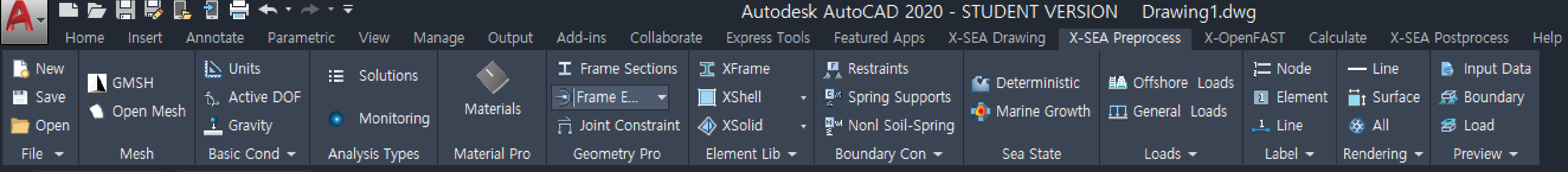
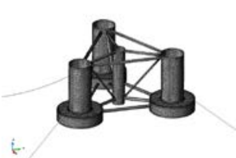


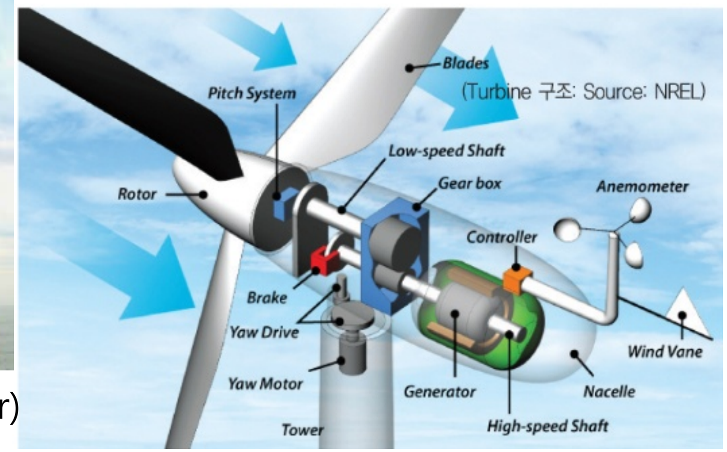
Application: Offshore Wind Turbine Structural Engineering

X-WIND

Part 2: X-OpenFAST

(GUI for Analysis and Design of OpenFASTwind turbine analysis)





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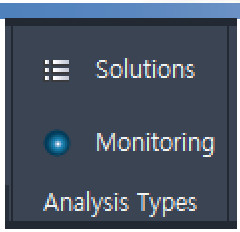
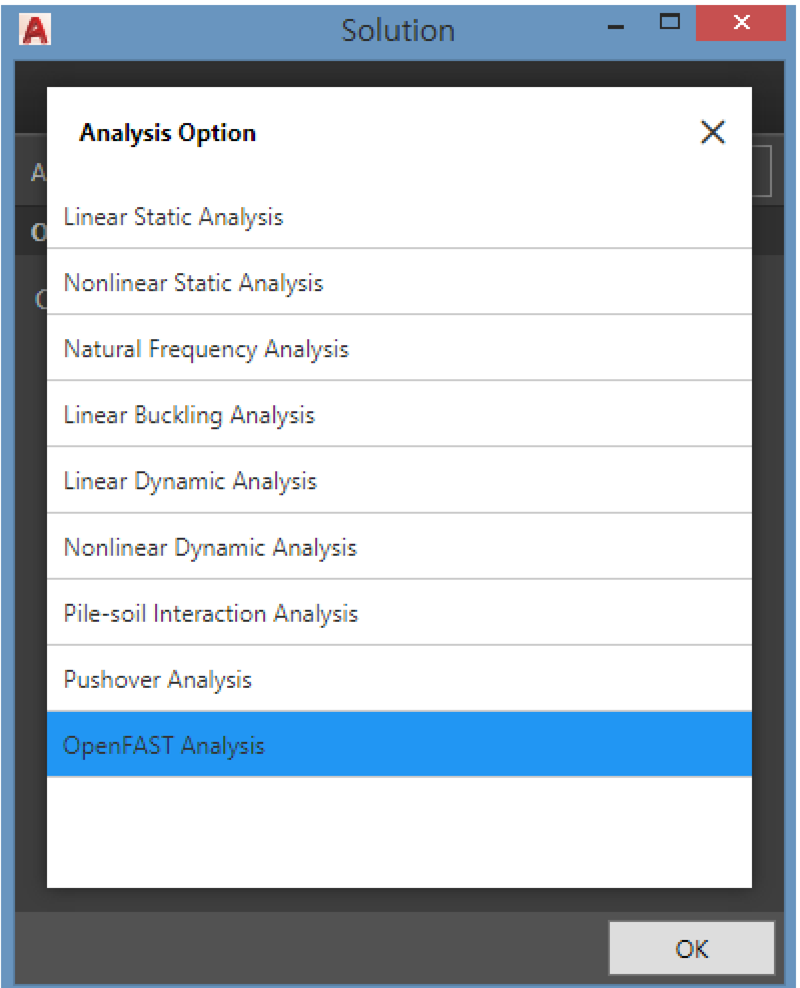
409 Ho, College of Singonghak-gwan Building 120 Neungdong-ro, Gwangjin-gu,
Konkuk University, Seoul 143-701, Korea, tel) 82-2-2049-6074 fax) 82-2-452-8619

2022-12

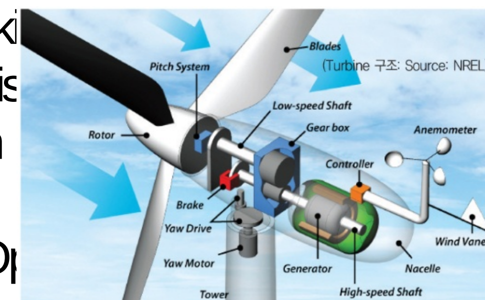
X-OpenFAST 3.0: Wind Turbine Analysis GUI Software



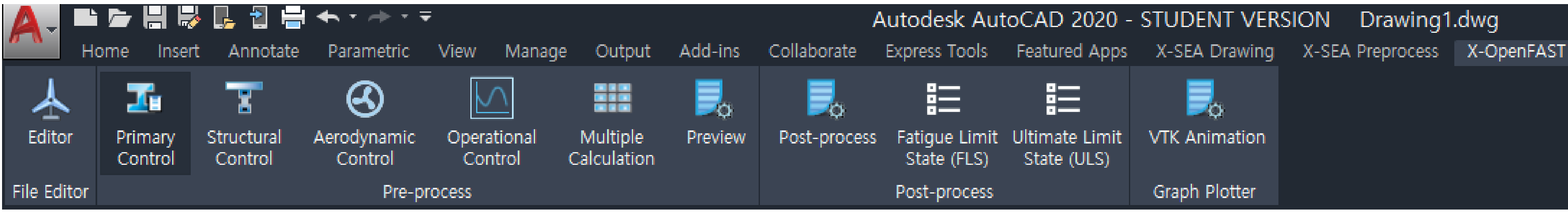
The OpenFAST analysis is executed independently in "**Solution**".



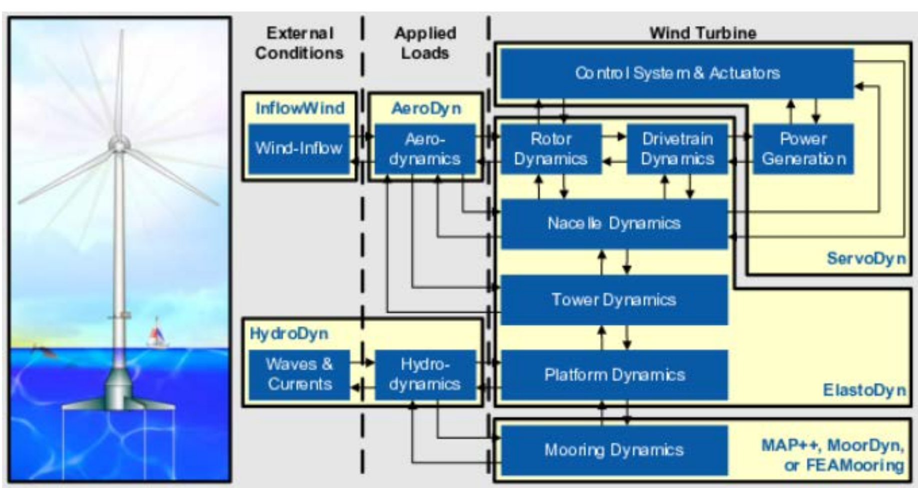
- The OpenFAST by NREL, USA is an integrated software package for wind turbine performance and loading calculation in onshore and fixed/floating offshore wind turbine.
- Pre & Post Processor of OpenFAST is developed using user-friendly AutoCAD Graphic User Interface (description in the f.
- OpenFAST is coupled with X-SEA substructure and independently worki
- Fully coupled analysis substructure-pile can OpenFAST.
- The load cases of O created and combined with X-SEA.
- The X-Y graph of OpenFAST will be available.
- Geometry of offshore wind turbine support structures is created by drawing tools or Template of AutoCAD

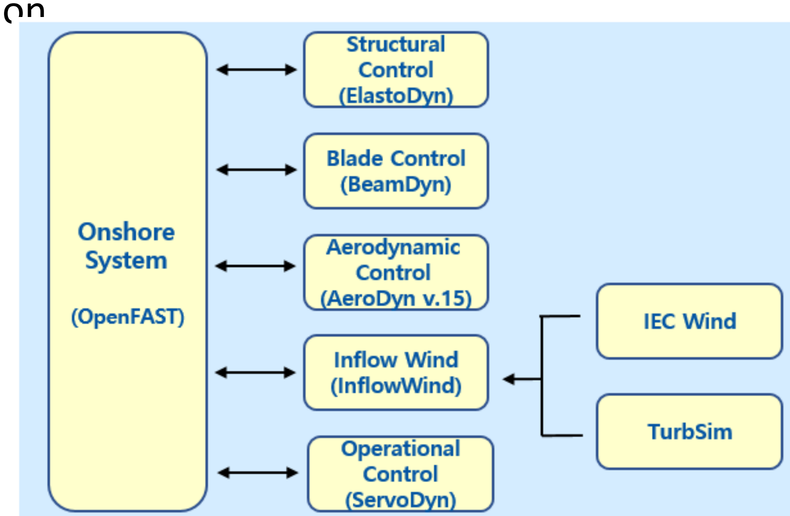


Introduction of OpenFAST in AutoCAD

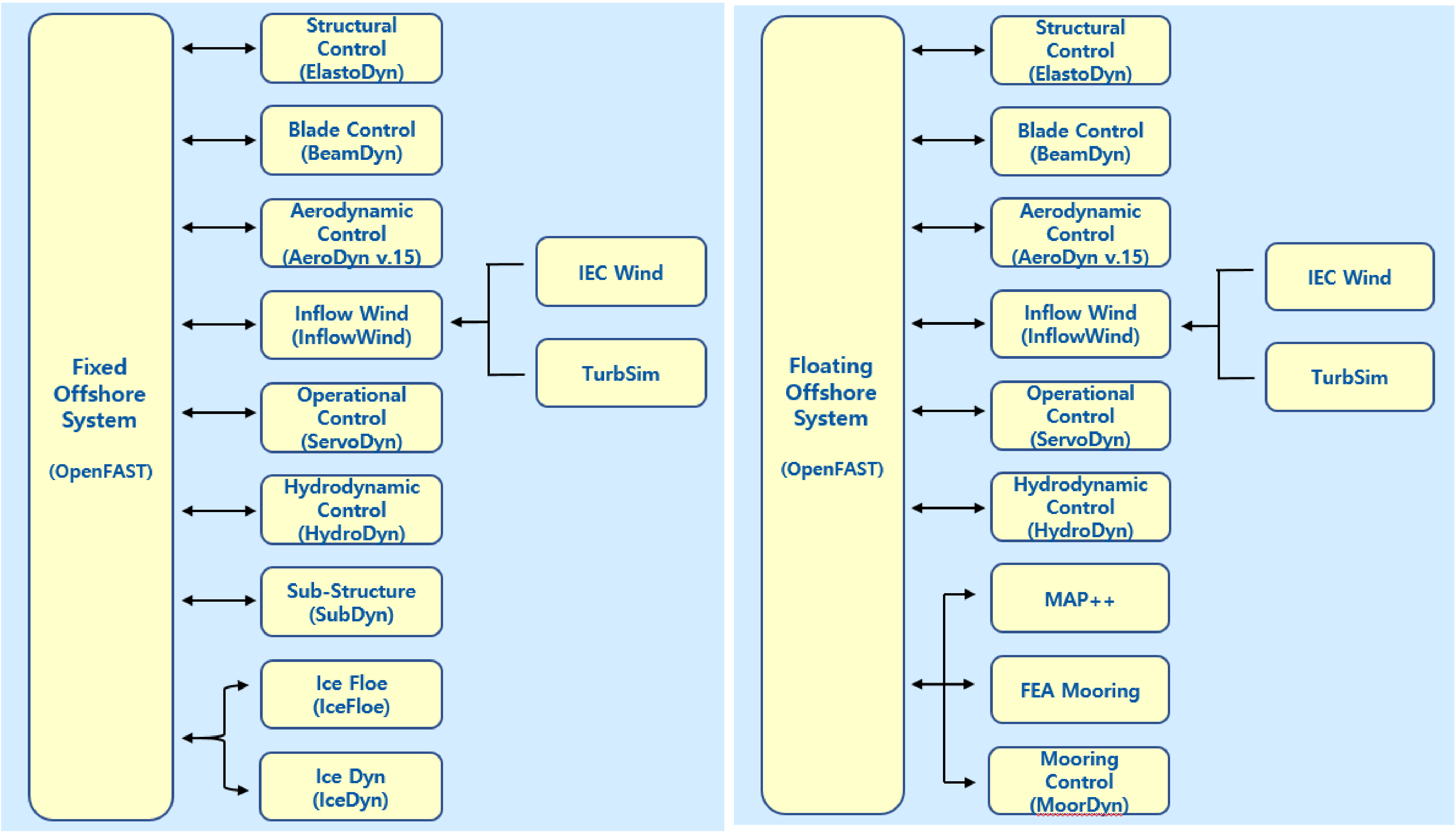


- Modules & relations between modules
  - Several modules work interactively
  - Each moudle has unique features
    - ✓ Aerodynamic/structural analysis including aeroelasticity.
    - ✓ Pitch/yaw & structural control.
    - ✓ Power generated & torque on generator computation



