User’s Guide to BModes
(Software for Computing Rotating Beam Coupled Modes)

Gunjit S. Bir

September 2007

National Renewable Energy Laboratory,

1617, Cole Blvd, Golden, CO 80401

About this Guide

BModes is a finite-element code that provides coupled modes for a turbine blade or a tower. Both the blade, rotating or non-rotating, and the tower can have arbitrary distribution of structural properties along their length. Both allow tip attachment. The tip attachment is assumed to be rigid body with mass, six moments of inertia, and a mass centroid that may be offset from the blade or tower axis. Examples of tip attachments are aerodynamic brakes for blades and nacelle-rotor subassemblies for towers. The tower can have optional tension-wire supports.

BModes allows computation of coupled modes for both the blade and the tower. A coupled mode implies presence of coupled flexural, axial, and torsion motions in a natural mode of vibration. Knowledge of flap-lag-torsion-axial coupled modes is crucial to several applications. Examples are: modeling of major flexible components for modal-based aeroelastic codes such as FAST [1], validation of flexible component models using experimental data, modal-based fatigue analysis, and interpretation of aeroelastic-stability behavior of turbines, both onshore and offshore.

Obtaining rotating-blade coupled modes accurately, however, is one of the most challenging tasks in the dynamics field, and only a few codes address this. BModes is perhaps the most accurate because it uses a finite-element approach in conjunction with analytical linearization and a special finite-element assembly that captures Coriolis and centrifugal effects. The finite-element method (FEM) is based on a 15- degree of freedom (dof) element with three internal and two boundary nodes. A salient feature of BModes is its potential to handle a complex range of boundary conditions.

BModes requires specification of rotor speed, blade geometry, precone, pitch control setting, and structural properties distribution along the blade as inputs. The structural properties along the blade length, are specified in terms of the flap bending, lag bending, torsion, and axial stiffness; mass; section moments of inertia; and chordwise offsets of section shear center, tension center, and center-of-mass along the blade. These properties may be obtained from experimental tests, blade manufacturer, or a properties-extractor code, such as PreComp [2] or BPE [3]. Currently, BModes can handle only metallic or isotropic composite blades. With the aforementioned inputs, the code uses FEM followed by an eigenanalysis to compute mode shapes and frequencies.

The current version of BModes, which replaces the older version (v1.02.00), is modernized to the current Fortran 2003 standards. Also, it does not require recompilation if number of finite elements to discretize the blade or the tower is altered.

This guide provides step-by-step instructions on how to prepare input files (specify blade geometry, section properties, and finite-element discretization), how to execute the code, and how to interpret the outputs. The code runs fast (usually in a few seconds). If this guide does not help resolve a problem you may have with input files or code execution, contact us. In future, we will integrate BModes with FAST to provide tower and blade modes as rotor speed and blade pitch control settings change during a simulation.

DOCUMENT REVISION RECORD

Revision	Date	Description
1.00	21-Nov-2005	First publication. Supports BModes v1.0
1.10	06-Jan-2006	Included tip inertia effects in modal analysis of towers and blades.
	27-Jan-2006	Extended BModes to handle towers supported by tension wires.
	03-Feb-2006	Added additional input channels and modified output format.
		Supports BModes v1.10.
1.20	25-July-2006	Modified math routines to handle repeated eigenvalues. Eliminated numerical problem associated with large offset of blade section center of mass. Modified output format for mode shapes. Modified main input file. Modified screen display of run-time output.
1.30	27-Sep-2007	In Section 5, eliminated text stating users need to recompile the code if the number of elements is changed (current BModes version does not require recompiling). Added Echo input variable to the main input file. Compatible with BModes v1.03.01 (this numbering follows the most recent version numbering system).

Contents

1 Introduction

BModes is developed primarily to provide coupled mode shapes for FAST (Fatigue, Aerodynamics, Structures, and Turbulence), an aeroelastic code that has been certified for worldwide usage [4]. FAST uses an assumed-modes approach; it needs blade and tower modes as well as structural properties to compute modal integrals for its equations of motion. PreComp [2] provides the structural properties, and BModes provides the modes for both the blades and the tower. Currently, FAST uses uncoupled modes for flap and lag (edge-wise) degrees of freedom (dofs) of the blade and also for the fore and lateral motions of the tower. It ignores the torsion dof and offsets of shear center, tension center, and center of mass, which can cause significant dynamic couplings. BModes-computed flap-lag-torsion *coupled* modes will help overcome these limitations by implicitly accounting for the torsion dofs and the offsets mentioned earlier. The resulting FAST will be a far more capable code.

Although BModes is primarily developed for eventual integration with FAST, it may be used as a stand-alone code. The beam modes it generates may be used for other applications: structural validation using experimental data, interpretation of aeroelastic stability, and modal-based fatigue analysis, to name a few. A beam, for a wind turbine, can be a model of a rotor blade or a tower.

Both the blade and the tower can have a tip attachment. The tip attachment is assumed to be rigid body with mass, six moments of inertia, and a mass centroid that may be offset from the blade or tower axis. Examples of tip attachment are an aerodynamic brake for a blade and nacelle-rotor subassembly for a tower. In addition to the tip inertia, the tower can also have tension-wire supports. Both the tip inertias and tension support wires can substantially influence the coupled modes mentioned earlier, especially for a tower.

Accurately obtaining rotating-blade coupled modes is a challenging task, and only a few codes address this. BModes is perhaps the most accurate among these because it uses a finite-element approach in conjunction with analytical linearization and a special finite-element assembly that accurately captures Coriolis and centrifugal effects. Its finite-element approach, derived from its predecessor UMARC [5], is based on a 15-dofs element with three internal and two boundary nodes (Figure 1). The 15 dofs comprise 3 dofs for torsion deflection and 4 dofs each for axial, flap, and lag deflections.

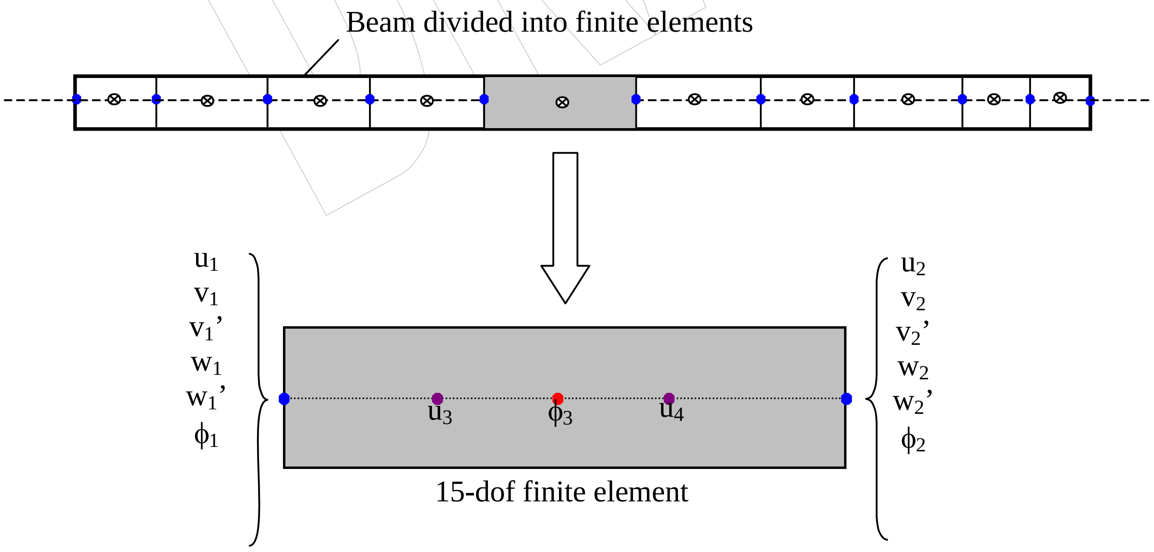


Figure 1: Beam discretization into 15-degrees-of-freedom finite elements.

