IMPLEMENTATION OF A FINITE ELEMENT FOUNDATION MODULE IN FLEX5 USING CRAIG-BAMPTON SUBSTRUCTURING

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SUMMARY

For aeroelastic analysis of wind turbines including tower and support structure the Flex5 code developed by Øye (1994,1999) is widely used within the wind industry. The existing Flex5 foundation module uses a simple monopile model where model parameters may be modified to mimic more complex foundations. The foundation module is limited in the ability to model substructures of arbitrary geometry and the correct stiffness and the correct energy dissipation from the soil, thus missing the correct load distribution below mudline.

Flex5 is a modal based programme and to maintain the modal scheme the original foundation module is substituted by a finite element (FE) model. This FE model is decomposed using a Craig-Bampton substructuring scheme and applied in Flex5 as a super-element. The new foundation module is based on tubular elements and is capable of treating stiff floating foundation and flexible foundations of arbitrary geometry.

A special treatment of the soil-structure interaction is planned implemented in the FE model using non-linear p-y springs as defined in API RP 2A LRFD, 1993.

KEY WORDS

Floating/Bottom-mounted foundation, mode shape, super-element, FE, Craig-Bampton substructuring, soil-structure interaction

1. INTRODUCTION

The aeroelastic code Flex5 is widely used in assessing the loads and the structural response for wind turbines. The foundation module is based on two times two shape functions with 6 DOF at the interface point to the tower and the soil-structure boundary is simulated by a 6 DOF constraint below mudline. By varying the depth of the 6-DOF clamping and stiffness below the mudline, both angular deflection at the mudline and horizontal deflection can be made to fit displacements of any structure. The fixity depth is normally calibrated to fit the 1. natural frequency of the wind turbine support structure using a separate soil-structure interaction model such as a FE model.

This approach works very well for numerous onshore and offshore locations but as offshore applications become more complex the simplified description in Flex5, only describing tubular monopile type and gravity type substructures, becomes too limited.

Figure 1 shows selected support structure concepts varying from the relatively simple gravity base and monopile structure applicable in fairly shallow water being the only types to date applied in existing commercial wind farms. For some of the existing offshore sites with a severe wave climate the wave loading is responsible for up to 50% of the total loading in the tower. As future sites are in deeper water and the sites become more exposed the wave loading increases and more complex or alternative support structure configurations are necessary in order for the wind farms to be commercially viable.

Besides the differences on complexity of the various structures, the soil-structure interaction is very different, especially the bucket foundation requires special geotechnical attention. Additionally, as the turbines become larger and the hub height and top-head mass increases, the natural frequency becomes design driving and a more accurate description of the soil-structure interaction is required.

Consequently it is decided to develop a FEM based foundation module integrated in to the Flex5 code. The main objective is to be able to describe arbitrary geometries based on tubular elements and it is intended to include a soil-structure interaction model enabling load assessment below mudline and evaluation of the natural frequency.