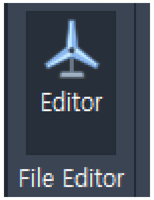


Introduction of OpenFAST in AutoCAD

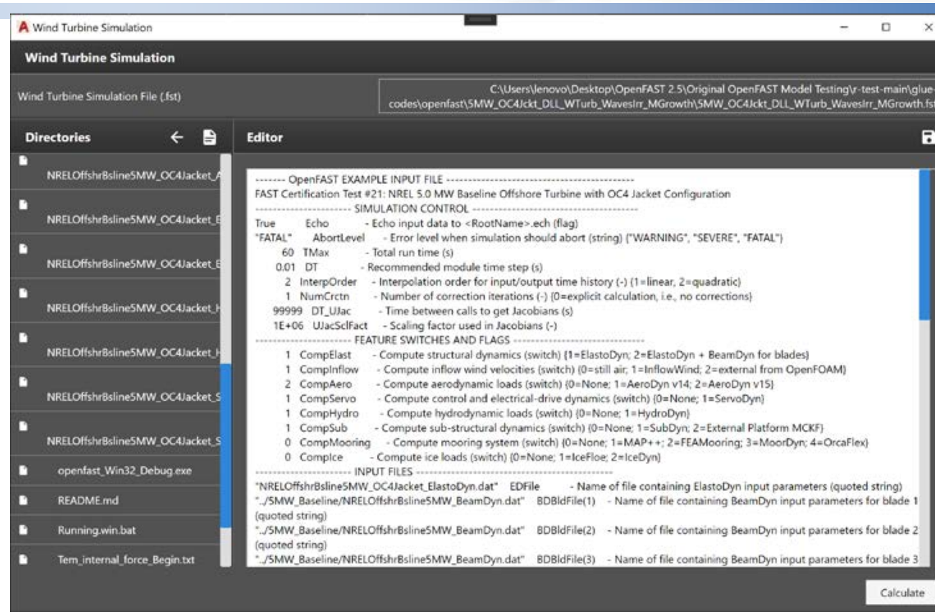


Editor & Preview in X-OpenFAST

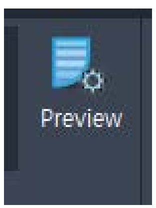
Editor



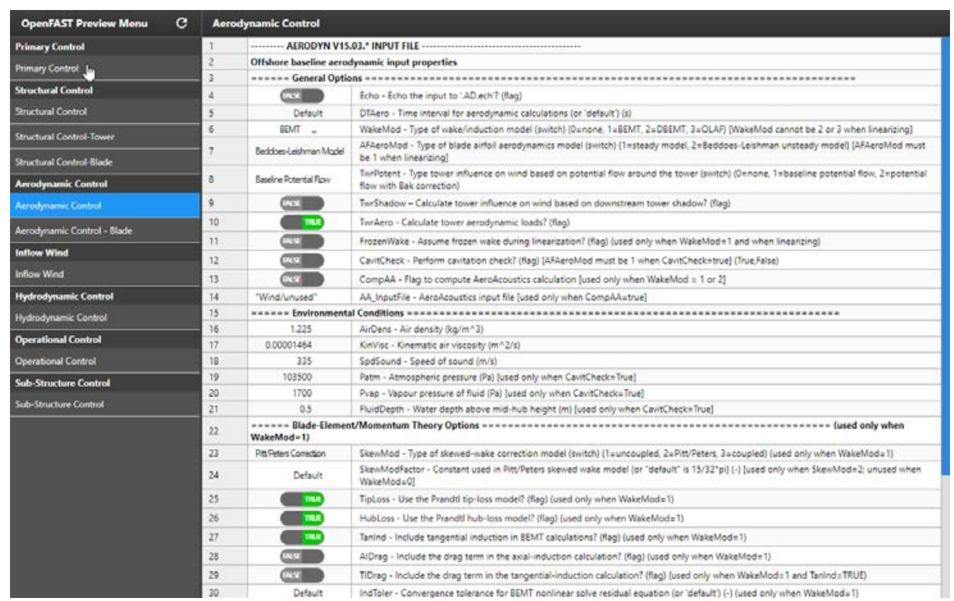
The OpenFAST data can be read, revised and saved in the text format of Editor menu.
The data can be executed in Editor.



Preview:



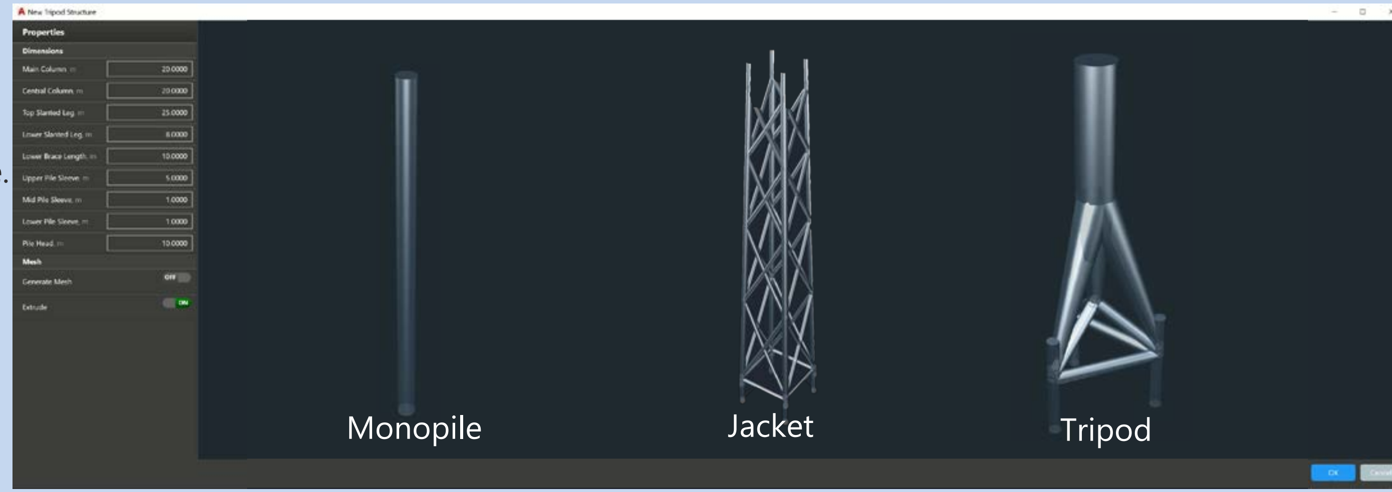
All the OpenFAST data in Ribbon Menu will be saved and visualized in in the table format of Preview Menu.

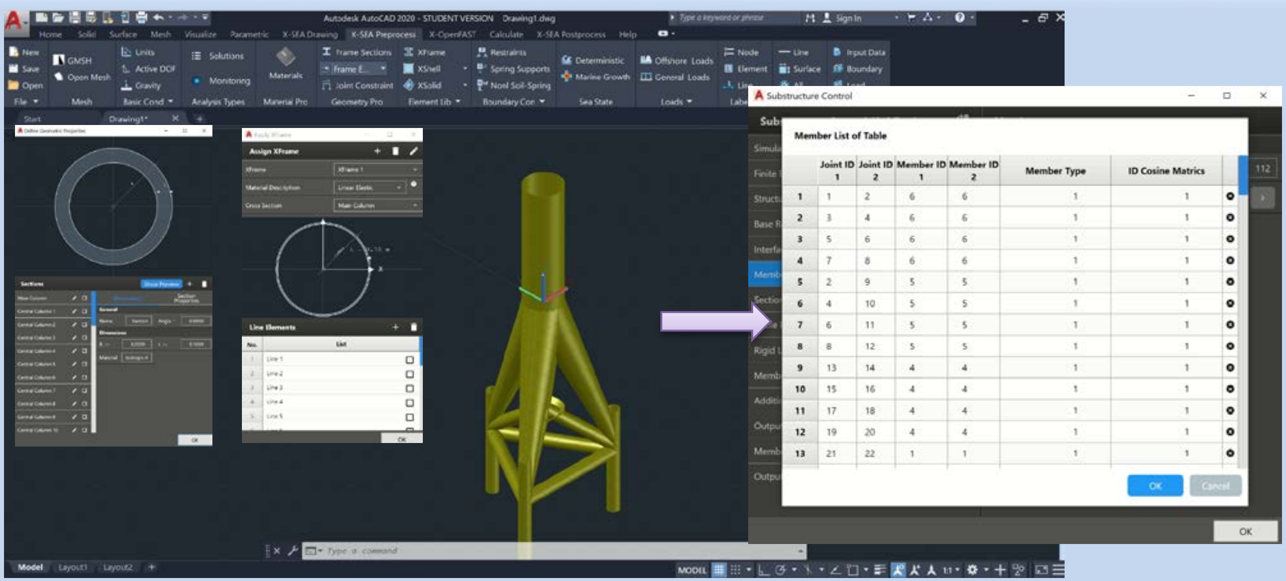


Pre-Process: OpenFAST CAD Modelling

Integrated three type of fixed-bottom template
- Monopile Sub-structure.
- Jacket Sub-structure.
- Tripod Sub-structure

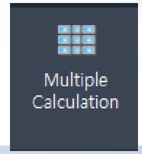
Including mesh generator.





Automatically, insert geometry from CAD system into spread sheet (OpenFAST) including cross sectional, material, element library and restrain.

Automatic Multiple Calculation

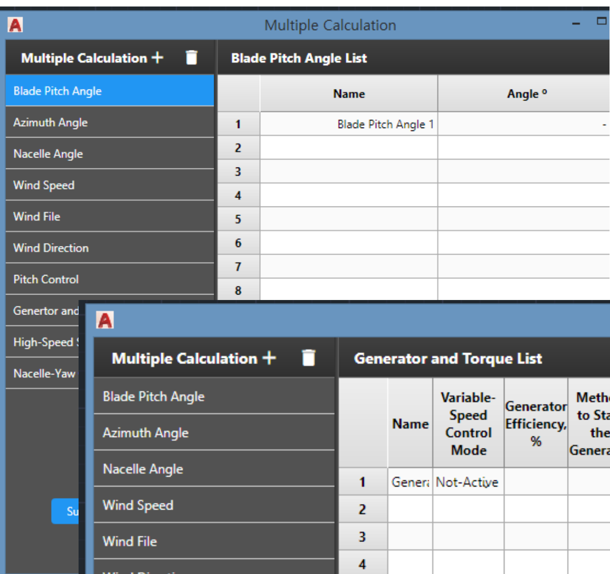


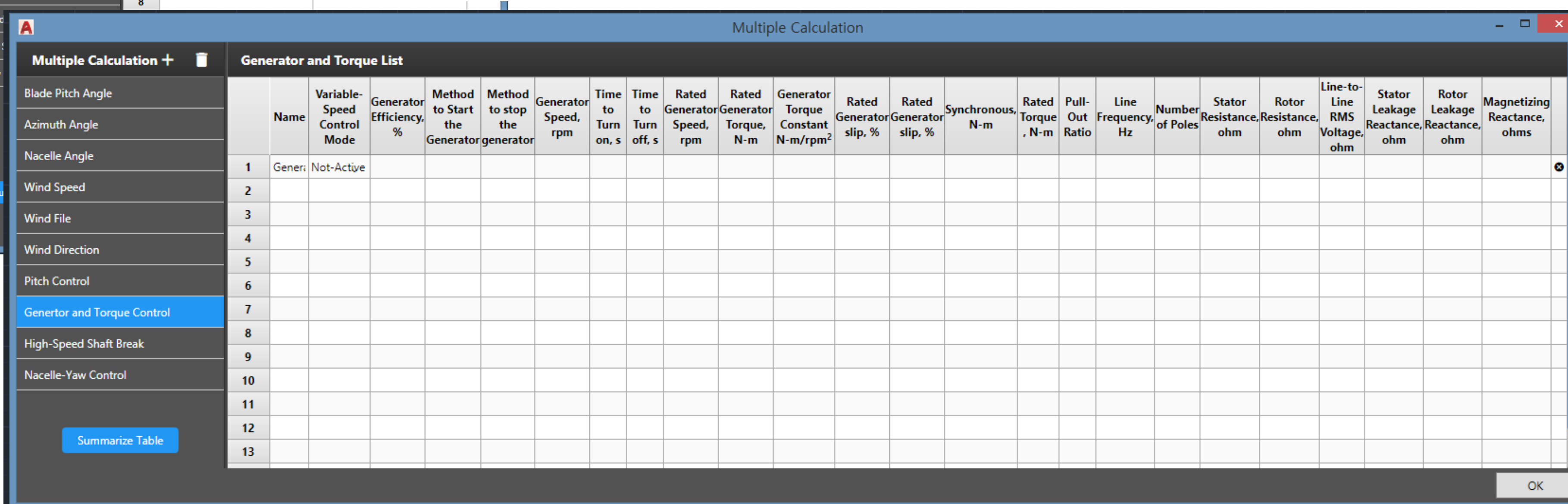
Input and output data and turbine loads with an unlimited number of load cases are sequentially generated to the load case folder.

The six components of force and moment of the tower top, bottom, and rotor part are additionally generated from each load case.

<Total Tower Base Loads>						
Components	F-X	F-Y	F-Z	M-X	M-Y	M-Z
Loadcase	kN	kN	kN	kN-m	kN-m	kN-m
1	548.75	105.691	-5504.62	4510.253	37554.32	708.194
2	810.41	113.574	-5505.42	4718.898	58247.79	794.56
3	1052.2	122.37	-5506.25	5002.379	77655.71	966.183
4	1226.854	135.288	-5506.8	5969.891	92156.03	1314.455
5	1337.052	138.243	-5507.02	6261.18	102375.7	1921.119
6	1464.248	140.096	-5507.76	7405.944	111306.8	2349.831

<Total Rotor Loads>				
	F-Z	M-X	M-Y	M-Z
	kN	kN-m	kN-m	kN-m
653	1159.452	2790.456	0	0
526	1137.565	3041.053	0	0
986	1111.048	3372.174	0	0
757	1111.563	3676.656	0	0
914	1127.914	4946.885	0	0
254	1139.106	5146.356	0	0



