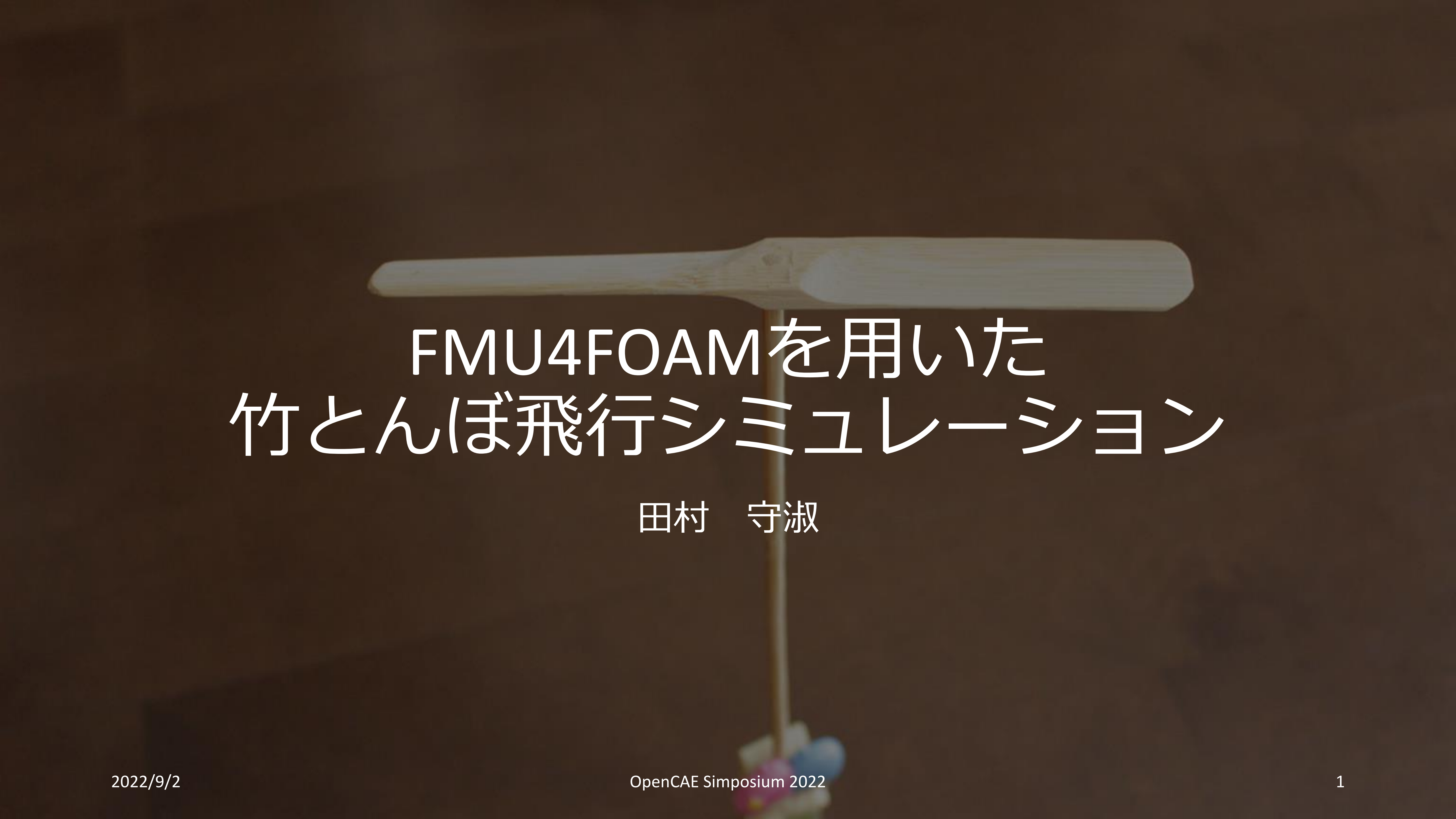
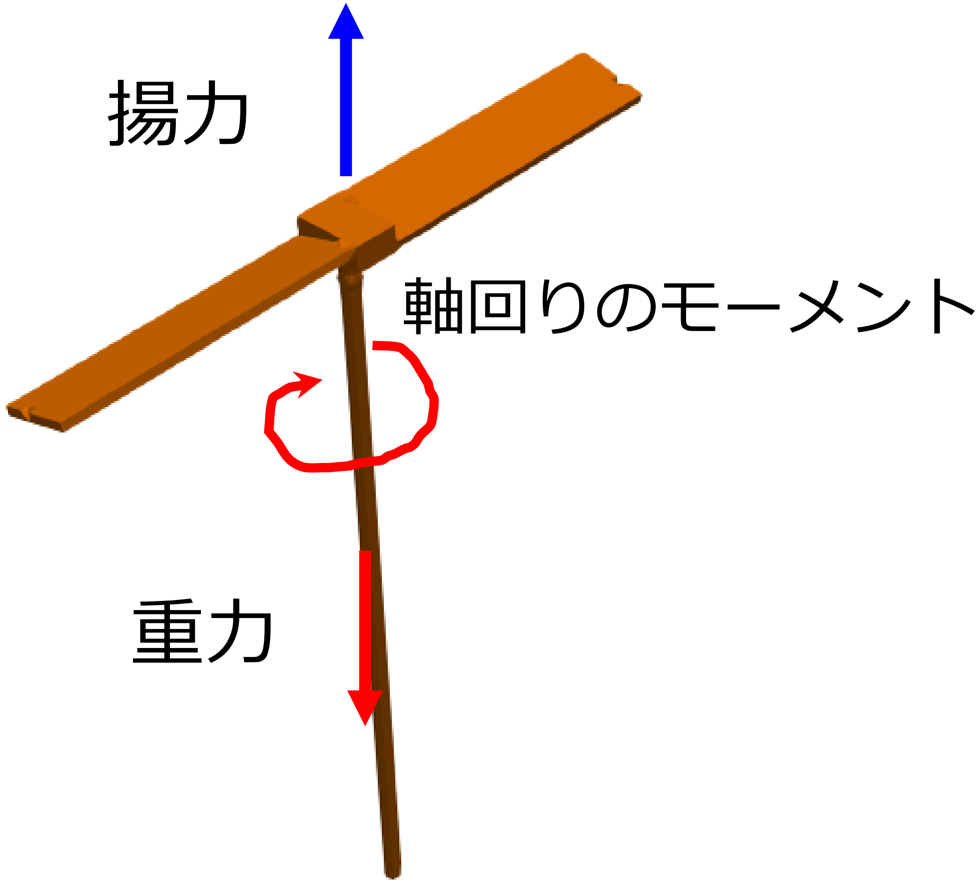


FMU4FOAMを用いた
竹とんぼ飛行シミュレーション

田村　守淑

はじめに



竹とんぼの飛行

回転による揚力　＞　重力

軸回りモーメントにより回転が減速

物体の非定常運動
→流体力学と剛体運動の連成シミュレーション

FMU4FOAM →　OpenFOAM + OpenModelica

どこまで高く飛ぶか？　どれくらい長く飛ぶか？

FMU4FOAM

https://pypi.org/project/FMU4FOAM/
by Henning Scheufler (DLR)

FMUs in OpenFOAM(OpenModelicaのfmuファイルと連成)

OpenFOAM® v2012 v2106

https://www.openfoam.com/

Co-Simulation ⟷ *.fmu

OpenModelica

https://www.openmodelica.org/

https://fmi-standard.org/

externalComm

<input 7+1 >

flowRateInlet, flowRateOutlet, unformValue, wallHeatFlux
accelarationSource
coupledTranslationMotion, externalCoupledForce
coupledRotatingMotion(New)

<output 3 >

extValue, extForces, extSensor

pyFMUSim

Interpretation →

OMSimulator

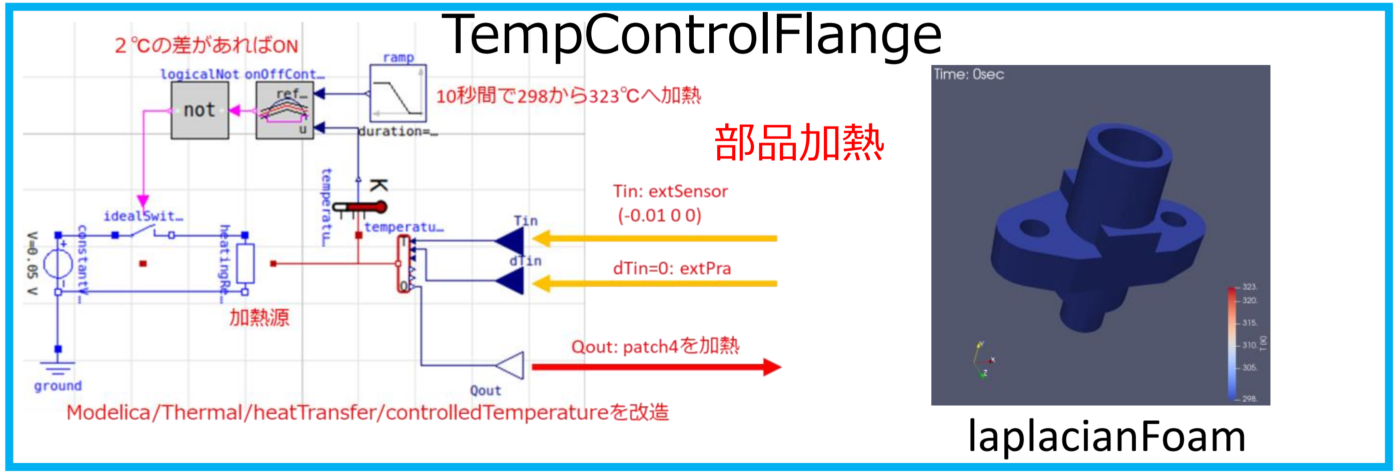
fmi Co-Simulation tool(python,lua)
Adams,Simulink, Beast,Dymola,OpenModelica

