

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

G. Bir

Technical Report
NREL/TP-500-39133
December 2005

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337

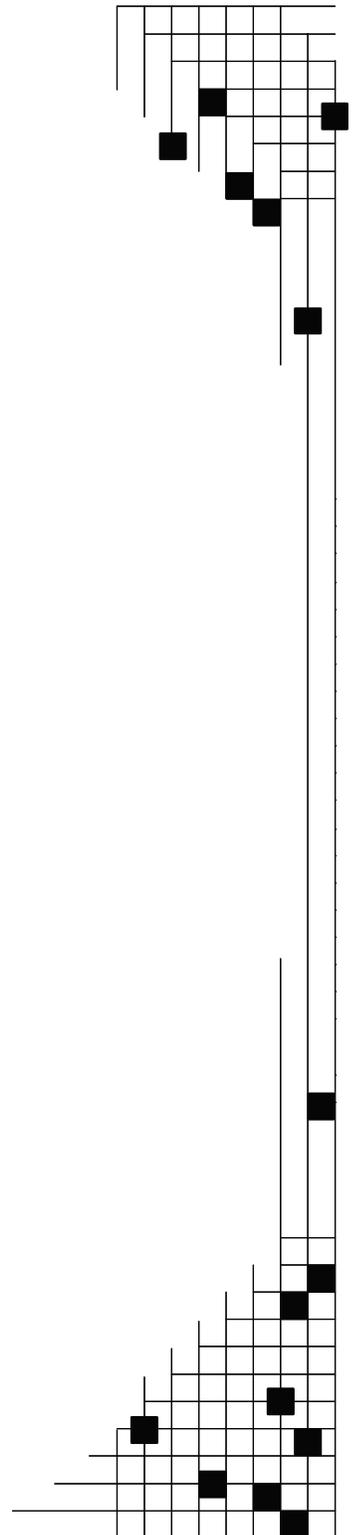


User's Guide to BModes (Software for Computing Rotating Beam Coupled Modes)

G. Bir

Prepared under Task No. WER6.2102

Technical Report
NREL/TP-500-39133
December 2005



National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



About this Guide

This guide explains data preparation and execution with BModes, a finite-element code that provides dynamically coupled modes for a beam. The beam can be a rotating or non-rotating rotor blade or a tower, and it can have arbitrary distribution of structural properties and geometry along its length. 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: accurate modeling of major flexible components for modal-based aeroelastic codes such as FAST (Fatigue, Aerodynamics, Structures, and Turbulence) [1], validation of flexible component models using experimental data, modal-based fatigue analysis, and interpretation of aeroelastic-stability behavior of turbines. Our plan is to eventually integrate BModes with FAST to provide tower and blade modes as rotor speed and blade pitch control settings change during a simulation.

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 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]. The current version of 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.

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.

Contents

Contents	iii
1 Introduction.....	1
2 Technical Approach.....	2
3 Underlying Assumptions	3
4 Input Data Preparation	4
4.1 Main Input File	4
4.2 Section Properties Input File	7
5 Executing BModes.....	10
6 Output Description.....	12
7 Future Plans	14
Acknowledgments.....	14
8 References.....	15

1 Introduction

BModes is developed primarily to provide coupled mode shapes for FAST (Fatigue, Aerodynamics, Structures, and Turbulence), an aeroelastic code that has recently been approved for worldwide certification [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.

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.

