 $a_i = a_{p_i} + a_{q_i} = \rho_w \frac{\pi}{4} d^2 l \left[C_{an} \left(I - \hat{q}_i \hat{q}_i{}^T \right) + C_{at} \left(\hat{q}_i \hat{q}_i{}^T \right) \right]$

절점의 운동방정식

$$[m_i + a_i]\, \ddot{r}_i = T_{i+(1/2)} - T_{i-(1/2)} + C_{i+(1/2)} - C_{i-(1/2)} + W_i + B_i + D_{p_i} + D_{q_i}$$

Mass & Added Mass | Internal Stiffness & Internal Damping | Weight & Bottom Contact | Drag

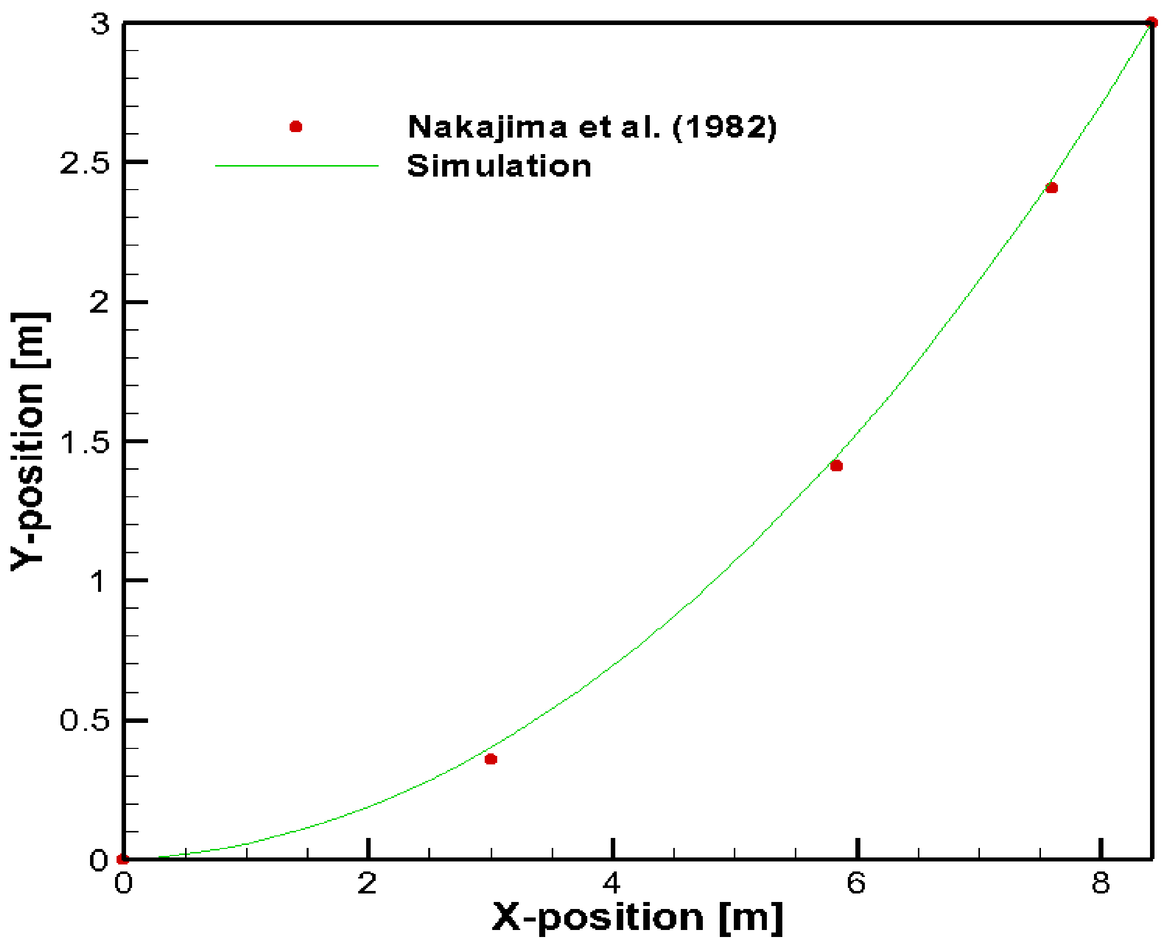
3. 계류계해석 라이브러리의 검증

□ 계류계 정적 하중 검증 (Irvine, 1981)

Length from Anchor [m]	Exact Solution [N]	Mooring Module [N]	Error [%]
S = 55.55	655,966	656,119	0.02%
S = 111.10	726,777	726,170	0.08%
S = 166.65	822,934	821,526	0.17%
S = 222.20	936,663	934,420	0.24%
S = 277.75	1,062,335	1,059,250	0.29%
S = 333.30	1,196,193	1,192,310	0.32%
S = 388.85	1,335,778	1,331,210	0.34%
S = 444.40	1,479,469	1,474,390	0.34%
S = 500.00	1,626,178	1,620,780	0.33%