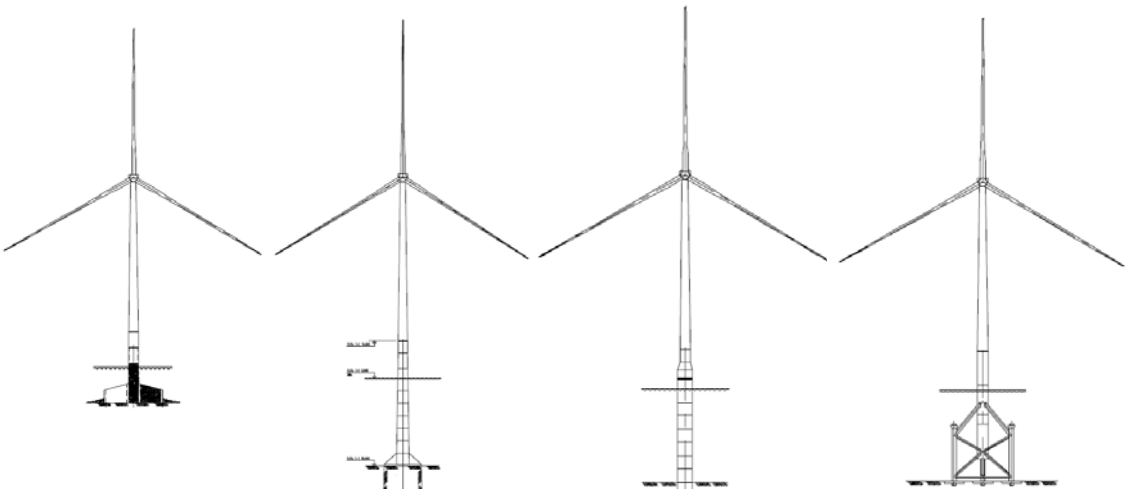

Figure 1 Different support structure concepts (DNV-OS-J101, Draft Feb 2004)

2. EXISTING FLEX5 FOUNDATION MODULE

The aeroelastic load model applied by Vestas is based on the Flex5 code developed by Øye (1999) combined with a model of the Vestas Converter System. The original Flex5 model has continuously been developed in order to encompass the special needs within Vestas. In summary the present aeroelastic modelling tool (VTS: Vestas Turbine Simulator) comprises the following features:

- 36 DOF combined mode shape and multibody formulation
- Each sub-structure is treated using linear Bernoulli-Euler beam theory

- Bearings/Actuators are modelled by lumped parameter models
- Power control (Vestas Converter System) is implemented directly
- All loads (Internal inertia and external loads) are based on the deformed state
- External load models cover aerodynamic loads, gravity and hydrodynamic loads
- Foundation model is treated separately in FLEX5

The existing Flex5 foundation module is based on a super-element formulation with the top node of the element linked to the tower bottom, also termed the interface point, in 6 DOF (F_x,F_y,F_z,M_x,M_y,M_z) forming the boundary to the support structure. The super-element is constructed from two shape functions derived as the static deformation of the super-element from a unit deformation and a unit rotation of the top node. The shape functions are calculated according to the actual geometrical properties specified by a finite number of elements defining the entire support structure. The element formulation is limited to tubular beam elements defined in the centerline of the tower, and consequently only monopile or monopile-type structures can be modelled, i.e. a tripod or gravity base structure must be converted into an equivalent monopile with identical dynamics as the original structure at the interface to the tower.

Mass, damping and stiffness properties of the super-element and a generalized loading on the element are calculated from the two static shape functions. The super-element properties and generalized load are assembled into the global mass, damping and stiffness matrices and load vector for time domain solution of the equation of motion. Kinematics of the internal DOFs and sectional loads inside the super-element are distributed inside the super-element according to the shape functions. This approach is very similar to the traditional FEM ignoring the effect of internal modes from the internal DOFs in the super-element. Figure 2 depicts the static shape function as well as the shape functions for a selected internal DOFs in the super-element.

This approach describes the static response of the support structure (Inertia loads are applied in deformed state) and the only error in the dynamic response is solely due to inertia loads from possible internal modes. However, the effect from the internal modes is expected to be negligible as the eigenfrequency of the internal modes typically are much higher than the eigenfrequencies of interest.

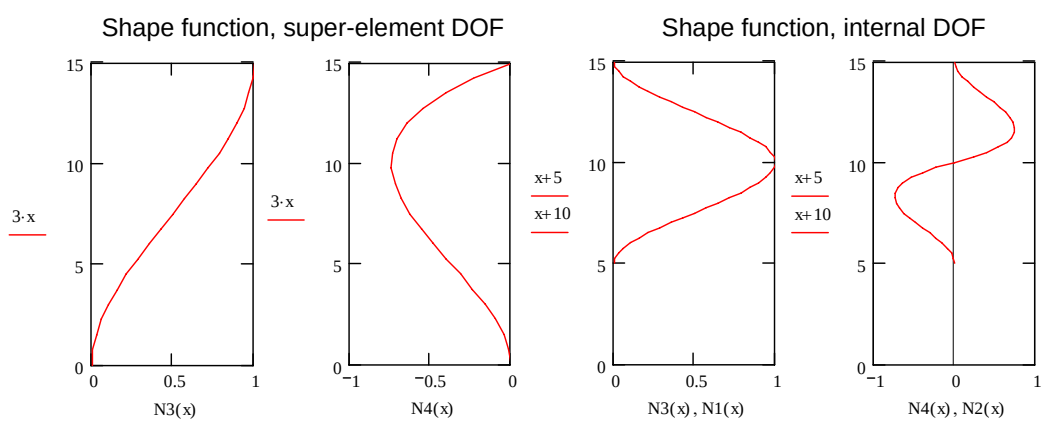

Figure 2 Super-element shape functions and internal shape functions for unit deformation and unit rotation of node of master node and one internal slave node. 0 being 6 DOF constraint at mudline and N1, N2, N3, N4 being cubic element shape functions.