A salient feature of BModes is its potential to handle a complex range of boundary conditions. Currently, it offers only one option: a cantilevered boundary condition at the blade root. In the near future, we plan to extend BModes to offer more options; e.g., a flap hinge at the root followed by a pitch bearing. BModes also has the potential to handle both composite and metallic blades. The current version handles only metallic or isotropic composite blades.

BModes inputs require specification of rotor speed, blade geometry, precone, pitch control setting, tip-attachment inertia properties, and structural properties distribution along the blade. The structural properties are specified in terms of the flap bending, lag bending, torsion, and axial stiffness; mass; section moments of inertia; and chordwise offsets of the shear center, tension center, and center-of-mass at each section along the blade. These properties may be obtained from experimental tests, blade manufacturer, or a properties-extractor code, such as PreComp [2] or BPE [3].

This guide provides step-by-step instructions on how to prepare input files (i.e., specify blade geometry, section properties, and finite-element discretization), how to execute the code, and how to interpret modal output. The code runs fast, usually in a few seconds. It requires no knowledge of the finite-element method (FEM) and only a modest knowledge of the definition of blade properties.

We have verified BModes for uniform and tapered beams for which analytical results are available and also for a typical non-uniform turbine blade using code-to-code comparison with RCAS [6]. More verification studies are planned and will be published upon completion.

This guide is divided into seven sections, including this introduction:

- **Section 2** outlines the technical approach BModes uses for computation of coupled modes.
- **Section 3** lists the underlying assumptions.
- **Section 4** provides step-by-step instructions on input data preparation along with sample input files.
- **Section 5** shows how to execute the code.
- **Section 6** describes how to interpret the BModes output.
- **Section 7** concludes the report with discussions of planned upgrades and verification studies.

2 Technical Approach

A full discussion of the BModes theory basis is outside the scope of this manual. However, we provide an outline of the technical approach (Figure 2). First, we idealize the blade as an Euler-Bernoulli beam that undergoes flap bending, lag bending, elastic twist, and axial deflection. Next, we formulate energy expressions and use Hamilton’s principle to derive coupled integro-partial differential equations (PDEs) governing the beam dynamics. These PDEs are nonlinear and include spatial integral terms, which represent Coriolis and centrifugal effects. We then use finite element analysis (FEA), the basis of modern structural analysis, to discretize the spatial (radial) variables in the PDEs. This FEA is compatible with Hamilton’s principle. The blade is divided into a number of elements (Figure 1), each with 15 dofs: four for axial deflection (u_1, u_2, u_3, u_4), four for flap deflection and slope (w_1, w'_1, w_2, w'_2), four for lag deflection and slope (v_1, v'_1, v_2, v'_2), and three for elastic twist (ϕ_1, ϕ_2, ϕ_3). Continuity of displacement and slope for flap and lag deflections, and continuity of displacement for elastic twist and axial deflections are maintained between elements. Besides the two end nodes, each element has three internal nodes, two for axial deflection and one for elastic twist. The elastic twist is represented by a quasi-coordinate (non-Euler); this eliminates radial integral terms which otherwise would appear in orientation matrices for an elastic beam. Finite elements assembly, specialized for integro-partial differential equations, followed by application of boundary conditions, yields nonlinear ordinary differential equations (ODEs) in nodal coordinates. Analytical linearization (distinct from finite-differencing) yields inertia, gyroscopic, and stiffness matrices. We then cast these matrices in the standard first-order form and perform an eigenanalysis to obtain the desired coupled modes and frequencies.

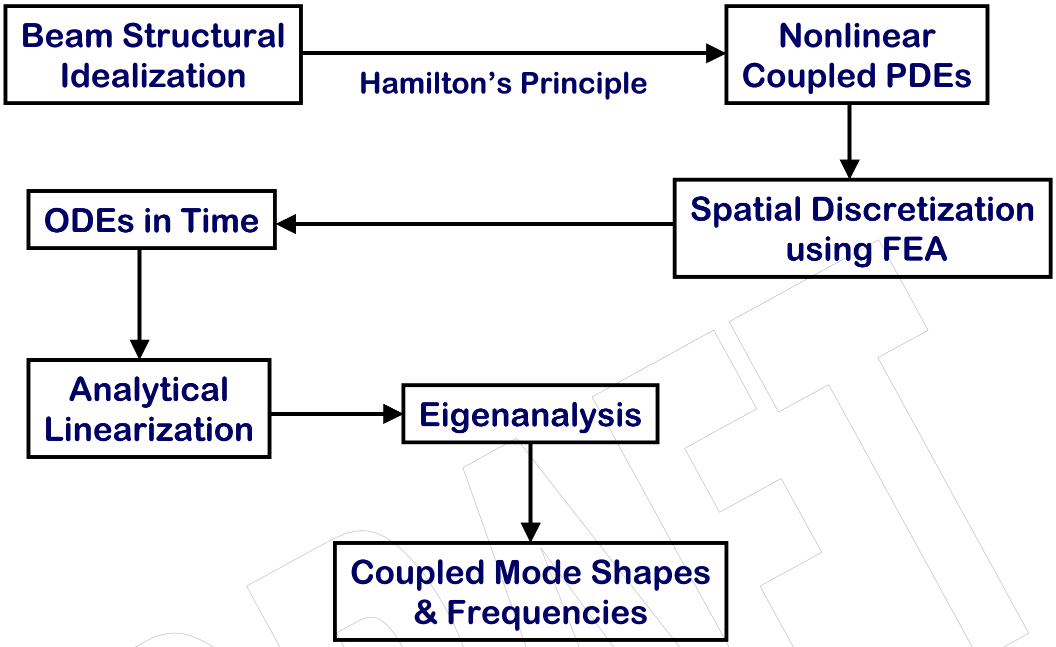

Beam Structural Idealization
Hamilton's Principle
Nonlinear Coupled PDEs
Spatial Discretization using FEA
ODEs in Time
Analytical Linearization
Eigenanalysis
Coupled Mode Shapes & Frequencies

Figure 2: Technical approach for computation of beam coupled modes.

3 Underlying Assumptions

Knowledge of the following assumptions underlying BModes will help you understand the applicability and limitations of the code.

- The beam, blade or tower, is straight (no built-in curvature).
- The beam is idealized as an Euler-Bernoulli beam. Transverse shear effects are ignored. Warping is not modeled explicitly, though its effect may be included implicitly via torsion stiffness, e.g., that computed by PreComp [2].
- For a blade, the effect of chordwise offsets of the center of mass, shear center, and tension center normal to the chord is ignored. This is a fairly valid assumption because their effect on modal dynamics is usually negligible. Also, in practice, these normal offsets are difficult to estimate or measure.

- The beam is built with an isotropic material, including metal as a special case of an isotropic material.
- The beam root is cantilevered. This, though, is not an inherent limitation of BModes; other root conditions (e.g., a blade flap hinge followed by a pitch bearing) will be included in later versions of BModes.
- The tower structure is axi-symmetric about its vertical axis.
- For wires-supported tower, the wires remain in tension whether the tower is in static equilibrium or in motion. Wires may be attached to the tower at a maximum of two height locations. At each location, a minimum of three wires must be attached and these must be axi-symmetrically oriented with respect to the tower axis. The spring constant is assumed identical for all wires in a particular set. Also, mass of wires is assumed to be negligible in comparison to the tower mass.

4 Input Data Preparation

You will need to specify the following before BModes can compute coupled modes:

- Blade distributed geometric and structural properties
- Rotational speed
- Pitch control setting
- Blade precone
- Blade division into finite elements
- Tip-attachment inertia properties
- Stiffness and orientation of tension wires, if used for tower support
- Number of modes to be output.

These data are provided to BModes via two files: a main input file and an auxiliary input file containing distributed properties. Both file names are user-specifiable. The files are written in a simple text format and may be created or modified with any text editor. Any line in these files is a comment line, a blank line, or a BModes-readable line. Comment lines aid understanding of the data that follow the comment lines (see sample input files, Figures 3 and 4). Although one may alter text in a comment line, one should not add or remove any comment line. Blank lines delineate blocks of data and help clarify data organization. Like the comment lines, these also cannot be added or deleted. A readable line can have two formats. It may have a single value followed by associated parameter name and a brief description of that parameter (the parameter name and its description are not read by BModes). Or a readable line may have a set of values separated by commas, tabs, or spaces; any number of tabs or spaces may be inserted for clarity. A description of the input files follows.