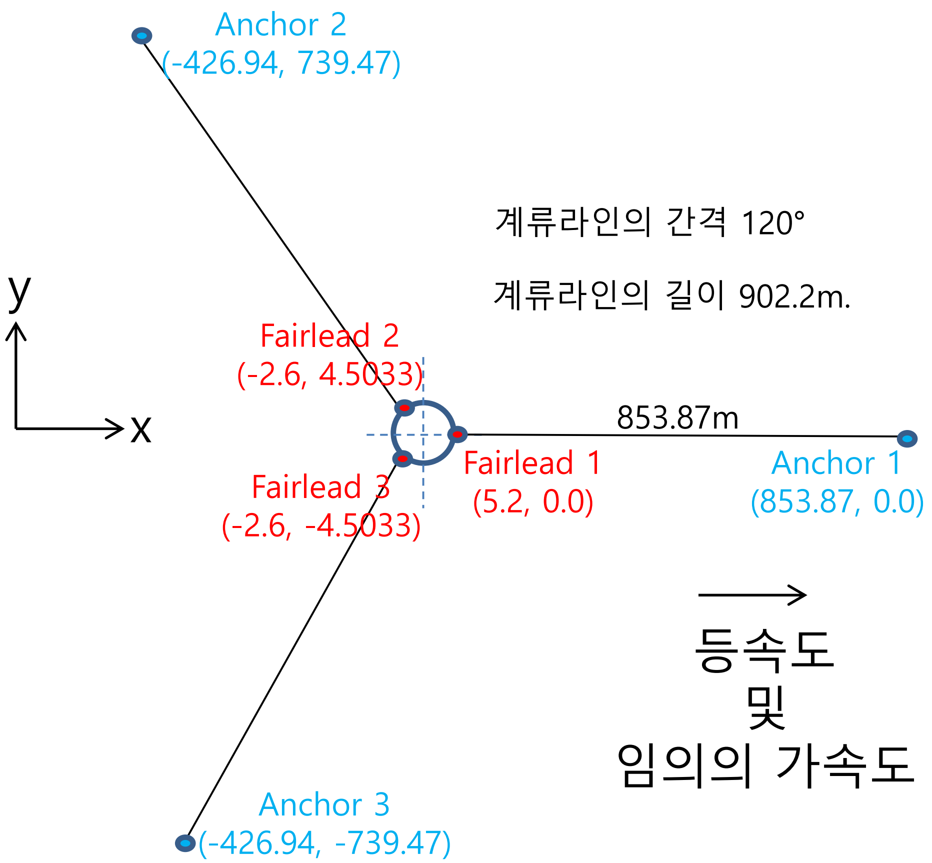
3. 계류계해석 라이브러리의 검증

□ 절점 위치 검증 (Nakajima et al., 1982)