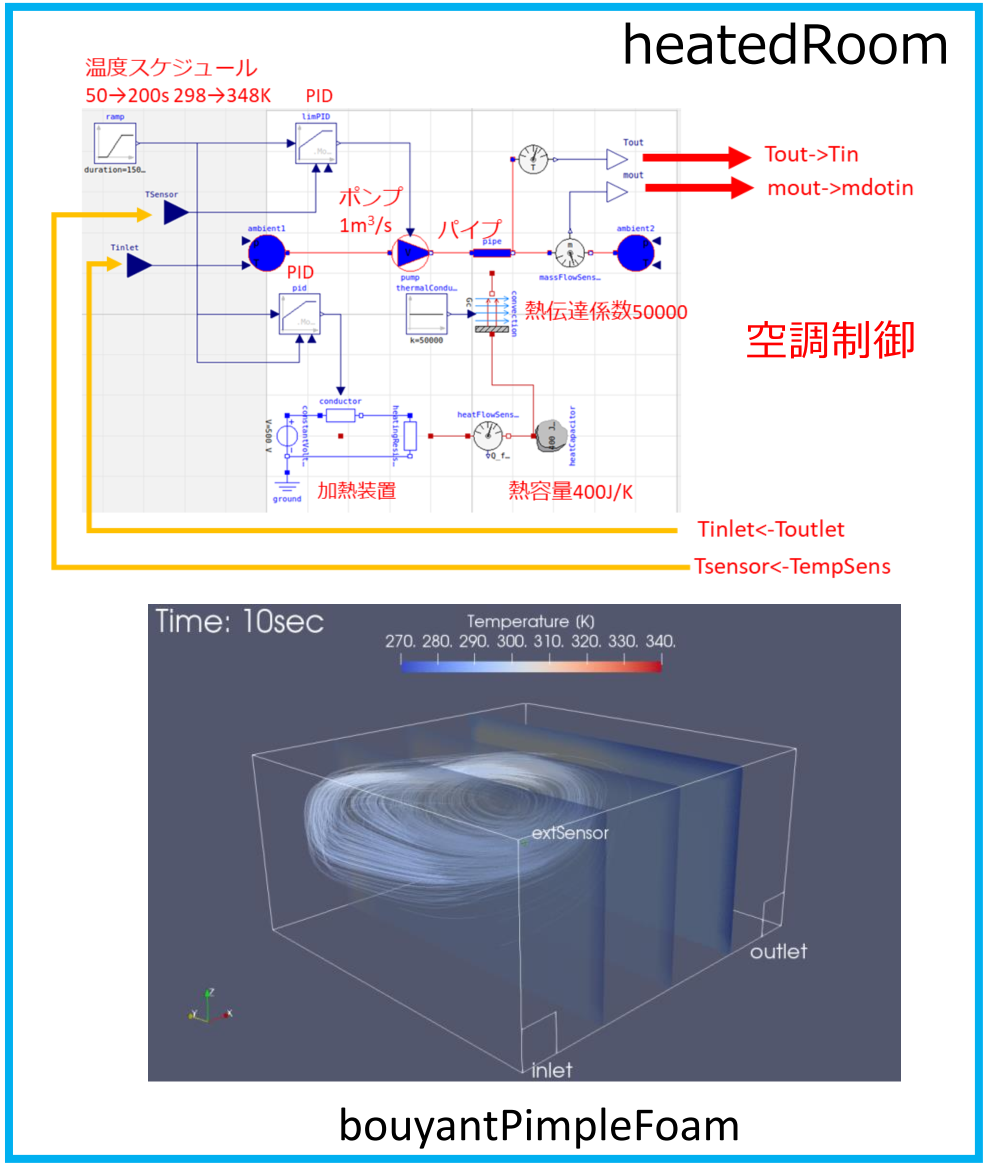
pyfm

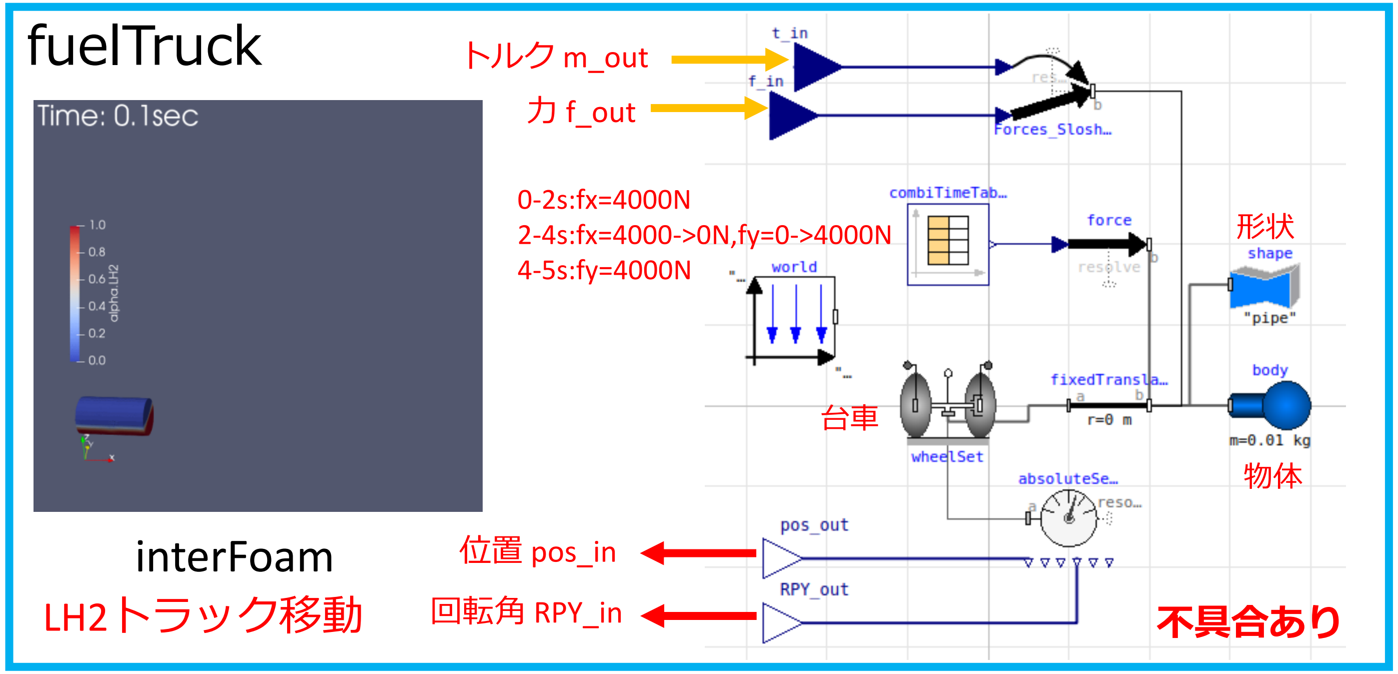
fmi python library
Co-Simulation, Model Exchange

FMU4FOAM/examples

https://pypi.org/project/FMU4FOAM/





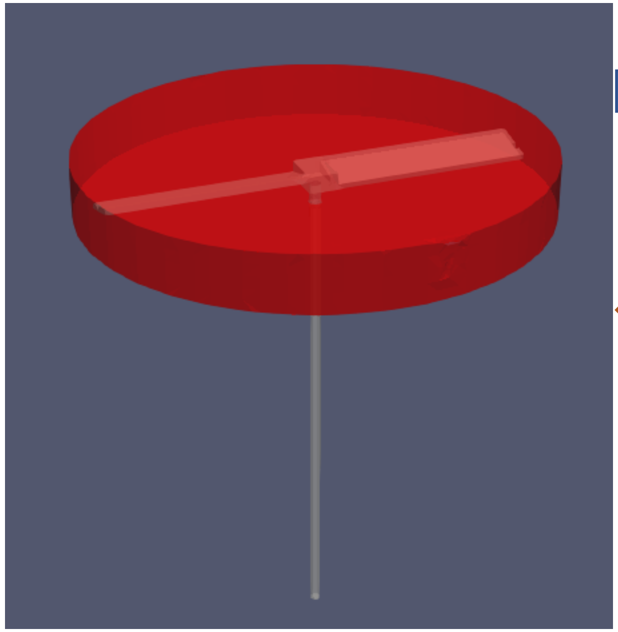


計算概要

竹とんぼの鉛直方向（Z方向）のみの運動を対象し,空力シミュレーションで揚力とトルクを取得し,剛体運動シミュレーションと連成

流体力学シミュレーション

空気中で赤の領域メッシュを回転



pimpleFoam
meshmotions: coupledRotatingMotion(*New*)

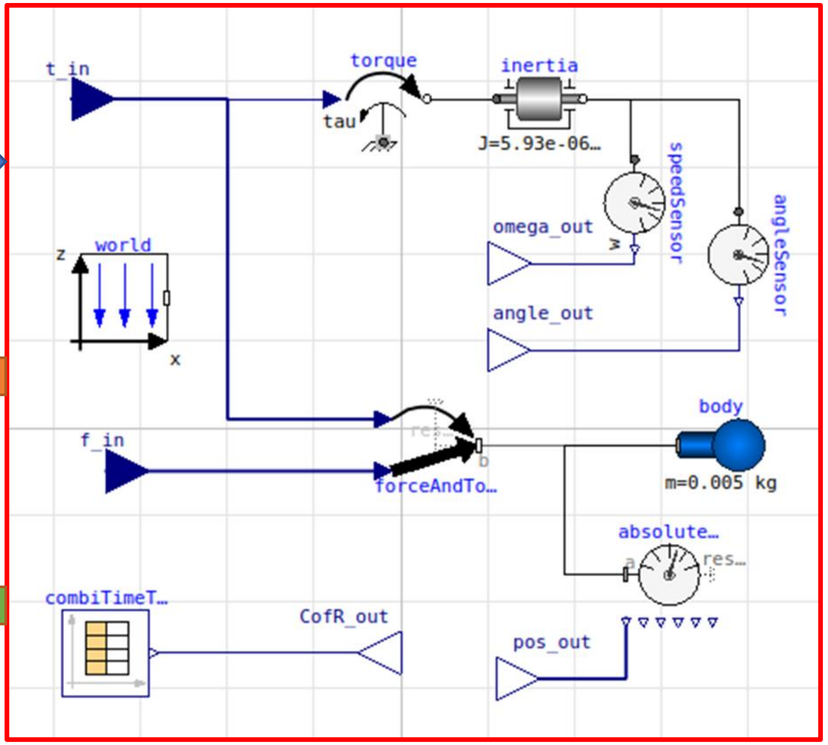
externalCoupledForce

力 f_in（fx,fy,fz）
トルク t_in (tx,ty,tz)

z軸角度 angle_out
回転中心CofR_out(x,y,z)

重心 pos_out(x,y,z)
角速度 omega_out

剛体運動シミュレーション



OpenModelica(FMU)

coupledRotatingMotion.C

rotatingMotion.Cを改造

commDataLayerクラス

ディクショナリ変数の取得

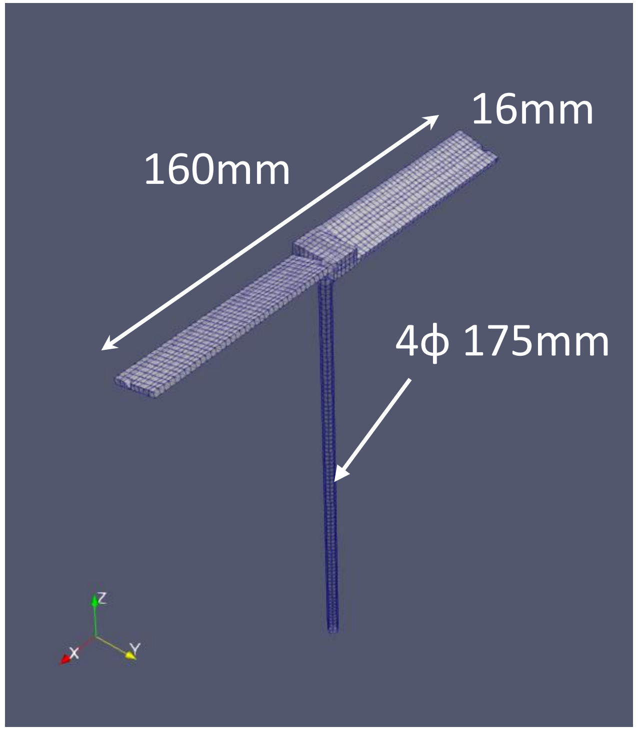
```
#include "coupledRotatingMotion.H"
#include "addToRunTimeSelectionTable.H"
#include "commDataLayer.H"

// * * * * * * * * * * * * * * Static Data Members * * * * * * * * * * * * * * //

namespace Foam
{
namespace solidBodyMotionFunctions
{
    defineTypeNameAndDebug(coupledRotatingMotion, 0);
    addToRunTimeSelectionTable
    (
        solidBodyMotionFunction,
        coupledRotatingMotion,
        dictionary
    );
}
}

// * * * * * * * * * * * * * * * * Constructors  * * * * * * * * * * * * * * //

Foam::solidBodyMotionFunctions::coupledRotatingMotion::coupledRotatingMotion
(
    const dictionary& SBMFCoeffs,
    const Time& runTime
)
:
    solidBodyMotionFunction(SBMFCoeffs, runTime),
    origin_(SBMFCoeffs_.get<vector>("origin")),
    axis_(SBMFCoeffs_.get<vector>("axis")),
  // omega_(Function1<scalar>::New("omega", SBMFCoeffs_)),
    omegaName_(SBMFCoeffs.get<word>("omegaName")),
    angleName_(SBMFCoeffs.get<word>("angleName"))

{
    read(SBMFCoeffs);
}
```