4.1 Main Input File

Figure 3 shows a sample main input file. The first line is comment line ignored, but expected, by BModes. The second line is a title line, which BModes reads as a character string. You may insert any text (up to 99 characters); the text is repeated in the output file. Next is a blank line followed by a data block of general information. Table 1 describes the parameters that appear in this data block. The parameters are identified in *italics*. The last column in the table identifies the associated units. A dash indicates a non-dimensional parameter.

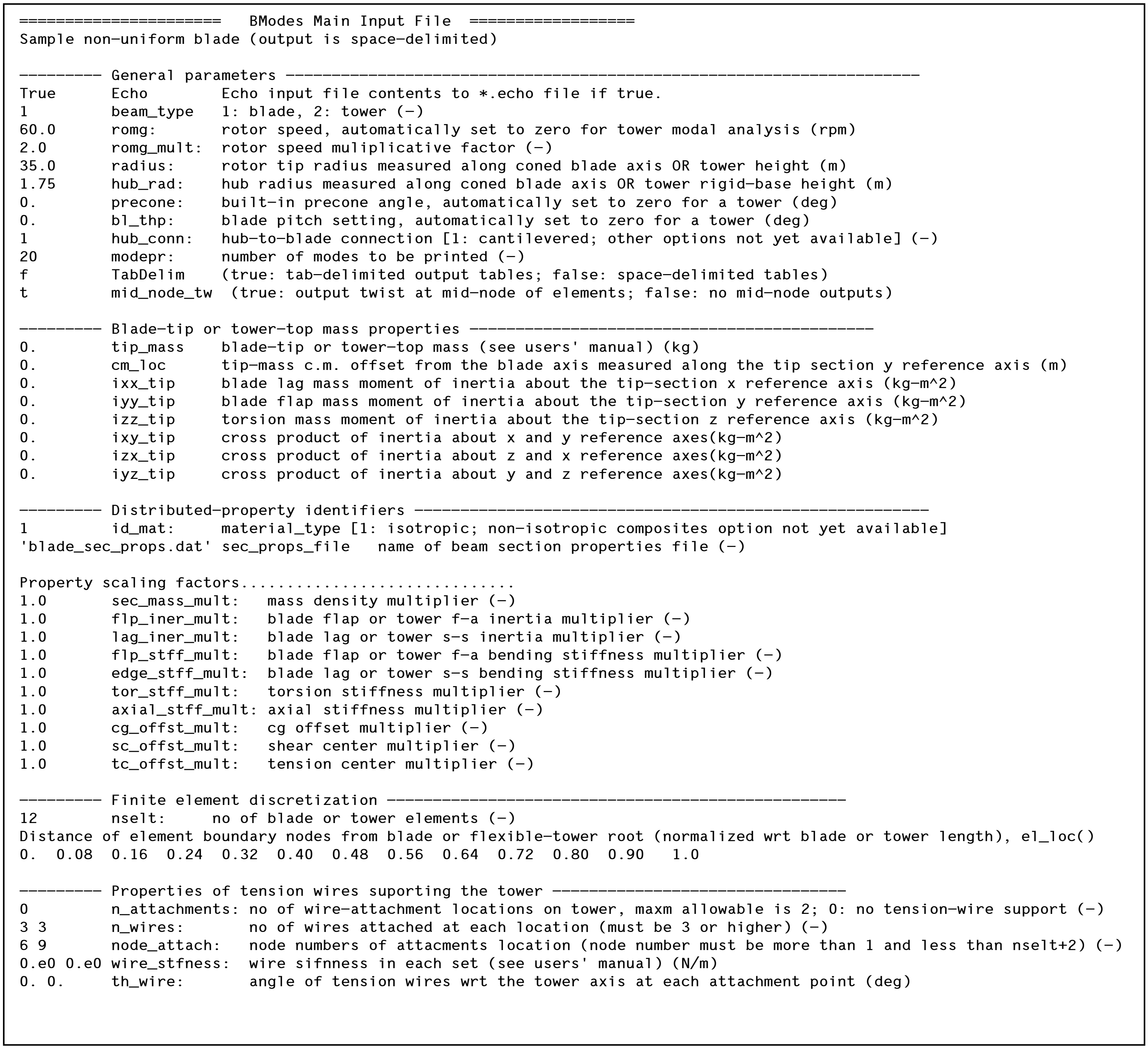
The following data block specifies blade-tip inertia properties if *beam_type* is 1 in the previous data block; else it specifies tower-top properties (see Table 2).

The next data block has two parameters, which identify distributed properties. Table 3 describes these identifying parameters. The properties are input via a section-properties input file and are described in Section 4.2.

Next is a data block of scaling factors for the distributed properties. These are described in Table 4. Note that the 10 multiplicative factors listed in the table would normally be unity. However, you may tune these, probably using a trial-and-error approach, until select BModes-computed modal properties match the desired frequencies and/or mode shapes; e.g., those obtained experimentally.

The next data-block parameters specify blade finite element discretization; these are explained in Table 5. The last data block pertains to the tension wires supporting the tower. A zero value of n_attachments, the first parameter in this block, implies no tension-wire support and the subsequent parameters are ignored. Otherwise, the remaining parameters are read, which identify orientation and stiffness properties of the tension wires (see Table 6).

Note: This manual shows only one sample input file (Figure 3). More sample files, covering blade and tower, are provided at our website.



```
======================   BModes Main Input File  ==================
Sample non-uniform blade (output is space-delimited)

--------- General parameters ---------------------------------------------------------------------
True      Echo        Echo input file contents to *.echo file if true.
1         beam_type   1: blade, 2: tower (-)
60.0      romg:       rotor speed, automatically set to zero for tower modal analysis (rpm)
2.0       romg_mult:  rotor speed muliplicative factor (-)
35.0      radius:     rotor tip radius measured along coned blade axis OR tower height (m)
1.75      hub_rad:    hub radius measured along coned blade axis OR tower rigid-base height (m)
0.        precone:    built-in precone angle, automatically set to zero for a tower (deg)
0.        bl_thp:     blade pitch setting, automatically set to zero for a tower (deg)
1         hub_conn:   hub-to-blade connection [1: cantilevered; other options not yet available] (-)
20        modepr:     number of modes to be printed (-)
f         TabDelim    (true: tab-delimited output tables; false: space-delimited tables)
t         mid_node_tw  (true: output twist at mid-node of elements; false: no mid-node outputs)

--------- Blade-tip or tower-top mass properties ----------------------------------------------
0.        tip_mass    blade-tip or tower-top mass (see users' manual) (kg)
0.        cm_loc      tip-mass c.m. offset from the blade axis measured along the tip section y reference axis (m)
0.        ixx_tip     blade lag mass moment of inertia about the tip-section x reference axis (kg-m^2)
0.        iyy_tip     blade flap mass moment of inertia about the tip-section y reference axis (kg-m^2)
0.        izz_tip     torsion mass moment of inertia about the tip-section z reference axis (kg-m^2)
0.        ixy_tip     cross product of inertia about x and y reference axes(kg-m^2)
0.        izx_tip     cross product of inertia about z and x reference axes(kg-m^2)
0.        iyz_tip     cross product of inertia about y and z reference axes(kg-m^2)

--------- Distributed-property identifiers --------------------------------------------------------
1         id_mat:     material_type [1: isotropic; non-isotropic composites option not yet available]
'blade_sec_props.dat' sec_props_file   name of beam section properties file (-)

Property scaling factors..............................
1.0       sec_mass_mult:   mass density multiplier (-)
1.0       flp_iner_mult:   blade flap or tower f-a inertia multiplier (-)
1.0       lag_iner_mult:   blade lag or tower s-s inertia multiplier (-)
1.0       flp_stff_mult:   blade flap or tower f-a bending stiffness multiplier (-)
1.0       edge_stff_mult:  blade lag or tower s-s bending stiffness multiplier (-)
1.0       tor_stff_mult:   torsion stiffness multiplier (-)
1.0       axial_stff_mult: axial stiffness multiplier (-)
1.0       cg_offst_mult:   cg offset multiplier (-)
1.0       sc_offst_mult:   shear center multiplier (-)
1.0       tc_offst_mult:   tension center multiplier (-)

--------- Finite element discretization --------------------------------------------------
12        nselt:     no of blade or tower elements (-)
Distance of element boundary nodes from blade or flexible-tower root (normalized wrt blade or tower length), el_loc()
0.  0.08  0.16  0.24  0.32  0.40  0.48  0.56  0.64  0.72  0.80  0.90   1.0

--------- Properties of tension wires suporting the tower ----------------------------------
0         n_attachments: no of wire-attachment locations on tower, maxm allowable is 2; 0: no tension-wire support (-)
3 3       n_wires:       no of wires attached at each location (must be 3 or higher) (-)
6 9       node_attach:   node numbers of attacments location (node number must be more than 1 and less than nselt+2) (-)
0.e0 0.e0 wire_stfness:  wire sifnness in each set (see users' manual) (N/m)
0. 0.     th_wire:       angle of tension wires wrt the tower axis at each attachment point (deg)
```