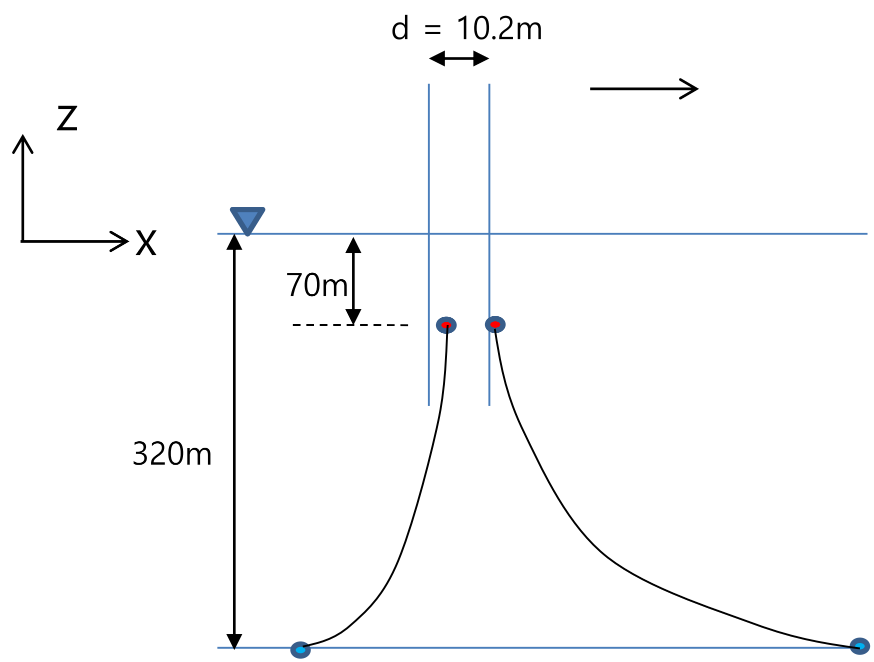


3. 계류계해석 라이브러리의 검증

□ 계류계 동적 하중 검증

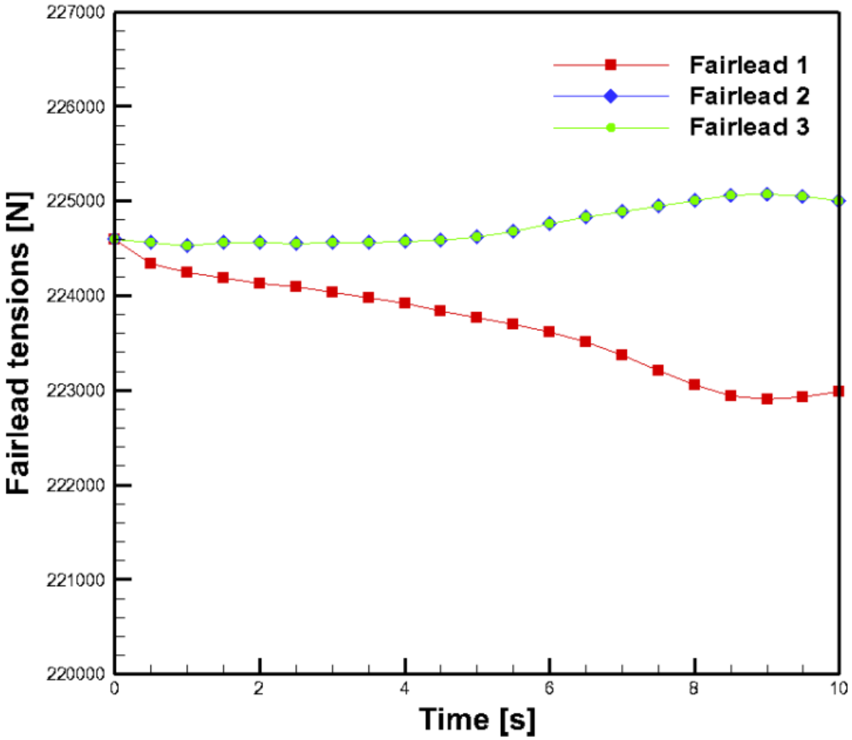


평면도

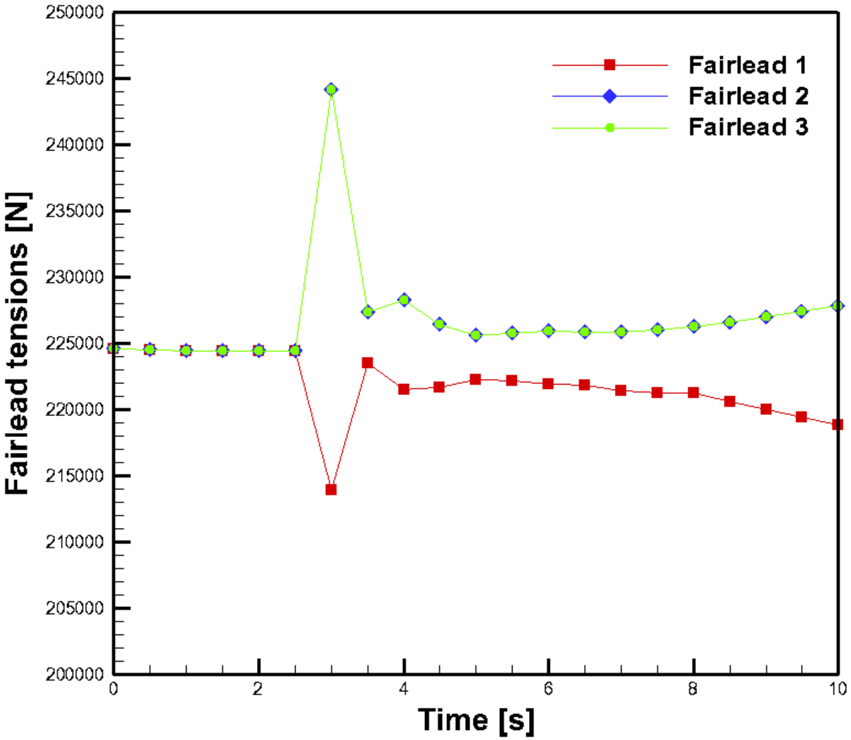


측면도

□ 계류계 동적 하중 검증 (계속)