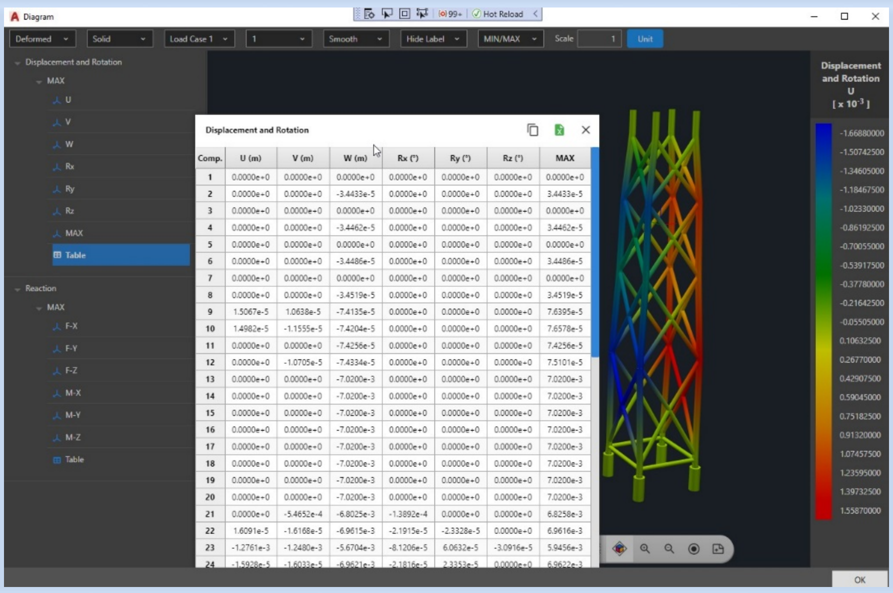


Post-Process: OpenFAST Result

Adding the array program to print the result of output which is suitable for postprocess view.

```
! REACTION
WRITE (7100,220) FILENUMBERINTER
WRITE (7100,221)
WRITE (7100,222)
ALLOCATE ( ReactNs(6*p%nNodes_C), STAT = ErrStat )
ReactNs = 0.0_ReKi !Initialize
ReactNs_IN = 0.0D0
  DO I=1,p%nNodes_C   !Do for each constrained node, they are ordered as given in th
     FK_elm2=0._ReKi !Initialize for cumulative force
     FM_elm2=0._ReKi !Initialize
     pLst_XSEA => p%MOutLst3_XSEA(I)
     !Find the joint forces
     DO J=1,SIZE(pLst_XSEA%ElmIDs(1,:))  !for all the elements connected (normally 1
        iiNode = 1
        call ElementForce(pLst_XSEA, iiNode, J, FM_elm, FK_elm, sgn, DIRCOS, .false.
        !transform back to global, need to do 3 at a time since cosine matrix is 3x3
        DO L=1,2
           FM_elm2((L-1)*3+1:L*3) = FM_elm2((L-1)*3+1:L*3) + matmul(transpose(DIRCOS
           FK_elm2((L-1)*3+1:L*3) = FK_elm2((L-1)*3+1:L*3) + matmul(transpose(DIRCOS
           ! I believe this is all fixed in terms of signs now ,RRD 5/20/13
        ENDDO
     ENDDO
```

```
Result "Local-Force"  "Load Case 1"     1  Matrix  OnGaussPoints  "XFrame2"
ComponentNames "Fx" "Fy" "Fz" "Mx" "My" "Mz"
Values
   1  -0.47988E+05  -0.37576E+05   0.55009E+07   0.12056E+06  -0.17079E+06   0.53593E+04
       0.47988E+05   0.37576E+05  -0.55009E+07  -0.10174E+06   0.14675E+06  -0.53593E+04
   2  -0.48279E+05   0.36291E+05   0.55056E+07  -0.12965E+06  -0.16999E+06  -0.28841E+04
       0.48279E+05  -0.36291E+05  -0.55056E+07   0.11147E+06   0.14580E+06   0.28841E+04
   3   0.27646E+05  -0.35569E+05   0.55094E+07   0.10897E+06   0.73811E+05  -0.28803E+04
      -0.27646E+05   0.35569E+05  -0.55094E+07  -0.91154E+05  -0.59961E+05   0.28803E+04
   4   0.28038E+05   0.34090E+05   0.55147E+07  -0.12031E+06   0.74131E+05   0.53964E+04
      -0.28038E+05  -0.34090E+05  -0.55147E+07   0.10323E+06  -0.60084E+05  -0.53964E+04
   5  -0.42777E+05  -0.37513E+05   0.51153E+07   0.10175E+06  -0.14066E+06   0.52842E+04
       0.42777E+05   0.37513E+05  -0.51153E+07   0.48302E+05  -0.30451E+05  -0.52842E+04
   6  -0.42806E+05   0.36251E+05   0.51205E+07  -0.11154E+06  -0.13956E+06  -0.29248E+04
       0.42806E+05  -0.36251E+05  -0.51205E+07  -0.33463E+05  -0.31666E+05   0.29248E+04
   7   0.30112E+05  -0.35591E+05   0.51241E+07   0.91075E+05   0.62832E+05  -0.28599E+04
      -0.30112E+05   0.35591E+05  -0.51241E+07   0.51289E+05   0.57615E+05   0.28599E+04
   8   0.30241E+05   0.34139E+05   0.51299E+07  -0.10321E+06   0.62802E+05   0.54920E+04
      -0.30241E+05  -0.34139E+05  -0.51299E+07  -0.33345E+05   0.58162E+05  -0.54920E+04
   9   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
       0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
  10   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
       0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
  11   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
       0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
  12   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
       0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
  13   0.25365E+04  -0.50739E+04   0.16191E+06   0.13833E+05  -0.21366E+04  -0.63921E+04
      -0.25365E+04   0.50739E+04  -0.16191E+06   0.20280E+05   0.19190E+05   0.63921E+04
  14   0.16244E+04  -0.32136E+05   0.17515E+06   0.11167E+06   0.13068E+05   0.95843E+03
      -0.16244E+04   0.32136E+05  -0.17515E+06   0.12423E+06  -0.11437E+04  -0.95843E+03
  15  -0.25259E+04   0.50800E+04   0.15683E+06  -0.20487E+05  -0.19252E+05   0.62949E+04
```



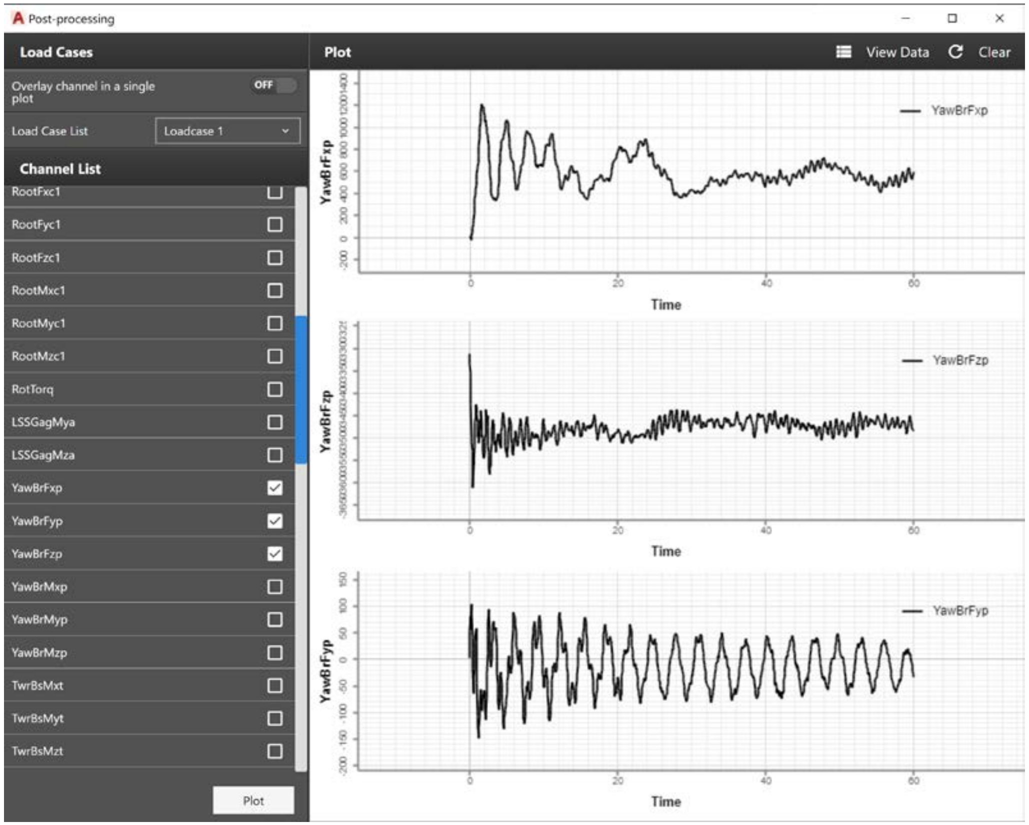
Displacement and Rotation

Comp.	U (m)	V (m)	W (m)	Rx (°)	Ry (°)	Rz (°)	MAX
1	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
2	0.0000e+0	0.0000e+0	-3.4433e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4433e-5
3	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
4	0.0000e+0	0.0000e+0	-3.4462e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4462e-5
5	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
6	0.0000e+0	0.0000e+0	-3.4486e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4486e-5
7	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
8	0.0000e+0	0.0000e+0	-3.4519e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4519e-5
9	1.5067e-5	1.0638e-5	-7.4135e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.6395e-5
10	1.4982e-5	-1.1555e-5	-7.4204e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.6578e-5
11	0.0000e+0	0.0000e+0	-7.4256e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.4256e-5
12	0.0000e+0	-1.0705e-5	-7.4334e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.5101e-5
13	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
14	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
15	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
16	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
17	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
18	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
19	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
20	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
21	0.0000e+0	-5.4652e-4	-6.8025e-3	-1.3892e-4	0.0000e+0	0.0000e+0	6.8258e-3
22	1.6091e-5	-1.6168e-5	-6.9615e-3	-2.1915e-5	-2.3328e-5	0.0000e+0	6.9616e-3
23	-1.2761e-3	-1.2480e-3	-5.6704e-3	-8.1206e-5	6.0632e-5	-3.0916e-5	5.9456e-3
24	-1.5928e-5	-1.6033e-5	-6.9621e-3	-2.1816e-5	2.3353e-5	0.0000e+0	6.9622e-3

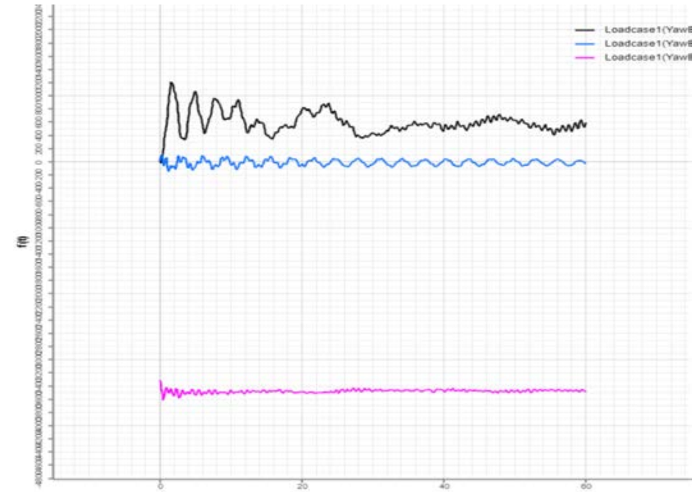
Dynamic post-processing with OpenFAST in 3D shape.

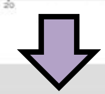
Post-Process

- Provided a multiple plot and overlay in a single channel plot



Multiple plot





View Data

Table Data

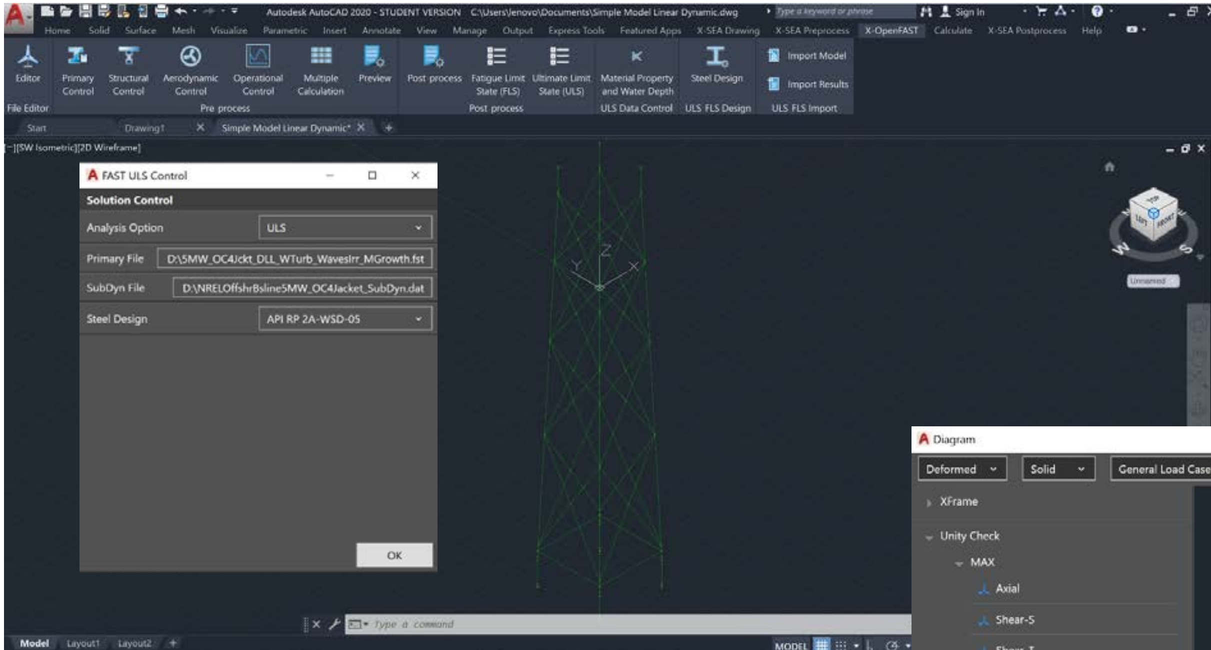
YawBrFxp | YawBrFyp | YawBrFzp | Overlay Channel Data

	Time	YawBrFxp-lc 1	YawBrFyp-lc 1	YawBrFzp-lc 1
1	0	16.67	3.066	-3313
2	0.05	0.6211	53.23	-3334
3	0.1	-16.02	80.96	-3356
4	0.15	-19.32	56.28	-3365
5	0.2	10.58	68.75	-3426
6	0.25	45.78	103.1	-3499
7	0.3	92.39	85.15	-3510
8	0.35	113.5	41.47	-3529
9	0.4	122.3	18.91	-3596
10	0.45	156.9	-18.4	-3610
11	0.5	216.7	-64.06	-3563
12	0.55	293	-61.21	-3551
13	0.6	352.5	-32.84	-3562
14	0.65	385.8	-17.01	-3517
15	0.7	414.5	0.3034	-3465
16	0.75	434	33.89	-3462
17	0.8	468.3	51.79	-3455
18	0.85	515.4	52.4	-3425