インプットデータ取得

インプットデータ保管

```
Foam::septernion
Foam::solidBodyMotionFunctions::coupledRotatingMotion::transformation() const
{
    scalar t = time_.value();

    commDataLayer& data = commDataLayer::New(time_);
    const scalar omega = data.getObj<scalar>(omegaName_,commDataLayer::causality::in);
    const scalar angle = data.getObj<scalar>(angleName_,commDataLayer::causality::in);

    // Rotation around axis

    Info << "omega = " << omega << endl;
    Info << "angle = " << angle << endl;

    //scalar angle = omega_->integrate(0, t);

    quaternion R(axis_, angle);
    septernion TR(septernion(-origin_)*R*septernion(origin_));

    DebugInFunction << "Time = " << t << " transformation: " << TR << endl;

    return TR;
}

bool Foam::solidBodyMotionFunctions::coupledRotatingMotion::read
(
    const dictionary& SBMFCoeffs
)
{
    solidBodyMotionFunction::read(SBMFCoeffs);

    commDataLayer& data = commDataLayer::New(time_);
    data.storeObj(omega_in_,omegaName_,commDataLayer::causality::in);
    data.storeObj(angle_in_,angleName_,commDataLayer::causality::in);

    /*
    omega_.reset
    (
        Function1<scalar>::New("omega", SBMFCoeffs_)
    );
    */

    return true;
}
```

OpenFOAM計算モデル概要

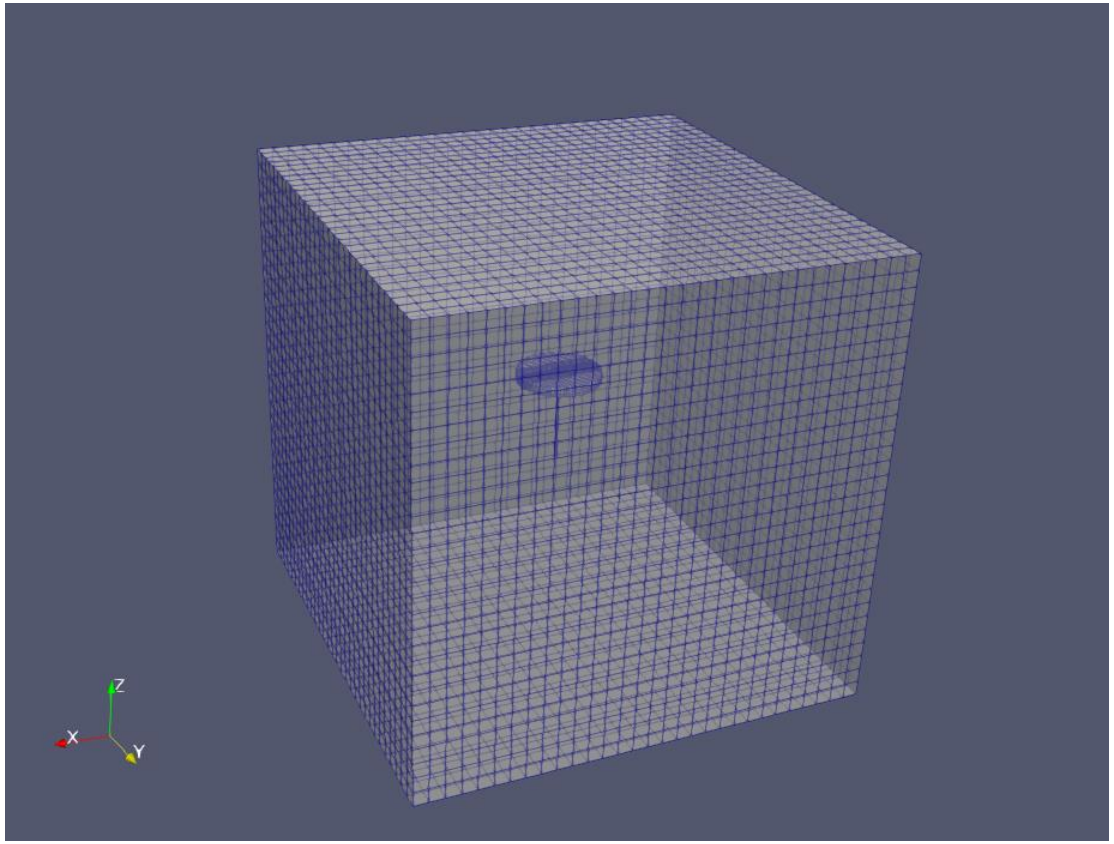


翼角度	15°
質量	0.005kg
重心	(0 0 -0.0253)
慣性モーメント	$0.0451kgm^2$

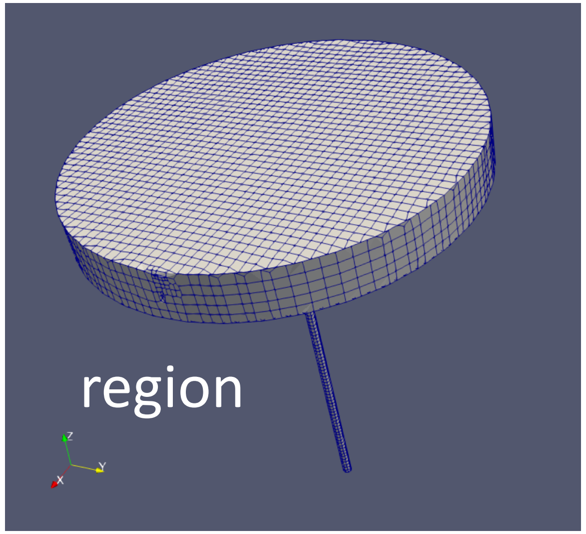
item	content
solver	pimpleFoam (openfoam_v2012)
dynamicFvMesh	fvMotionSolvers/solidBody coupledRotatingMotion
turbulent model	laminar
deltTime	2e-5sec
adjustTimestep	no　yesでは計算が不安定
endTime	2.25sec
rhoInfo	$1.2kg/m^3$
nu	$1.5e\text{-}5\ m^2/s$

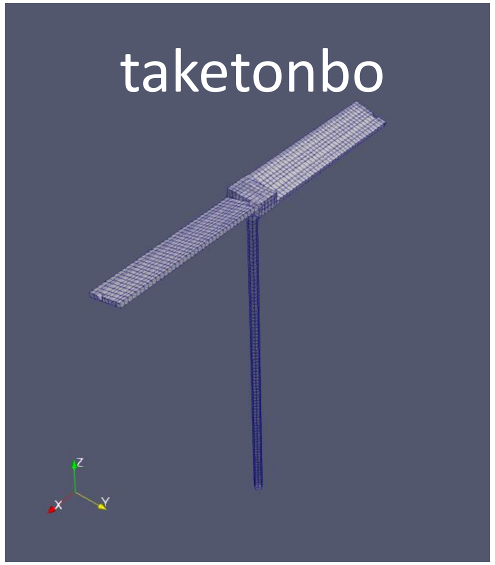
item	content
CPU	icore5 1cpu　並列計算が不能
Memory	8GBytes
Execution Time	53.2hour