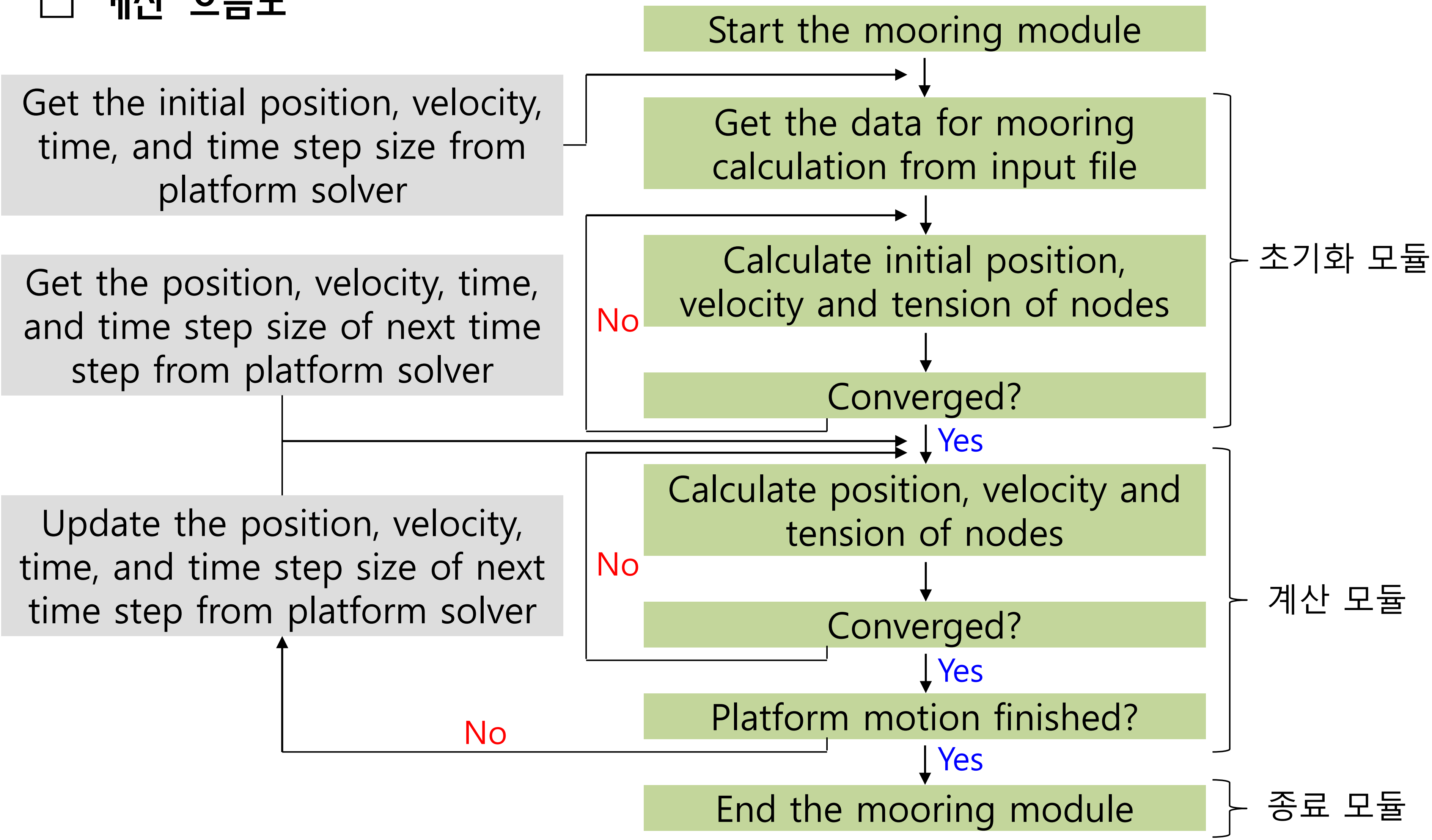
등속도



임의의 가속도

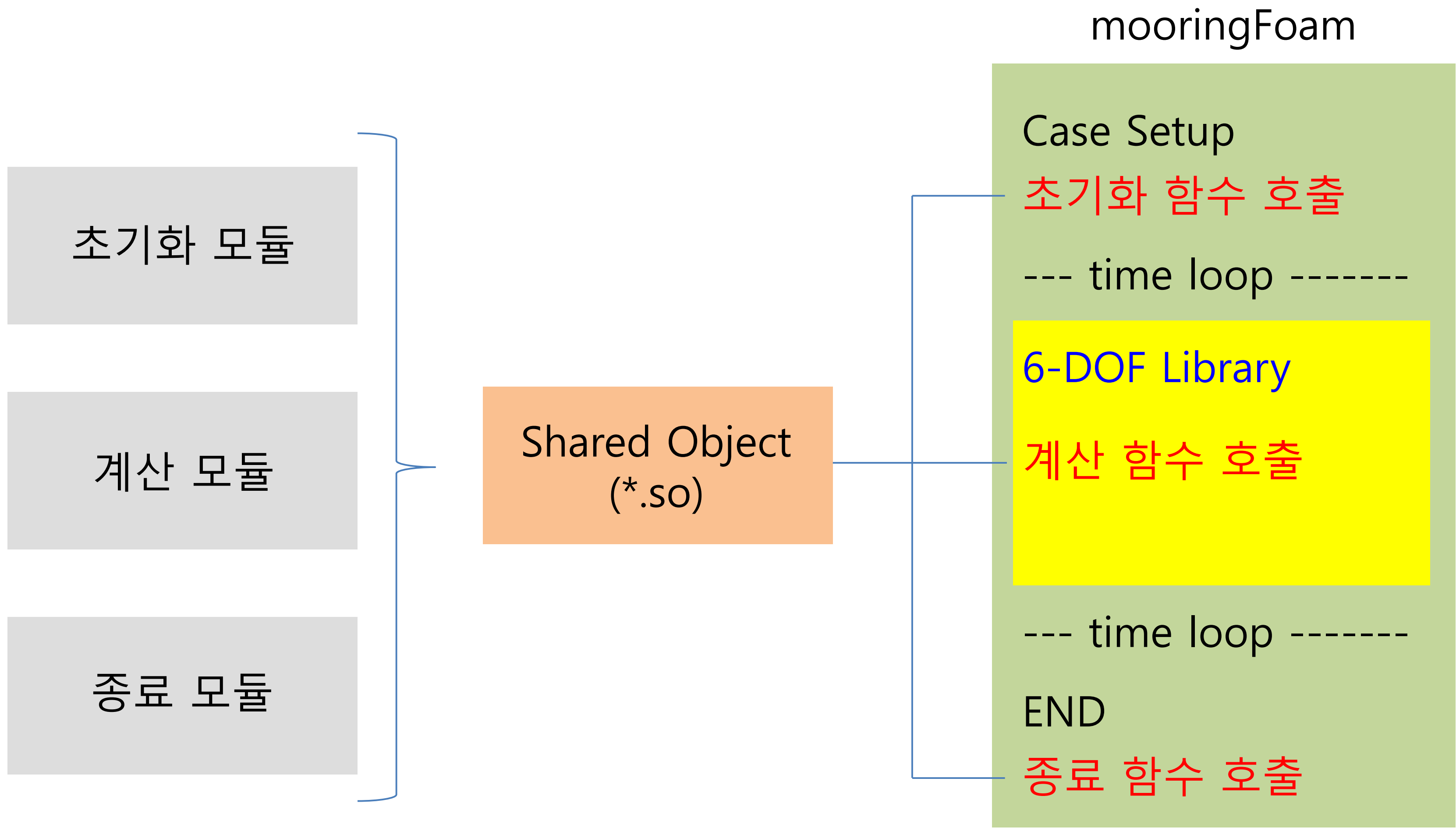
4. 플랫폼거동-계류계 연성해석

□ 계산 흐름도

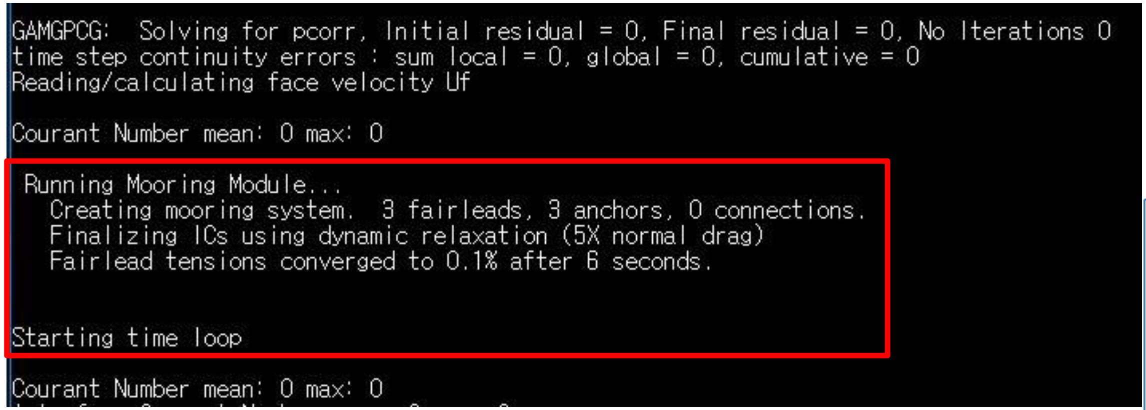


4. 플랫폼거동-계류계 연성해석

□ OpenFOAM과의 양방향 연성

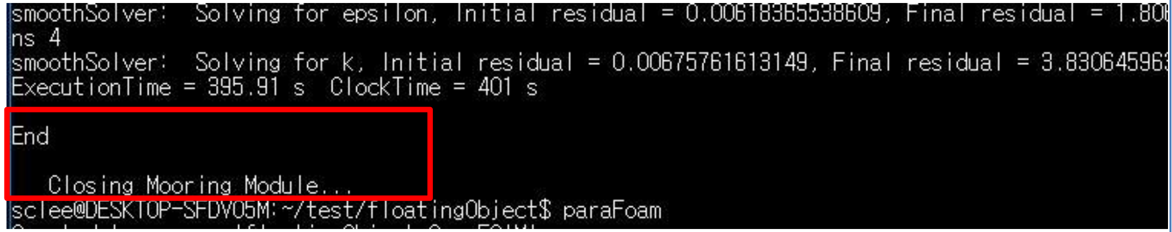


□ OpenFOAM과의 양방향 연성 (계속)



```
GAMGPCG:  Solving for pcorr, Initial residual = 0, Final residual = 0, No Iterations 0
time step continuity errors : sum local = 0, global = 0, cumulative = 0
Reading/calculating face velocity Uf

Courant Number mean: 0 max: 0

 Running Mooring Module...
   Creating mooring system.  3 fairleads, 3 anchors, 0 connections.
   Finalizing ICs using dynamic relaxation (5X normal drag)
   Fairlead tensions converged to 0.1% after 6 seconds.


Starting time loop

Courant Number mean: 0 max: 0
```

Shared Object
(*.so)