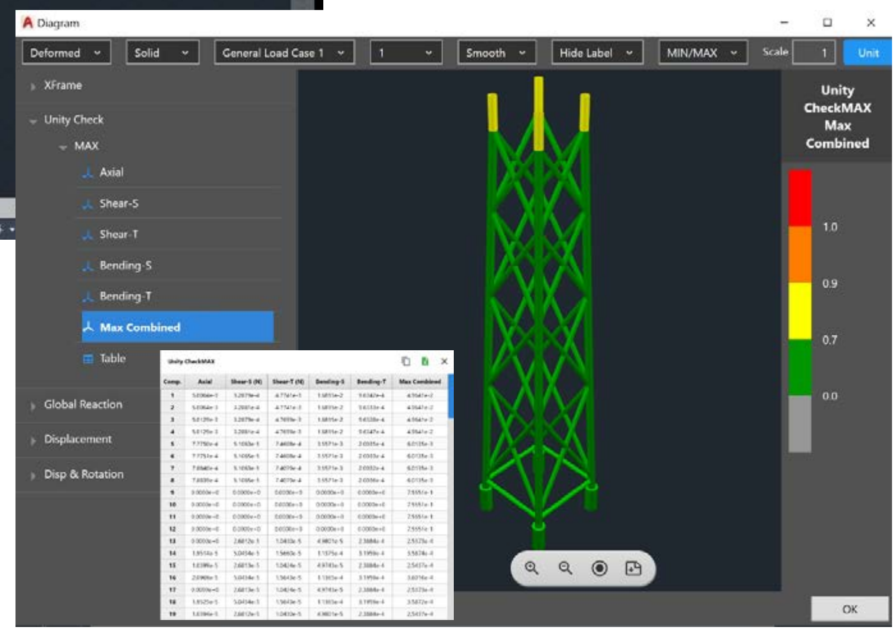
OK | Cancel

Overlay data in a single channel

Post-Process: Ultimate Limit State Analysis

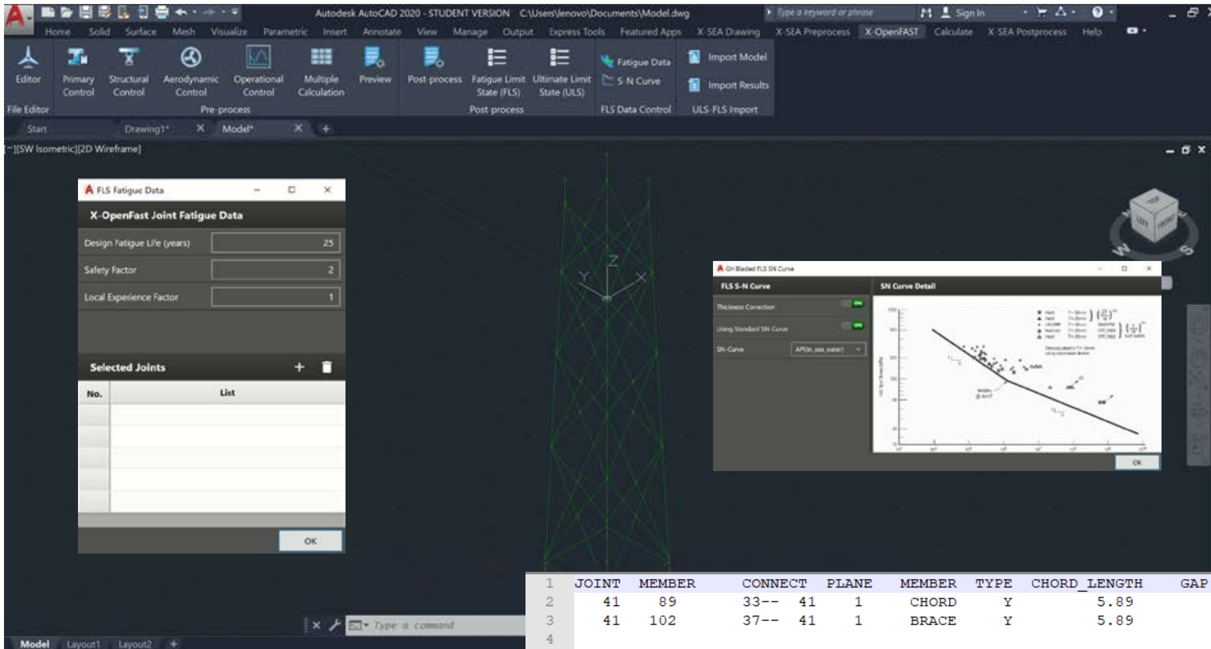


Design code based on design standard
- API RP 2A-WSD
- API RP 2A-LRFD
- AISC ASD
- AISC LRFD
- Eurocode 3
- ISO
- Korean
- NORSOK



Result Import functionality is provided for specific detail of design parameter and show a result with color contour, including table result and export a result into excel program.

Post-Process: Fatigue Limit State Analysis



Import a OpenFAST result, selecting analysis joint, and choose a type of SN-curve based on offshore standard.

OpenFAST post processing provided two method of fagitue analysis
- Deterministic method
- Stochastic method (Mlife)

JOINT	MEMBER	CONNECT	PLANE	MEMBER TYPE		CHORD_LENGTH	GAP	AX-CR	AX-SD	IN-PL	OU-PL	DAMAGE	FATIGUE_LIFE
41	89	33-- 41	1	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.1287E-09	0.1554E+12
41	102	37-- 41	1	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.5058E-10	0.3954E+12
41	89	33-- 41	2	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.5936E-08	0.3369E+10
41	106	39-- 41	2	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.1717E-08	0.1165E+11
42	92	34-- 42	1	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.2602E-09	0.7686E+11
42	104	38-- 42	1	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.9092E-10	0.2200E+12
42	92	34-- 42	2	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.2089E-08	0.9576E+10
42	105	39-- 42	2	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.1998E-08	0.1001E+11
43	95	35-- 43	1	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.2137E-09	0.9360E+11
43	101	37-- 43	1	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.7866E-10	0.2543E+12
43	95	35-- 43	2	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.1731E-08	0.1155E+11
43	108	40-- 43	2	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.1820E-08	0.1099E+11
44	98	36-- 44	1	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.1528E-09	0.1309E+12
44	103	38-- 44	1	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.5577E-10	0.3586E+12
44	98	36-- 44	2	CHORD	Y	5.89		2.78	4.64	2.04	4.09	0.6178E-08	0.3237E+10
44	107	40-- 44	2	BRACE	Y	5.89		2.11	3.26	2.90	3.33	0.1682E-08	0.1189E+11

Result of fatigue life.

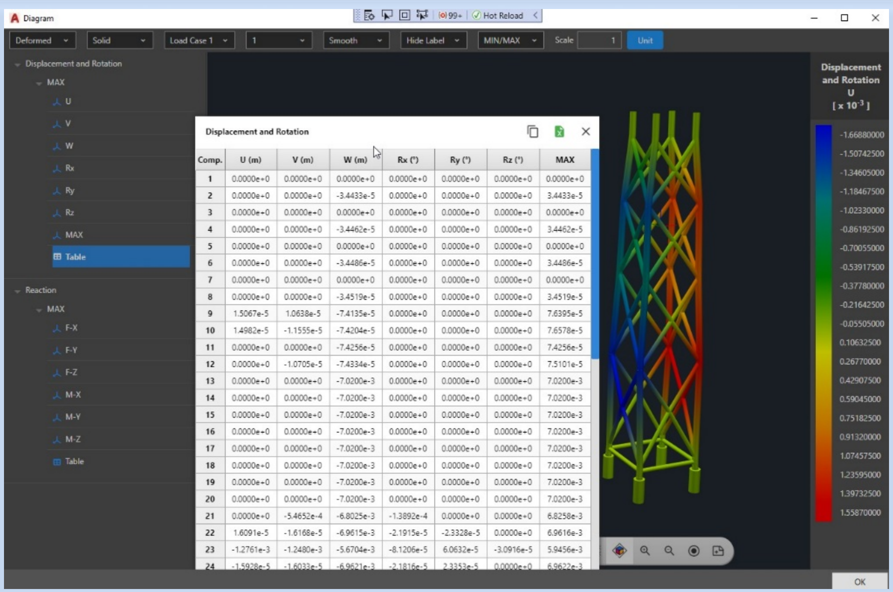
Prof. Ki-Du Kim Konkuk University, Seoul, Korea

Post-Process: OpenFAST Result

Adding the array program to print the result of output which is suitable for postprocess view.

```
! REACTION
WRITE (7100,220) FILENUMBERINTER
WRITE (7100,221)
WRITE (7100,222)
ALLOCATE ( ReactNs(6*p%nNodes_C), STAT = ErrStat )
ReactNs = 0.0_ReKi !Initialize
ReactNs_IN = 0.0D0
  DO I=1,p%nNodes_C   !Do for each constrained node, they are ordered as given in th
     FK_elm2=0._ReKi !Initialize for cumulative force
     FM_elm2=0._ReKi !Initialize
     pLst_XSEA => p%MOutLst3_XSEA(I)
     !Find the joint forces
     DO J=1,SIZE(pLst_XSEA%ElmIDs(1,:))  !for all the elements connected (normally 1
        iiNode = 1
        call ElementForce(pLst_XSEA, iiNode, J, FM_elm, FK_elm, sgn, DIRCOS, .false.
        !transform back to global, need to do 3 at a time since cosine matrix is 3x3
        DO L=1,2
           FM_elm2((L-1)*3+1:L*3) = FM_elm2((L-1)*3+1:L*3) + matmul(transpose(DIRCOS
           FK_elm2((L-1)*3+1:L*3) = FK_elm2((L-1)*3+1:L*3) + matmul(transpose(DIRCOS
           ! I believe this is all fixed in terms of signs now ,RRD 5/20/13
        ENDDO
     ENDDO
```

```
Result "Local-Force"  "Load Case 1"     1  Matrix  OnGaussPoints  "XFrame2"
ComponentNames "Fx" "Fy" "Fz" "Mx" "My" "Mz"
Values
    1  -0.47988E+05  -0.37576E+05   0.55009E+07   0.12056E+06  -0.17079E+06   0.53593E+04
        0.47988E+05   0.37576E+05  -0.55009E+07  -0.10174E+06   0.14675E+06  -0.53593E+04
    2  -0.48279E+05   0.36291E+05   0.55056E+07  -0.12965E+06  -0.16999E+06  -0.28841E+04
        0.48279E+05  -0.36291E+05  -0.55056E+07   0.11147E+06   0.14580E+06   0.28841E+04
    3   0.27646E+05  -0.35569E+05   0.55094E+07   0.10897E+06   0.73811E+05  -0.28803E+04
       -0.27646E+05   0.35569E+05  -0.55094E+07  -0.91154E+05  -0.59961E+05   0.28803E+04
    4   0.28038E+05   0.34090E+05   0.55147E+07  -0.12031E+06   0.74131E+05   0.53964E+04
       -0.28038E+05  -0.34090E+05  -0.55147E+07   0.10323E+06  -0.60084E+05  -0.53964E+04
    5  -0.42777E+05  -0.37513E+05   0.51153E+07   0.10175E+06  -0.14066E+06   0.52842E+04
        0.42777E+05   0.37513E+05  -0.51153E+07   0.48302E+05  -0.30451E+05  -0.52842E+04
    6  -0.42806E+05   0.36251E+05   0.51205E+07  -0.11154E+06  -0.13956E+06  -0.29248E+04
        0.42806E+05  -0.36251E+05  -0.51205E+07  -0.33463E+05  -0.31666E+05   0.29248E+04
    7   0.30112E+05  -0.35591E+05   0.51241E+07   0.91075E+05   0.62832E+05  -0.28599E+04
       -0.30112E+05   0.35591E+05  -0.51241E+07   0.51289E+05   0.57615E+05   0.28599E+04
    8   0.30241E+05   0.34139E+05   0.51299E+07  -0.10321E+06   0.62802E+05   0.54920E+04
       -0.30241E+05  -0.34139E+05  -0.51299E+07  -0.33345E+05   0.58162E+05  -0.54920E+04
    9   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
        0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
   10   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
        0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
   11   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
        0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
   12   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
        0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
   13   0.25365E+04  -0.50739E+04   0.16191E+06   0.13833E+05  -0.21366E+04  -0.63921E+04
       -0.25365E+04   0.50739E+04  -0.16191E+06   0.20280E+05   0.19190E+05   0.63921E+04
   14   0.16244E+04  -0.32136E+05   0.17515E+06   0.11167E+06   0.13068E+05   0.95843E+03
       -0.16244E+04   0.32136E+05  -0.17515E+06   0.12423E+06  -0.11437E+04  -0.95843E+03
   15  -0.25259E+04   0.50800E+04   0.15683E+06  -0.20487E+05  -0.19252E+05   0.62949E+04
```



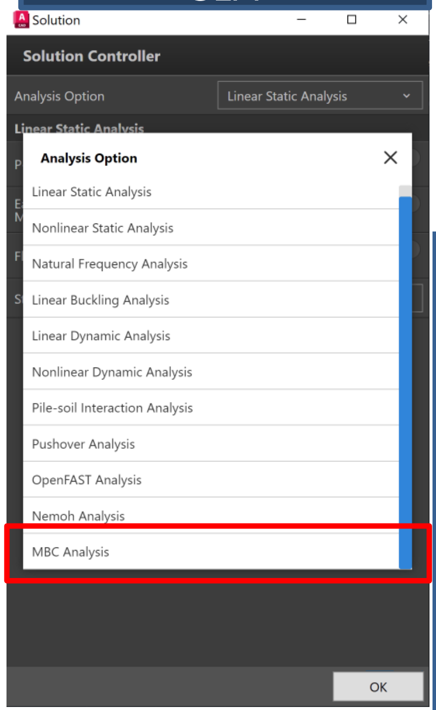
Comp.	U (m)	V (m)	W (m)	Rx (°)	Ry (°)	Rz (°)	MAX
1	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
2	0.0000e+0	0.0000e+0	-3.4433e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4433e-5
3	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
4	0.0000e+0	0.0000e+0	-3.4462e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4462e-5
5	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
6	0.0000e+0	0.0000e+0	-3.4486e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4486e-5
7	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0	0.0000e+0
8	0.0000e+0	0.0000e+0	-3.4519e-5	0.0000e+0	0.0000e+0	0.0000e+0	3.4519e-5
9	1.5067e-5	1.0638e-5	-7.4135e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.6395e-5
10	1.4982e-5	-1.1555e-5	-7.4204e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.6578e-5
11	0.0000e+0	0.0000e+0	-7.4256e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.4256e-5
12	0.0000e+0	-1.0705e-5	-7.4334e-5	0.0000e+0	0.0000e+0	0.0000e+0	7.5101e-5
13	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
14	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
15	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
16	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
17	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
18	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
19	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
20	0.0000e+0	0.0000e+0	-7.0200e-3	0.0000e+0	0.0000e+0	0.0000e+0	7.0200e-3
21	0.0000e+0	-5.4652e-4	-6.8025e-3	-1.3892e-4	0.0000e+0	0.0000e+0	6.8258e-3
22	1.6091e-5	-1.6168e-5	-6.9615e-3	-2.1915e-5	-2.3328e-5	0.0000e+0	6.9616e-3
23	-1.2761e-3	-1.2480e-3	-5.6704e-3	-8.1206e-5	6.0632e-5	-3.0916e-5	5.9456e-3
24	-1.5928e-5	-1.6033e-5	-6.9621e-3	-2.1816e-5	2.3353e-5	0.0000e+0	6.9622e-3

Dynamic post-processing with OpenFAST in 3D shape.