mesh

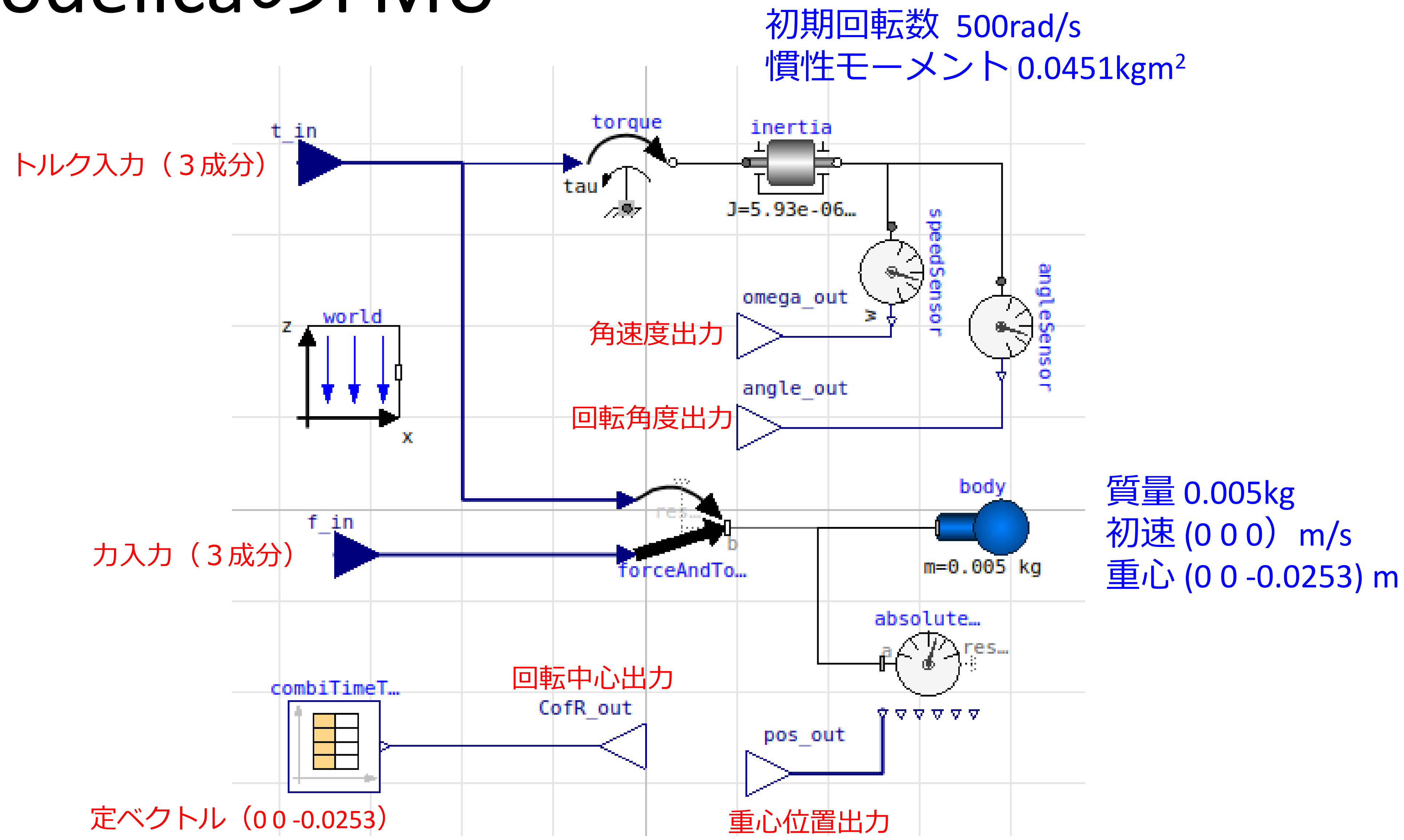


900×900×900mm　71280cells

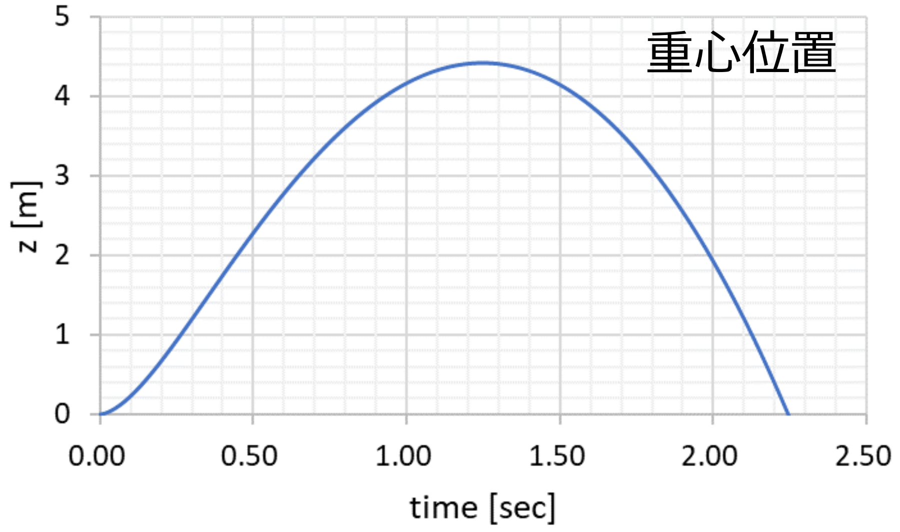


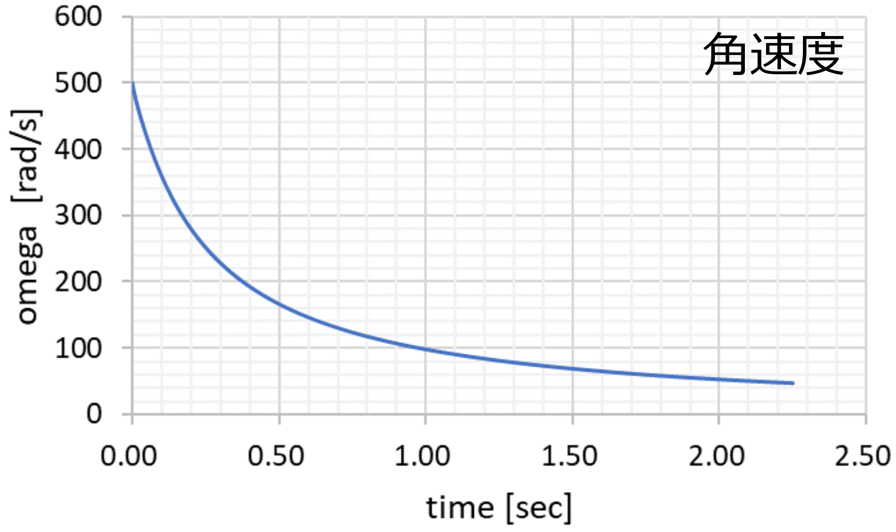


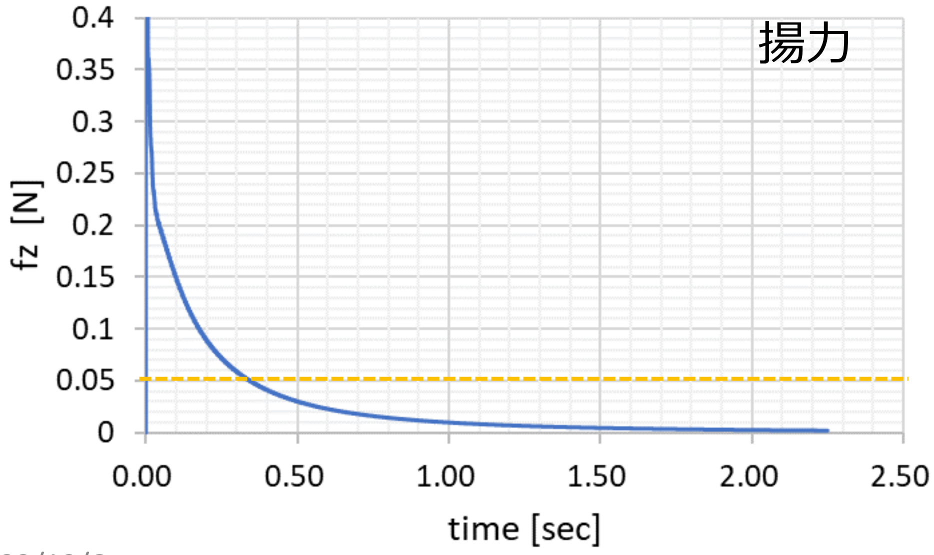
OpenModelicaのFMU

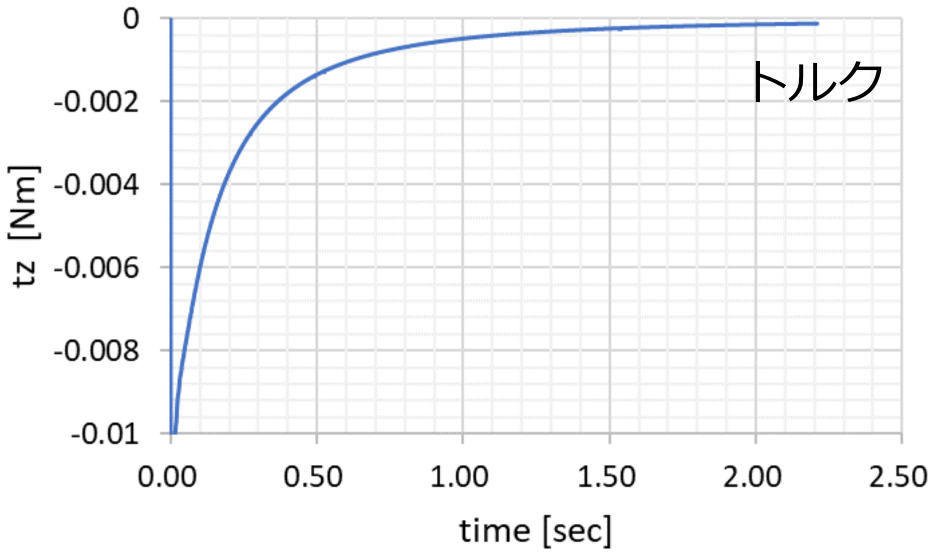


計算結果

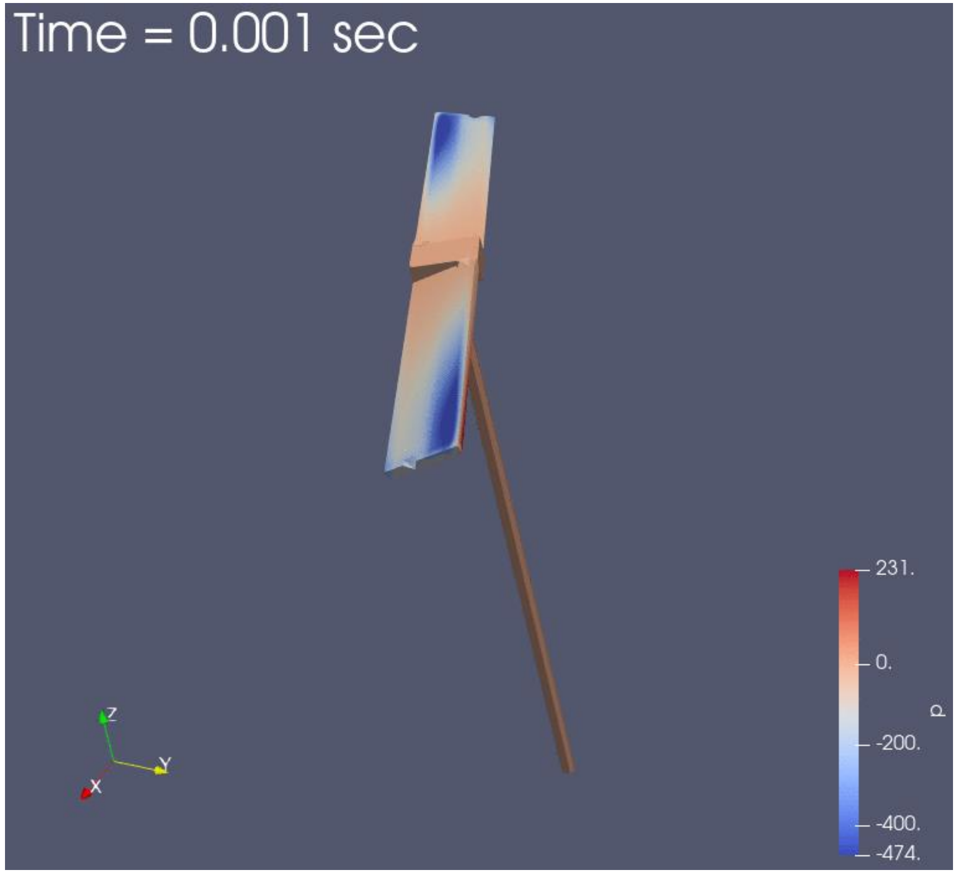

重心位置
z [m]
5
4
3
2
1
0
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]


角速度
omega [rad/s]
600
500
400
300
200
100
0
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]

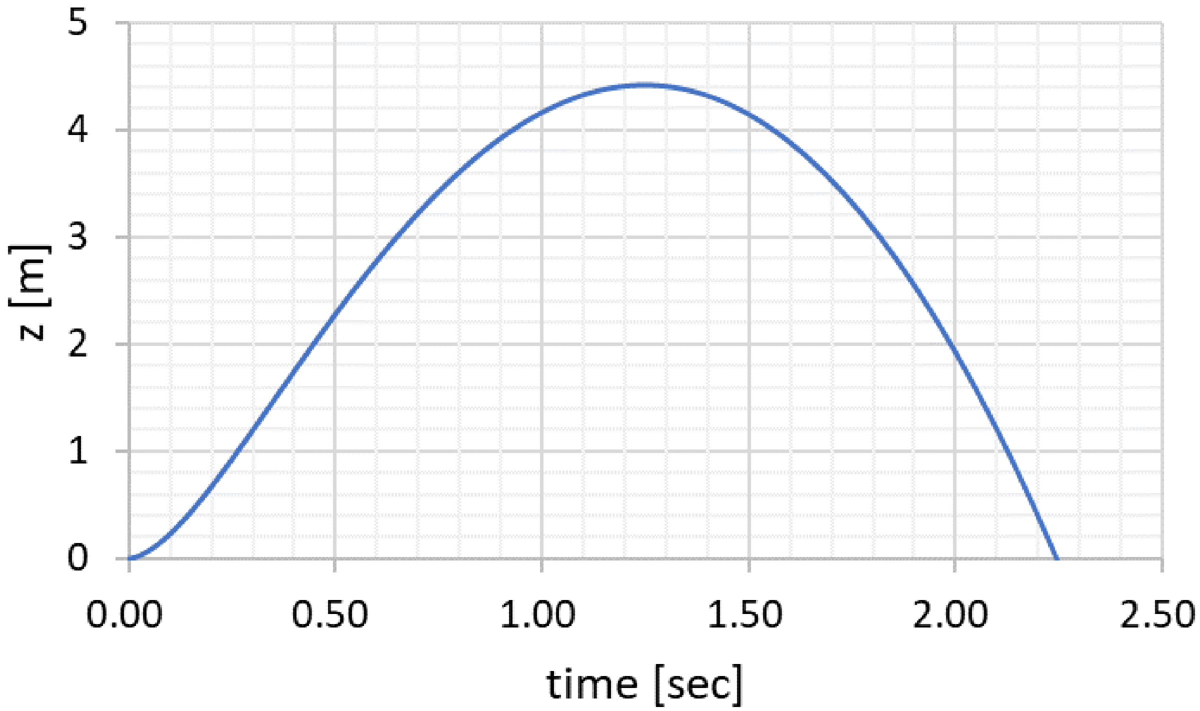

揚力
fz [N]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]


トルク
tz [Nm]
0
-0.002
-0.004
-0.006
-0.008
-0.01
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]

計算結果



最高高さ:4.42m
滞空時間:2.24sec



おわりに

- FMU4FOAMを用いて市販の形状の竹とんぼの飛行シミュレーションを行った.
- 流体力学シミュレーションはOpenFOAMのpimpleFoamソルバー,剛体運動はOpenModelicaを用いた.
- 竹とんぼの回転角度のデータ交換のため新たなクラスcoupledRotatingMotionを開発して用いた.
- adjustTimeStepの計算制御で計算が不安定化や並列計算が不能であるとの課題が判明
- 計算の結果,初期回転数が500rad/sの場合,最高飛行高さは４.42m,飛行時間は2.24秒であった.