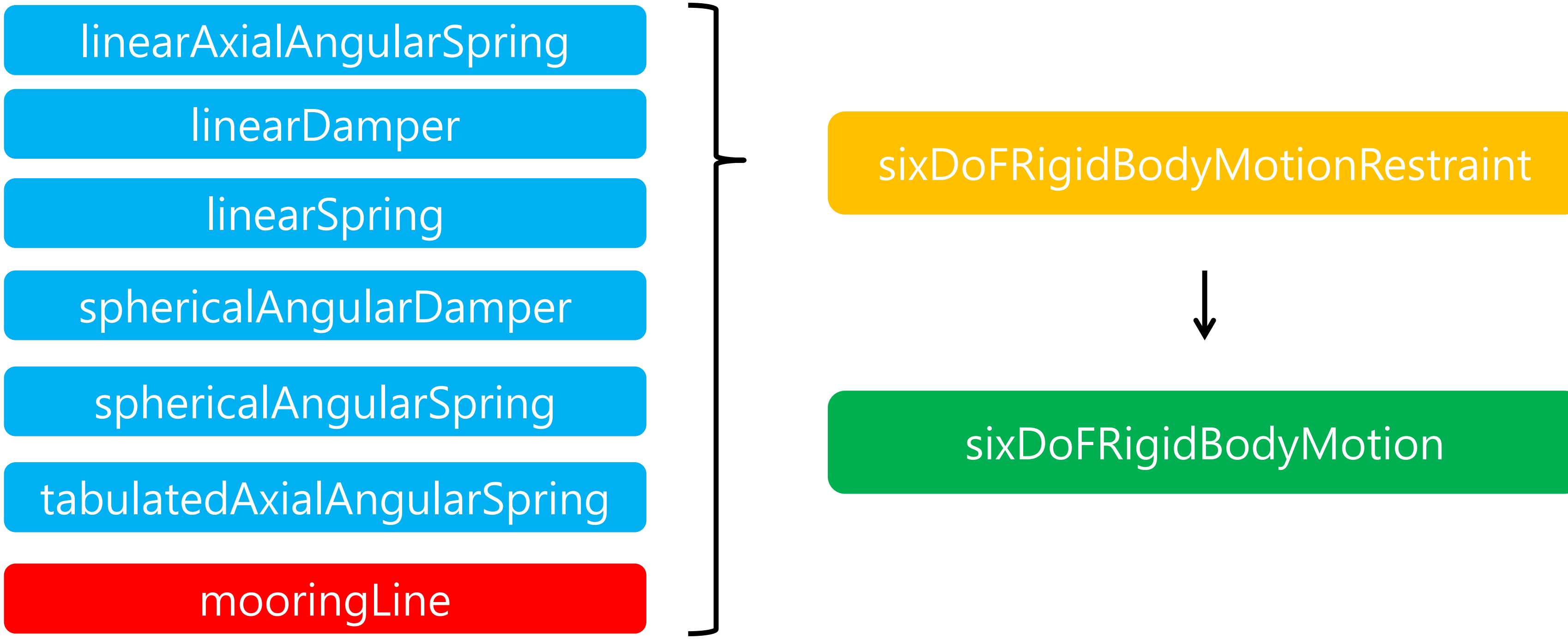


```
smoothSolver:  Solving for epsilon, Initial residual = 0.00618365538609, Final residual = 1.80
ns 4
smoothSolver:  Solving for k, Initial residual = 0.00675761613149, Final residual = 3.83064596
ExecutionTime = 395.91 s  ClockTime = 401 s

End

  Closing Mooring Module...
sclee@DESKTOP-SFDV05M:~/test/floatingObject$ paraFoam
```

mooringFoam

Case Setup
Call I-Function
--- time loop -------
6-DOF Library
Call C-Function
--- time loop -------
END
Call T-Function

□ OpenFOAM과의 양방향 연성 (계속)



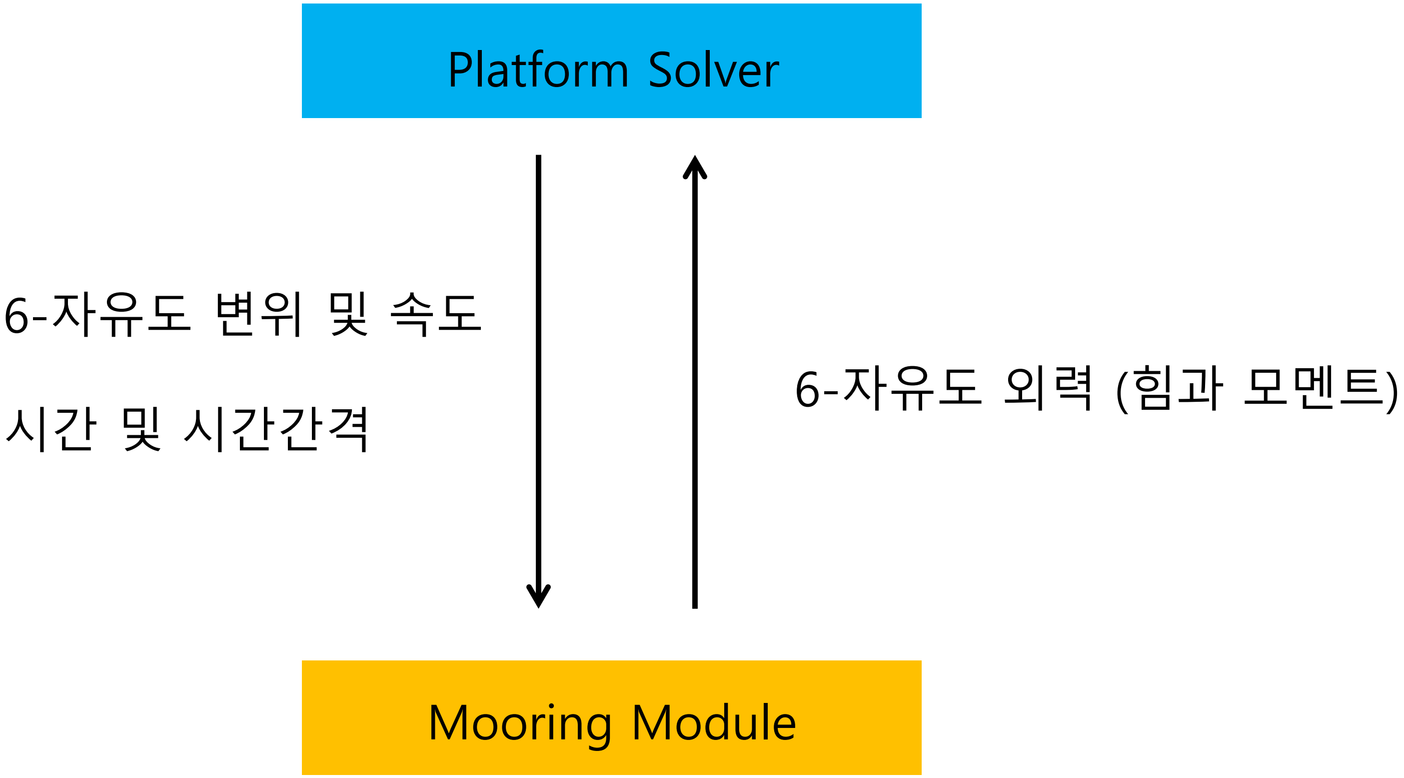

```
sclee@master:~/OpenFOAM/sclee-4.1/src/mooringSixDoFRigidBodyMotion/sixDoFRigidBo
dyMotion/restraints$ ls
linearAxialAngularSpring   sixDoFRigidBodyMotionRestraint
linearDamper               sphericalAngularDamper
linearSpring               sphericalAngularSpring
mooringLine                tabulatedAxialAngularSpring
```