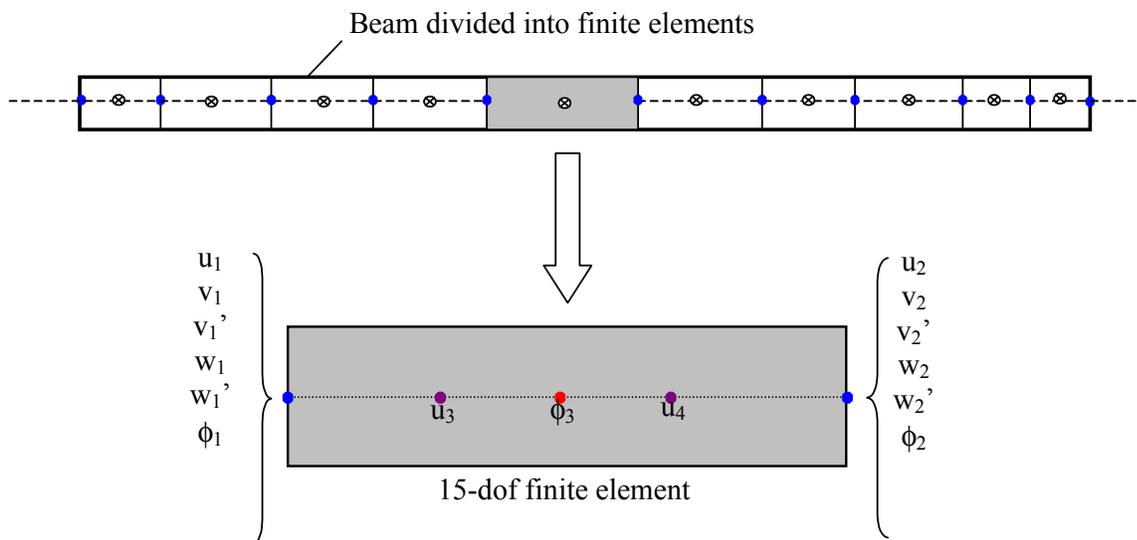


Figure 1: Beam discretization into 15-degrees-of-freedom finite elements.

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 requires specification of rotor speed, blade geometry, precone, pitch control setting, and structural properties distribution along the blade for inputs. 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

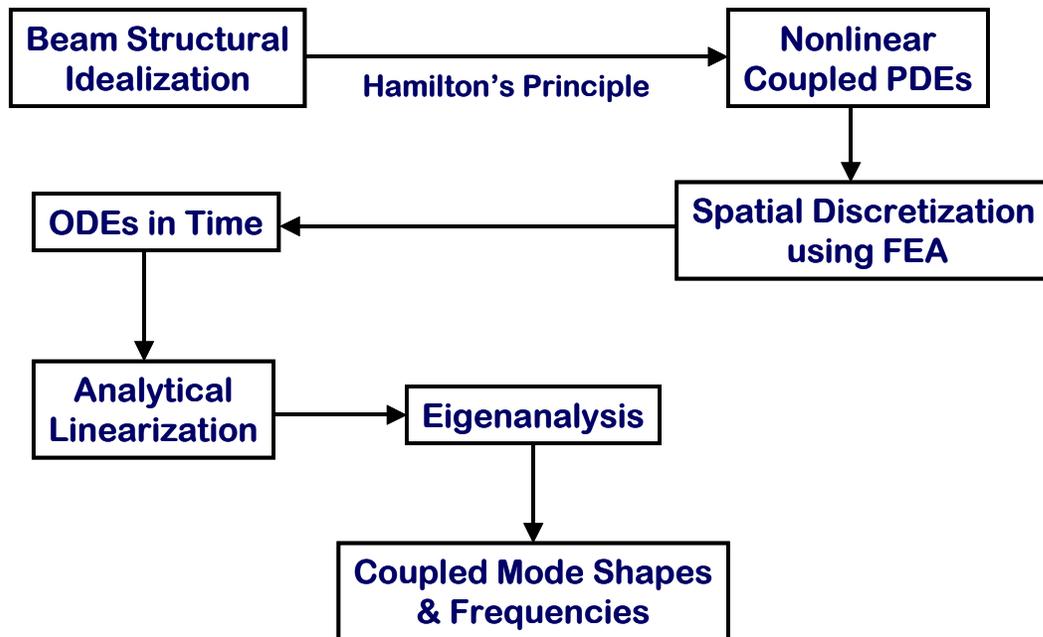


Figure 2: Technical approach for computation of beam coupled modes.

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.