The tower is modelled using the 1. and 2. mode shape of tower and addition of the super-element simply results in a deformation of the full support structure including tower and foundation equal to the tower modes, see Figure 3. The boundary towards the soil is treated as a fixity constraint below mudline calibrated to fit the 1. mode natural frequency, which poses an additional limitation of the existing foundation module. The correct stiffness and energy dissipation from the soil is not correct, in particular as the fixity level of the 2. mode is different from the 1. mode. Furthermore, as no soil structure interaction is modelled it is not possible to obtain information about the distribution of loads below mudline.

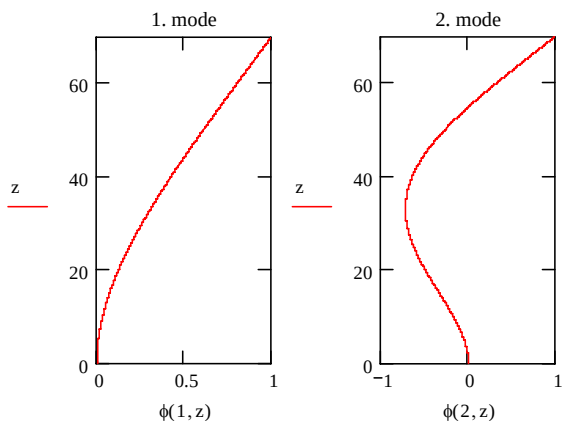

Figure 3 1. and 2. mode for tower and substructure.

The load impact depends on the shape of the 2. mode, i.e. the distribution of stiffness over the entire structure. Hence for stiff substructures the load impact is limited whereas flexible substructures contribute more to the 2. mode bending. In extreme cases the consequences on the loading can be up to 10% on the equivalent overturning moment in tower bottom and 5% at mudline and tower top, respectively.

3. FEM FOUNDATION MODULE

In order to solve some of the limitations with the existing foundation module a new foundation module based on finite elements is currently being developed. The new FEM foundation module consists of the following features:

- A stiff element model capable of treating floating substructures is applied and a rigid body transformation of the foundation mass matrix to the interface point integrates the model in Flex5
- Internal flexibility is introduced by applying a FEM model using tubular Timoshenko beam elements
- Craig-Bampton substructuring is applied to transform the mass and stiffness matrix of the FE model to the interface point, consequently integrating the foundation model in Flex5 as a super-element similar to the original foundation module

The foundation module is capable of describing an arbitrary geometry using tubular elements taking into account the external loads: gravity, elastic or pre-tensioned anchor cables, buoyancy and hydrodynamic loading.

4. ELEMENT FORMULATION

The applied elements are tubular Timoshenko beam elements described by:

- 6 DOF at each node
- Outer diameter
- Plate thickness
- Water filling factor, 1 for full and 0 for empty
- Mass and stiffness factor
- Drag and added mass coefficient in normal and tangential direction

The element definition forms a 12×12 mass and stiffness matrix as defined by Pedersen and Jensen (2000) and Petersen (1990). From the elements the foundation mass matrix and foundation stiffness matrix are assembled.