補足資料

externalComm

- ✓ 外部データIOを制御するexternalCommライブラリはFMI Standardに似た構成で設計.
- ✓ commDataLayerクラスは３つのobjectRegistriesクラスがある

  commDataLayer::causality::in

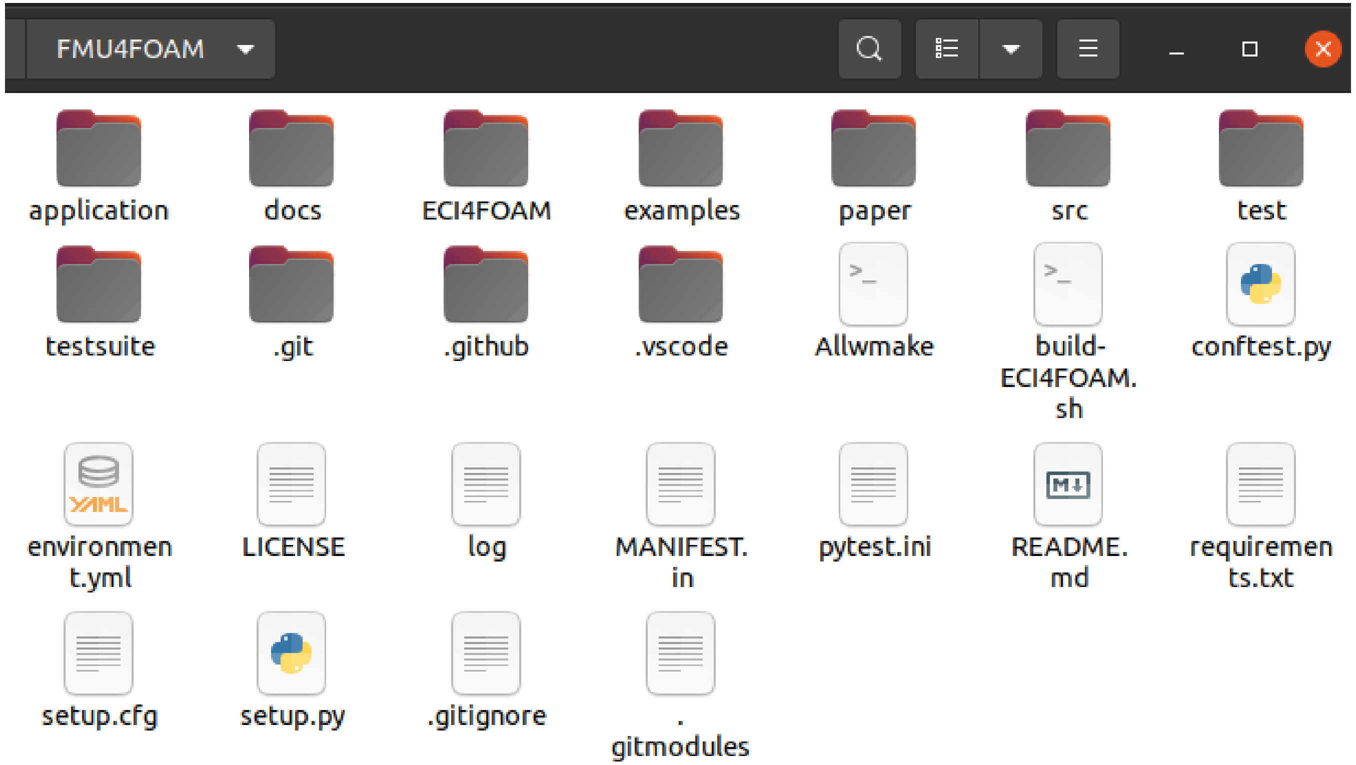
  commDataLayer::causality::parameter

  commDataLayer::causality::out

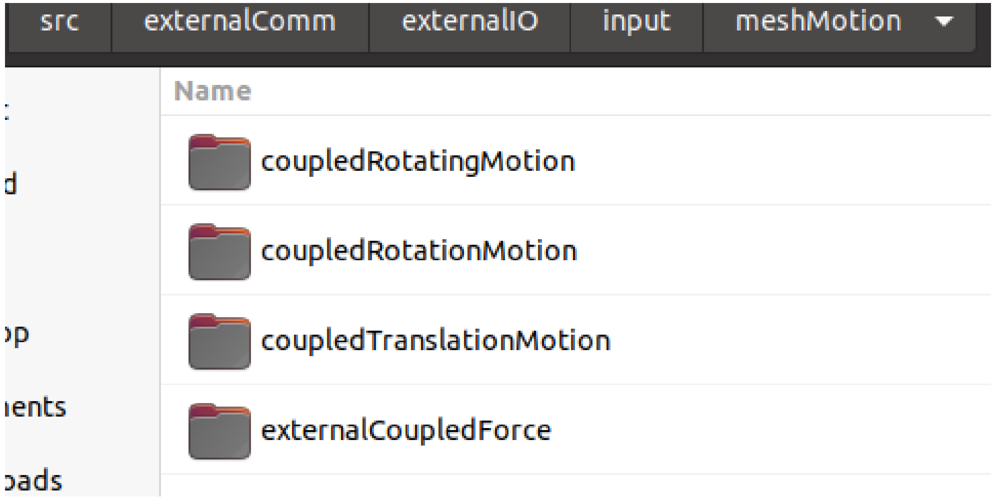
commDataLayer::causality::inの使用例

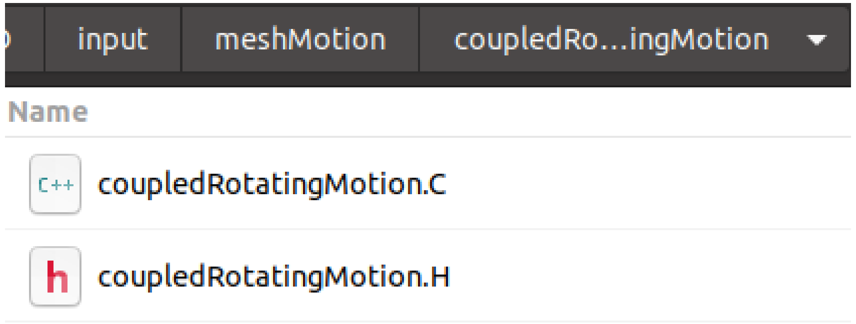
```
// create new entry
const Time& runTime = mesh_.time(); // we need the singleton time
commDataLayer& data = commDataLayer::New(runTime);
scalar varName = "varName";
scalar varValue = "varValue";
data.storeObj(varValue,varName,commDataLayer::causality::in);

// work with data
commDataLayer& data = commDataLayer::New(runTime);
// get varName from registry
scalar& val = data.getObj<scalar>("varName",commDataLayer::causality::in);
val = newValue;
```

FMU4FOAM


FMU4FOAM
application
docs
ECI4FOAM
examples
paper
src
test
testsuite
.git
.github
.vscode
Allwmake
build-ECI4FOAM.sh
conftest.py
environment.yml
LICENSE
log
MANIFEST.in
pytest.ini
README.md
requirements.txt
setup.cfg
setup.py
.gitignore
.gitmodules

coupledRotatingMotion





coupledRotatingMotion.H

rotatingMotion.Hを改造

```
class coupledRotatingMotion
:
    public solidBodyMotionFunction
{
    // Private Data

        //- Origin of the axis
        const vector origin_;

        //- Axis vector
        const vector axis_;

        //- Angular velocity (rad/sec)
        autoPtr<Function1<scalar>> omega_;

        word omegaName_;
        scalar omega_in_;

        word angleName_;
        scalar angle_in_;

```

input

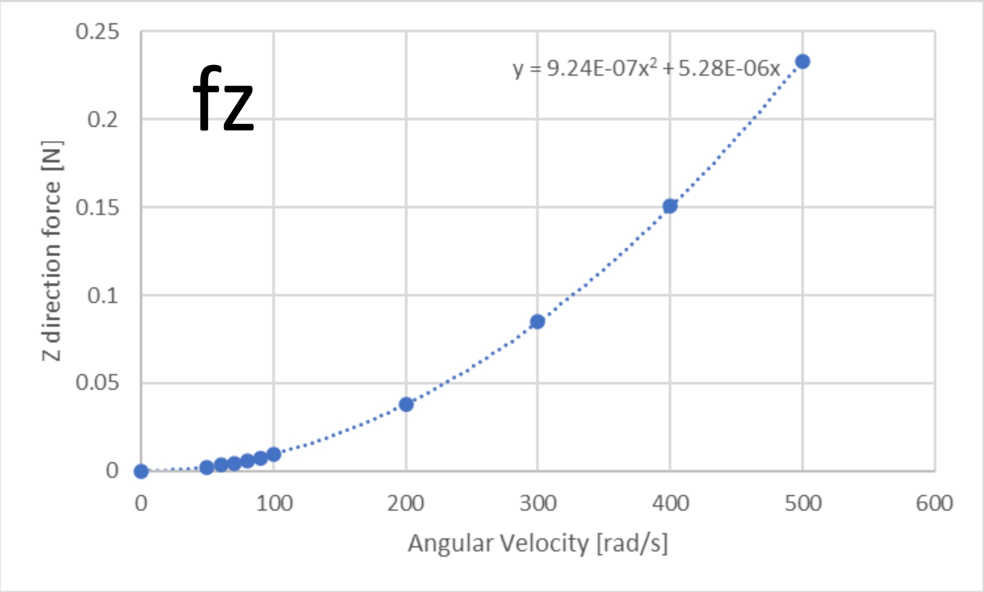
Boundary Conditions	flowRateInlet	patchに流入する質量流量が入力
	flowRateOutlet	patchから流出する質量流量が入力
	uniformValue	patchのする物理量を一定値が入力
	wallHeatFlux	patchへ流入する熱流束が入力
fvOptions	coupledAccelarationSource	加速度,角速度,角加速度が入力
MeshMotions	coupledTranlationMotion	6DoF(surge,sway,heave,roll,pitch,yaw)が入力
	externalCoupledForce	location(x,y,z)に力が入力