Figure 3: Sample of main input file (SampleBlade.bmi).

Table 1. General Parameters

Parameter	**Description**	**Unit**
echo	Echo input file contents to *.echo file	-
beam_type	Integer identifying beam type (1: blade, 2: tower)	-
romg	Nominal rotor speed, automatically set to zero if *beam_type* is 2 (i.e. for tower modal analysis).	rpm
romg_mult	Multiplicative (scaling) factor for rotor speed. The actual rotor speed is, therefore, *romg∗romg_mult*.	-
radius	Blade radius. For a blade, it is the distance of the blade tip from the axis of rotation measured along the coned blade axis. For a tower, it is the tower height from the ground.	m
hub_rad	Hub radius. For a blade, it is the distance of the blade root from the axis of rotation measured along the coned blade axis. For a tower, it is the rigid-base height.	m
precone	Blade built-in precone angle; the angle between the blade reference axis, usually the pitch axis, and the plane of rotation normal to the shaft. For a tower, this is automatically set to zero.	deg
bl_thp	Blade pitch setting. This may be a built-in or a control pitch setting for the whole blade. The actual twist at any section is this pitch setting plus a section twist angle (defined later). For a tower, this is automatically set to zero.	deg
hub_conn	An integer switch defining the type of blade-to-hub or tower-to-ground connectivity. Currently, only the cantilevered connectivity option is available, which is identified by integer 1. In the near future, we will add other connectivity options; e.g., blade flap hinge followed by a pitch bearing.	-
modepr	Number of blade or tower modes you would like BModes to print to the output file. If this exceeds the maximum computable modes, which is *9*nselt*, a warning is issued and the maximum computable modes are printed. The *nselt* is the number of beam finite elements defined in Table 4. We recommend that *modepr* should not exceed 3**nselt*; higher modes, even if printed, may not be accurate because of numerical considerations.	-
TabDelim	A logical switch. If set to *t* or *true*, the output properties, printed as a table, are tab-delimited. Such a table, when exported to a spreadsheet such as Excel, automatically converts to columns. If this switch is set to *f* or *false*, the output properties, printed as a table, are space-delimited. Such a table (see Figure 6) helps easy reading of output properties. In the sample input file, this switch is set to *false*.	-
mid_node_tw	A logical switch. If set to *t* or *true*, twist distribution in a mode is output for both the end- and mid-node of beam elements. If set to *false*, twist distribution is output for end nodes only.	

Table 2. Beam-Tip-Attachment Inertia Properties

Parameter	**Description**	**Unit**
tip_mass	Blade-tip or tower-top mass	kg
cm_loc	For a blade, it is the offset of the tip-mass c.m. from the blade axis measured along the tip section Y_R reference axis (Figure 5 shows the reference axes). For a tower, it is the offset from the tower axis measured along the fore-aft x_T axis (see Figure 6).	m
ixx_tip	For a blade, it is the tip-mass edgewise moment of inertia about the tip-section X_R reference axis. For a tower, it is the side-to-side moment of inertia of the tip mass about the tip-section x_T reference axis.	kg-m^2
iyy_tip	For a blade, it is the tip-mass flap moment of inertia about the tip-section Y_R reference axis. For a tower, it is the fore-aft moment of inertia of the tip mass about the tip-section y_T reference axis.	kg-m^2
izz_tip	For a blade, it is the tip-mass torsion moment of inertia about the tip-section Z_R reference axis. For a tower, it is the torsion moment of inertia of the tip mass about the Z_T reference axis.	kg-m^2
ixy_tip	For a blade, it is the tip-mass cross moment of inertia with respect to the tip-section X_R and Y_R reference axes. For a tower, it is the cross moment of inertia of the tip mass with respect to the tip-section x_T and y_T reference axes.	kg-m^2
izx_tip	For a blade, it is the tip-mass cross moment of inertia with respect to the tip-section Z_R and X_R reference axes. For a tower, it is the cross moment of inertia of the tip mass with respect to the tip-section z_T and x_T reference axes.	kg-m^2
iyz_tip	For a blade, it is the tip-mass cross moment of inertia with respect to the tip-section Y_R and Z_R reference axes. For a tower, it is the cross moment of inertia of the tip mass with respect to the tip-section y_T and z_T reference axes.	kg-m^2

Table 3. Distributed-Property Identifiers

Parameter	**Description**	**Unit**
id_mat	An integer identifying whether the blade material is isotropic or anisotropic. Any metal may be treated as an isotropic material. Currently, BModes allows only an isotropic material, identified by integer 1.	-
sec_props_file	User-specifiable name for the section properties input file. The name must appear within quotes and can have a maximum of 99 characters.	-

Table 4. Distributed-Property Scaling Factors

Parameter	Description	Unit
sec_mass_mult	Multiplicative (scaling) factor for the distributed *mass_den* property defined in Section 4.2.	-
flp_iner_mult	Multiplicative (scaling) factor for the distributed *flp_iner* property defined in Section 4.2.	-
lag_iner_mult	Multiplicative (scaling) factor for the distributed *edge_iner* property defined in Section 4.2.	-
flp_stff_mult	Multiplicative (scaling) factor for the distributed *flp_stff* property defined in Section 4.2.	-
edge_stff_mult	Multiplicative (scaling) factor for the distributed *edge_stff* property defined in Section 4.2.	-
tor_stff_mult	Multiplicative (scaling) factor for the distributed *tor_stff* property defined in Section 4.2.	-
axial_stff_mult	Multiplicative (scaling) factor for the distributed *axial_stff* property defined in Section 4.2.	-
cg_offst_mult	Multiplicative (scaling) factor for the distributed *cg_offst* property defined in Section 4.2.	-
sc_offst_mult	Multiplicative (scaling) factor for the distributed *sc_offst* property defined in Section 4.2.	-
tc_offst_mult	Multiplicative (scaling) factor for the distributed *tc_offst* property defined in Section 4.2.	-

Table 5. Finite-Element Discretization Parameters

Parameter	Description	Unit
nselt	Number of elements desired for beam finite-element discretization.	-
el_loc	A subscripted variable with *el_loc(i)* defining location of the inboard end of the element *i* with respect to the blade root and *el_loc(i+1)* defining its outboard end location. These element end locations are normalized with respect to the blade length, which equals *radius* minus *hub_rad*. The user may readily infer that that *el_loc(1)* is always zero and *el_loc(nselt+1)*is always unity (see sample input file, last line).	-