□ OpenFOAM과의 양방향 연성 (계속)

대표적인 restraint 모델들 및 restraint( ) 함수의 인수들

	motion	rP	rF	rM
linear spring	need	- Used for the force calculation - Forces are acting on this point - motion.transform(refAttachmentPt_)'	calculate	no use
angular springs	need	- Not used for the moment calculation - Moments are acting on this point - motion.centreOfRotation()'	no use	calculate
linear damper	need	- Never used in the model - Use initialized value in 'appyRestraints()'	calculate	no use
angular damper	need	- Never used in the model - Use initialized value in 'appyRestraints()'	no use	calculate

□ OpenFOAM과의 양방향 연성 (계속)



□ OpenFOAM과의 양방향 연성 (계속)

Mooring module에서는 net mooring force & moment를 하나의 배열로 생성

- mooring line 1
- mooring line 2
- mooring line 3

} Flines = (Fx, Fy, Fz, Mx, My, Mz)

OpenFOAM에서는 모든 restraint의 계산결과를 합산하여 하나의 힘(가속도)과 모멘트로 표현하고 이를 플랫폼의 운동에 대한 외력으로 적용

- restraint 1
- restraint 2
- restraint 3

} One restraint force (or acceleration) vector
&
One restraint moment vector

□ OpenFOAM과의 양방향 연성 (계속)

constant/dynamicMeshDict

```
    class       dictionary;
    object      motionProperties;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

dynamicFvMesh       dynamicMotionSolverFvMesh;

motionSolverLibs    ("libmooringSixDoFRigidBodyMotion.so");

solver              sixDoFRigidBodyMotion;

sixDoFRigidBodyMotionCoeffs
{
    patches         (cylinder);


    restraints
    {
        mooring1
        {
            sixDoFRigidBodyMotionRestraint mooringLine;

            anchor      (6.9325 0 -0.9);
            refAttachmentPt     (0.3865 0 0);
        }
    }
```

- mooringLine 모델을 포함한 라이브러리
- 하나의 restraint 모델만 사용

□ OpenFOAM과의 양방향 연성 (계속)

Mooring/lines.txt

```
---------------------- LINE DICTIONARY ---------------------------------------------------
LineType  Diam     MassDenInAir    EA         BA/-zeta     Can      Cat     Cdn     Cdt
(-)       (m)        (kg/m)        (N)        (Pa-s/-)     (-)      (-)     (-)     (-)
main      4.786E-3  0.1447        1.6E3        -0.95       3.8      0.0     2.5     0.5
---------------------- NODE PROPERTIES ---------------------------------------------------
Node      Type      X         Y         Z         M        V        FX       FY      FZ     CdA    CA
(-)       (-)      (m)       (m)       (m)      (kg)     (m^3)     (kN)     (kN)    (kN)   (m^2)  (-)
1         Fix     -6.9325    0        -0.9       0        0        0        0       0      0      0
2         Fix      3.4663   6.0037    -0.9       0        0        0        0       0      0      0
3         Fix      3.4663  -6.0037    -0.9       0        0        0        0       0      0      0
4         Vessel  -0.2725    0.0      0.096      0        0        0        0       0      0      0
5         Vessel   0.1363    0.236    0.096      0        0        0        0       0      0      0
6         Vessel   0.1363   -0.236    0.096      0        0        0        0       0      0      0
---------------------- LINE PROPERTIES ---------------------------------------------------
Line     LineType  UnstrLen  NumSegs   NodeAnch  NodeFair  Flags/Outputs
(-)       (-)       (m)        (-)       (-)       (-)       (-)
1        main      6.95       100        1         4        ptcsd
2        main      6.95       100        2         5        ptcsd
3        main      6.95       100        3         6        ptcsd
```

□ 디렉토리 구조

Case Directory

- 0
- constant
- system
- Mooring (input & output files)
- Results directories

솔버 시작 전

```
sclee@DESKTOP-SFDV05M:~/test/floatingObject/Mooring$ ls
lines.txt
sclee@DESKTOP-SFDV05M:~/test/floatingObject/Mooring$ cd ..
```

솔버 시작 후

```
sclee@DESKTOP-SFDV05M:~/test/floatingObject/Mooring$ ls
Line1.out  Line2.out  Line3.out  Lines.out  lines.txt
sclee@DESKTOP-SFDV05M:~/test/floatingObject/Mooring$
```

□ 양방향 연성해석 검증

Paredes et al. (2016)

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Experimental investigation of mooring configurations for wave energy converters

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A R T I C L E I N F O

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Compact moorings
Catenary

A B S T R A C T

Mooring systems are required to keep floating wave energy converters (WECs) on station. The mooring concept might impact the performance of the WEC, its cost and its integrity. With the aim of clarifying the pros and cons of different mooring designs, we present the results from physical model experiments of three different mooring concepts in regular and irregular waves, including operational and survival conditions. The parameters investigated are the tension in the cables, the motions of the device in the different degrees of freedom and the seabed footprint in each case. We can see that the mooring system affects the performance of the wave energy converter, but the magnitude of the impact depends on the parameter analysed, on the mode of motion studied and on the conditions of the sea. Moreover, different configurations have similar performances in some situations and the choice of one over another might come down to factors such as the type of soil of the seabed, the spacing desired between devices, or environmental impacts. The results of our experiments provide information for a better selection of the mooring system for a wave energy converter when several constraints are taken into account (power production, maximum displacements, extreme tensions, etc).

1. Introduction

A good mooring system for a floating wave energy converter must not only ensure the survivability of the device, but also account for its effects on the motions and on the power take-off. Furthermore, the moorings should be easy to monitor and maintain, while minimising material and installation costs. It is also desirable that the mooring system takes as little space as possible on the seabed, in order to allow the devices to be installed close to each other in parks, something that usually is not important or allowed for other offshore structures.