Floating model

For use in the floating model the mass matrix is reduced to a 6×6 matrix by a rigid body mode shape transformation to the interface point, thus fitting exactly into the original modal scheme of Flex5 by substituting the original super-element. The reduced mass matrix is given in the form:

$$\tilde{\boldsymbol{M}} = \boldsymbol{\varphi}_r^T \boldsymbol{M}\, \boldsymbol{\varphi}_r = \begin{bmatrix} m & 0 & 0 & 0 & S_z & -S_y \\ 0 & m & 0 & -S_z & 0 & S_x \\ 0 & 0 & m & S_y & -S_x & 0 \\ 0 & -S_z & S_y & J_{xx} & -J_{xy} & -J_{xz} \\ S_z & 0 & -S_x & -J_{yx} & J_{yy} & -J_{yz} \\ -S_y & S_x & 0 & -J_{zx} & -J_{zy} & J_{zz} \end{bmatrix}$$

where $\boldsymbol{\varphi}_r$: rigid body modes, 6N×6 matrix

m : structural mass

S_x : static moment about *x*-axis defining CoG

J_{xx} : mass moment of inertia about *x*-axis defining the inertia tensor

Boundary conditions

In the floating model the foundation is assumed stiff, however the boundary condition is an anchoring at specified nodes by either elastic or pre-tensioned anchor cables, thus imposing a stiffness constraint to be implemented in the 6×6 foundation stiffness matrix. The effect of anchoring is calculated as the force/moment pr unit deformation by imposing a unit deformation and unit rotation at each DOF individually.

In the FE model it is intended to include a soil-structure interaction model enabling load assessment below mudline and evaluation of the natural frequency. The following soil models are planned to be implemented in the foundation module:

- An external 6x6 soil stiffness matrix is applied at mudline. This matrix must be calculated beforehand in a separate soil-structure interaction model
- The soil forces are applied as external loads to elements nodes by:
  i. Linear stiffness model with linearization of p-y force deformation curves at the Centre-of-Damage loads, or alternatively
  ii. Non-linear stiffness model with full p-y curves

Loading

External loads are calculated in the deformed state covering:

- Buoyancy and gravity
- 3D hydrodynamic forces according to Morison equation with McCamy-Fuchs correction for large volume structures
- Elastic or pretensioned anchor forces
- Non-linear structural inertia loads (with the linear terms being included in the mass matrix)

Time integrator

In original Flex5 the time integrator is a 4 step Runge-Kutta-Nystrøm (RKN) algorithm for 2nd order differential equations. Unfortunately the RKN time integrator is only conditionally stable as it requires minimum 3 (here 4) steps pr. period of each mode, hence a very small time step is required to resolve the highest frequencies.

In the FE model the inclusion of all 6 DOF results in stiff systems, i.e. a large ratio between highest and lowest eigenfrequency, this is especially pronounced for the axial stiffness of the monopile. Consequently a Newmark-Wilson algorithm (Clought and Penzien, 1993) for linear step-by-step integration has been implemented.

The 2nd order differential equation system given in the form:

$$\boldsymbol{M}\,\ddot{u} + \boldsymbol{C}\,\dot{u} + \boldsymbol{K}\,u = F^{G}$$

is integrated on incremental form:

$$\boldsymbol{M}_0\,\Delta\ddot{u} + \Delta\boldsymbol{M}\,\ddot{u} + \boldsymbol{C}\,\Delta\dot{u} + \boldsymbol{K}\,\Delta u = \Delta F^{G}$$

where $\Delta\ddot{u},\ \Delta\dot{u},\ \Delta u$ are approximated by Taylor expansions

The velocity increments are found as solution of effective equation:

$$\boldsymbol{K}^{*}\Delta u = \Delta F^{*}$$

where $\Delta F^{*} = \Delta F + \boldsymbol{C}(2\dot{u}_0) + \boldsymbol{M}_0\left(\dfrac{4\dot{u}_0}{\Delta t} + 2\ddot{u}_0\right) - (\boldsymbol{M} - \boldsymbol{M}_0)\ddot{u}$

$$\boldsymbol{K}^{*} = \left(\boldsymbol{K} + \frac{2\boldsymbol{C}}{\Delta t} + \frac{4\boldsymbol{M}_0}{\Delta t^2}\right)$$

The method assumes constant average acceleration and assumes in the present implementation that the foundation stiffness forces F_K and damping forces F_C can be written on the form

$$F_K = \boldsymbol{K}\,u$$
$$F_C = \boldsymbol{C}\,u$$

In contrast to the RKN algorithm, the Newmark-Wilson algorithm is unconditionally stable and is capable of treating stiffer systems without requiring small time steps.