3 Underlying Assumptions

BModes makes a number of assumptions, an understanding of which will help you scope the applicability and limitations of the code. It assumes that:

- The blade is straight (no built-in curvature).
- The blade 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].
- 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 blade is built with an isotropic material, including metal as a special case of an isotropic material.
- The blade root is cantilevered. This, though, is not an inherent limitation of BModes; other blade root conditions (e.g., a flap hinge followed by a pitch bearing) will be included in later versions of BModes.

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
- 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 next data block has two parameters, which identify distributed properties. Table 2 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 3. 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 last data-block parameters specify blade finite element discretization; these are explained in Table 4.

```

*=====      BModes Input File      =====
*
*          comments: test file for bmodes
*-----
' isolated cantilevered blade frequencies' <-- title must be enclosed within quotes
*-----
* note1: input data is in SI units except as noted
* note2: rotor tip radius = blade length + hub radius
*-----
60.0      romg:      rotor speed (rpm)
2.0      romg_mult: rotor speed multiplicative factor (-)
35.0      radius:   rotor tip radius: measured along coned blade axis (m)
1.75     hub_rad:   hub radius: measured along coned blade axis (m)
0.        precone:  built-in precone angle (deg)
0.        bl_thp:   blade pitch setting (deg), fixed or controlled
1        hub_conn:  hub-to-blade connection [1: cantilevered; other options not yet available]

----- data related to distributed structural properties -----
1        id_mat:    material_type [1: isotropic; non-isotropic composites option not yet available]
21       n_secs:    number of blade sections at which properties are specified (-)
'test_blade_sec_props.inp' sec_props_file  name of section properties file (-)

Properties scaling factors -----
1.0      sec_mass_mult: mass density multiplier (-)
1.0      flp_iner_mult: flap inertia multiplier (-)
1.0      lag_iner_mult: lag inertia multiplier (-)
1.0      flp_stff_mult: flap stiffness multiplier (-)
1.0      edge_stff_mult: edge 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 elements (-)
Distance of element boundaries from blade root (normalized wrt blade 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
-----
20       modepr:    number of modes to be printed

```

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

Table 1. General Parameters

Parameter	Description	Unit
<i>romg</i>	Nominal rotor speed.	rpm
<i>romg_mult</i>	Multiplicative (scaling) factor for rotor speed. The actual rotor speed is, therefore, $romg * romg_mult$.	-
<i>radius</i>	Rotor radius; the distance of the blade tip from the axis of rotation measured along the coned blade axis.	m
<i>hub_rad</i>	Hub radius; the distance of the blade root from the axis of rotation measured along the coned blade axis.	m
<i>precone</i>	Bblade built-in precone angle; the angle between the blade reference axis, usually the pitch axis, and the plane of rotation normal to the shaft.	deg
<i>bl_thp</i>	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).	deg
<i>hub_conn</i>	An integer switch defining the type of blade-to-hub 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.	-
<i>modepr</i>	Number of blade 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 <i>nselt</i> is the number of beam finite elements defined in Table 4. We recommend that <i>modepr</i> should not exceed $3 * nselt$; higher modes, even if printed, may not be accurate because of numerical considerations.	-
<i>TabDelim</i>	A logical switch. If set to <i>t</i> or <i>true</i> , 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 <i>f</i> or <i>false</i> , 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 <i>false</i> .	-

Table 2. Distributed-Property Identifiers

Parameter	Description	Unit
<i>id_mat</i>	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.	-
<i>sec_props_file</i>	User-specifiable name for the section properties input file. The name must appear within quotes and can have a maximum of 99 characters.	-

Table 3. Distributed-Property Scaling Factors

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

Table 4. Finite-Element Discretization Parameters

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

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 2). 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. Before we describe these properties, we need to understand Figure 5, which 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 4 shows a sample section properties inputs file. 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 5 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.