Because of the differences between wave energy converter concepts, the mooring system employed must be tailored to the particular needs of each technology concept. Therefore, varied solutions for mooring systems of wave energy converters have been proposed. The diversity of solutions occurs even for similar devices. For example, in [1] a mooring system composed of taut synthetic cables is suggested for the FLOW wave energy converter, a hinged attenuator, while in [2], the standard chain catenary is used for the DEXA, another hinged attenuator. The catenary is also used in the South West Mooring

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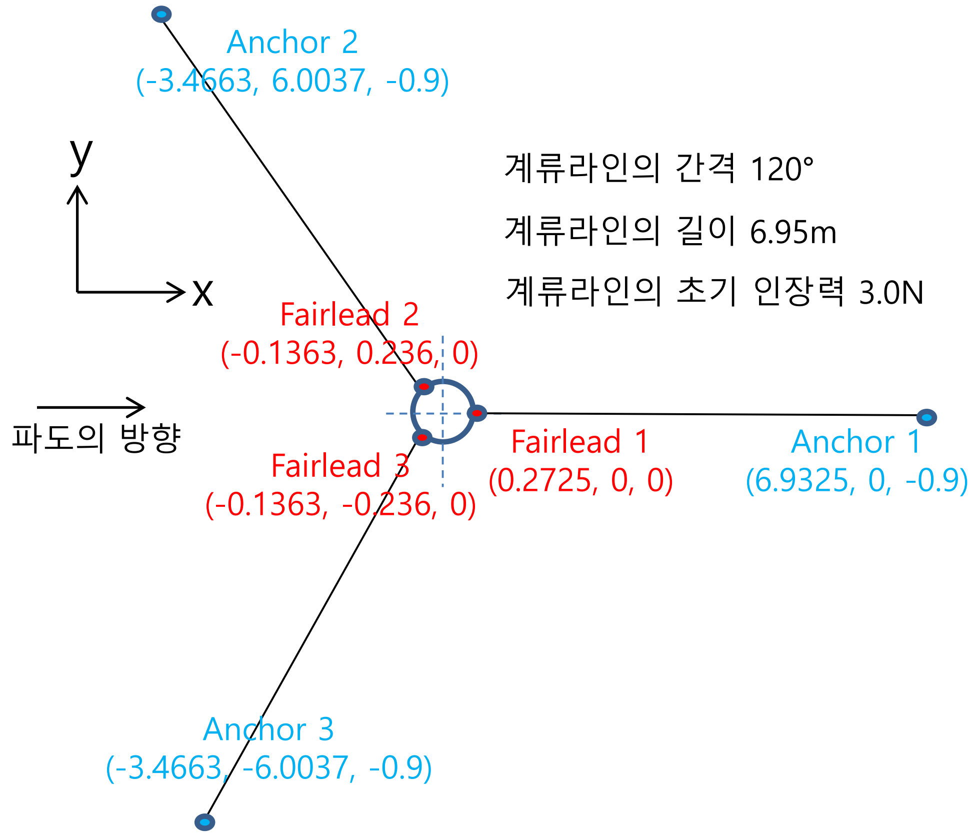


계류라인의 간격 120°

계류라인의 길이 6.95m

계류라인의 초기 인장력 3.0N

평형상태의 위치

☐ 양방향 연성해석 검증 (계속)

부유체 정보

직경 / 높이 : 0.515m(D) / 0.4m(H)

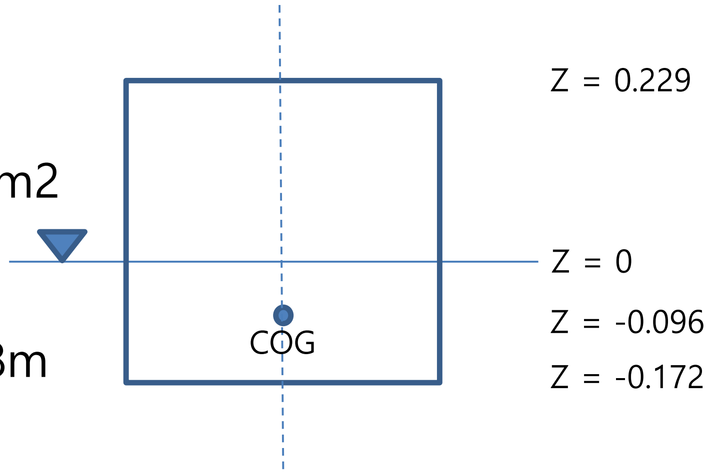
무게 / 관성모멘트 : 35.85kg / (0.9, 0.9, 1.1885)kgm2

초기 draft : 0.172m

COG의 위치 : 부유체의 바닥으로부터 위로 0.0758m

초기 surge offset : + 0.114m

초기 pitch offset : + 11.353°



계류라인(chain) 정보

길이 / 직경 / 무게 / EA : 6.95m / 4.786E-3m / 0.1447kg/m / 1.6E6N

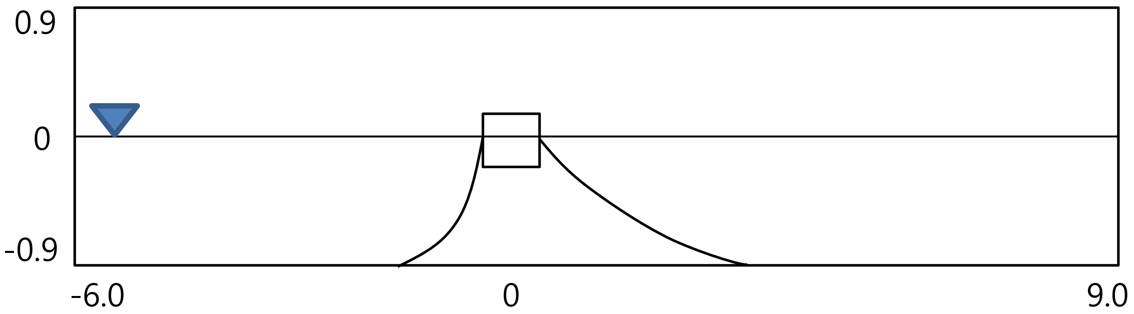
접선 및 법선방향의 부가질량계수 (Cat / Can) : 0 / 3.8

접선 및 법선방향의 항력계수 (Cdt / Cdn) : 0.5 / 2.5

바닥 접촉력 탄성계수/감쇠계수(ratio) : 300MPa/m / 1 (바닥마찰은 무시)

□ 양방향 연성해석 검증 (계속)