5. CRAIG-BAMPTON SUBSTRUCTURING

The Craig-Bampton method is a more practical method for solving large dynamic problems than a full finite element solution. The full size of the FE model is reduced by a Craig-Bampton transformation which combines motion of boundary point with modes of the structure assuming the boundary points are held fixed, and the reduced system is coupling to other components in the specified boundary DOFs. The Craig-Bampton transformation can be used to calculate physical responses from the Craig-Bampton responses using load transformation matrices (LTM). Basically, the Craig-Bampton substructuring is similar to other reduction schemes such as Guyan reduction and modal decoupling, however unlike Guyan reduction, the method accounts for both mass and stiffness as the Craig-Bampton mass and stiffness fully defines the system.

The methodology is in short described in the following by considering the equation of motion (ignoring damping):

$$\boldsymbol{M}\ddot{u} + \boldsymbol{K}u = F(t)$$

The Craig-Bampton transform is defined as:

$$u = \begin{Bmatrix} u_b \\ u_i \end{Bmatrix} = \begin{bmatrix} \boldsymbol{I} & 0 \\ \boldsymbol{\varphi_c} & \boldsymbol{\varphi_i} \end{bmatrix} \begin{Bmatrix} u_b \\ q \end{Bmatrix} = \boldsymbol{\varphi_{CB}} \begin{Bmatrix} u_b \\ q \end{Bmatrix}$$

where

u_b : boundary DOFs

u_i : internal DOFs, i.e. $u_i = \boldsymbol{\varphi_c}^T u_b + \boldsymbol{\varphi_i}^T q$

$\boldsymbol{\varphi_c}$: static modes (or constrained modes) containing the deformation influence coefficients for internal DOFs

$\boldsymbol{\varphi_i}$: fixed base mode shapes containing the contribution from internal vibration modes

$\boldsymbol{\varphi_{CB}}$: Craig-Bampton transformation matrix

q : modal DOFs

Ignoring the inertia forces, the internal DOFs can be calculated by static condensation, i.e. the static mode matrix is:

$$\boldsymbol{\varphi_c} = -\boldsymbol{K_{ii}}^{-1}\boldsymbol{K_{ib}}$$

When the Craig-Bampton transformation is inserted into the equation of motion and premultiplied by $\boldsymbol{\varphi}_{CB}^T$, the modified equation of motion becomes:

$$\boldsymbol{\varphi_{CB}^T M\, \varphi_{CB}} \begin{Bmatrix} \ddot{u}_b \\ \ddot{q} \end{Bmatrix} + \boldsymbol{\varphi_{CB}^T K\, \varphi_{CB}} \begin{Bmatrix} u_b \\ q \end{Bmatrix} = \boldsymbol{\varphi_{CB}^T} \begin{Bmatrix} F_b \\ F_i \end{Bmatrix}$$

where the Craig-Bampton mass and stiffness matrices are defined as:

$$\boldsymbol{M_{CB}} = \boldsymbol{\varphi_{CB}^T M\, \varphi_{CB}} = \begin{bmatrix} \boldsymbol{M_{bb}} & \boldsymbol{M_{bq}} \\ \boldsymbol{M_{qb}} & \boldsymbol{M_{qq}} \end{bmatrix}$$

$$\boldsymbol{K_{CB}} = \boldsymbol{\varphi_{CB}^T K\, \varphi_{CB}} = \begin{bmatrix} \boldsymbol{K_{bb}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{K_{qq}} \end{bmatrix}$$

The boundary matrix $\boldsymbol{M_{bb}}$ contains the total mass properties translated to the boundary points and the internal stiffness matrix $\boldsymbol{K_{bb}}$ contains the stiffness associated with displacing one boundary DOF while all others are held fixed

The implementation in Flex5 is described in the following.