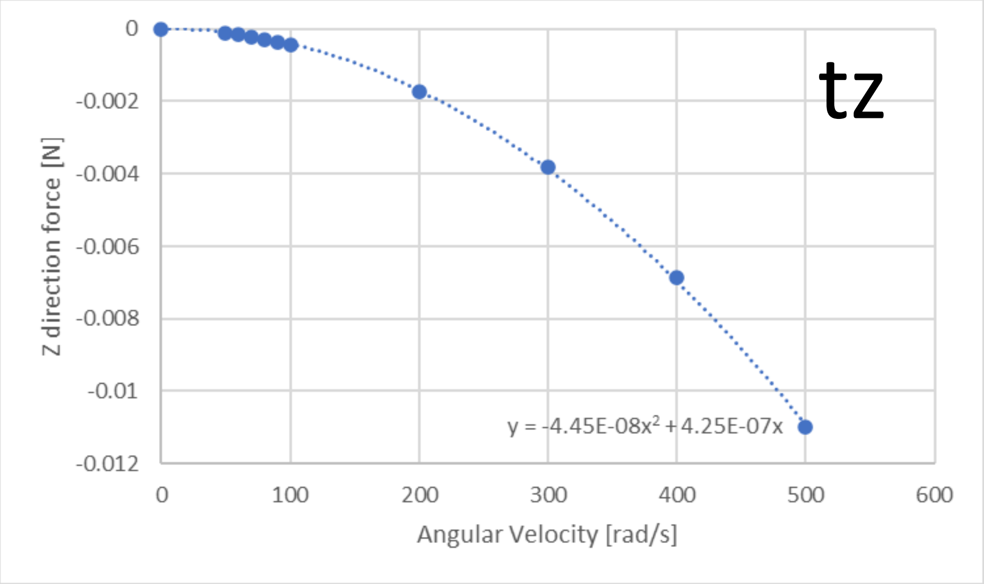
output

One Dimensional	extForces	patchに作用する力とモーメントを出力
	extFunction	functionの値を出力
	extSensor	sensorPosion(x,y,z)の物理量を出力

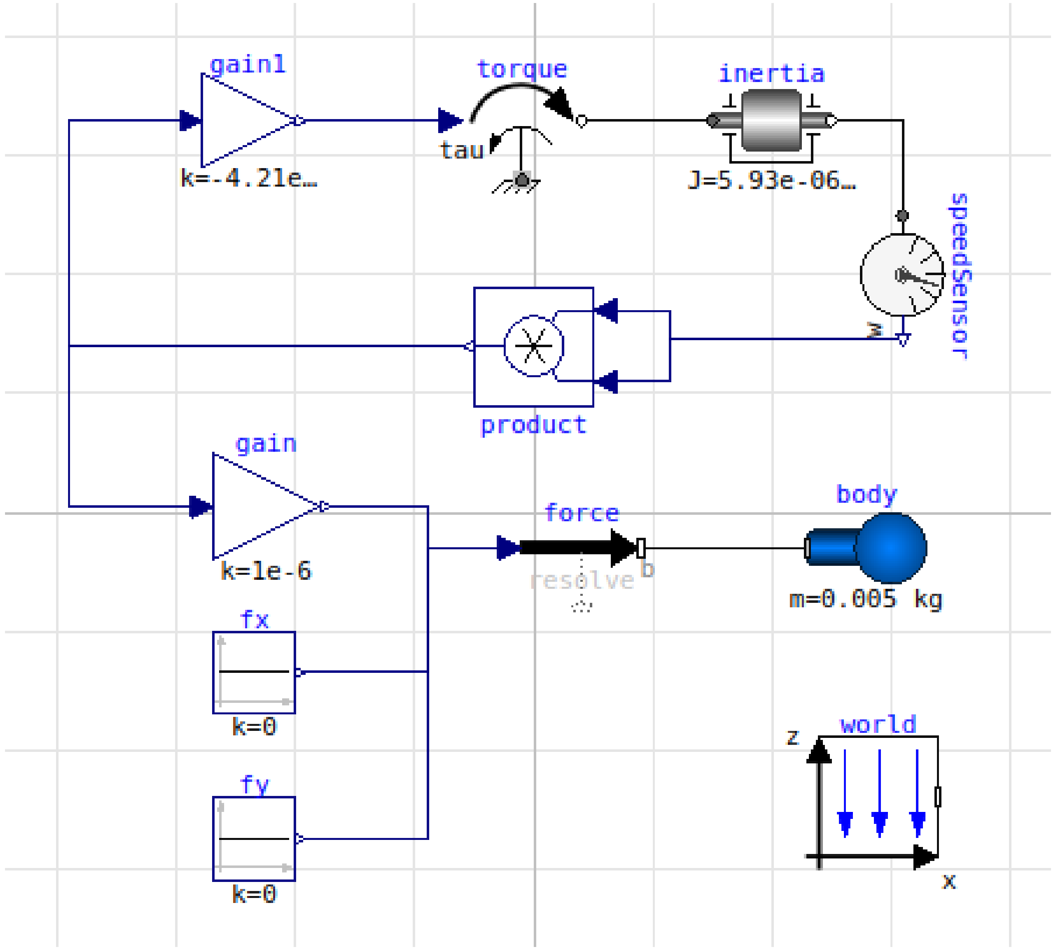
定常状態の角速度とfz,tzの関係

omega[rad/s]	fz [N]	tz [Nm]
0	0	0
50	2.34E-03	-1.14E-04
60	3.39E-03	-1.62E-04
70	4.64E-03	-2.18E-04
80	6.07E-03	-2.83E-04
90	7.70E-03	-3.57E-04
100	9.53E-03	-4.38E-04
200	3.79E-02	-1.72E-03
300	8.50E-02	-3.83E-03
400	1.51E-01	-6.85E-03
500	2.33E-01	-1.10E-02