Table 6. Tower Support-Wire Parameters

Parameter	Description	Unit
n_attachments	Number of heights on tower at which support wires are attached. At each height, BModes assumes that a set of three or more wires is attached and that these wires are attached axi-symmetrically with respect to the tower axis. Maximum allowable integer value for *n_attachments* is 2. A zero value implies no tension-wires are attached to the tower.	(-)
n_wires	A row vector identifying number of wires attached at each location (must be 3 or higher). The number of entries in this row must equal *n_attachments*.	(-)
node_attach	A row of tower node numbers identifying heights (locations on tower) at which support-wire sets are attached. Each attachment node must be selected from the *nselt+1* tower nodes specified in the previous data block via the parameter *el_loc* (see Table 5). The number of entries in the *node_attach* parameter equals *n_attachments*. Each entry must be more than *1*, which identifies the flexible-tower-root node, and less than or equal to *nselt+1*, which identifies the tower-tip node.	(-)
wire_stfness	A row vector identifying spring constant of a support wire in each set. The number of entries in this row must equal *n_attachments*. BModes assumes that the spring constant is identical for all wires in a particular set. BModes also assumes that each support wire remains in tension when tower vibrates. Also, wires are assumed to be massless.	N/m
th_wire	A row vector specifying the angle each tension wire in a particular set makes with respect to the tower axis. The number of entries in this row must equal *n_attachments*. BModes assumes that *th_wire* is identical for all wires in a particular set.	deg

4.2 Section Properties Input File

This auxiliary input file is used for specifying distributed properties, and the user identifies its name in the main input file via the parameter *sec_props_file* (see Table 3). In our sample main input file, we identify the auxiliary input file name as *blade_sec_props.dat*. The distributed properties are specified at a number of user-specified sections along the blade or tower length. Before we describe these properties, we need to understand Figures 5 and 6.

Figure 5 shows axes systems at a typical blade section. These axes systems conform to the IEC specifications [7], and the section properties are referred to these axes. The X_R-Y_R are the section reference axes with origin at *R*, where point *R* is the intersection of the section with the blade reference axis, usually the blade pitch axis. The Y_R axis coincides with the section chord and points toward the trailing edge. The X_R axis is normal to Y_R and points toward the upper (suction) side of the blade. Point E is the section shear center and is the origin for the principal elastic axes, X_E-Y_E. All the elastic properties are referred to this frame. The θ_E is the orientation of the chordwise principal elastic axis, Y_E, with respect to blade reference plane *BB*. For a non-coned blade, the blade reference plane is the same as the hub plane (the hub plane is a plane normal to the shaft and located at the intersection of the shaft axis with the blade reference axis). For a coned blade, it is a plane that passes through the blade reference axis and makes an angle *precone* with the hub plane. More rigorously, the blade reference plane *BB* is a plane spanned by two lines, one of which is the coned blade reference axis and the other a line normal to the blade reference axis and lying in the hub plane. Point *T* is the tension center and point *G* is the center of mass of the section. The principal inertia axes, X_G-Y_G, originate at *G* with Y_G axis oriented at an angle θ_I with respect to the reference plane *BB*. All the section inertia properties are referred to this frame. Note that points *E*, *G*, and *T* are assumed to lie on the section chord; their offsets normal to the chord are ignored.

Figure 6 shows axes systems at a typical tower section. These axes systems conform to the IEC specifications [7], and the tower section properties are referred to these axes. The (X_T,Y_T,Z_T) is the tower reference frame with its origin at the tower base and its X_T axis, the fore-aft axis, aligned with the nominal wind direction. The Z_T is the tower axis of symmetry and Y_T is the lateral axis, also called the side-side axis.. The (x_T,y,Z_T) are typical-section reference axes. The x_T and y_T axes lie in the section plane and are parallel to the X_T and Y_T axes respectively. The tower-tip mass c.m. may be offset from the tower axis only in the fore-aft direction as shown in the figure.

Figure 4 shows a sample section properties inputs file for a blade. The first, fourth, and fifth lines are comment lines, and the third is a blank line. These lines are required but ignored by BModes. The fourth comment line lists section properties, and the fifth comment line identifies the associated units. For each blade section, BModes needs specification of 12 properties along with specification of its span location; these are specified via 13 columns (Figure 4). The number of lines in this columnar data block equals the number of blade sections at which the user specifies properties. Table 7 describes the parameters in this file.

Note that offsets of the center of mass, shear center, and tension center in a direction normal to the chord are ignored in the current version of BModes and therefore are not required as inputs. In practice, these normal offsets are extremely difficult to estimate/measure. Also, their effect on modal dynamics is usually negligible.

The section properties inputs file pertains to a tower if *beam_type* is set to 2 in the main input file. The section properties input file for a tower (see NREL website for a sample) has the same format as the blade-section properties file. However, because we assume the tower structure to be axi-symmetric about its vertical Z_T axis, the following apply.

- The edgewise inertia *edge_iner* is set equal to the flap inertia *flp_iner*. Note that for a tower, *edge_iner* is defined as the mass moment of inertia about the section fore-aft x_T reference axis and *flp_iner* is defined as the mass moment of inertia about the section side-side Y_T reference axis.

- The edgewise bending stiffness *edge_stff* is set equal to the flap bending stiffness *flp_stff*. Note that for a tower, *edge_stff* is defined as the bending stiffness about the section fore-aft x_T reference axis and *flp_stff* is defined as the bending stiffness about the section side-side Y_T reference axis.

- BModes automatically sets the following tower section parameters to zero: structural twist *str_tw*, principal axes orientation *tw_iner*, c.m. offset *cg_offst*, tension-center offset *tc_offst*, and shear-center offset *sc_offst*.

```
blade section properties

sec_loc   str_tw   tw_iner   mass_den flp_iner   edge_iner  flp_stff     edge_stff      tor_stff     axial_stff  cg_offst   sc_offst tc_offst
(-)       (deg)     (deg)    (kg/m)    (kg-m)     (kg-m)     (Nm^2)       (Nm^2)         (Nm^2)        (N)         (m)        (m)      (m)
0.00000  11.100   11.100 1447.607  646.044    646.044  7681.46E+06  7681.46E+06  2655.23E+06  17152.7E+06    0.000      0.000    0.0
0.02105  11.100   11.100  180.333   80.480     80.480  1169.87E+06  1169.87E+06   408.80E+06   2640.8E+06    0.000      0.000    0.0
0.05263  11.100   11.100  181.672   68.241     80.113  1020.62E+06  1092.28E+06   343.81E+06   2611.3E+06    0.032     -0.005    0.0
0.10526  11.100   11.100  183.905   47.842     79.502   771.88E+06   962.97E+06   235.50E+06   2562.1E+06    0.086     -0.014    0.0
0.15789  11.100   11.100  186.138   27.444     78.892   523.14E+06   833.66E+06   127.19E+06   2512.9E+06    0.140     -0.023    0.0
0.21053  11.100   11.100  188.370    7.045     78.281   274.40E+06   704.35E+06    18.87E+06   2463.6E+06    0.194     -0.032    0.0
0.26316   9.500    9.500  178.321    5.963     68.302   234.57E+06   614.65E+06    16.80E+06   2332.8E+06    0.188     -0.020    0.0
0.31579   7.900    7.900  168.271    4.881     58.323   194.74E+06   524.96E+06    14.72E+06   2202.0E+06    0.182     -0.007    0.0
0.36842   6.300    6.300  158.222    3.799     48.344   154.90E+06   435.26E+06    12.64E+06   2071.2E+06    0.176      0.005    0.0
0.42105   4.700    4.700  148.172    2.717     38.366   115.07E+06   345.57E+06    10.56E+06   1940.4E+06    0.170      0.018    0.0
0.47368   3.100    3.100  138.123    1.635     28.387    75.23E+06   255.87E+06     8.48E+06   1809.6E+06    0.164      0.030    0.0
0.52632   2.600    2.600  122.896    1.367     24.050    62.49E+06   217.87E+06     7.12E+06   1605.3E+06    0.168      0.038    0.0
0.57895   2.100    2.100  107.669    1.099     19.714    49.75E+06   179.86E+06     5.76E+06   1401.1E+06    0.172      0.047    0.0
0.63158   1.600    1.600   92.442    0.831     15.377    37.01E+06   141.86E+06     4.40E+06   1196.8E+06    0.176      0.055    0.0
0.68421   1.100    1.100   77.215    0.564     11.041    24.27E+06   103.85E+06     3.04E+06    992.6E+06    0.179      0.063    0.0
0.73684   0.600    0.600   61.988    0.296      6.704    11.53E+06    65.85E+06     1.68E+06    788.3E+06    0.183      0.071    0.0
0.78947   0.480    0.480   51.861    0.240      5.513     9.27E+06    54.25E+06     1.38E+06    654.3E+06    0.190      0.077    0.0
0.84211   0.360    0.360   41.734    0.185      4.322     7.01E+06    42.66E+06     1.08E+06    520.4E+06    0.198      0.082    0.0
0.89474   0.240    0.240   31.607    0.130      3.130     4.75E+06    31.06E+06     0.78E+06    386.4E+06    0.205      0.087    0.0
0.94737   0.120    0.120   21.480    0.074      1.939     2.49E+06    19.47E+06     0.48E+06    252.4E+06    0.212      0.092    0.0
1.00000   0.000    0.000   11.353    0.019      0.747     0.23E+06     7.87E+06     0.18E+06    118.5E+06    0.220      0.098    0.0
```

Figure 4: Sample input file for section properties (blade_sec_props.dat).