Equation of motion for the turbine without foundation (ignoring damping):

$$\begin{bmatrix} \boldsymbol{M_{mm}} & \boldsymbol{M_{mb}} \\ \boldsymbol{M_{bm}} & \boldsymbol{M_{qq}} \end{bmatrix} \begin{Bmatrix} \ddot{u}_m \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K_{mm}} & \boldsymbol{K_{mb}} \\ \boldsymbol{K_{bm}} & \boldsymbol{K_{bb}} \end{bmatrix} \begin{Bmatrix} u_m \\ u_b \end{Bmatrix} = \begin{Bmatrix} F_m \\ F_b \end{Bmatrix}$$

where $\{u\} = \begin{Bmatrix} u_m \\ u_b \end{Bmatrix} = \begin{Bmatrix} \text{DOF for tower + rotor/nacelle assembly} \\ \text{Boundary DOF for interface} \end{Bmatrix}$

Equation of motion for the foundation (ignoring damping):

$$\begin{bmatrix} \boldsymbol{M_{bb}} & \boldsymbol{M_{bi}} \\ \boldsymbol{M_{ib}} & \boldsymbol{M_{ii}} \end{bmatrix} \begin{Bmatrix} \ddot{u}_b \\ \ddot{u}_i \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K_{bb}} & \boldsymbol{K_{bi}} \\ \boldsymbol{K_{ib}} & \boldsymbol{K_{ii}} \end{bmatrix} \begin{Bmatrix} u_b \\ u_i \end{Bmatrix} = \begin{Bmatrix} F_b \\ F_i \end{Bmatrix}$$

where $\{u\} = \begin{Bmatrix} u_b \\ u_i \end{Bmatrix} = \begin{Bmatrix} \text{Boundary DOF for interface} \\ \text{Internal DOF for foundation} \end{Bmatrix}$

If the internal mode shapes (q = 0) are neglected similarly to the super-element formulation in the original Flex5 foundation module, the CB transformation reduces to the static condensation method:

$$u = \begin{Bmatrix} u_b \\ u_i \end{Bmatrix} = \begin{bmatrix} \boldsymbol{I} \\ \boldsymbol{\varphi_c} \end{bmatrix} u_b = \begin{bmatrix} \boldsymbol{I} \\ -\boldsymbol{K_{ii}^{-1}} \boldsymbol{K_{ib}} \end{bmatrix} u_b$$

and

$$\boldsymbol{M_{CB}} = \boldsymbol{\varphi_{CB}^T} \boldsymbol{M}\, \boldsymbol{\varphi_{CB}} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{\varphi_c^T} \end{bmatrix} \begin{bmatrix} \boldsymbol{M_{bb}} & \boldsymbol{M_{bi}} \\ \boldsymbol{M_{ib}} & \boldsymbol{M_{ii}} \end{bmatrix} \begin{bmatrix} \boldsymbol{I} \\ \boldsymbol{\varphi_c} \end{bmatrix} = \boldsymbol{\varphi_c^T} \boldsymbol{M_{ii}}\, \boldsymbol{\varphi_c} + \boldsymbol{M_{bi}}\, \boldsymbol{\varphi_c} + \boldsymbol{\varphi_c^T} \boldsymbol{M_{ib}} + \boldsymbol{M_{bb}}$$

$$\boldsymbol{K_{CB}} = \boldsymbol{\varphi_{CB}^T} \boldsymbol{K}\, \boldsymbol{\varphi_{CB}} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{\varphi_c^T} \end{bmatrix} \begin{bmatrix} \boldsymbol{K_{bb}} & \boldsymbol{K_{bi}} \\ \boldsymbol{K_{ib}} & \boldsymbol{K_{ii}} \end{bmatrix} \begin{bmatrix} \boldsymbol{I} \\ \boldsymbol{\varphi_c} \end{bmatrix} = \boldsymbol{K_{bb}} - \boldsymbol{\varphi_c^T} \boldsymbol{K_{ii}}\, \boldsymbol{\varphi_c}$$

$$F_{CB} = \boldsymbol{\varphi_{CB}^T} \begin{Bmatrix} F_b \\ F_i \end{Bmatrix} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{\varphi_c^T} \end{bmatrix} \begin{Bmatrix} F_b \\ F_i \end{Bmatrix} = F_b + \boldsymbol{\varphi_c^T} F_i$$

The final equation of motion in Flex5 (ignoring damping) becomes:

$$\begin{bmatrix} \boldsymbol{M_{mm}} & \boldsymbol{M_{mb}} \\ \boldsymbol{M_{bm}} & \boldsymbol{M_{bb}} + \boldsymbol{M_{CB}} \end{bmatrix} \begin{Bmatrix} \ddot{u}_m \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K_{mm}} & \boldsymbol{K_{mb}} \\ \boldsymbol{K_{bm}} & \boldsymbol{K_{bb}} + \boldsymbol{K_{CB}} \end{bmatrix} \begin{Bmatrix} u_m \\ u_b \end{Bmatrix} = \begin{Bmatrix} F_m \\ F_b + F_{CB} \end{Bmatrix}$$

The solution of the equation of motion describes the deformation, velocity and acceleration of each individual master DOF, and the corresponding response of internal DOFs in the FE model can subsequently be calculated.

