OpenFAST: Using a Stiffness Matrix as Boundary Condition in SubDyn

Version 2
06/25/2020 (mm/dd/yyyy)

Roger Bergua

Rev.	Date (*mm/dd/yyyy*)	Description
0	06/11/2020	Creation of the document.
1	06/22/2020	Corrected signs for directions *Kxty* and *Kytx* in Figure 4. *OpenFAST_model_v1.zip* updated accordingly in Confluence site.
2	06/25/2020	Figure 2 updated with the latest SubDyn input file.

In the Confluence site, it is possible to find a new version of OpenFAST solver. This version (based on OpenFAST v2.3.0) includes enhancements in the SubDyn module. Note that this solver is not publicly available yet, but it can already be used in OC6 phase II.

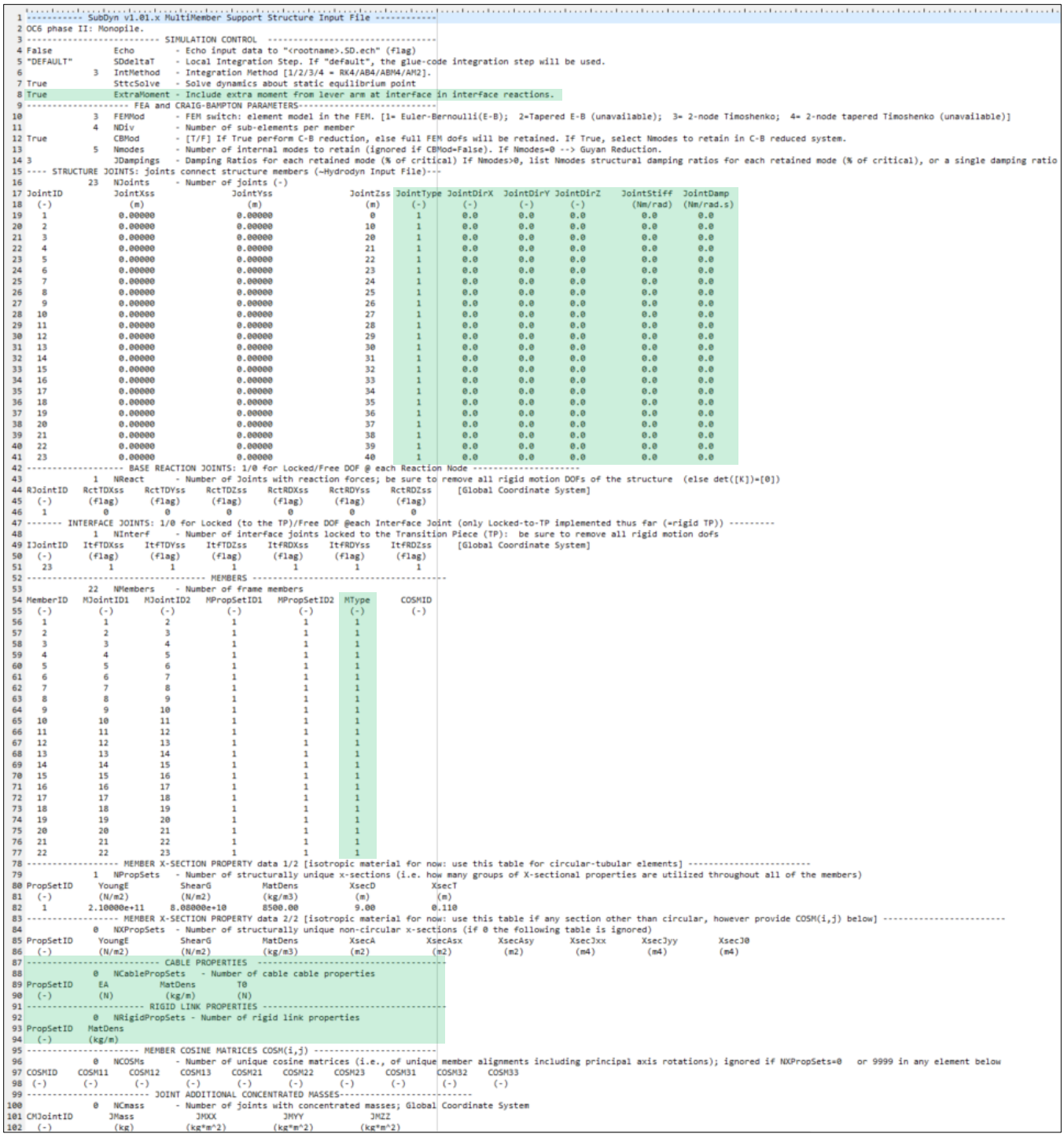
In order to use this new OpenFAST solver it's necessary to use the new main input file. In Figure 1, the new inputs are highlighted in red:

```
------- OpenFAST example INPUT FILE -------------------------------------------
OpenFAST model: OC6 phase II. SubDyn (monopile) + ElastoDyn (tower). Land-based case. IMPORTANT: New template to account for SoildDyn.
---------------------- SIMULATION CONTROL --------------------------------------
False         Echo            - Echo input data to <RootName>.ech (flag)
"FATAL"       AbortLevel      - Error level when simulation should abort (string) {"WARNING", "SEVERE", "FATAL"}
       300    TMax            - Total run time (s)
     0.001    DT              - Recommended module time step (s)
         2    InterpOrder     - Interpolation order for input/output time history (-) {1=linear, 2=quadratic}
         0    NumCrctn        - Number of correction iterations (-) {0=explicit calculation, i.e., no corrections}
     99999    DT_UJac         - Time between calls to get Jacobians (s)
     1E+06    UJacSclFact     - Scaling factor used in Jacobians (-)
---------------------- FEATURE SWITCHES AND FLAGS ------------------------------
         1    CompElast       - Compute structural dynamics (switch) {1=ElastoDyn; 2=ElastoDyn + BeamDyn for blades}
         0    CompInflow      - Compute inflow wind velocities (switch) {0=still air; 1=InflowWind; 2=external from OpenFOAM}
         0    CompAero        - Compute aerodynamic loads (switch) {0=None; 1=AeroDyn v14; 2=AeroDyn v15}
         1    CompServo       - Compute control and electrical-drive dynamics (switch) {0=None; 1=ServoDyn}
         1    CompHydro       - Compute hydrodynamic loads (switch) {0=None; 1=HydroDyn}
         1    CompSub         - Compute sub-structural dynamics (switch) {0=None; 1=SubDyn; 2=External Platform MCKF}
         0    CompMooring     - Compute mooring system (switch) {0=None; 1=MAP++; 2=FEAMooring; 3=MoorDyn; 4=OrcaFlex}
         0    CompIce         - Compute ice loads (switch) {0=None; 1=IceFloe; 2=IceDyn}
         0    CompSoil        - Compute soil-structural dynamics (switch) {0=None; 1=with SubDyn mesh}
---------------------- INPUT FILES ---------------------------------------------
"OC6_phaseII_Definition\OC6_phaseII_ElastoDyn_LC11.dat"                  EDFile          - Name of file containing ElastoDyn input parameters (quoted string)
"unused"                                                                 BDBldFile(1)    - Name of file containing BeamDyn input parameters for blade 1 (quoted string)
"unused"                                                                 BDBldFile(2)    - Name of file containing BeamDyn input parameters for blade 2 (quoted string)
"unused"                                                                 BDBldFile(3)    - Name of file containing BeamDyn input parameters for blade 3 (quoted string)
"unused"                                                                 InflowFile      - Name of file containing inflow wind input parameters (quoted string)