Table 7. Parameters for the Section Properties Input File

Parameter	Description	Unit
n_secs	Number of beam sections at which the user specifies blade section properties. Two sections, one at the blade root and the other at the blade tip, must always be specified. Thus, *n_secs* is always two or more.	-
sec_loc	Location of the section measured with respect to the beam root and normalized by the beam length. For a blade, the beam length is the distance between the blade root and the blade tip (*radius- hub_rad*) along the pitch axis. For a tower, it is the distance between the tower-to-rigid-base joint and the tip. For both the blade and the tower, the first section (root) is always located at *0.0* and the last section (tip) at *1.0*.	-
str_tw	For a blade, it is the angle the chordwise principal elastic axis (Figure 5) would make with the blade reference plane if the blade pitch setting, *bl_thp*, were made zero. The total structural twist at any section equals *str_tw+bl_thp*. For a tower, this parameter is over-written and set to zero.	deg
tw_iner	For a blade, it is the angle the chordwise principal inertia axis (Figure 5) would make with the blade reference plane if *bl_thp* were zero. The net twist of inertia reference frame at any section equals *tw_iner+bl_thp*. For a tower, this parameter is over-written to zero.	deg
mass_den	Section mass per unit length.	kg/m
flp_iner	For a blade, it is the section flap inertia per unit length about the Y_G inertia axis. For a tower, it is mass moment of inertias per unit length about the side-side y_T axis.	kg-m
edge_iner	For a blade, it is the section lag (edgewise) inertia per unit length about the X_G inertia axis. For a tower, it is mass moment of inertias per unit length about the fore-aft x_T axis.	kg-m
flp_stff	For a blade, it is the section flap bending stiffness about the Y_E elastic axis. For a tower, it is bending stiffness about the side-side y_T axis.	Nm^2
edge_stff	For a blade, it is the section lag bending stiffness about the X_E elastic axis. For a tower, it is bending stiffness about the fore-aft x_T axis.	Nm^2
tor_stff	Section torsion stiffness.	Nm^2
axial_stff	Section axial stiffness.	N
cg_offst	Chordwise offset of the section center of mass with respect to *R*, the origin for the section reference axes. For a tower, this parameter is over-written to zero.	m
sc_offst	Chordwise offset of the section shear center with respect to *R*. For a tower, this parameter is over-written to zero.	m
tc_offst	Chordwise offset of the section tension center with respect to *R*. For a tower, this parameter is over-written to zero.	m

5 Executing BModes

First create the input files. Use the sample input files supplied with the BModes code and modify these to suit your blade or tower for which you need coupled modes. Ensure that your modifications follow guidelines listed in Section 4.

Open a command window, change over to the directory you wish to work in, and issue the following command:

```
bmodes [inputs path name]\main_input_file_name
```

where *inputs path name* is the path name for the directory in which the BModes input file resides and *main_input_file_name* is the name of the main input file. Follow the instructions at http://wind.nrel.gov/designcodes/setup.pdf, and that will eliminate the need to specify the executable path name. For example, if the main input file resides in the working directory, and *SampleBlade.bmi* is the name of the main input file, then the command would be:

```
bmodes SampleBlade.bmi
```

If BModes detects[+] any errors during input reading or computations, errors or warning messages will be issued on the screen. If no errors are detected, BModes computes coupled modes and writes them to an output file *SampleBlade.out*, which is generated in the same directory where the main input file resides. The name of the output file is the same as that of the main input file except that the extension is changed to *out*. In our example, the name of the output file would be *SampleBlade.out*. The next section describes the output file.

[+] Some errors may not be detected. We are working on this, and a later version of BModes will have a more elaborate error detection scheme. Contact us if program execution does not go smoothly.

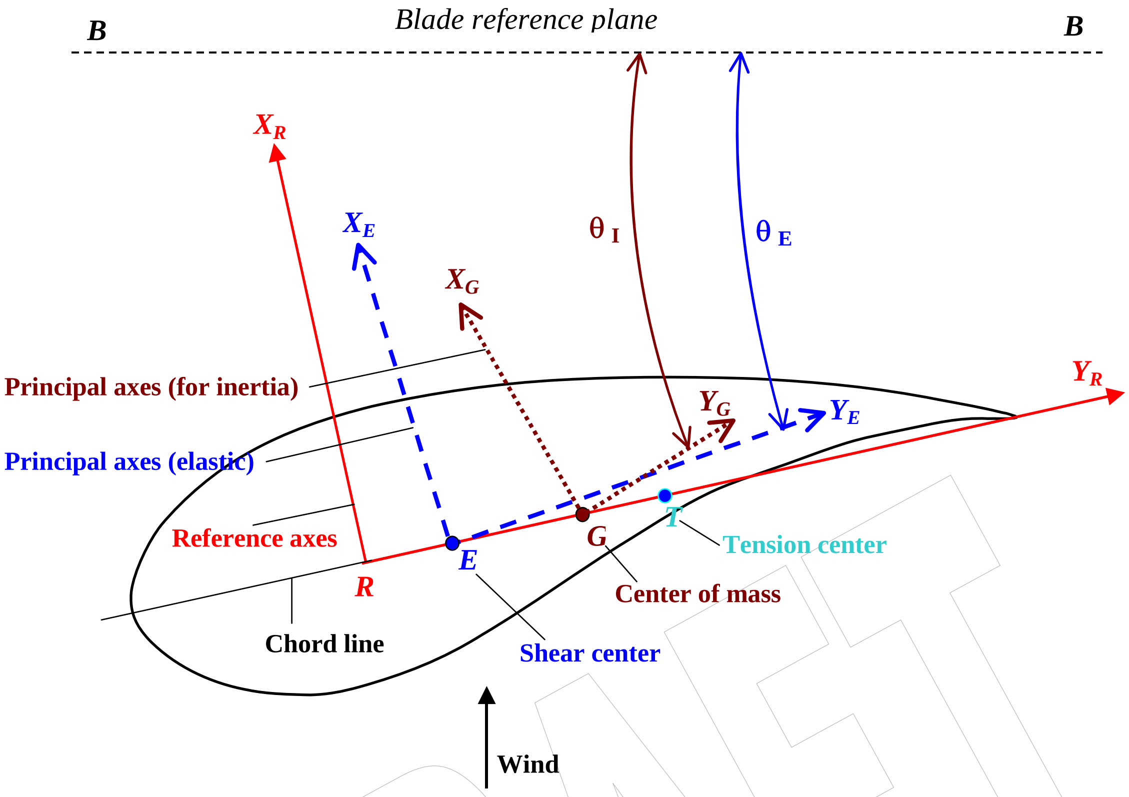


Figure 5: Axes systems at a typical blade section.