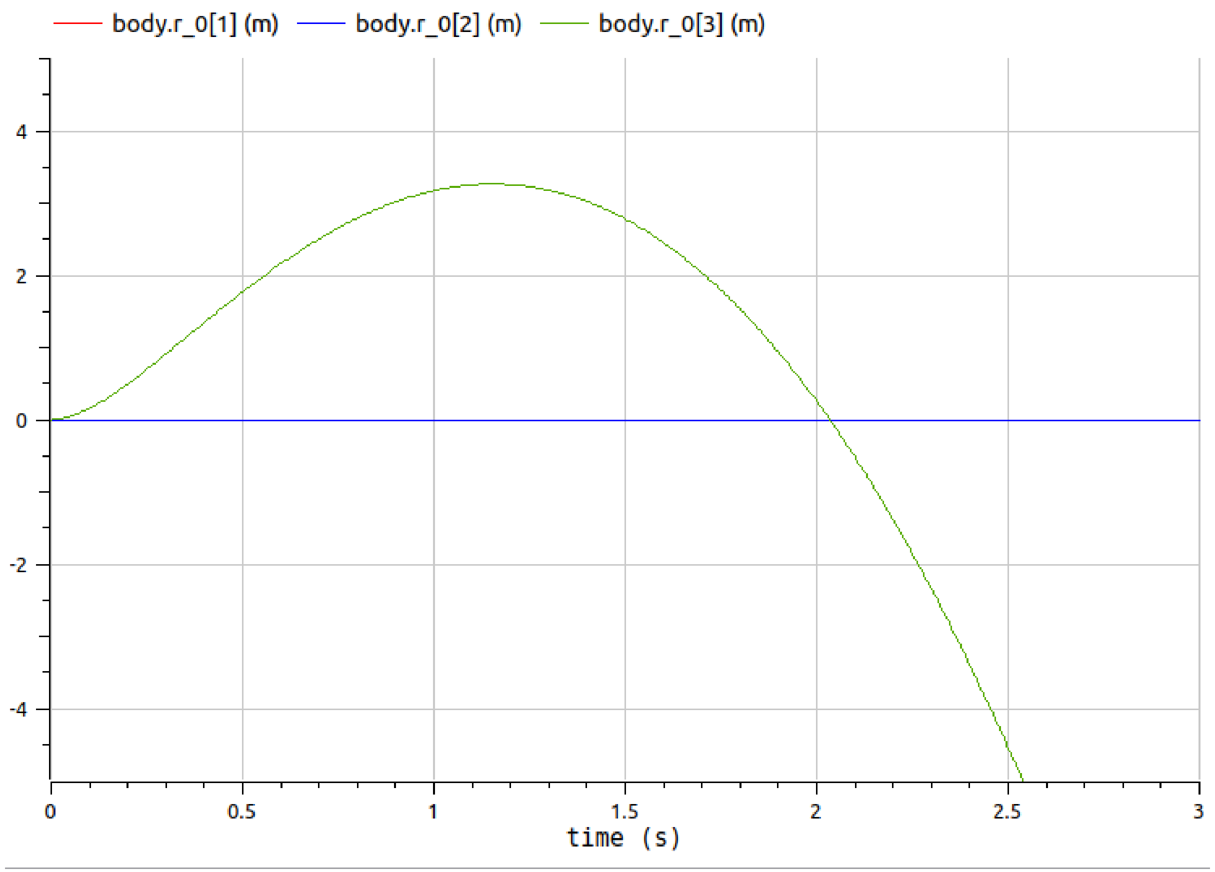




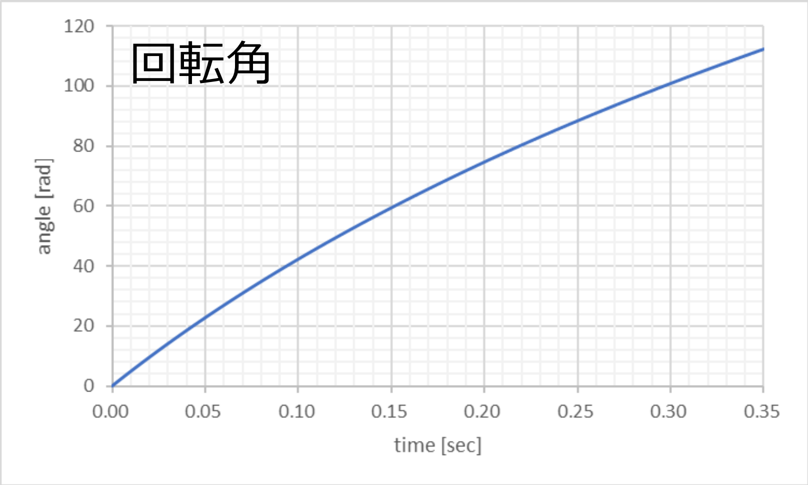
竹とんぼ準定常モデル

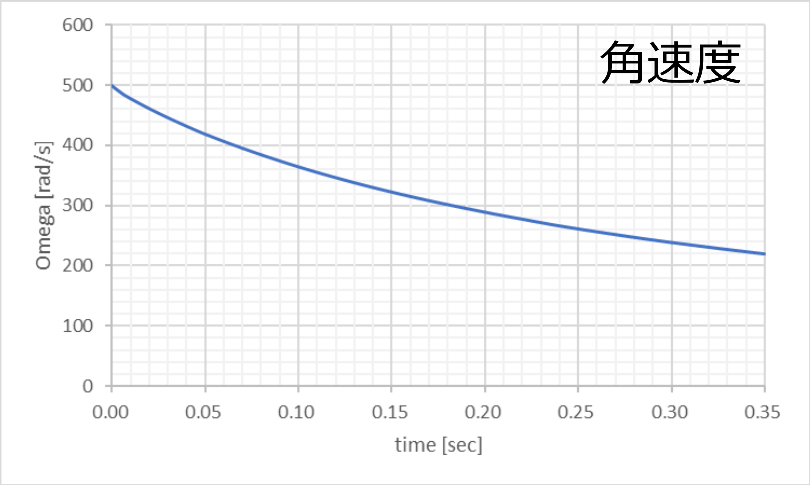


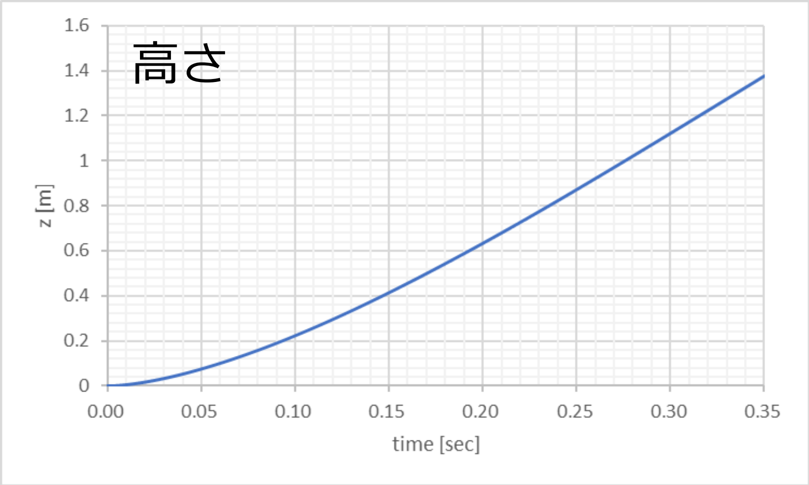
初期回転数=500rad/s

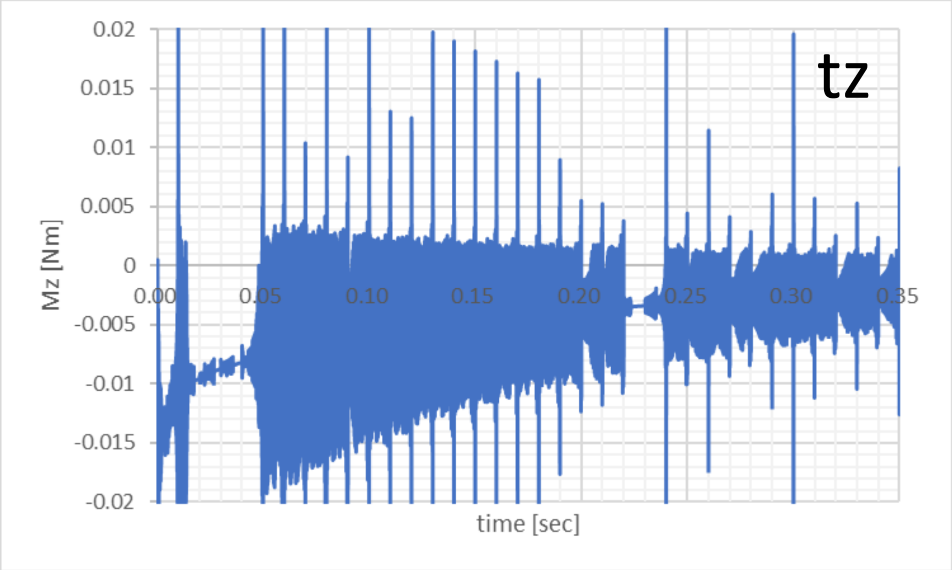


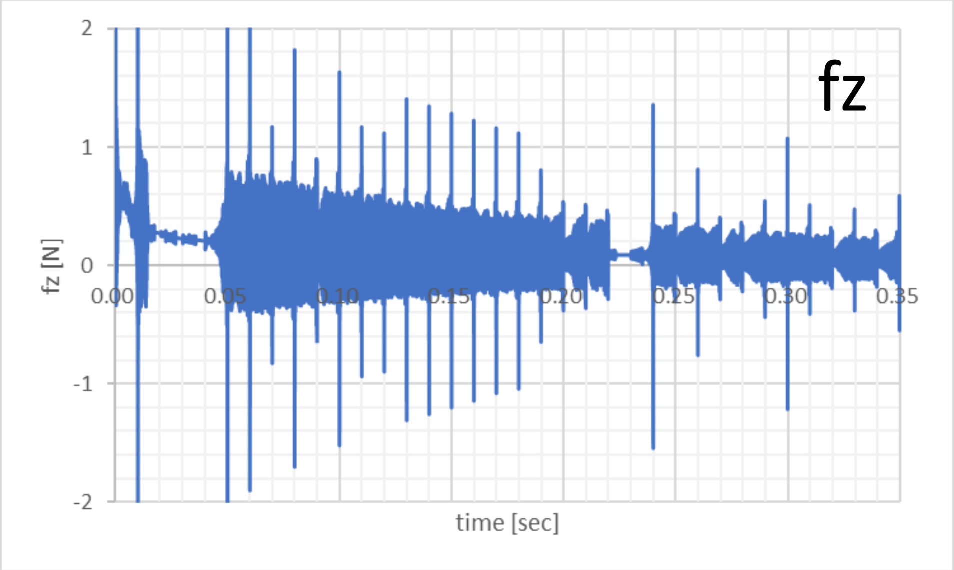
adjustTimeStep=on









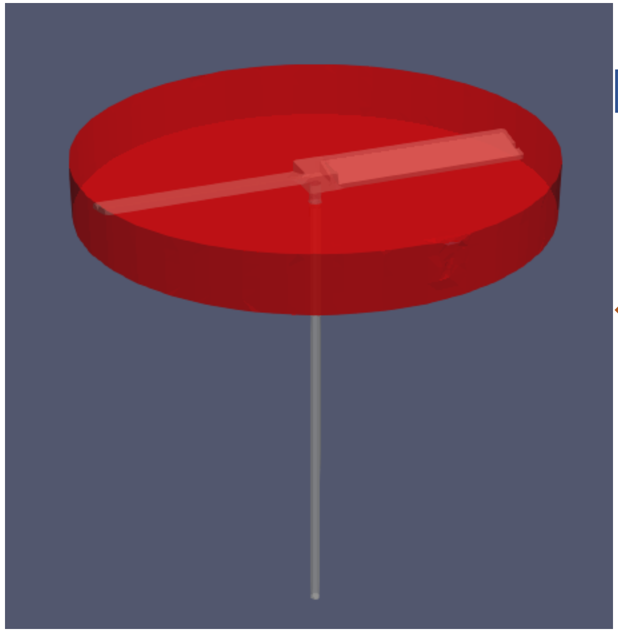


Outline

竹とんぼの鉛直方向（Z方向）のみの運動を対象し,空力シミュレーションで揚力とトルクを取得し,剛体運動シミュレーションと連成

Fluid Dynamics

Mesh rotation in the red region of air



pimpleFoam

meshmotions: coupledRotatingMotion(*New*)

extermalCoupledForce

Forces f_in (fx,fy,fz)

Torqus t_in (tx,ty,tz)

Z axis angle angle_out

Center of rotation

CofR_out(x,y,z)

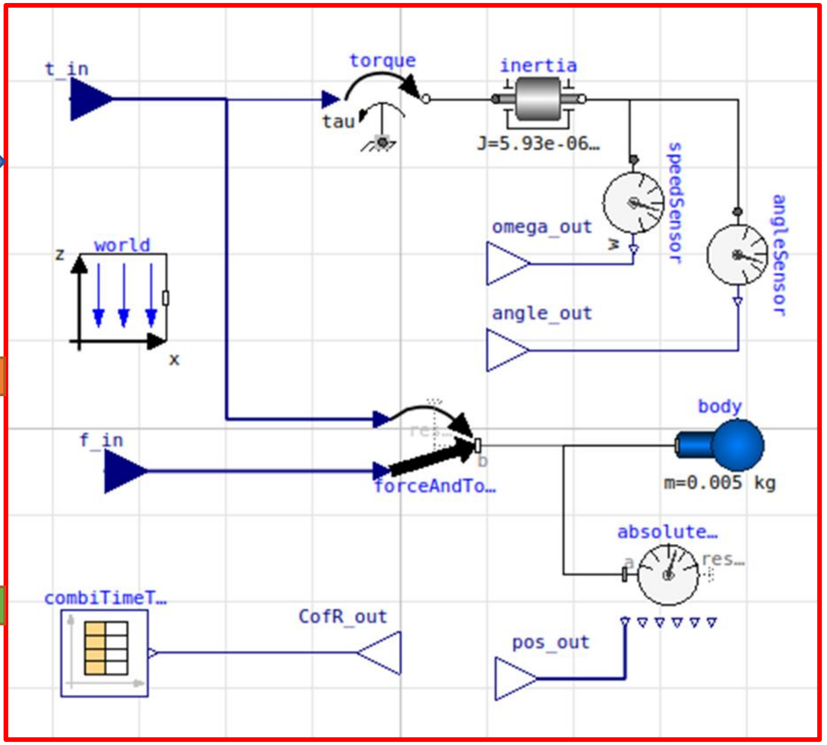
Center of gravity

pos_out(x,y,z)

Angular velocity

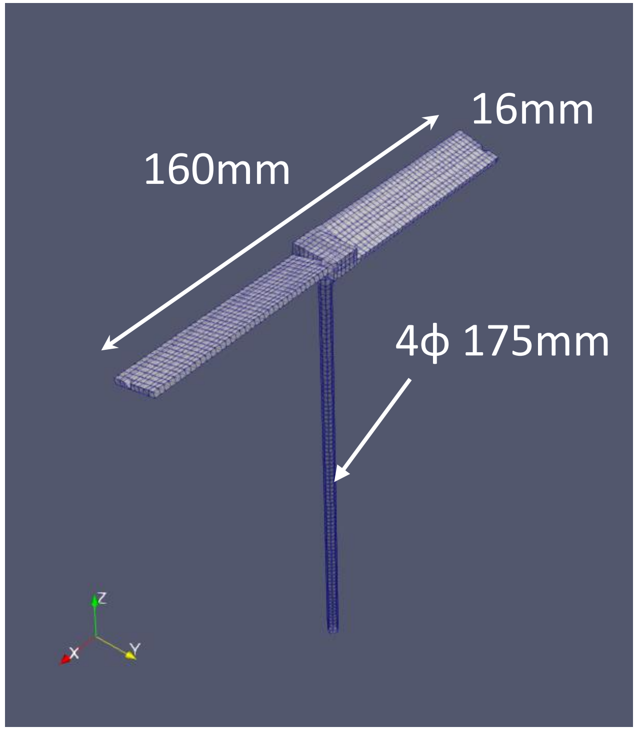
omega_out

Solid body motion



OpenModelica(FMU)