"unused"                                                                 AeroFile        - Name of file containing aerodynamic input parameters (quoted string)
"unused"                                                                 ServoFile       - Name of file containing control and electrical-drive input parameters (quoted string)
"OC6_phaseII_Definition\OC6_phaseII_Platform_HydroDyn_damping_LC11.dat"   HydroFile       - Name of file containing hydrodynamic input parameters (quoted string)
"OC6_phaseII_Definition\OC6_phaseII_Monopile_SubDyn.dat"                  SubFile         - Name of file containing sub-structural input parameters (quoted string)
"unused"                                                                 MooringFile     - Name of file containing mooring system input parameters (quoted string)
"unused"                                                                 IceFile         - Name of file containing ice input parameters (quoted string)
"unused"                                                                 SoilFile        - Name of the file containing the SoilDyn input parameters (quoted string)
---------------------- OUTPUT --------------------------------------------------
True          SumPrint        - Print summary data to "<RootName>.sum" (flag)
           5  SttsTime        - Amount of time between screen status messages (s)
       99999  ChkptTime       - Amount of time between creating checkpoint files for potential restart (s)
        0.05  DT_Out          - Time step for tabular output (s) (or "default")
           0  TStart          - Time to begin tabular output (s)
           1  OutFileFmt      - Format for tabular (time-marching) output file (switch) {1: text file [<RootName>.out], 2: binary file [<RootName>.outb], 3: both}
True          TabDelim        - Use tab delimiters in text tabular output file? (flag) {uses spaces if false}
"ES10.3E2"    OutFmt          - Format used for text tabular output, excluding the time channel.  Resulting field should be 10 characters. (quoted string)
---------------------- LINEARIZATION -------------------------------------------
False         Linearize       - Linearization analysis (flag)
           1  NLinTimes       - Number of times to linearize (-) [>=1] [unused if Linearize=False]
0             LinTimes        - List of times at which to linearize (s) [1 to NLinTimes] [unused if Linearize=False]
           2  LinInputs       - Inputs included in linearization (switch) {0=none; 1=standard; 2=all module inputs (debug)} [unused if Linearize=False]
           1  LinOutputs      - Outputs included in linearization (switch) {0=none; 1=from OutList(s); 2=all module outputs (debug)} [unused if Linearize=False]
False         LinOutJac       - Include full Jacobians in linearization output (for debug) (flag) [unused if Linearize=False; used only if LinInputs=LinOutputs=2]
True          LinOutMod       - Write module-level linearization output files in addition to output for full system? (flag) [unused if Linearize=False]
---------------------- VISUALIZATION -------------------------------------------
           0  WrVTK           - VTK visualization data output: (switch) {0=none; 1=initialization data only; 2=animation}
           1  VTK_type        - Type of VTK visualization data: (switch) {1=surfaces; 2=basic meshes (lines/points); 3=all meshes (debug)} [unused if WrVTK=0]
True          VTK_fields      - Write mesh fields to VTK data files? (flag) {true/false} [unused if WrVTK=0]
          15  VTK_fps         - Frame rate for VTK output (frames per second){will use closest integer multiple of DT} [used only if WrVTK=2]
```