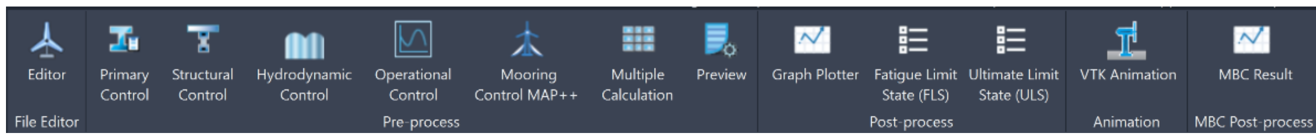
Improve Program Performance (MBC Analysis)

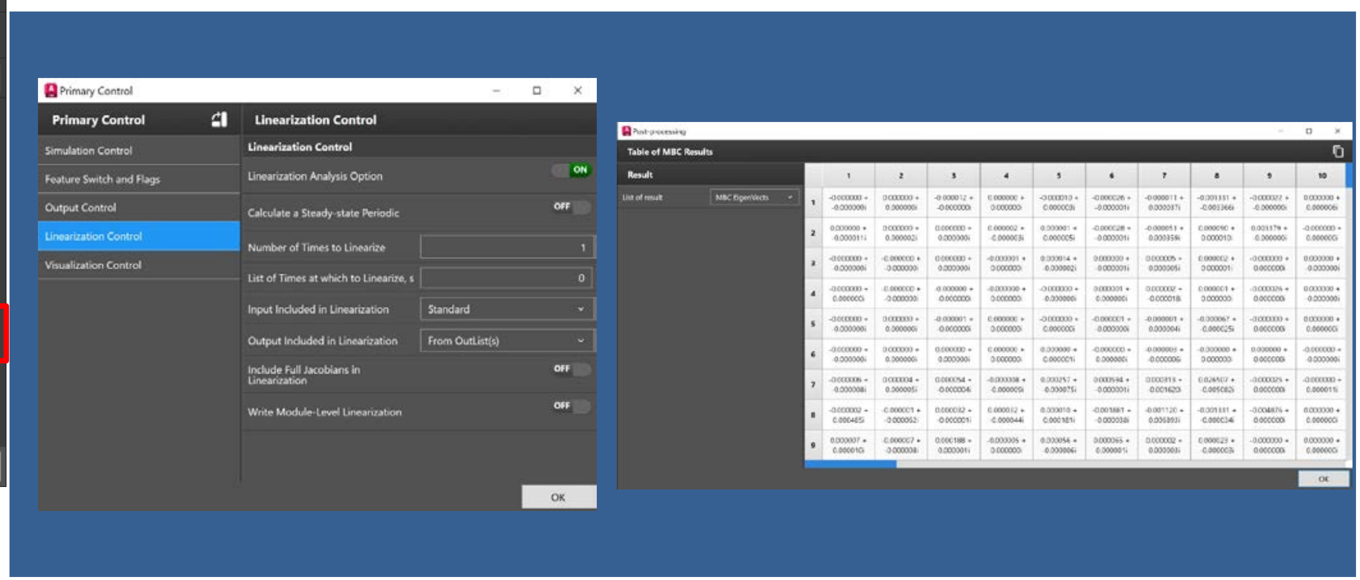
Multi-blade coordinate transformation (MBC) helps integrate the dynamics of individual blades and express them in a fixed (nonrotating) frame. MBC involves two steps: transformation of the rotating degrees of freedom, and transformation of the equations of motion

Last version of X-SEA



Present version of X-OpenFAST





Improve Program Performance (MBC Analysis)

The present version Includes file requirement of floating for MBC analysis, which published and announced by NREL

Previous version of X-SEA

barge.1	9/1/2022 4:44 PM	1 File	56 KB
barge.3	9/1/2022 4:44 PM	3 File	1,995 KB
barge.hst	9/1/2022 4:45 PM	HST File	2 KB
barge.ss	9/1/2022 4:45 PM	SS File	17 KB
marin_semi.1	9/1/2022 4:44 PM	1 File	492 KB
marin_semi.3	9/1/2022 4:45 PM	3 File	9,933 KB
marin_semi.12d	9/1/2022 4:45 PM	12D File	1,188 KB
marin_semi.12s	9/1/2022 4:45 PM	12S File	1,188 KB
marin_semi.hst	9/1/2022 4:44 PM	HST File	2 KB
spar.1	9/1/2022 4:44 PM	1 File	56 KB
spar.3	9/1/2022 4:45 PM	3 File	1,995 KB
spar.hst	9/1/2022 4:45 PM	HST File	2 KB
tlpmit.1	9/1/2022 4:44 PM	1 File	56 KB
tlpmit.3	9/1/2022 4:45 PM	3 File	1,995 KB
tlpmit.hst	9/1/2022 4:45 PM	HST File	2 KB

Present version of X-SEA

barge.1	9/2/2022 4:50 PM	1 File	56 KB
barge.3	9/2/2022 4:50 PM	3 File	1,995 KB
barge.hst	9/2/2022 4:51 PM	HST File	2 KB
barge.ss	9/2/2022 4:51 PM	SS File	17 KB
marin_semi.1	9/2/2022 4:50 PM	1 File	492 KB
marin_semi.3	9/2/2022 4:51 PM	3 File	9,933 KB
marin_semi.12d	9/2/2022 4:51 PM	12D File	1,188 KB
marin_semi.12s	9/2/2022 4:51 PM	12S File	1,188 KB
marin_semi.hst	9/2/2022 4:50 PM	HST File	2 KB
marin_semi.ss	9/2/2022 4:51 PM	SS File	53 KB
marin_semi.ssexctn	9/2/2022 4:51 PM	SSEXCTN File	21 KB
spar.1	9/2/2022 4:50 PM	1 File	56 KB
spar.3	9/2/2022 4:51 PM	3 File	1,995 KB
spar.hst	9/2/2022 4:51 PM	HST File	2 KB
tlpmit.1	9/2/2022 4:50 PM	1 File	56 KB
tlpmit.3	9/2/2022 4:51 PM	3 File	1,995 KB
tlpmit.hst	9/2/2022 4:51 PM	HST File	2 KB

Post-Process: Visualization Animation (Surface)

Compatible with visualization animation file (VTK)

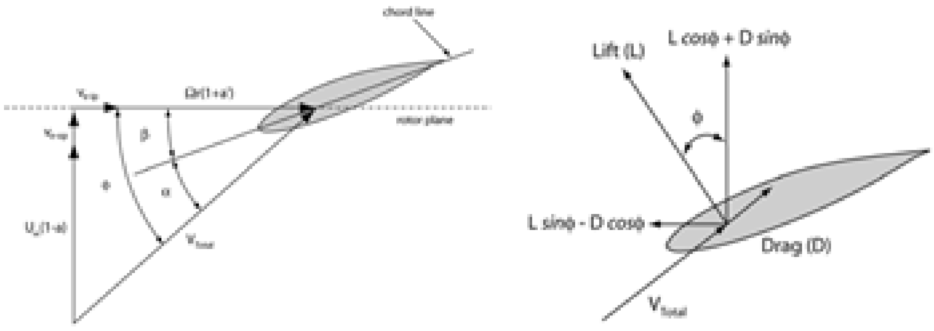
AeroDyn

- Theoretical background

- Blade Element Momentum(BEM)

  Breaking the blades into elements along the

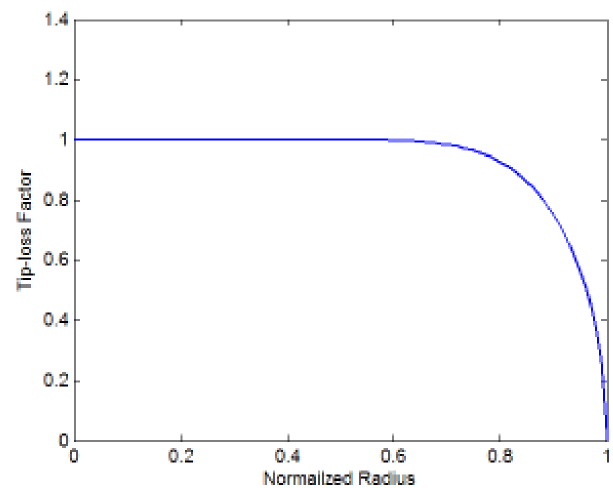
- Two dimensional airfoil analysis
  - ✓ Simple and fast.
  - ✓ Have some limitations



$$dT = B\frac{1}{2}\rho V_{total}^{2}(C_l\cos\varphi + C_d\sin\varphi)cdr$$

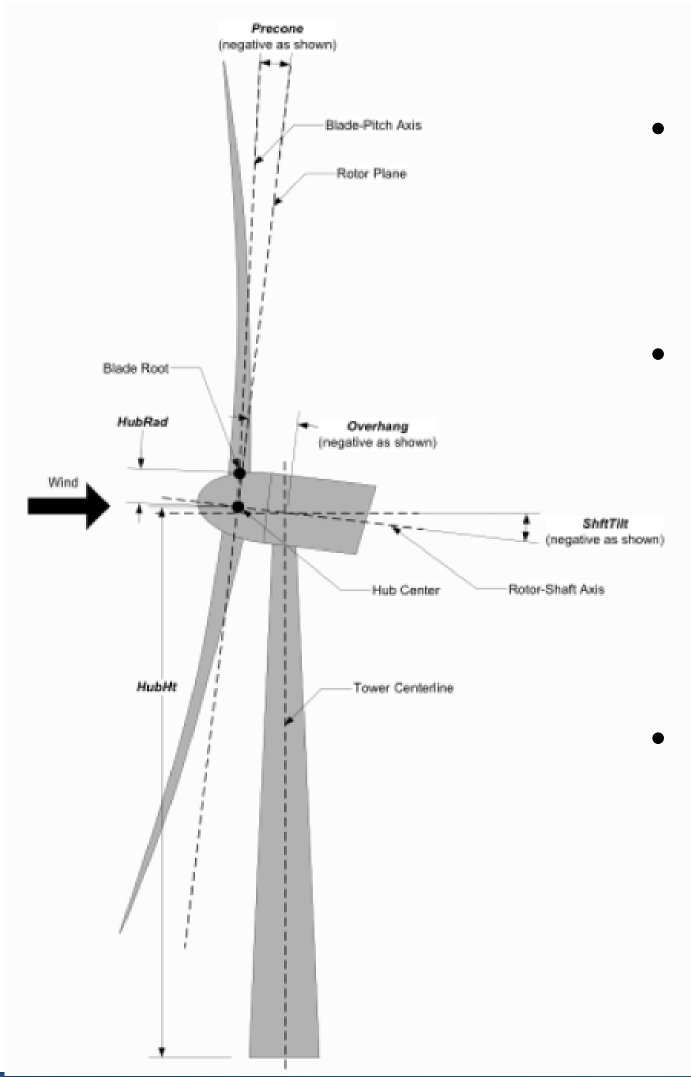
$$dQ = B\frac{1}{2}\rho V_{total}^{2}(C_l\sin\varphi - C_d\cos\varphi)crdr$$

- Correction methods
  - ✓ Hub-Loss Model : correct the induced velocity resulting from a vortex near the hub of the rotor
  - ✓ Tip-Loss Model : correct the influence of vortices shed from the blade tips



AeroDyn

- Time-domain wind turbine aerodynamics module

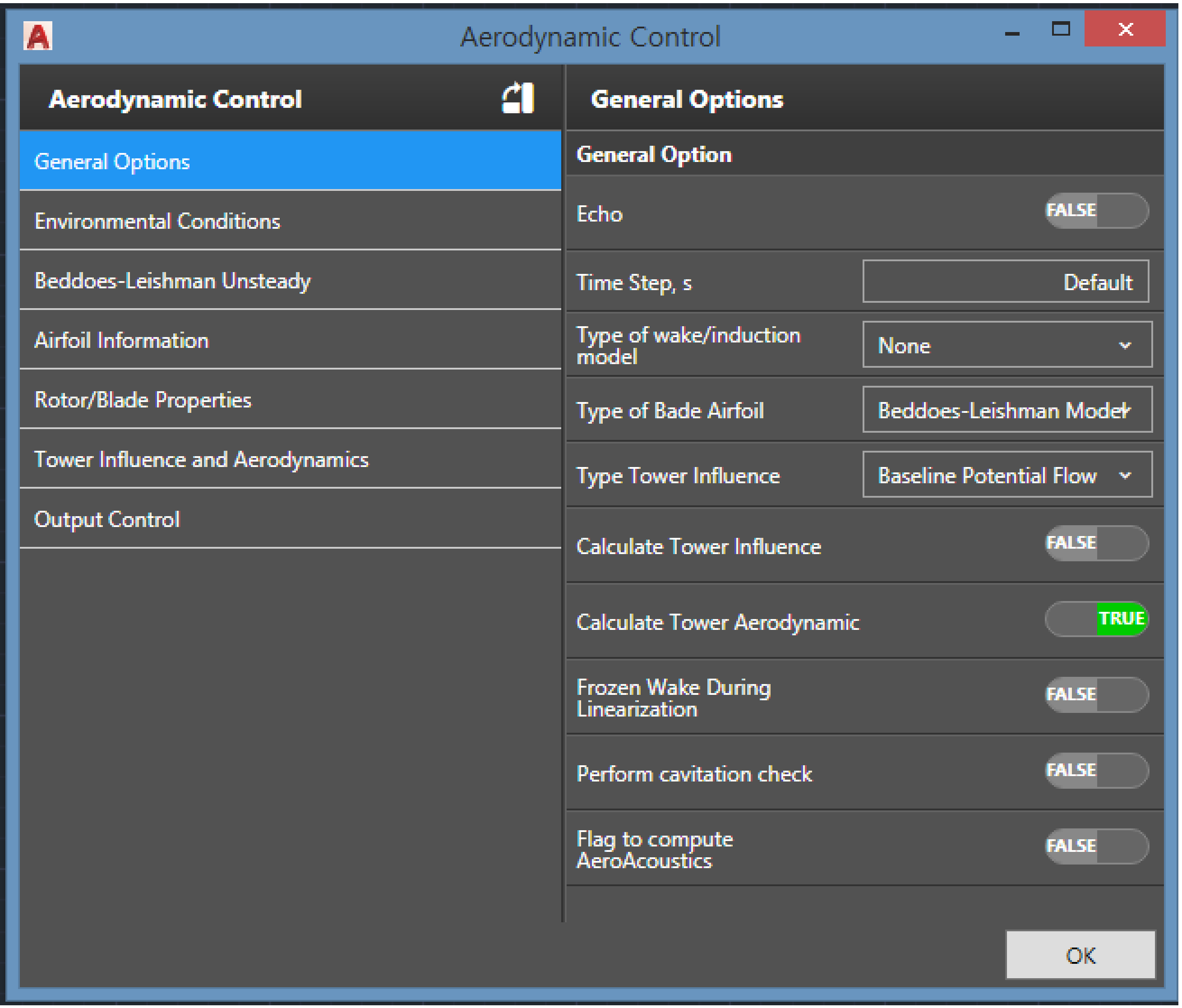


- **Turbine geometry options**

  Set values of tilt angle, hub height, etc... as input paramters.

- **General/Theory options**
  - ✓ Wake mod options.
  - ✓ Skewed-wake correction model.
  - ✓ Tip/Hub loss model.
  - ✓ Envitionmental conditions.
- **Airfoil & Rotor/Blade properties**
  - ✓ Aerodynamic data
  - ✓ Blade nodal data

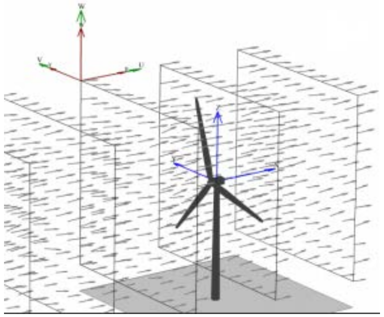
AeroDyn


Aerodynamic Control
Aerodynamic Control
General Options
General Options
Environmental Conditions
Beddoes-Leishman Unsteady
Airfoil Information
Rotor/Blade Properties
Tower Influence and Aerodynamics
Output Control
General Option
Echo
FALSE
Time Step, s
Default
Type of wake/induction model
None
Type of Bade Airfoil
Beddoes-Leishman Model
Type Tower Influence
Baseline Potential Flow
Calculate Tower Influence
FALSE
Calculate Tower Aerodynamic
TRUE
Frozen Wake During Linearization
FALSE
Perform cavitation check
FALSE
Flag to compute AeroAcoustics
FALSE
OK

TurbSim

▪ Stochastic,full-field,turbulent wind simulator

- Numerically simulates time sereis of wind velocity in a vertical rectangular grid.
- Spectral models: modified version of the Sandia method
  - ✓ The NREL Wind Farm Models
  - ✓ The NWTC Model
  - ✓ The Great Plains Model