케이스 정보



경계조건

옆면 및 바닥 : wall

부유체 : moving wall

윗면 : atmosphere

솔버설정

솔버 : mooringFoam
(interDyMFoam)

난류모델 : RNG k-epsilon

O/F 시간간격 : 1E-3 초

Mooring 시간간격 : 1E-6 초

PIMPLE iteration : 1

격자정보

격자 수 : 4.0M

최초격자 높이 : 1.5mm

수치기법

시간항 : CrankNicolson

대류항 : TVD (vanLeer)

Gradient 및 확산항 : CD

□ 양방향 연성해석 검증 (계속)

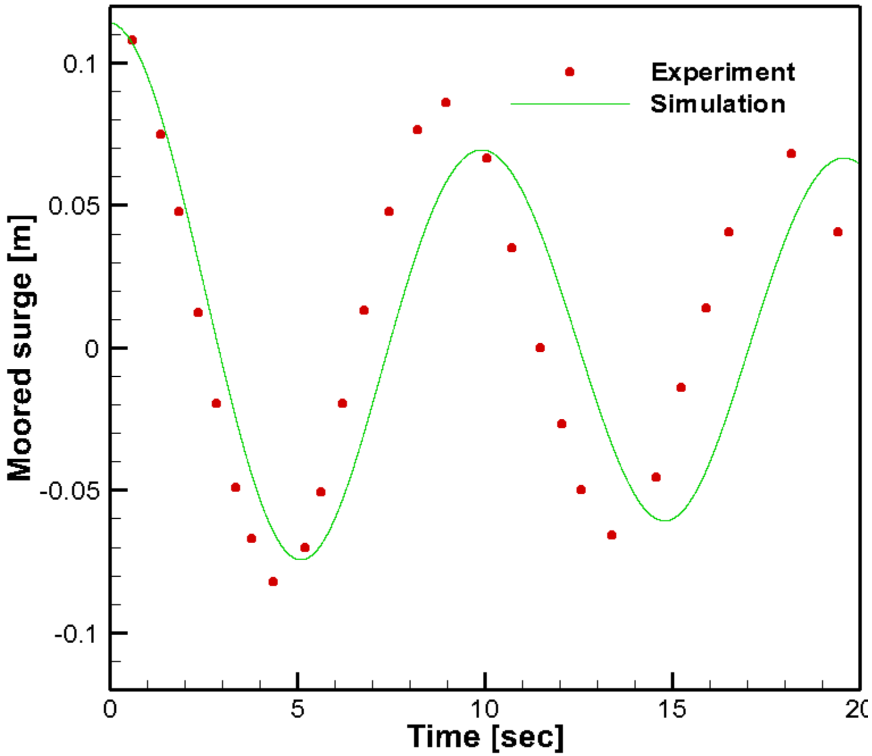
```
Interface Courant Number mean: 0.00648071134098
deltaT = 0.0125
Time = 5.975

PIMPLE: iteration 1
forces forces:
    Not including porosity effects
Restraint mooring1:  t = 5.975 , dt = 0.0125
 In the LinesCalc : dt = 0.0125, t = 5.975
```

```
Interface Courant Number mean: 0.00670517110035
deltaT = 0.0125
Time = 5.9875

PIMPLE: iteration 1
forces forces:
    Not including porosity effects
Restraint mooring1:  t = 5.9875 , dt = 0.0125
 In the LinesCalc : dt = 0.0125, t = 5.9875
```

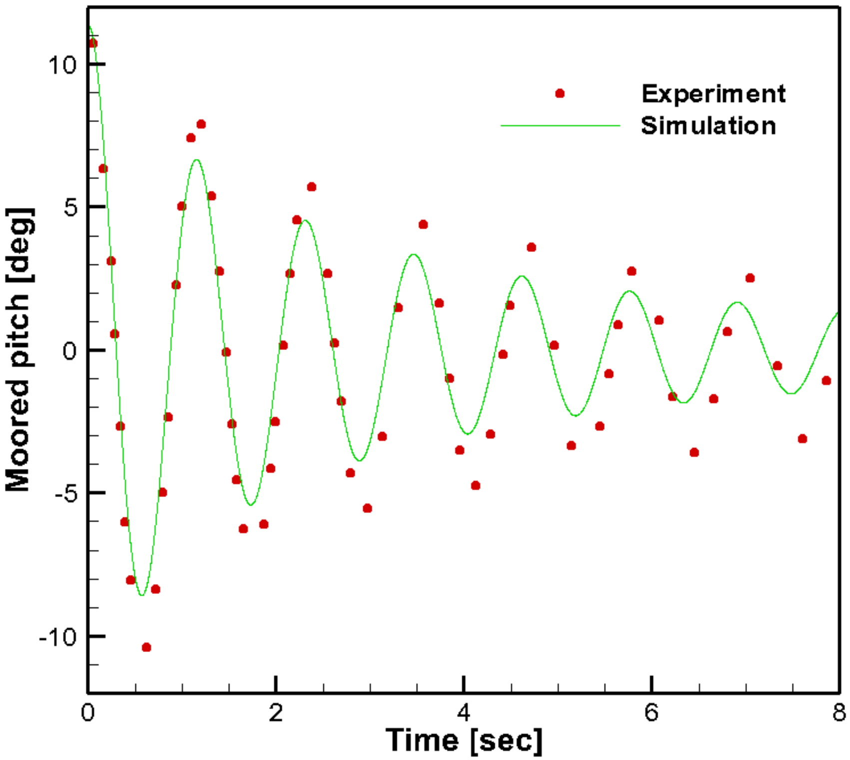
```
Interface Courant Number mean: 0.0067022157
deltaT = 0.0125
Time = 6

PIMPLE: iteration 1
forces forces:
    Not including porosity effects
Restraint mooring1:  t = 6 , dt = 0.0125
 In the LinesCalc : dt = 0.0125, t = 6
```

5.9375	130938	130565	130299
5.95	131309	130728	130369
5.9625	131708	130929	130479
5.975	132096	131130	130597
5.9875	132470	131325	130706
6	132887	131575	130878

□ 양방향 연성해석 검증 (계속)



moored surge: 0.114m



moored pitch: 11.353°

5. 결론

□ 결론

- 계류계 해석을 위한 라이브러리 개발
- OpenFOAM과의 양방향 연성해석 솔버 개발 및 검증 완료

□ 진행 사항

- 파랑 중 플랫폼거동과 계류계 인장하중의 양방향 연성해석에 대한 검증

THANK YOU

Q&A