6 Output Description

Figure 7 shows a sample output file. It has a number of comment and blank lines, which either contain useful information or serve as separators. The second line shows a BModes version that generates the output along with the date and time at which it creates the output file. The third line is a repetition of the *title* specified in the main input file. The sixth line identifies whether the output frequencies and mode shapes are for a blade or a tower. The seventh line shows the number of modes printed (in accordance with the input parameter *modepr* in Table 1). All the following lines show computed modes; i.e., modal frequencies and associated mode shapes, which are printed as tabular data blocks. These tables may be viewed with a simple text editor. These may also be exported to a plotting utility such as an Excel Spreadsheet or to a modal-based aeroelastic code such as FAST. In fact, the main motivation for BModes development is to eventually integrate it with FAST to provide coupled modes for the tower and the blades. FAST would use these to compute modal integrals.

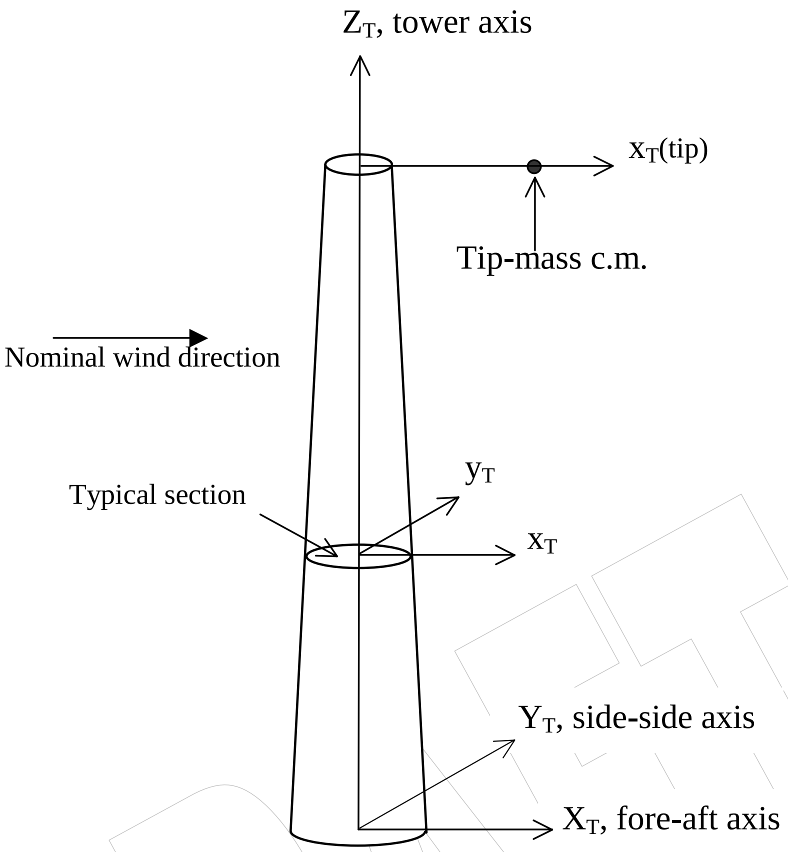


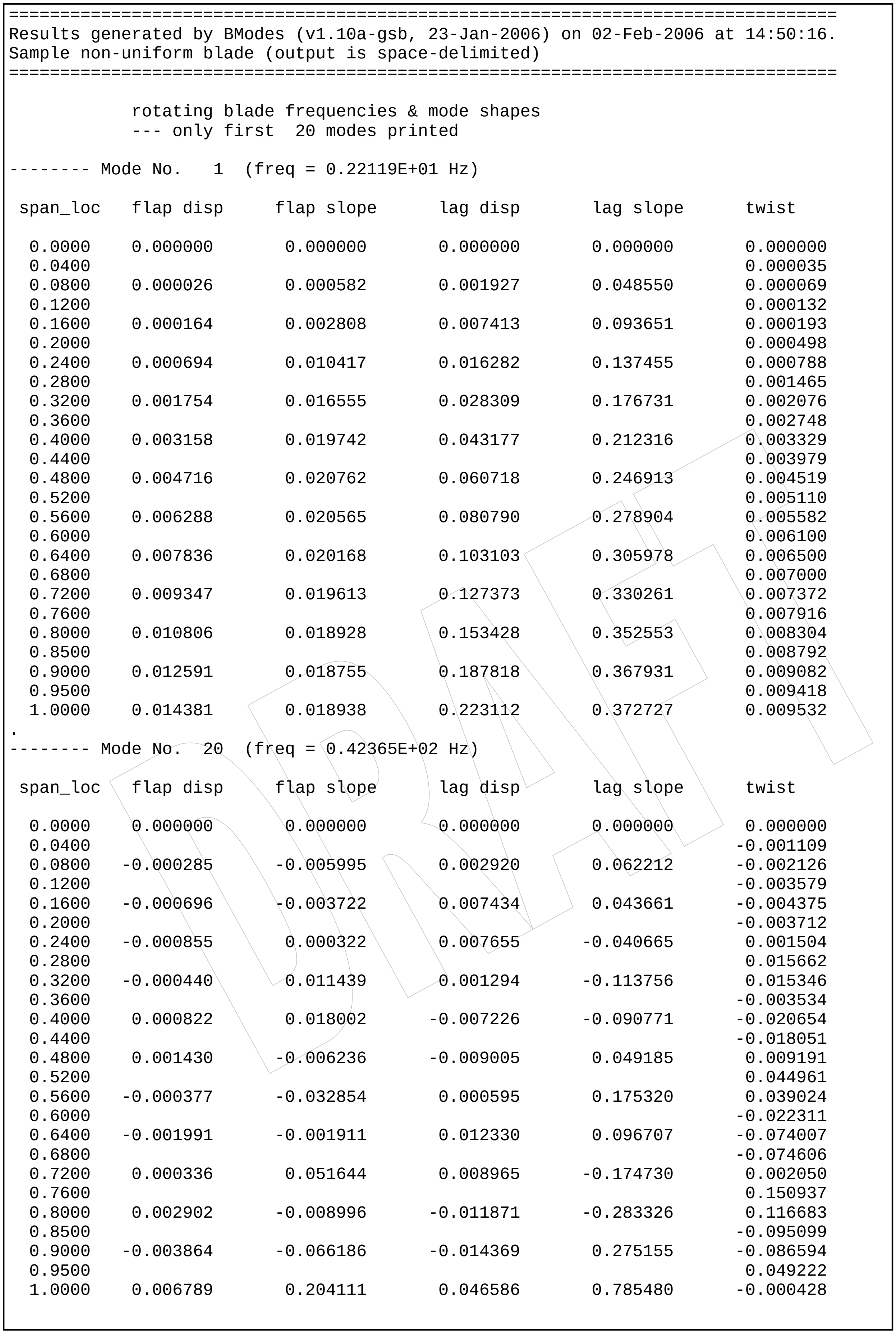
Figure 6: Tower axes systems.

Note that only the lowest *modepr* fundamental modes are output. These are output in blocks; the first block corresponds to the lowest-frequency mode, and the subsequent blocks correspond to higher modes with ascending frequencies. In our case, 20 blocks are printed because *modepr* is 20. For brevity, however, the sample file shows blocks for modes 1 and 20 only. Let us examine the first modal data block, which is associated with mode number 1 (frequency = 2.211 Hz). Following the line that shows the mode number and the frequency, a header line identifies the six parameters for the six columns of mode shape data that follow. These parameters are described in Table 8.

A coupled mode shape shows the spanwise distribution of flap, lag, twist, and axial displacement components in a particular mode. BModes computes this distribution in terms of flap deflection, flap slope, lag deflection, lag slope, and elastic twist at different locations along the blade. The axial displacements, though computed by BModes, are not printed. These displacements usually are comparatively small, and aeroelastic codes such as FAST ignore it. The mode shape data, for any mode, appears in six columns and *2*nselt+1* lines. In our case, *nselt* is 12 (see input file). Therefore, the coupled mode shape data appears in 25 lines.