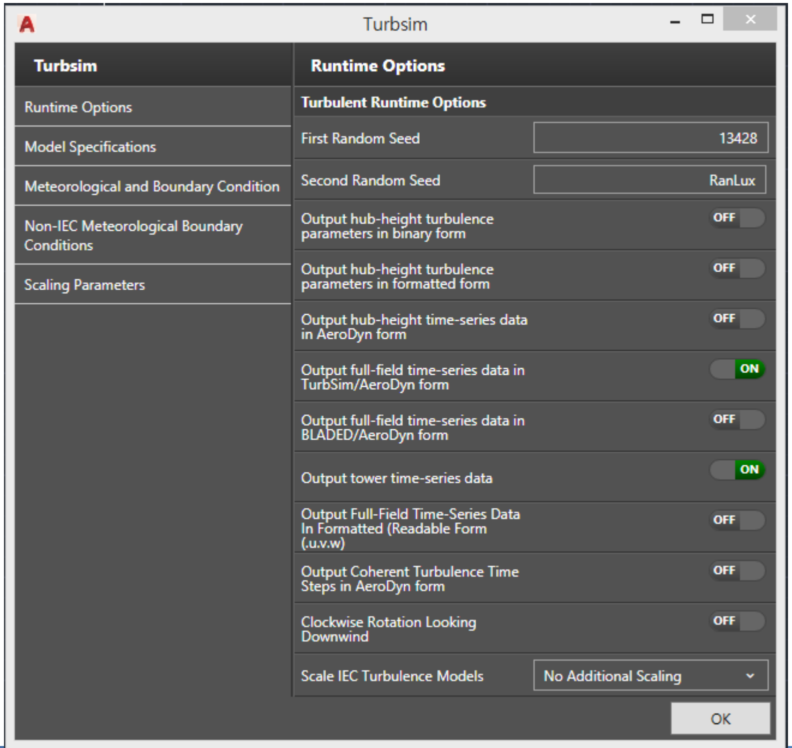
- Wind profiles: profiles for the mean wind speed
  - ✓ Power Law wind profile

$$V(z) = V(z_{ref})\left(\frac{z}{z_{ref}}\right)^{a}$$

  - ✓ Logarithmic Wind profile

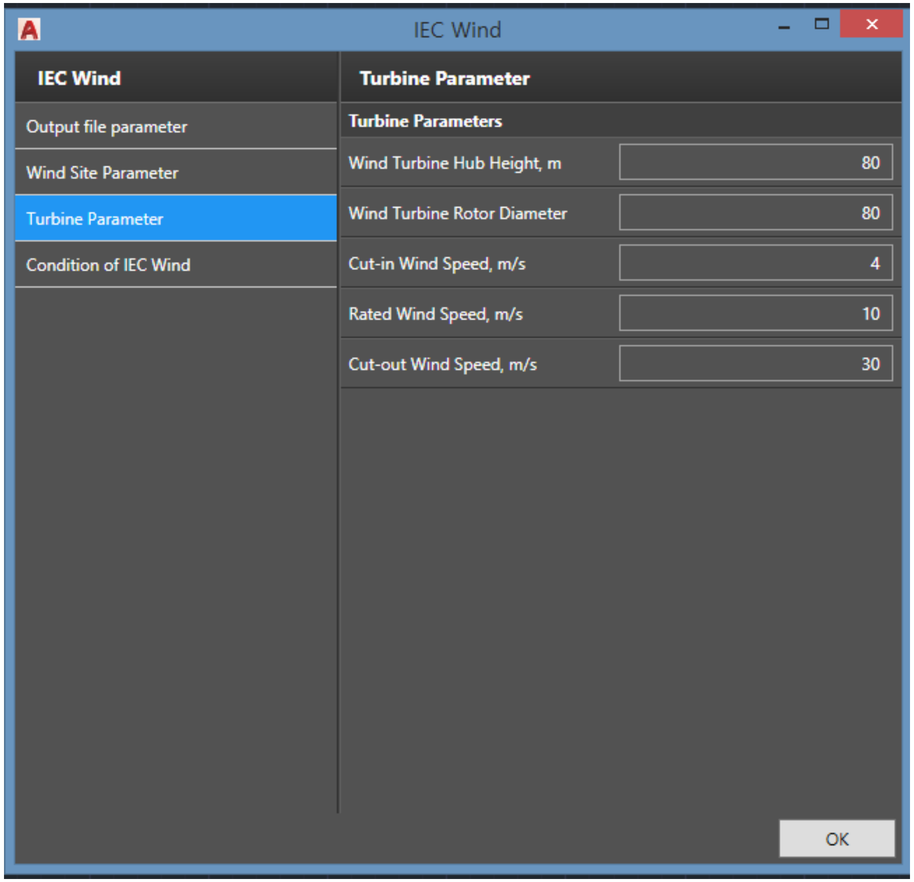
$$V(z) = V(z_{ref})\frac{\ln(z/z_0) - \psi_m}{\ln(z_{ref}/z_0) - \psi_m}$$

  - ✓ Low-Level jet wind profile
- Spatial coherence models
  - ✓ Coherence for IEC spectral models
  - ✓ Coherence for Non-IEC spectral models



IECWIND

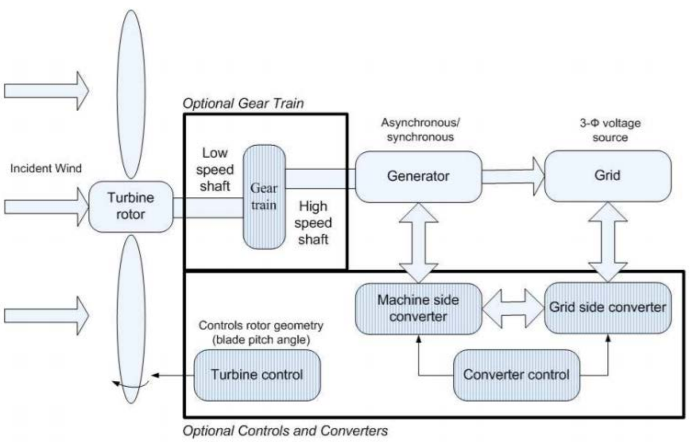
IECWind is a utility program used to create wind files for Inflow Wind-based programs.
IECWind creates wind files that model the extreme conditions outlined by
the International Electrotechnical Commission.
This software was developed by Marshall Buhl and supported by Jason Jonkman of NREL.



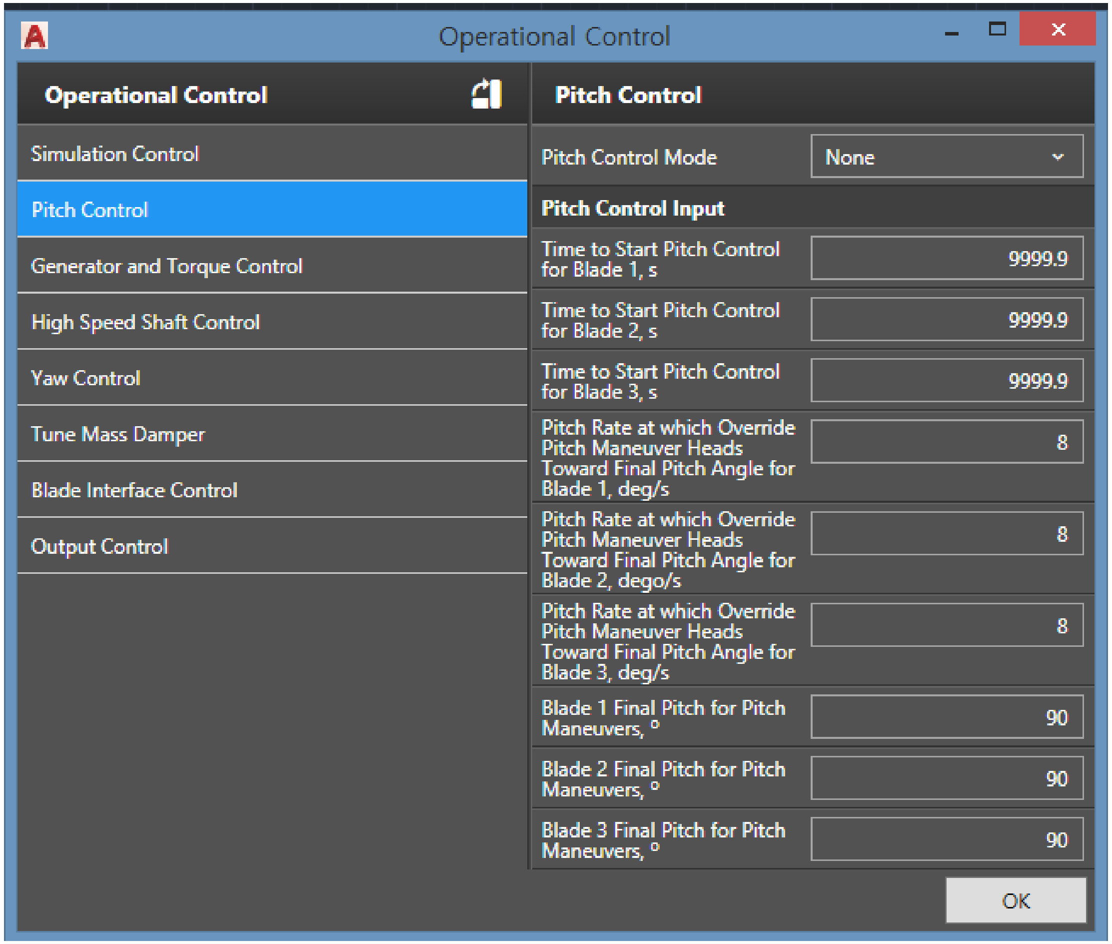
ServoDyn (Operational Control)

- Control and electrical drive dynamics module
  - Wind turbine controller module including structural control
  - Control options
    - ✓ Pitch control
    - ✓ Generator and Torque Control
    - ✓ Shaft Brake
    - ✓ Nacelle-yaw control
    - ✓ Structural control

Output
- Electrical generator power and torque



Wind turbine diagram



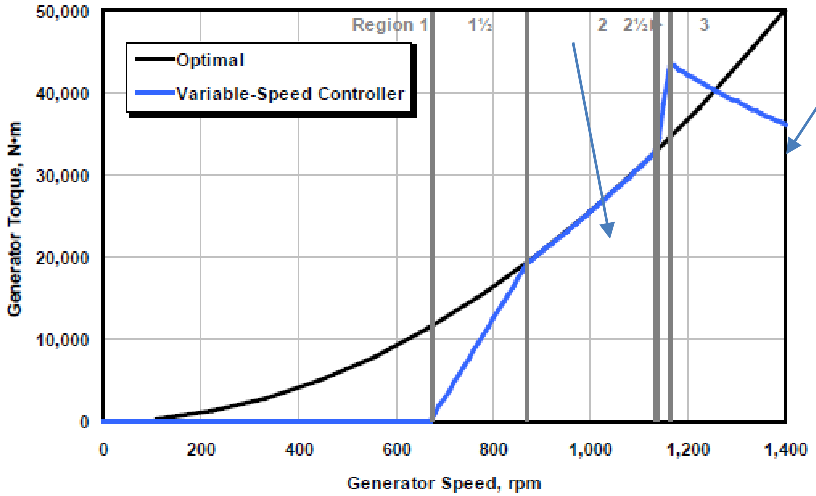
ServoDyn

- NREL 5-MW baseline wind turbine

  - Variable-speed controller
  - Control system
    - ✓ Control-Measurement filter
    - ✓ **Generator-Torque controller**
    - ✓ **Blade-Pitch controller**

Torque Cont

Pitch Cont

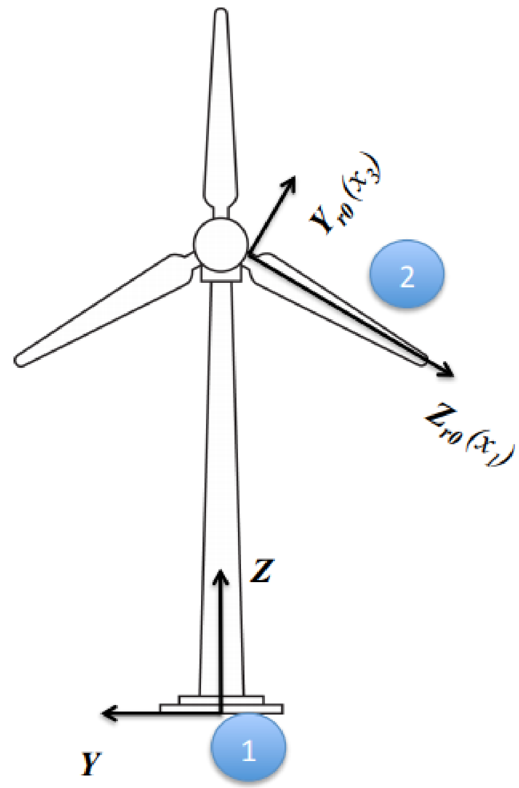


Torque-versus-speed response of the variable-speed controller

- Generator torque is computed as a tabulated function of the filtered generator speed.
- 5 control regions
  - ✓ Region 1 : Before cut-in speed. Generator torque is zero and no power is generated.
  - ✓ Region 1.5 : Linear transition between Regions 1 and 2.
  - ✓ Region 2 : Control region for optimizing power capture.
  - ✓ Region 2.5 : Linear transition between Regions 2 and 3.
  - ✓ Region 3 : Generator power is held constant.

BeamDyn (Blade Control)

- Theoretical background
  - Geometrically Exact Beam Theory(GEBT)
  - Capability of beams
    - ✓ Initially curved and twisted
    - ✓ Subjected to large displacement and rotations.
    - ✓ Coupling effects between all six DOFs including extension,bending,shear and torsion.