Accuracy

Apparently, the present implementation of the Craig-Bampton decoupling seems to be a crude approximation of the real conditions with a dynamic structure exposed to external loading. This, however, is not the case as the static response is determined without errors and the only error in the dynamic response is due to possible internal vibration modes affecting the inertia forces. Typically, the internal vibration modes are of very high frequencies leaving them unimportant.

In order for the error only to arise from internal modes the contribution form the external loading to the deformation of the interface node must be represented correctly. I.e. the condensed loads and stiffness must provide the correct deformation of the interface node for an external load acting at any node.

If the condensed 6 DOF transformation matrix is supplemented by an additional *N*-6 DOFs represented by shape functions corresponding to the unit deformations of the internal DOF, see Figure 2, the following transformation is obtained:

$$u = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{\varphi_c} & \boldsymbol{I} \end{bmatrix} \begin{Bmatrix} u_b \\ u_i \end{Bmatrix}$$

where the shape functions for the internal DOFs have 1 in the diagonal and 0 for all other DOFs.

The condensed coordinates for the additional DOF now defines the deformation relative to the deformation determined by the first 6 shape functions. Subsequently the condensed stiffness can be calculated:

$$\begin{bmatrix} \boldsymbol{K_{CB}} & 0 \\ 0 & \boldsymbol{K_2} \end{bmatrix} \begin{Bmatrix} u_b \\ u_i \end{Bmatrix} = \begin{Bmatrix} F_b \\ F_i \end{Bmatrix}$$

Because of the block structure it is observed that any external loading will be transformed to the condensed load only through the first 6 DOFs while the remaining internal DOFs cannot contribute to the deformation. Hence full accuracy with respect to the static deformation of the interface node is achieved by only 6 DOFs.

If necessary for the description of internal loading in the FE model additional DOFs and mode shapes must be implemented in the global system of equations. The new mass and stiffness matrices are simply defined by the CB transformation with $q \neq 0$ and the time integrator requires an update to be capable of solving for more DOFs.

6. VERIFICATION - TEST CASE

The FE model is compared to the original Flex5 foundation model based on the test case described below:

- WTG model is an artificial 1.0 MW
- Monopile with OD = 3000 mm and t = 30 mm fixed at mudline -3m
- Shear stiffness neglected, i.e. the Timoshenko elements converts to Bernoulli-Euler elements.
- Tower interface at 12.0m
- Steady wind speed: 12-14-16 m/s
- No wave loading