Table 8. Parameters in the Output File

Parameter	Description	Unit
span_loc	Span location of a point on the beam reference axis measured with respect to the beam root and normalized by the beam length.	-
flap disp	For a blade, it is the component of modal displacement normal to the blade reference plane BB defined in Section 4.2. For a tower (Figure 6), it is the modal-displacement component parallel to the X_T axis.	-
flap slope	For a blade, it is the slope of modal displacement curve projected onto a plane that passes through the undeformed blade reference axis and is normal to the blade reference plane BB. For a tower, it is the slope of the projection of the modal-displacement curve on to the X_T-Z_T plane.	rad
lag disp	For a blade, it is the projection of modal displacement in the blade reference plane. For a tower (Figure 6), it is the modal-displacement component parallel to the Y_T axis.	-
lag slope	For a blade, it is the slope of modal displacement curve projected in the blade reference plane. For a tower, it is the slope of the projection of the modal-displacement curve on to the Y_T-Z_T plane.	rad
twist	This is strictly a quasi-coordinate [5]. However, for practical purposes and for modal-based codes such as FAST, it may quite accurately be defined as the projection of section twist in a plane that is normal to both the blade reference plane and the blade reference axis. For a tower, it is roughly the projection of section twist in the X_T-Y_T plane.	rad



```
=================================================================================
Results generated by BModes (v1.10a-gsb, 23-Jan-2006) on 02-Feb-2006 at 14:50:16.
Sample non-uniform blade (output is space-delimited)
=================================================================================

            rotating blade frequencies & mode shapes
            --- only first  20 modes printed

-------- Mode No.   1  (freq = 0.22119E+01 Hz)

 span_loc   flap disp     flap slope      lag disp       lag slope      twist

  0.0000    0.000000       0.000000       0.000000       0.000000       0.000000
  0.0400                                                                0.000035
  0.0800    0.000026       0.000582       0.001927       0.048550       0.000069
  0.1200                                                                0.000132
  0.1600    0.000164       0.002808       0.007413       0.093651       0.000193
  0.2000                                                                0.000498
  0.2400    0.000694       0.010417       0.016282       0.137455       0.000788
  0.2800                                                                0.001465
  0.3200    0.001754       0.016555       0.028309       0.176731       0.002076
  0.3600                                                                0.002748
  0.4000    0.003158       0.019742       0.043177       0.212316       0.003329
  0.4400                                                                0.003979
  0.4800    0.004716       0.020762       0.060718       0.246913       0.004519
  0.5200                                                                0.005110
  0.5600    0.006288       0.020565       0.080790       0.278904       0.005582
  0.6000                                                                0.006100
  0.6400    0.007836       0.020168       0.103103       0.305978       0.006500
  0.6800                                                                0.007000
  0.7200    0.009347       0.019613       0.127373       0.330261       0.007372
  0.7600                                                                0.007916
  0.8000    0.010806       0.018928       0.153428       0.352553       0.008304
  0.8500                                                                0.008792
  0.9000    0.012591       0.018755       0.187818       0.367931       0.009082
  0.9500                                                                0.009418
  1.0000    0.014381       0.018938       0.223112       0.372727       0.009532
.
-------- Mode No.  20  (freq = 0.42365E+02 Hz)

 span_loc   flap disp     flap slope      lag disp       lag slope      twist

  0.0000    0.000000       0.000000       0.000000       0.000000       0.000000
  0.0400                                                               -0.001109
  0.0800   -0.000285      -0.005995       0.002920       0.062212      -0.002126
  0.1200                                                               -0.003579
  0.1600   -0.000696      -0.003722       0.007434       0.043661      -0.004375
  0.2000                                                               -0.003712
  0.2400   -0.000855       0.000322       0.007655      -0.040665       0.001504
  0.2800                                                                0.015662
  0.3200   -0.000440       0.011439       0.001294      -0.113756       0.015346
  0.3600                                                               -0.003534
  0.4000    0.000822       0.018002      -0.007226      -0.090771      -0.020654
  0.4400                                                               -0.018051
  0.4800    0.001430      -0.006236      -0.009005       0.049185       0.009191
  0.5200                                                                0.044961
  0.5600   -0.000377      -0.032854       0.000595       0.175320       0.039024
  0.6000                                                               -0.022311
  0.6400   -0.001991      -0.001911       0.012330       0.096707      -0.074007
  0.6800                                                               -0.074606
  0.7200    0.000336       0.051644       0.008965      -0.174730       0.002050
  0.7600                                                                0.150937
  0.8000    0.002902      -0.008996      -0.011871      -0.283326       0.116683
  0.8500                                                               -0.095099
  0.9000   -0.003864      -0.066186      -0.014369       0.275155      -0.086594
  0.9500                                                                0.049222
  1.0000    0.006789       0.204111       0.046586       0.785480      -0.000428
```

Figure 7: Sample of output file (SampleBlade.out).

All mode shape data, except the twist, refer to the end nodes of the finite elements (identified by blue dots in Figure 1). The location of these end nodes should be the same as those specified on the last line of the input file (see description of input parameter *el_loc*, Table 1). The modal twist displacements refer to both end and mid nodes of the finite elements (the mid nodes are identified by crossed small circles in Figure 1).

Note 1: Each mode shape is mass-normalized [5]. You may, however, multiply a mode shape by any non-zero scalar to suit your normalization preference.

Note 2: This manual shows only one sample output file (Figure 7). More sample files, covering both blade and tower, are provided at our website.

7 Future Plans

We have provided step-by-step instructions for preparing input files, executing the code, and interpreting the output modal data. For a blade, preparing input files requires knowledge of rotor speed, pitch control setting, precone, and span-distributed geometric and structural properties. For a tower, we need structural properties distributed over the tower length. If the tower is tension-wires supported, we will also need the spring constants and attachment configurations of these wires. The distributed properties may be obtained from the blade/tower manufacturer, from experiment, or from blade/tower drawings. For the last option (drawings), the user would need a properties extractor such as BPE [3] or PreComp [2]. If PreComp is used, its output file may be directly used as the section properties input file for BModes.

A few BModes upgrades are planned for the future. Examples are new blade-to-hub connectivity options (e.g., flap hinge followed by pitch bearing) and option for specifying pitch-bearing-attached axes system for referencing mode shapes. The new option would be compatible with the FAST modal-based formulation. Later, we will extend BModes to handle composites and possibly curved blades. We may also upgrade BModes to model foundation for offshore towers.

We have verified BModes for uniform, tapered, and non-uniform metallic beams [6]. Following the upgrades mentioned above, we would perform and report additional verifications. If you encounter problems or have suggestions to improve the user interface, contact us. Also, let us know if you would like to see additional capabilities in the code within the constraints of the beam finite element theory.

Acknowledgments

Thanks to Sandy Butterfield for motivating the development of BModes, to Jason Jonkman for his useful suggestions, and to Marshall Buhl for his software-related support. Finally, the author would like to thank Mike Robinson for his constant encouragement. DOE supported this work under contract number DE-AC36-83CH10093.

8 References

1. Jonkman, J.M.; Buhl Jr., M.L. (2005). *FAST User's Guide.* NREL/EL-500-29798. Golden, CO: National Renewable Energy Laboratory.
2. Bir, G.S. (2005). *User’s Guide to PreComp (Pre-Processor for Computing Composite Blade Properties).* NREL/TP-500-38926. Golden, CO: National Renewable Energy Laboratory.
3. Malcolm, D.J., Laird D.L. “Identification and Use of Blade Physical Properties.” *Proceedings of the ASME/AIAA Wind Energy Symposium, Reno, Nevada, January 2005.*
4. Manjock, A. *Evaluation Report: Design Codes FAST and ADAMS for Load Calculations of Onshore Wind Turbines.* Germanischer Lloyd WindEnergie GmbH, Rept. 72042, Hamburg, Germany, May 2005.
5. Bir, G. S., and Chopra, I. “Status of the University of Maryland Advanced Rotorcraft Code (UMARC).” *Presented at the American Helicopter Society Aeromechanics Specialist Conference, San Francisco, California, January 19-21, 1994.*
6. Bir, G. S. (2005). *Structural Dynamics Verification of Rotorcraft Comprehensive Analysis System (RCAS).* NREL/TP-500-35328. Golden, CO: National Renewable Energy Laboratory.
7. Draft IEC 61400-13 TS, Ed. 1: Wind turbine generator systems – Part 13: Measurements of mechanical loads, Jan 21, 2000.