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 5. Parameters for the Section Properties Input File

Parameter	Description	Unit
<i>n_secs</i>	Number of blade 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, <i>n_secs</i> is always two or more.	-
<i>sec_loc</i>	Location of the section measured with respect to the blade root and normalized by the blade length. The blade length is the distance between the blade root and the blade tip (<i>radius-hub_rad</i>) along the pitch axis. Therefore, the first section (root) is always located at <i>0.0</i> and the last section (tip) at <i>1.0</i> .	-
<i>str_tw</i>	The angle the chordwise principal elastic axis (Figure 5) would make with the blade reference plane if the blade pitch setting, <i>bl_thp</i> , were made zero. The total structural twist at any section equals <i>str_tw+bl_thp</i> .	deg
<i>tw_iner</i>	The angle the chordwise principal inertia axis (Figure 5) would make with the blade reference plane if <i>bl_thp</i> were zero. The net twist of inertia reference frame at any section equals <i>tw_iner+bl_thp</i> .	deg
<i>mass_den</i>	Section mass per unit length.	kg/m
<i>flp_iner</i>	Section flap inertia per unit length about the Y_G inertia axis.	kg-m
<i>edge_iner</i>	Section lag (edgewise) inertia per unit length about the X_G inertia axis.	kg-m
<i>flp_stff</i>	Section flap bending stiffness about the Y_E elastic axis.	Nm ²
<i>edge_stff</i>	Section lag bending stiffness about the X_E elastic axis.	Nm ²
<i>tor_stff</i>	Section torsion stiffness.	Nm ²
<i>axial_stff</i>	Section axial stiffness.	N
<i>cg_offst</i>	Chordwise offset of the section center of mass with respect to <i>R</i> , the origin for the section reference axes.	m
<i>sc_offst</i>	Chordwise offset of the section shear center with respect to <i>R</i> .	m
<i>tc_offst</i>	Chordwise offset of the section tension center with respect to <i>R</i> .	m

5 Executing BModes

First create the input files. Use the two 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.

Next, open the file *para.inc* (supplied with the code). It contains a number of parameters. Ensure that the parameter *mselt* in this file equals variable *nselt* in your main input file. If it does, go to the next step described in the next paragraph. If it does not, set *mselt* equal to *nselt* (in our sample input file, *nselt* is 12; therefore *mselt* must also be 12). Save the modified *para.inc* file and compile the code*.

* In a later version of BModes, this step will not be required.