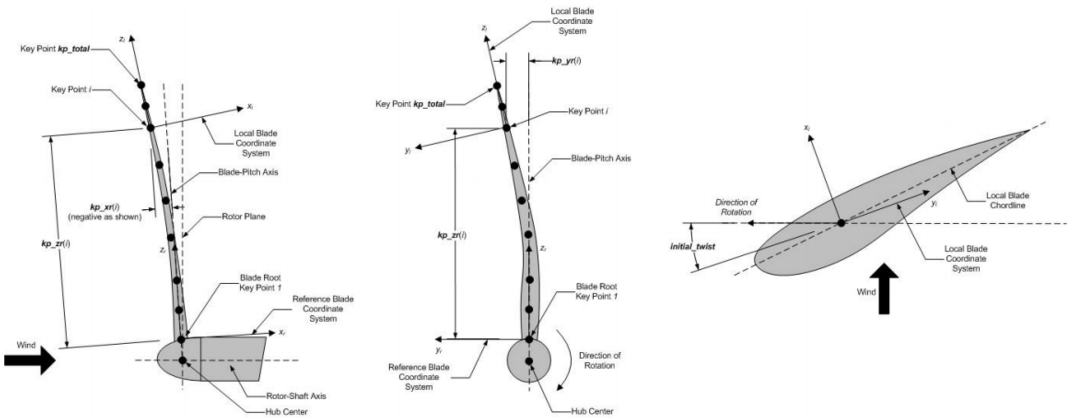
  - Governing Equation

$$\dot{\underline{h}} - \underline{F}'$$
$$\dot{\underline{g}} + \underline{f}\dot{\tilde{u}}\underline{h} - \underline{M}' + (\widetilde{x_0}' + \tilde{u}')^T \underline{F} = \underline{m}$$

- ✓ h and g are the linear and angular momentum
- ✓ F and M are beam's sectional force and moment resultants
- ✓ f and m are the distributed force and moment applied to the beam
- ✓ u is the 1D displacement of a point on the reference line
- ✓ x_0 is the position vector of a point along the beam's reference line

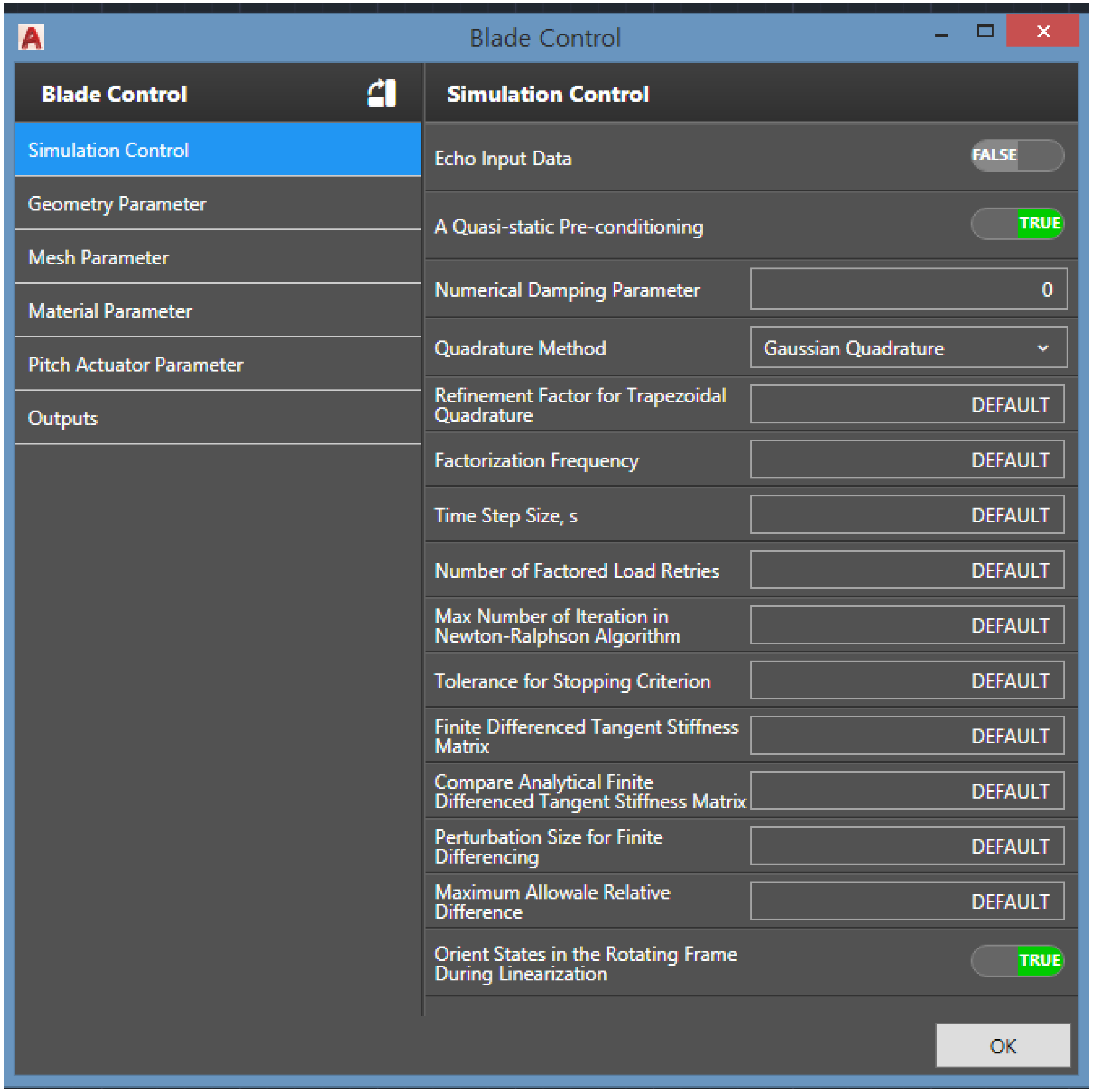
BeamDyn (Blade Control)

- Time-domain structural-dynamics module for slender structures
  - Seperate instance for eache blade.
  - Can calculate member internal reaction loads.
  - Defines the blade geometry, cross-sectional material mass,stiffness, and damping properties.



  - Computation at root node
    - ✓ Inputs: six displacements/velocities/accelerations(three translantions and three rotations)
    - ✓ Outputs: six reaction loads(three translational forces and three moments) . Blade displacement, velocities, and accelerations along the beam length

BeamDyn (Blade Control)



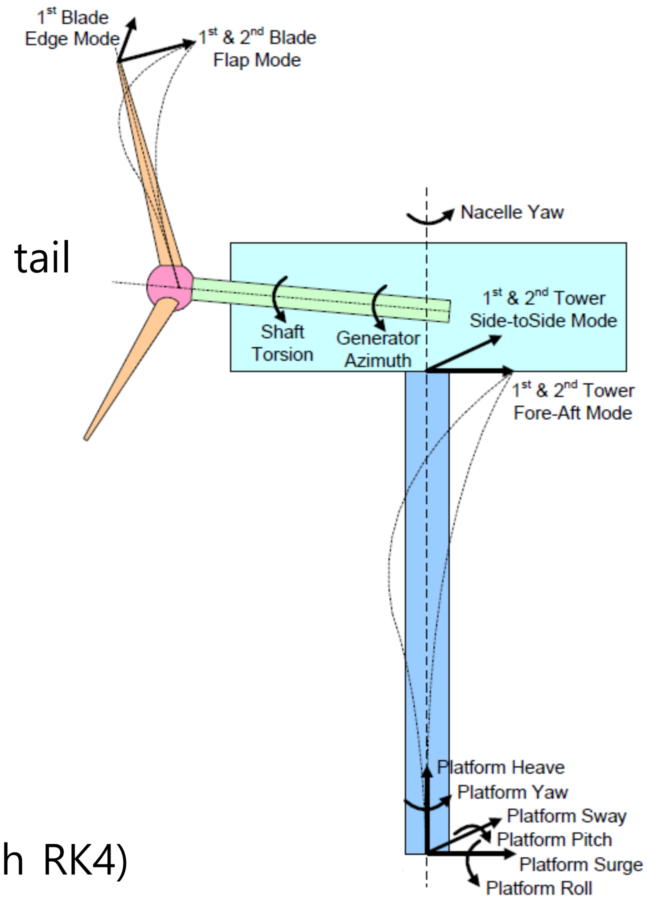
ElastoDyn (Structural Control)

- Theoretical background

- Nonlinear equations of motion are derived & implemented using Kane's method.
- Combined multi-body &modal-dynamics formulation
  - ✓ Modal: blades, tower
  - ✓ Multi-body: platform, nacelle, generator,gears, hub, tail
- Equation of motion

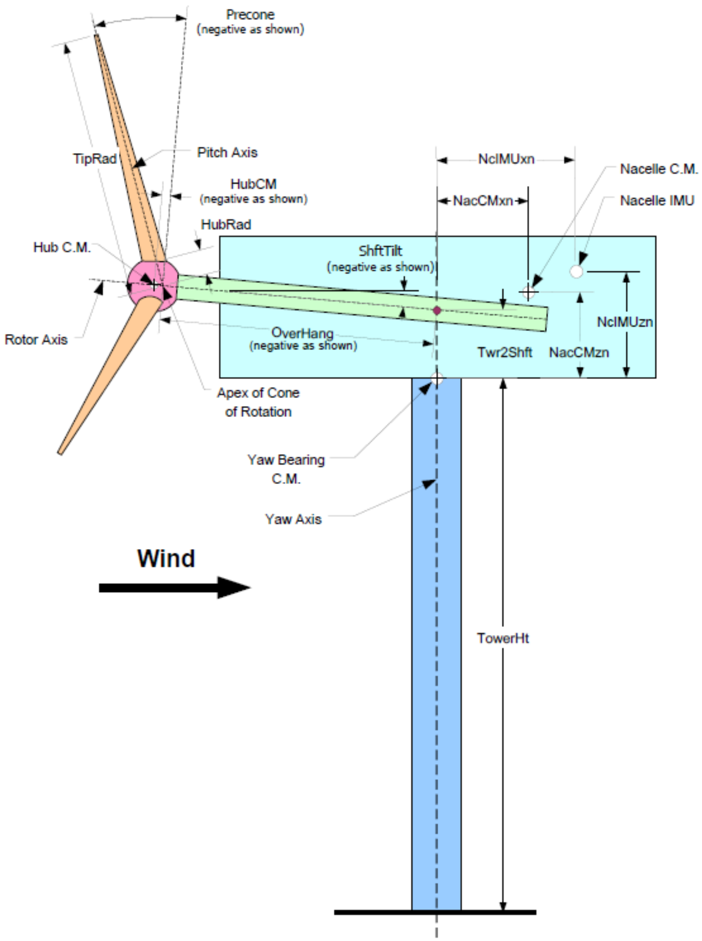
$$M(\underline{q},\underline{u},t)\underline{\ddot{q}} + \underline{f}(\underline{q},\underline{\dot{q}},\underline{u},\underline{u_d},t) = 0$$
$$\underline{Outdata = Y}(\underline{q},\underline{\dot{q}},\underline{u},\underline{u_d},t)$$
$$= Y_r(\underline{q},\underline{u},t)\underline{\ddot{q}} + \underline{Y_t}(\underline{q},\dot{q},\underline{u},\underline{u_d},t)$$

- Time integration using one of sevral options
  - ✓ 4th-order RK4 explicit
  - ✓ 4th-order AB4 multi-step explicit(with RK4)
  - ✓ 4th-order ABM4 multi-step predictor-corrector(with RK4)



ElastoDyn (Structral Control)

- Structural-dynamic module for horizontal-axis wind turbines

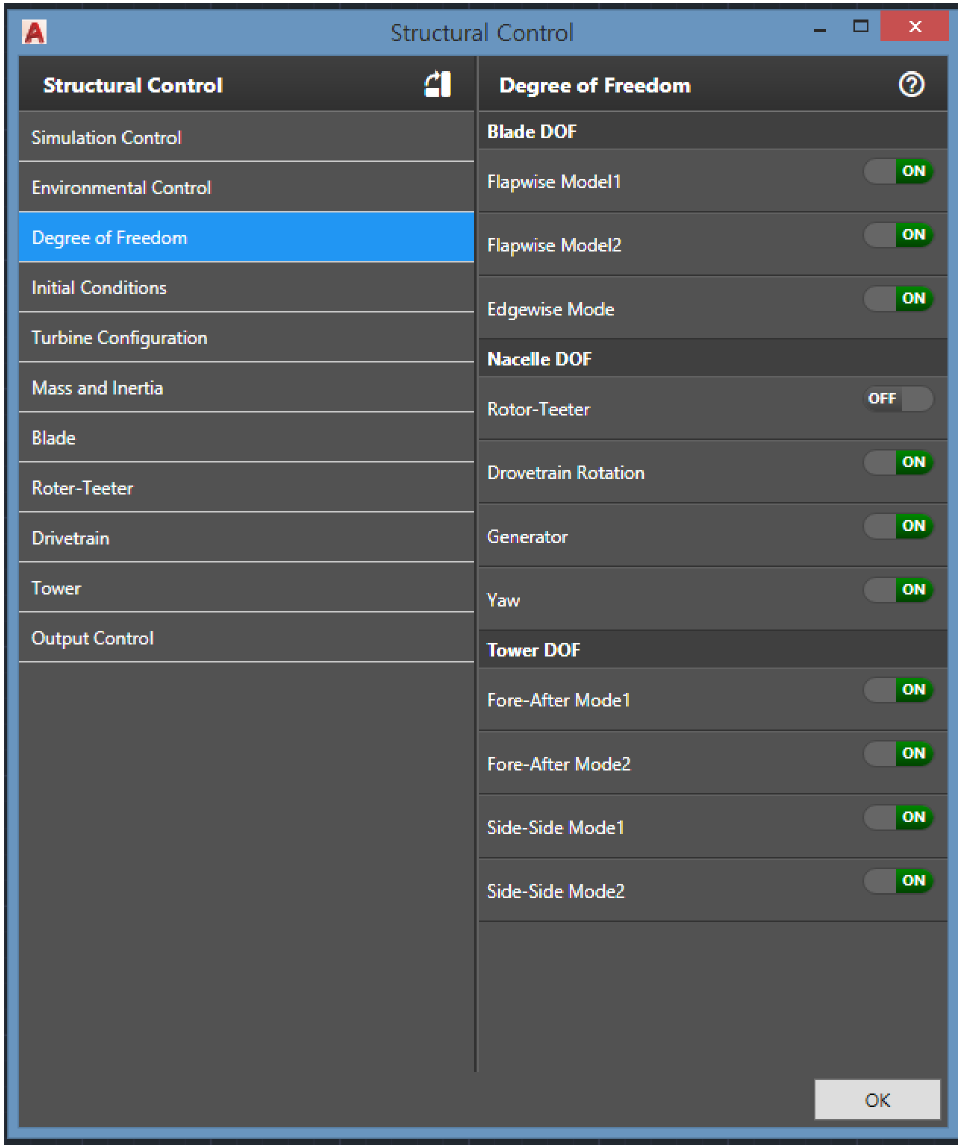


- Turbune geometry setting as in AeroDyn
- Computation based on wind turbine geometry
  - ✓ Windturbine property: Geometry, Mass/inertia

    Stiffness/Damping coefficient, Gravity
  - ✓ Inputs: Aerodynamic/Hydrodynamic loads, Controller

    commands, Substructure reactions
  - ✓ Outputs: Displacements, Velocities, Accelerations, Reaction loads
  - ✓ Continuous States: Displacements, Velocities

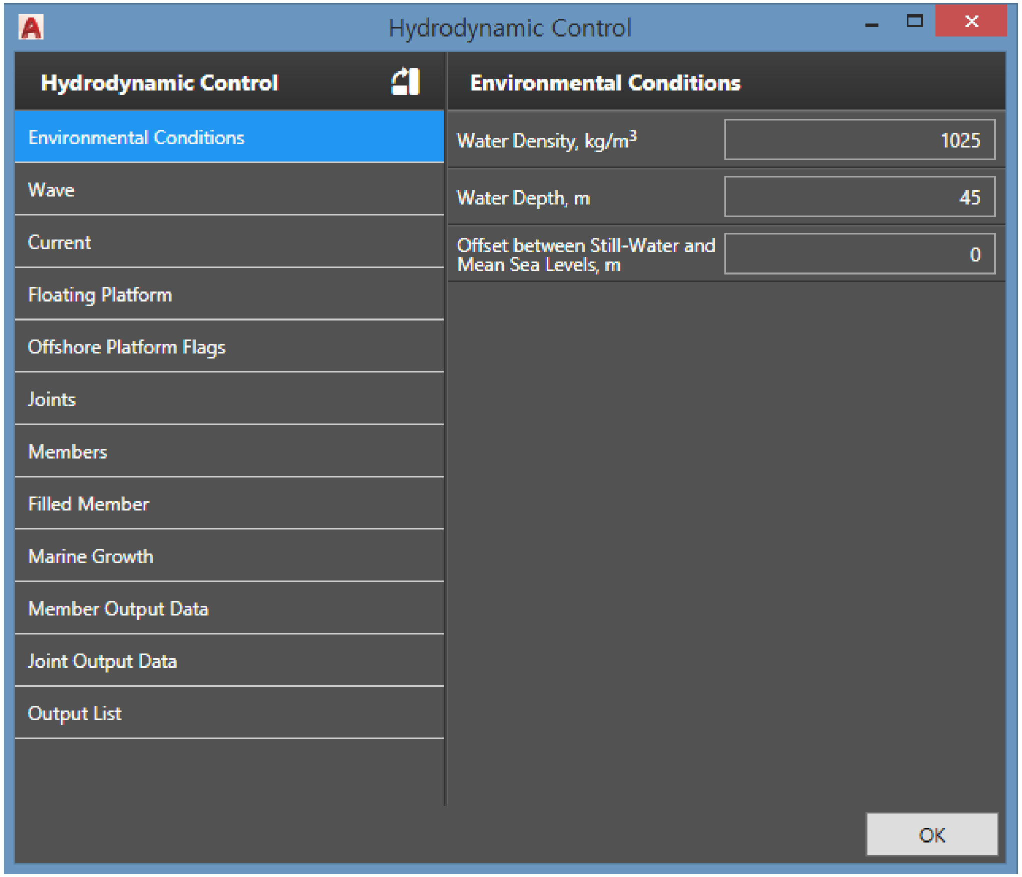
ElastoDyn (Structral Control)



HydroDyn

HydroDyn is a time-domain hydrodynamics module.