Figure 1. New OpenFAST main input file

In previous SubDyn versions, the user was always forced to use at least one clamp condition. The new SubDyn does not have this limitation anymore.

Figure 2 shows the new SubDyn input file with the new sections highlighted in green. As it can be observed, there are many new functionalities available in SubDyn: new kinematic joints (universal, pin, ball) and new members (pre-tensioned cables, rigid connections). These new capabilities are not used in OC6 phase II and therefore won't be covered in this document. But in the future, the corresponding documentation will be released to the OpenFAST community.



```
---------- SubDyn v1.01.x MultiMember Support Structure Input File ------------
OC6 phase II: Monopile.
---------------------------- SIMULATION CONTROL  ---------------------------------
False           Echo        - Echo input data to "<rootname>.SD.ech" (flag)
"DEFAULT"       SDdeltaT    - Local Integration Step. If "default", the glue-code integration step will be used.
             3  IntMethod   - Integration Method [1/2/3/4 = RK4/AB4/ABM4/AM2].
True            SttcSolve   - Solve dynamics about static equilibrium point
True            ExtraMoment - Include extra moment from lever arm at interface in interface reactions.
---------------------- FEA and CRAIG-BAMPTON PARAMETERS----------------------------
             3  FEMMod      - FEM switch: element model in the FEM. [1= Euler-Bernoulli(E-B);  2=Tapered E-B (unavailable);  3= 2-node Timoshenko;  4= 2-node tapered Timoshenko (unavailable)]
             4  NDiv        - Number of sub-elements per member
True            CBMod       - [T/F] If True perform C-B reduction, else full FEM dofs will be retained. If True, select Nmodes to retain in C-B reduced system.
             5  Nmodes      - Number of internal modes to retain (ignored if CBMod=False). If Nmodes=0 --> Guyan Reduction.
3               JDampings   - Damping Ratios for each retained mode (% of critical) If Nmodes>0, list Nmodes structural damping ratios for each retained mode (% of critical), or a single damping ratio
---- STRUCTURE JOINTS: joints connect structure members (~Hydrodyn Input File)---
            23  NJoints     - Number of joints (-)
JointID         JointXss              JointYss              JointZss JointType JointDirX  JointDirY JointDirZ    JointStiff  JointDamp
  (-)             (m)                   (m)                   (m)      (-)       (-)       (-)       (-)         (Nm/rad)  (Nm/rad.s)
    1           0.00000               0.00000                 0        1       0.0       0.0       0.0           0.0       0.0
    2           0.00000               0.00000                10        1       0.0       0.0       0.0           0.0       0.0
    3           0.00000               0.00000                20        1       0.0       0.0       0.0           0.0       0.0
    4           0.00000               0.00000                21        1       0.0       0.0       0.0           0.0       0.0
    5           0.00000               0.00000                22        1       0.0       0.0       0.0           0.0       0.0
    6           0.00000               0.00000                23        1       0.0       0.0       0.0           0.0       0.0
    7           0.00000               0.00000                24        1       0.0       0.0       0.0           0.0       0.0
    8           0.00000               0.00000                25        1       0.0       0.0       0.0           0.0       0.0
    9           0.00000               0.00000                26        1       0.0       0.0       0.0           0.0       0.0
   10           0.00000               0.00000                27        1       0.0       0.0       0.0           0.0       0.0
   11           0.00000               0.00000                28        1       0.0       0.0       0.0           0.0       0.0
   12           0.00000               0.00000                29        1       0.0       0.0       0.0           0.0       0.0
   13           0.00000               0.00000                30        1       0.0       0.0       0.0           0.0       0.0
   14           0.00000               0.00000                31        1       0.0       0.0       0.0           0.0       0.0
   15           0.00000               0.00000                32        1       0.0       0.0       0.0           0.0       0.0
   16           0.00000               0.00000                33        1       0.0       0.0       0.0           0.0       0.0
   17           0.00000               0.00000                34        1       0.0       0.0       0.0           0.0       0.0
   18           0.00000               0.00000                35        1       0.0       0.0       0.0           0.0       0.0
   19           0.00000               0.00000                36        1       0.0       0.0       0.0           0.0       0.0
   20           0.00000               0.00000                37        1       0.0       0.0       0.0           0.0       0.0
   21           0.00000               0.00000                38        1       0.0       0.0       0.0           0.0       0.0
   22           0.00000               0.00000                39        1       0.0       0.0       0.0           0.0       0.0