OpenFOAM計算モデル概要

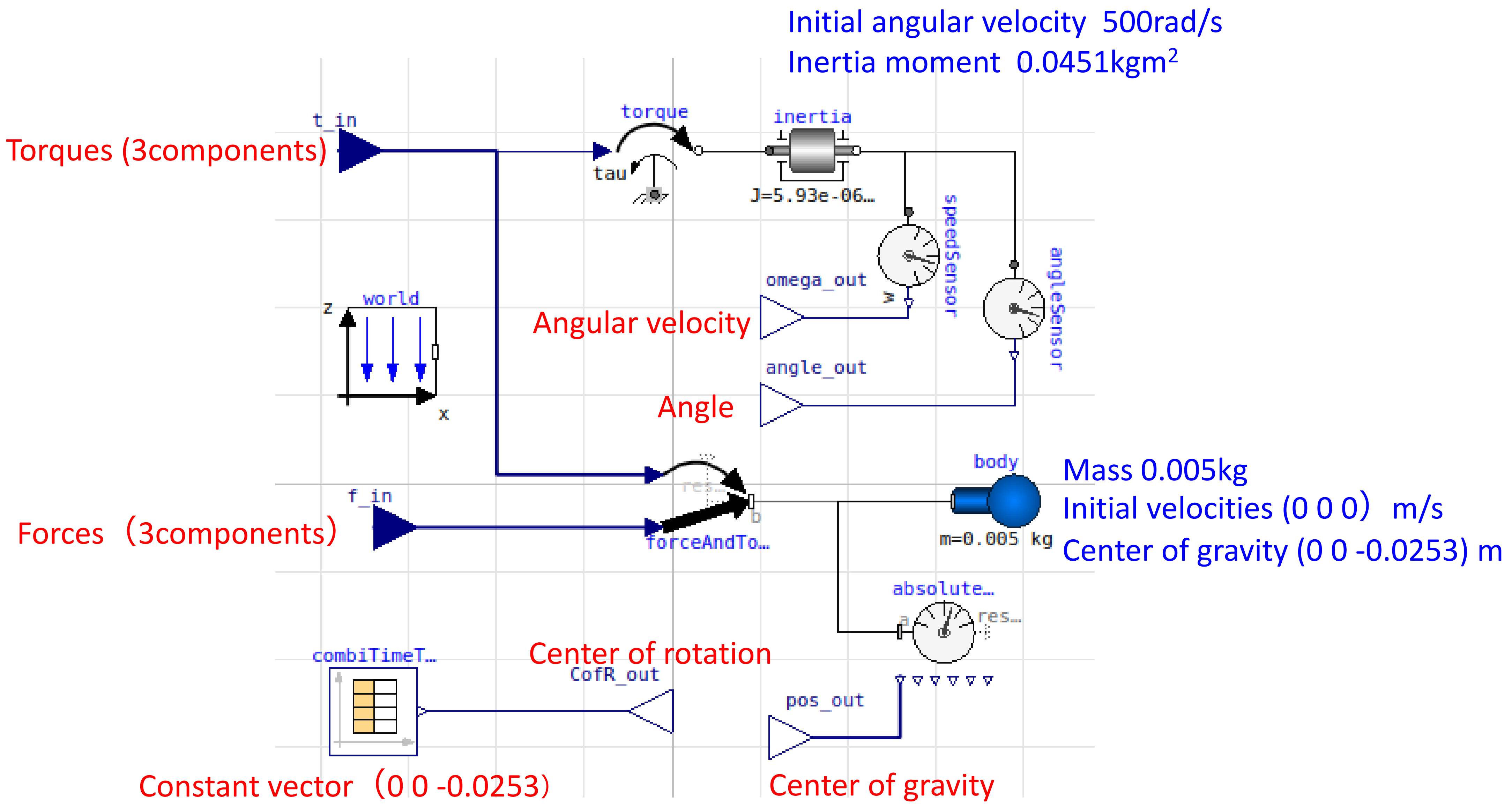


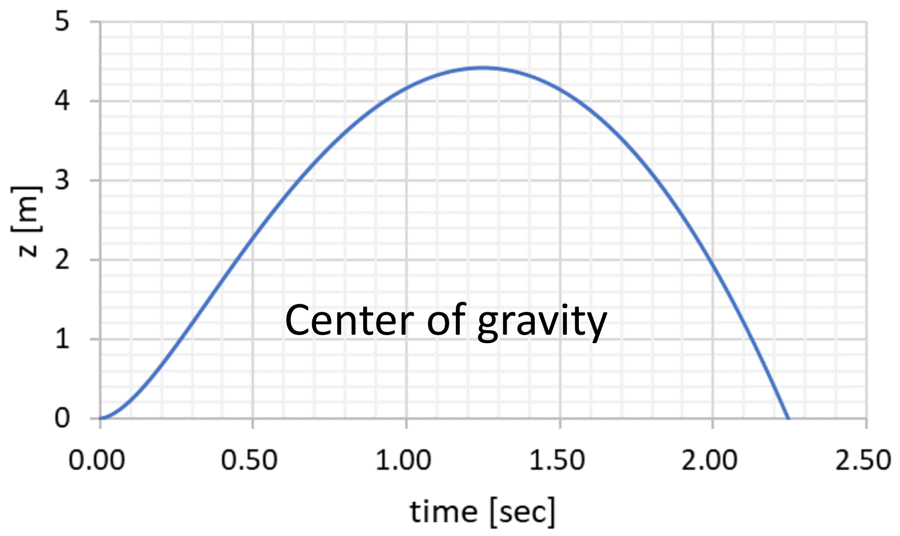
angle of wing	15°
mass	0.005kg
center of gravity	(0 0 -0.0253)
Z inetia moment	0.0451kgm²

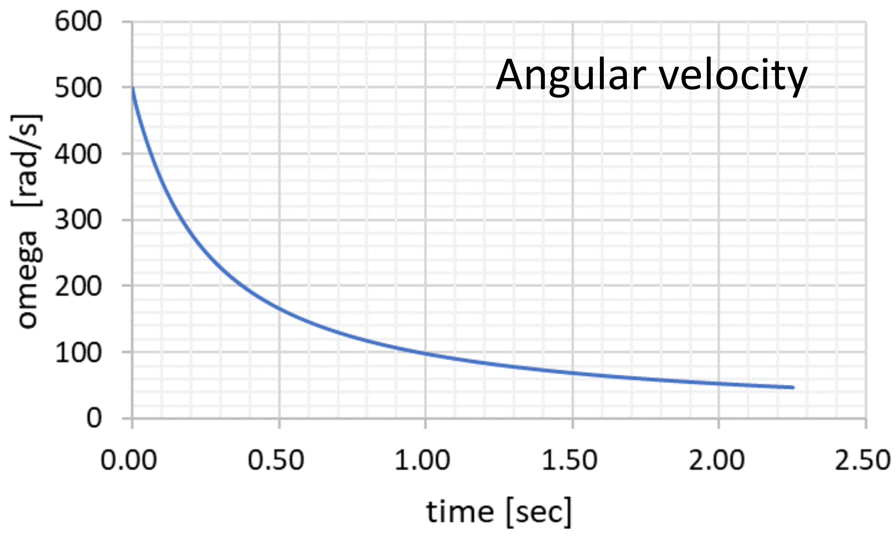
item	content
solver	pimpleFoam (openfoam_v2012)
dynamicFvMesh	fvMotionSolvers/solidBody coupledRotatingMotion
turbulent model	laminar
deltTime	2e-5sec
adjustTimestep	no yesでは計算が不安定
endTime	2.25sec
rhoInfo	1.2kg/m^3
nu	1.5e-5 m^2/s

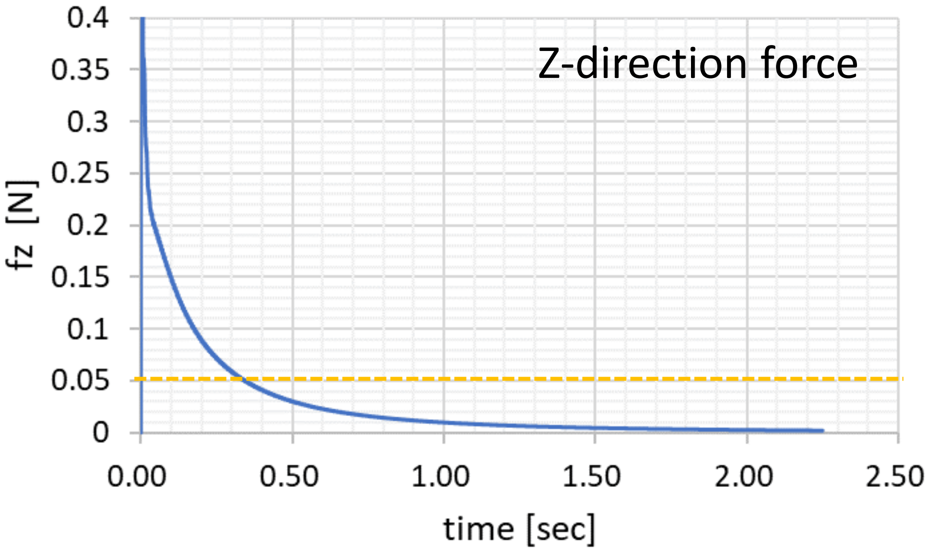
item	content
CPU	icore5 1cpu 並列計算が不能
Memory	8GBytes
Execution Time	53.2hour

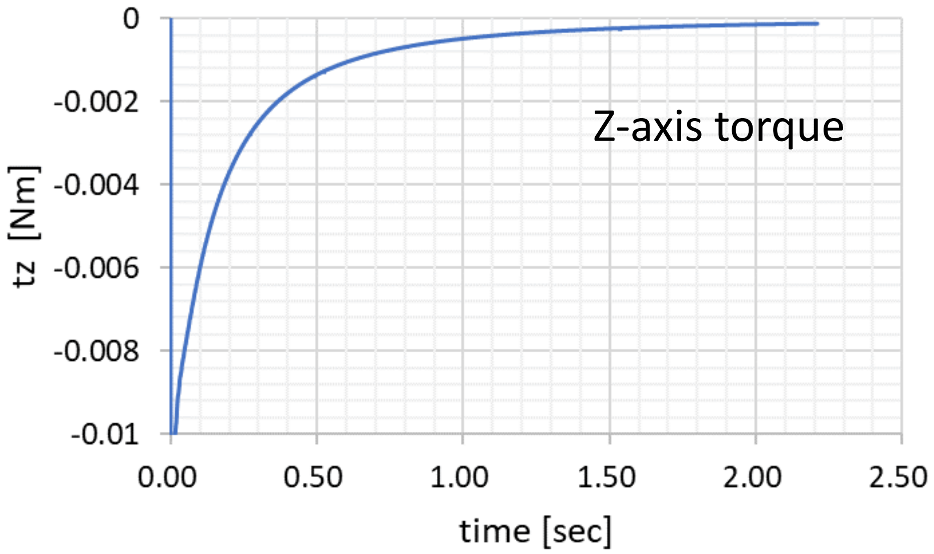
OpenModelicaのFMU

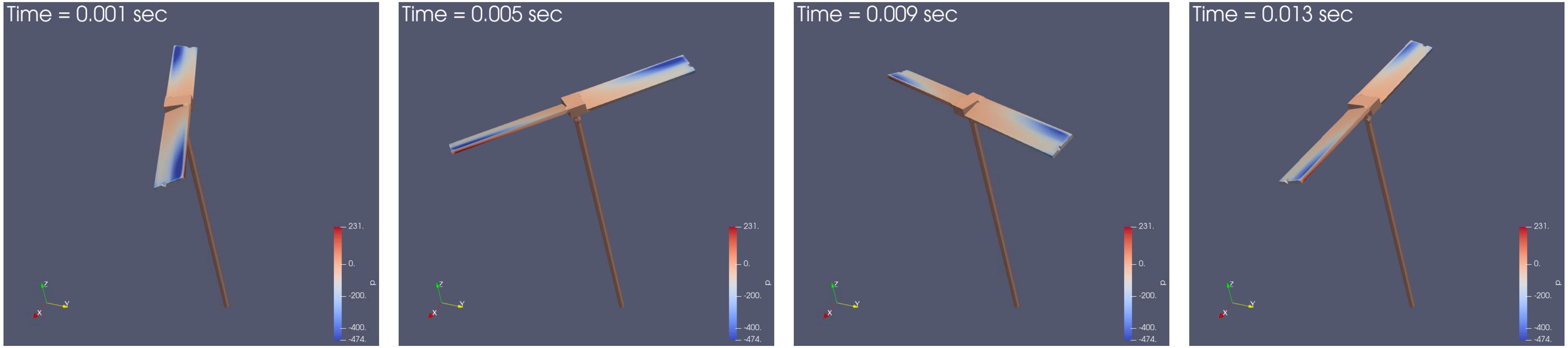



Center of gravity
z [m]
0
1
2
3
4
5
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]


Angular velocity
omega [rad/s]
0
100
200
300
400
500
600
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]


Z-direction force
fz [N]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]


Z-axis torque
tz [Nm]
0
-0.002
-0.004
-0.006
-0.008
-0.01
0.00
0.50
1.00
1.50
2.00
2.50
time [sec]


Time = 0.001 sec
Time = 0.005 sec
Time = 0.009 sec
Time = 0.013 sec
231.
0.
-200.
-400.
-474.
p

回転数について

- 竹とんぼ軸の直径＝4mm
- 手のひらの長さ＝150mm
- 手のひらの長さを竹とんぼ軸を転がすと約12回転
- 12回転は75.4rad
- 回転数500rad/sで竹とんぼを回すためには,

75.4÷500＝0.15秒　　　少し厳しい