It has been coupled into the FAST wind turbine engineering tool to enable aero-hydro-servo-elastic simulation of offshore wind turbines.
HydroDyn is applicable to both fixed-bottom and floating offshore substructures.
HydroDyn allows for multiple approaches for calculating the hydrodynamic loads on a structure: a potential-flow theory solution, a strip-theory (Morison equation) solution.



Waves in HydroDyn can be regular (periodic) or irregular (stochastic) and long-crested (unidirectional) or short-crested (with wave energy spread across a range of directions). HydroDyn treats waves using first-order (linear Airy) or first- plus second-order wave theory.
Current: Water velocity can be included due to a current mode.
Marine growth: causes (1) a static weight and mass to a member, applied as distributed loads along the member (2) increases the outer diameter of a member.

HydroDyn

Fixed-Bottom Substructures

When modeling a fixed-bottom system, the use of a strip-theory (Morison) only model is recommended. When HydroDyn is coupled to FAST, SubDyn is used for the substructure structural dynamics.

Floating Platforms: NEMOH is included in X-OpenFAST

When modeling a floating system, you may use potential-flow theory only, strip-theory (Morison) only, or a hybrid model containing both. Potential-flow theory based on frequency-to-time-domain transforms is enabled through WAMIT or NEMOH.

The WAMIT or NEMOH model should account for all of the members in the floating substructure, and Morison's equation is neglected in this case.

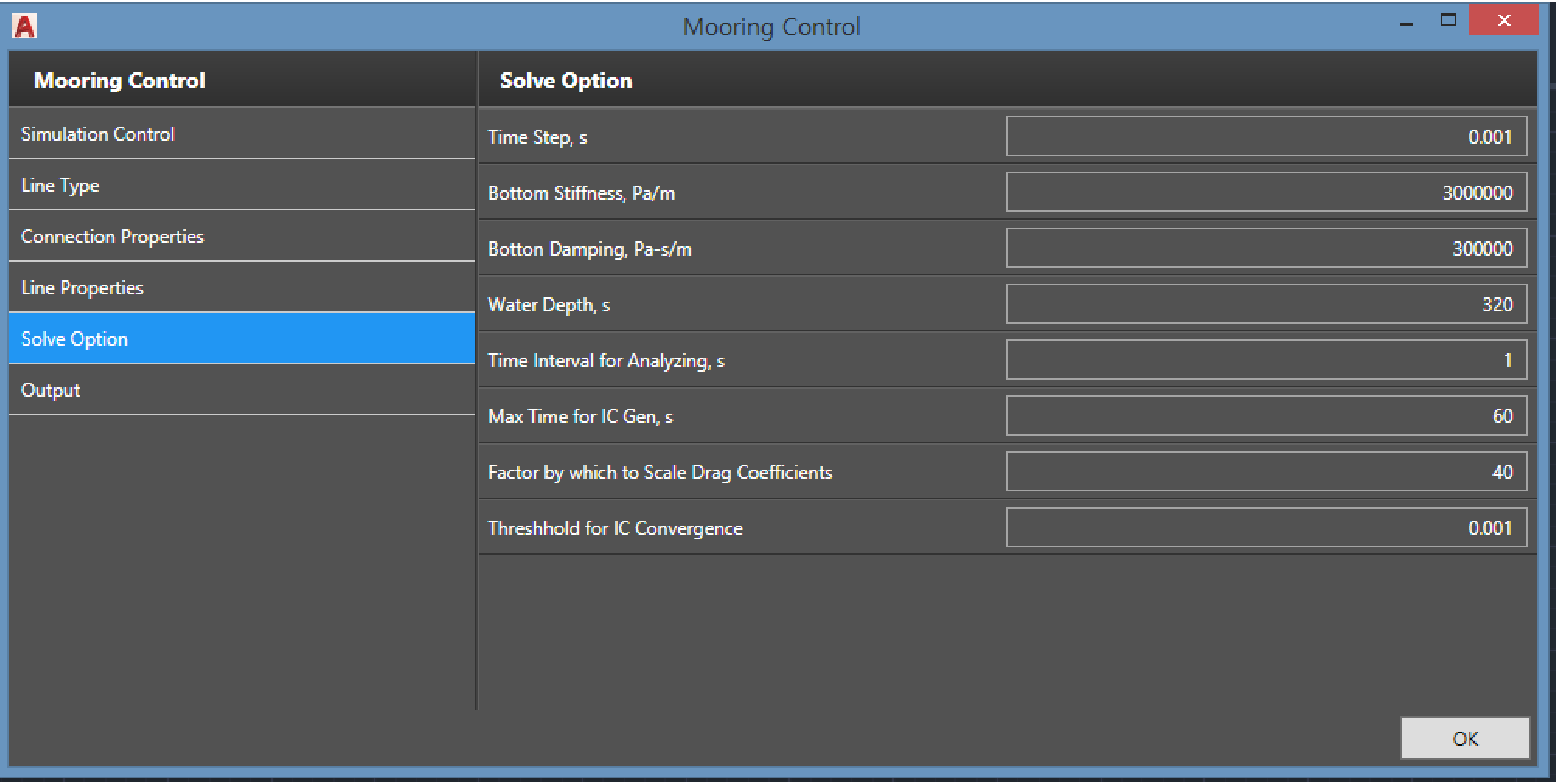
www.wamit.com: Commercial Software,
2nd order potential theory.

https://lheea.ec-nantes.fr › software-and-patents › nemo.: Open Source Software,
1st order potential theory

MoorDyn (Mooring Analysis)

MAP++: Mooring Analysis Program	MoorDyn
The Mooring Analysis Program (MAP++) is a library designed to be used in parallel with other engineering tools to model the steady-state forces on a Multi-Segmented, Quasi-Static (MSQS) mooring line. The MSQS model is developed based on an extension of conventional single line static solutions. Conceptually, MAP++'s MSQS module solves the algebraic equations for all elements simultaneously with the condition that the total force at connection points sum to zero. Seabed contact, seabed friction, and externally applied forces can be modeled with this tool. This allows multi-element mooring lines with arbitrary connection configurations to be analyzed.	MoorDyn is a lumped-mass mooring line model for simulating the dynamics of moorings connected to floating offshore structures. It accounts for internal axial stiffness and damping forces, weight and buoyancy forces, hydrodynamic forces from Morison's equation (assuming quiescent water so far), and vertical spring-damper forces from contact with the seabed. MoorDyn's input file format is based on that of MAP. The model supports arbitrary line interconnections, clump weights and floats, and different line properties.

MoorDyn (Mooring Analysis)



SubDyn (Structural Dynamic Analysis)

SubDyn is a time-domain structural-dynamics module for multi-member fixed-bottom substructures.

It has been coupled into the FAST aero-hydro-servo-elastic engineering tool.

Substructure types supported by SubDyn include monopiles, tripods, jackets, and other lattice-type substructures common for offshore wind installations in shallow and transitional water depths. SubDyn can also be used to model lattice support structures for land-based wind turbines.

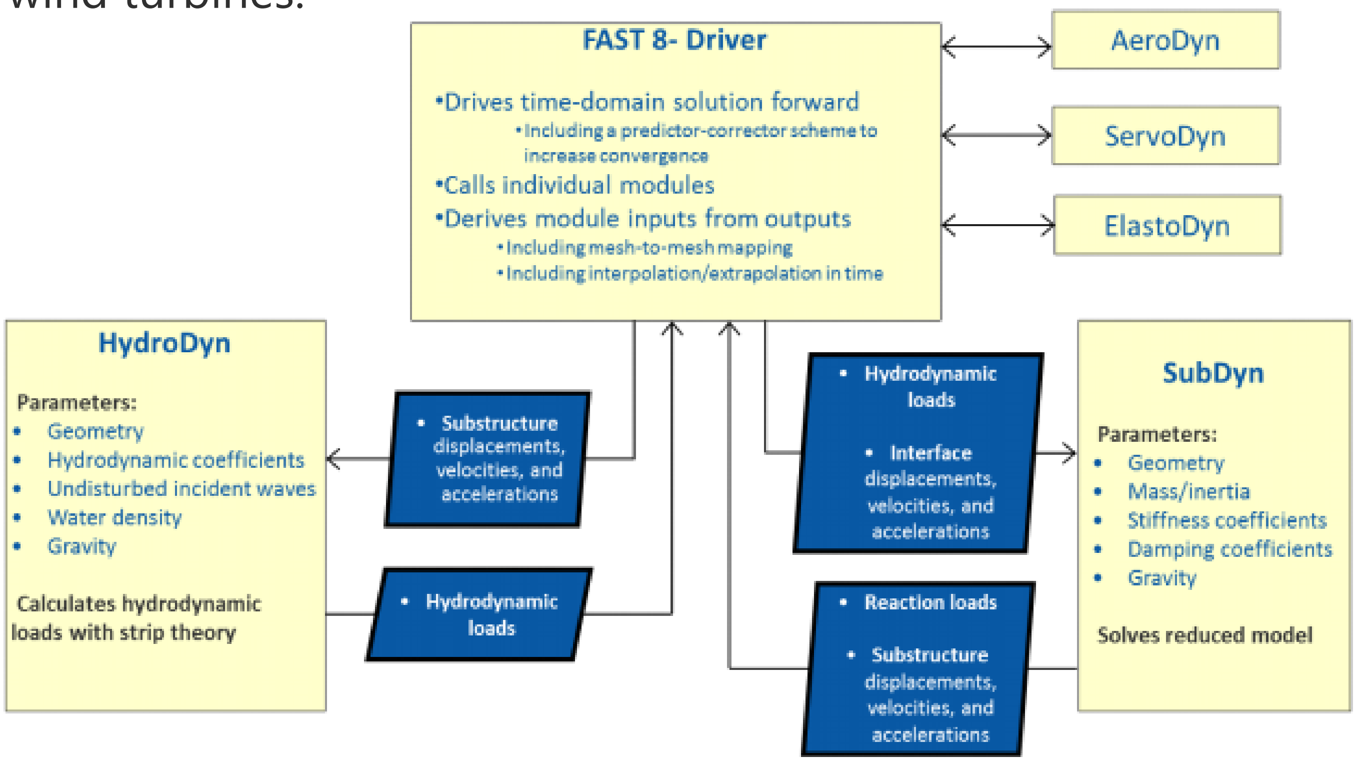
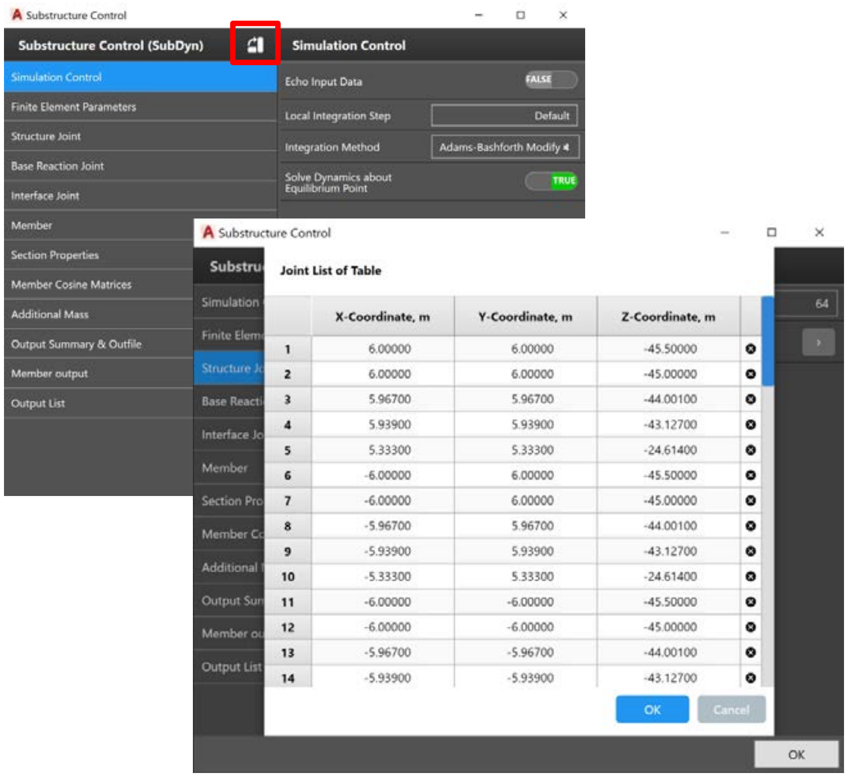


Figure 1. SubDyn, HydroDyn, and FAST 8 coupled interaction

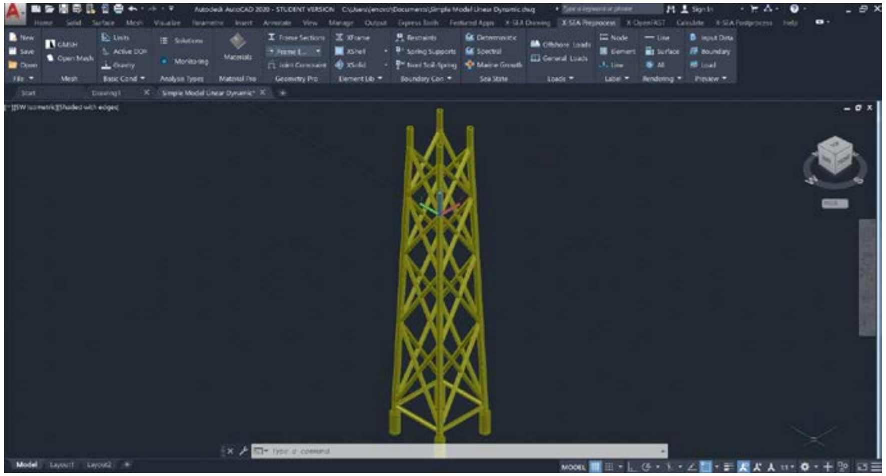
SubDyn: Geometry

OpenFAST solution.



Provided a spread sheet on UI and import functionality which insert original text into spread sheet.

Linear static and Linear Dynamic Solution
(Uncoupled and Coupled analysis)



CAD modelling tools supports a following performance.
- Template of jacket model
- Various type of section geometry and load condition
- Easier define a boundary condition and output of channel lists.
- Import functionality.
- Structural design based on offshore standard.
- Bill of material (BOM).
- Generate multiple load case.
- Animation of post-processing.

SubDyn (Structural Dynamic Analysis)

SubDyn relies on two main engineering schematizations:
1.A linear frame finite-element beam model (LFEB)
2.A dynamics system reduction via Craig-Bampton's (C-B) method, together with a Static-Improvement method, greatly reducing the number of modes needed to obtain an accurate solution.