   23           0.00000               0.00000                40        1       0.0       0.0       0.0           0.0       0.0
------------------ BASE REACTION JOINTS: 1/0 for Locked/Free DOF @ each Reaction Node ---------------------
             1  NReact      - Number of Joints with reaction forces; be sure to remove all rigid motion DOFs of the structure  (else det([K])=[0])
RJointID   RctTDXss    RctTDYss    RctTDZss    RctRDXss    RctRDYss    RctRDZss    [Global Coordinate System]
  (-)       (flag)      (flag)      (flag)      (flag)      (flag)      (flag)
    1            0           0           0           0           0           0
------- INTERFACE JOINTS: 1/0 for Locked (to the TP)/Free DOF @each Interface Joint (only Locked-to-TP implemented thus far (=rigid TP)) ---------
             1  NInterf     - Number of interface joints locked to the Transition Piece (TP):  be sure to remove all rigid motion dofs
IJointID   ItfTDXss    ItfTDYss    ItfTDZss    ItfRDXss    ItfRDYss    ItfRDZss    [Global Coordinate System]
  (-)       (flag)      (flag)      (flag)      (flag)      (flag)      (flag)
   23            1           1           1           1           1           1
---------------------------------- MEMBERS ------------------------------------
            22  NMembers    - Number of frame members
MemberID   MJointID1   MJointID2   MPropSetID1   MPropSetID2  MType      COSMID
  (-)         (-)         (-)         (-)           (-)       (-)        (-)
    1           1           2           1             1         1
    2           2           3           1             1         1
    3           3           4           1             1         1
    4           4           5           1             1         1
    5           5           6           1             1         1
    6           6           7           1             1         1
    7           7           8           1             1         1
    8           8           9           1             1         1
    9           9          10           1             1         1
   10          10          11           1             1         1
   11          11          12           1             1         1
   12          12          13           1             1         1
   13          13          14           1             1         1
   14          14          15           1             1         1
   15          15          16           1             1         1
   16          16          17           1             1         1
   17          17          18           1             1         1
   18          18          19           1             1         1
   19          19          20           1             1         1
   20          20          21           1             1         1
   21          21          22           1             1         1
   22          22          23           1             1         1
----------------- MEMBER X-SECTION PROPERTY data 1/2 [isotropic material for now: use this table for circular-tubular elements] ------------------------
             1  NPropSets   - Number of structurally unique x-sections (i.e. how many groups of X-sectional properties are utilized throughout all of the members)
PropSetID     YoungE          ShearG          MatDens         XsecD           XsecT
  (-)         (N/m2)          (N/m2)          (kg/m3)          (m)             (m)
    1       2.10000e+11     8.08000e+10       8500.00         9.00           0.110
----------------- MEMBER X-SECTION PROPERTY data 2/2 [isotropic material for now: use this table if any section other than circular, however provide COSM(i,j) below] ------------------------
             0  NXPropSets  - Number of structurally unique non-circular x-sections (if 0 the following table is ignored)
PropSetID     YoungE          ShearG          MatDens         XsecA          XsecAsx       XsecAsy       XsecJxx       XsecJyy       XsecJ0
  (-)         (N/m2)          (N/m2)          (kg/m3)         (m2)            (m2)          (m4)          (m4)          (m4)
------------------------- CABLE PROPERTIES  -------------------------------------
             0  NCablePropSets   - Number of cable cable properties
PropSetID     EA          MatDens         T0
  (-)         (N)           (kg/m)          (N)
---------------------- RIGID LINK PROPERTIES ---------------------------------
             0  NRigidPropSets - Number of rigid link properties
PropSetID   MatDens
  (-)       (kg/m)
--------------------- MEMBER COSINE MATRICES COSM(i,j) ------------------------
             0  NCOSMs      - Number of unique cosine matrices (i.e., of unique member alignments including principal axis rotations); ignored if NXPropSets=0   or 9999 in any element below
COSMID    COSM11    COSM12    COSM13    COSM21    COSM22    COSM23    COSM31    COSM32    COSM33
  (-)       (-)       (-)       (-)       (-)       (-)       (-)       (-)       (-)       (-)
----------------------- JOINT ADDITIONAL CONCENTRATED MASSES--------------------------
             0  NCmass      - Number of joints with concentrated masses; Global Coordinate System
CMJointID       JMass           JMXX            JMYY            JMZZ
  (-)           (kg)          (kg*m^2)        (kg*m^2)        (kg*m^2)
```