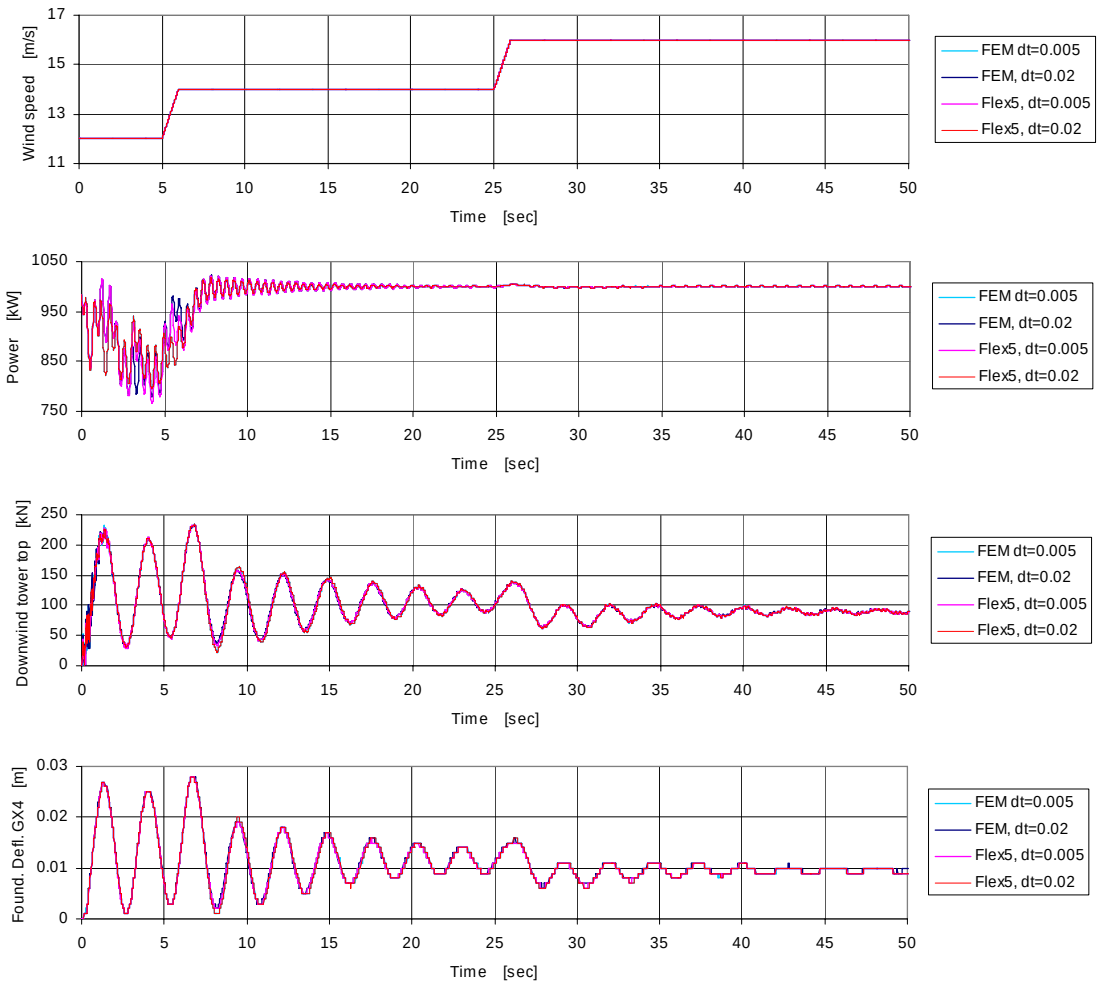

Figure 4 Comparative run test for monopile foundation in original Flex5 module and FE model

Figure 4 shows the wind speed, power output and downwind force in tower top and downwind foundation deflection at foundation top for simulations run with the original Flex5 foundation module and the FM module for two different time steps. The results show good correlation for a time step of 0.02 sec and almost identical results are observed for a time step of 0.005 sec.

7. OUTLOOK

Some of the present limitations of the existing foundation module in Flex5 lacking the ability to model substructures of arbitrary geometry has been discussed and premises for a fully general FE model using Timoshenko tubular beam elements have been described. The FE model is decomposed using Craig-Bampton substructuring in order to construct a super-element which fits in to the original modal scheme of Flex5.

Using the Craig-Bampton substructuring a super-element with 6 DOF at the interface point can be constructed. This super-element is almost identical to the original super-element in Flex5 in case a monopile is modelled by Bernoulli-Euler beam elements,

except for the additional axial and rotational stiffness. Simulation with the FE model shows very good agreement with the original foundation module in Flex5.

The FE model differs mainly in its ability to model structures of arbitrary geometry and both floating as well as bottom-mounted structures can be modelled. Furthermore, the FE model is prepared for full soil-structure interaction as the foundation in case of a pilled foundation simply is extended below mudline and the soil is modelled as soil spring forces in the element nodes. Other foundation types such as gravity based or bucket foundations are implemented directly by imposing a stiffness constraint in the foundation stiffness matrix at the effected DOFs.

Further work on the soil-structure interaction for various foundation concepts is part of a joint project between Vestas, Aalborg University, Risø National Laboratory, Elsam Engineering A/S and MBD supported by the Danish Energy Council under the EFP programme. The soil-structure model will be verified against data from ongoing measurements from the Horns Reef wind farm.

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