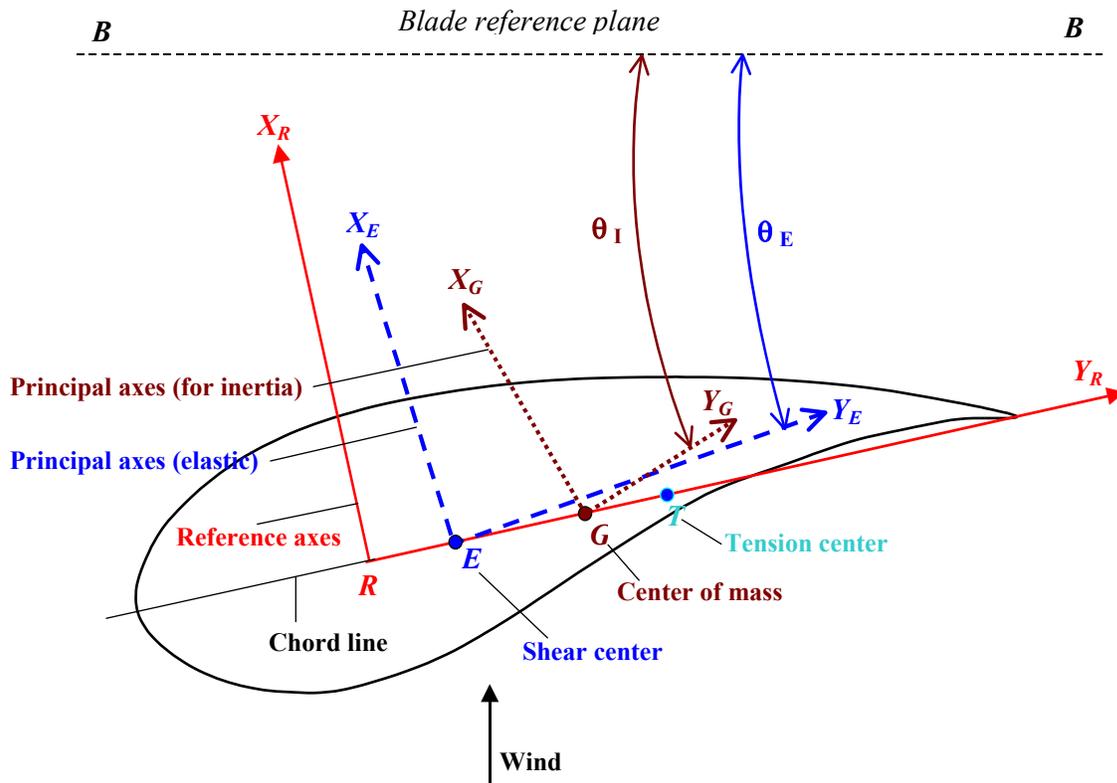


Figure 5: Axes systems at a typical blade section.

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.inp* is the name of the main input file, then the command would be:

bmodes SampleBlade.inp

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.

6 Output Description

Figure 6 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 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.

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 6.

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 6. Parameters in the Output File

Parameter	Description	Unit
<i>span_loc</i>	Span location of a point on the blade reference axis measured with respect to the blade root and normalized by the blade length.	-
<i>flap disp</i>	Component of modal displacement normal to the blade reference plane BB defined in Section 4.2.	-
<i>flap slope</i>	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.	rad
<i>lag disp</i>	Projection of modal displacement in the blade reference plane.	-
<i>lag slope</i>	Slope of modal displacement curve projected in the blade reference plane.	rad
<i>twist</i>	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.	rad

```

=====
Results generated by BModes (v1.00b-gsb, 10-Nov-2005) on 16-Nov-2005 at 14:50:31.
Sample Non-Uniform Blade
=====

```

```

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

7 Future Plans

We have provided step-by-step instructions for preparing input files, executing the code, and interpreting the output modal data. Preparing input files requires knowledge of rotor speed, pitch control setting, precone, and span-distributed geometric and structural properties. The distributed properties may be obtained from the blade manufacturer, from experiment, or from blade drawings. For the last option (blade 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 next year. Examples are the inclusion of new blade-to-hub connectivity options (e.g., flap hinge followed by pitch bearing) and provision for tension guy wires (e.g., those used for supporting towers). We may also add an 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 have verified BModes for uniform, tapered, and non-uniform metallic blades [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.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) December 2005		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To)		
4. TITLE AND SUBTITLE User's Guide to BModes (Software for Computing Rotating Beam Coupled Modes)			5a. CONTRACT NUMBER DE-AC36-99-GO10337			
			5b. GRANT NUMBER			
			5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S) G. Bir			5d. PROJECT NUMBER NREL/TP-500-39133			
			5e. TASK NUMBER WER6.2102			
			5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				8. PERFORMING ORGANIZATION REPORT NUMBER NREL/TP-500-39133		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) NREL		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER		
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT (Maximum 200 Words) This guide explains data preparation and execution with BModes, a finite-element code that provides dynamically coupled modes for a beam. The beam can be a rotating or non-rotating rotor blade or a tower, and it can have arbitrary distribution of structural properties and geometry along its length. 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: accurate modeling of major flexible components for modal-based aeroelastic codes such as FAST (Fatigue, Aerodynamics, Structures, and Turbulence), validation of flexible component models using experimental data, modal-based fatigue analysis, and interpretation of aeroelastic-stability behavior of turbines. Our plan is to eventually integrate BModes with FAST to provide tower and blade modes as rotor speed and blade pitch control settings change during a simulation. 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.						
15. SUBJECT TERMS wind energy; wind turbines; codes; software; rotor blade; tower						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18