Figure 2. New SubDyn input file

The new SubDyn module, allows the user to define a 6 by 6 stiffness matrix and/or a 6 by 6 mass matrix at a base reaction joint. Figure 3 shows the definition of a base reaction joint to account for a stiffness matrix instead of a clamp boundary condition.

```
------------------ BASE REACTION JOINTS: 1/0 for Locked/Free DOF @ each Reaction Node ---------------------
            1   NReact      - Number of Joints with reaction forces; be sure to remove all rigid motion DOFs of the structure  (else det([K])=[0])
RJointID   RctTDXss    RctTDYss    RctTDZss    RctRDXss    RctRDYss    RctRDZss    [Global Coordinate System]
  (-)       (flag)      (flag)      (flag)      (flag)      (flag)      (flag)
   1          0           0           0           0           0           0          "Stiffness_matrix.txt"
```

Figure 3. Definition of a stiffness matrix at a base reaction joint in SubDyn input file

As it can be observed in Figure 3, the six degrees of freedom of the reaction joint are defined as free (`0`) and the stiffness matrix is defined in a separate text file (for example *Stiffness_matrix.txt*). Figure 4 shows an example of stiffness matrix definition that is used as boundary condition for SubDyn.

```
 1 !---------------- K and M matrices ------------------!
 2 ! Equivalent Stiffness Constants: Kxx, Kyy, Kzz, Kxtx, Kxty..Kztx,Kzty,Kztz  in any order; max 21 elements.
 3 ! Roger comments: Interpret the 't' as rotation and the matrix is assumed to be symmetric. It's only necessary to define the upper half part of the matrix.
 4 6.336198E9              Kxx
 5 6.336198E9              Kyy
 6 1.119691E10             Kzz
 7 8.111942E11             Ktxtx
 8 8.111942E11             Ktyty
 9 2.552673E11             Ktztz
10 -5.015421E10            Kxty
11 5.015421E10             Kytx
```

Figure 4. Text file (e.g. *Stiffness_matrix.txt*) containing the stiffness matrix to be used by SubDyn as boundary condition

Note that this new capability in OpenFAST allows to take advantage of the coupled sprigs approach to simulate the OC6 phase II system.