

BeamDyn User's Guide and Theory Manual

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Preface

This document offers a quick reference guide for the BeamDyn software program. It is intended to be used by the general user in combination with other FAST manuals. The manual will be updated as new releases are issued and as needed to provide further information on advancements or modifications to the software.

Acknowledgments

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Table of Contents

1	Introduction	3
2	Running BeamDyn	6
2.1	Downloading the BeamDyn Software	6
2.1.1	Stand-Alone BeamDyn Archive	6
2.1.2	FAST Archive	6
2.2	Running BeamDyn	6
2.2.1	Running the Stand-Alone BeamDyn Program	6
2.2.2	Running BeamDyn Coupled to FAST	7
3	Input Files	8
3.1	Units	8
3.2	BeamDyn Driver Input File	8
3.2.1	Simulation Control Parameters	8
3.2.2	Gravity Parameters	8
3.2.3	Inertial Frame Parameters	8
3.2.4	Blade Floating Reference Frame Parameters	8
3.2.5	Applied Load	10
3.2.6	Primary Input File	11
3.3	BeamDyn Primary Input File	11
3.3.1	Simulation Controls	11
3.3.2	Geometry Parameter	12
3.3.3	Mesh Parameter	13
3.3.4	Material Parameter	13
3.3.5	Pitch Actuator Parameter	13
3.3.6	Outputs	15
3.4	Blade Input File	15
3.4.1	Blade Parameters	15
3.4.2	Damping Coefficient	15
3.4.3	Distributed Properties	16
4	Output Files	17
4.1	Echo File	17
4.2	Summary File	17
4.3	Results File	18
5	BeamDyn Theory	19
5.1	Coordinate Systems	19
5.1.1	Global Coordinate System	20
5.1.2	BD Coordinate System	20
5.1.3	Blade Reference Coordinate System	20
5.1.4	Local blade coordinate system	20
5.2	Geometrically Exact Beam Theory	20
5.3	Numerical Implementation with Legendre Spectral Finite Elements	21

5.4	Wiener-Milenković Rotation Parameter	23
5.5	Linearization Process	23
5.6	Damping Forces and Linearization	24
5.7	Convergence Criterion and Generalized- α Time Integrator	25
5.8	Calculation of Reaction Loads	26
5.9	Calculation of Blade Loads	26
6	Future Work	27
A	BeamDyn Driver Input File	28
B	BeamDyn Primary Input File: NREL 5-MW Reference Wind Turbine	30
C	BeamDyn Blade Input File: NREL 5-MW Reference Wind Turbine Blade	34
D	BeamDyn List of Output Channels	55
	References	57

List of Figures

Figure 1.	Coupled interaction between BeamDyn and FAST	4
Figure 2.	Global and blade coordinate systems in BeamDyn	9
Figure 3.	Member and key point definition. Case 1: one member defined by four key points; and Case 2: two members defined by six key points.	13
Figure 4.	BeamDyn Blade Geometry - Top: Side View; Middle: Front View (Looking Downwind); Bottom: Cross Section View (Looking Toward the Tip, from the Root)	14
Figure 5.	Global, blade reference, and internal coordinate systems in BeamDyn. Illustration by Al Hicks, NREL	19
Figure 6.	Representative $p + 1$ Lagrangian-interpolant shape functions in the element natural coordinates for (a) fourth- and (b) eighth-order LSFs, where nodes are located at the Gauss-Lobatto-Legendre points.	22

List of Tables

Table 1.	Transformation between blade coordinate system and BD coordinate system.	20
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1 Introduction

BeamDyn is a time-domain structural-dynamics module for slender structures created by the National Renewable Energy Laboratory (NREL) through support from the U.S. Department of Energy Wind and Water Power Program and the NREL Laboratory Directed Research and Development (LDRD) program through the grant “High-Fidelity Computational Modeling of Wind-Turbine Structural Dynamics”, see References Wang et al. (2015); Wang and Sprague (2013); Wang et al. (2014, 2013). The module has been coupled into the FAST aero-hydro-servo-elastic wind turbine multi-physics engineering tool where it used to model blade structural dynamics. The BeamDyn module follows the requirements of the FAST modularization framework, see References Jonkman (2013); Gasmi et al. (2013); Jonkman and Jonkman (2013); Sprague et al. (2014), couples to FAST version 8, and provides new capabilities for modeling initially curved and twisted composite wind turbine blades undergoing large deformation. BeamDyn can also be driven as a stand-alone code to compute the static and dynamic responses of slender structures (blades or otherwise) under prescribed boundary and applied loading conditions uncoupled from FAST.

The model underlying BeamDyn is the geometrically exact beam theory (GEBT) Hodges (2006). GEBT supports full geometric nonlinearity and large deflection, with bending, torsion, shear, and extensional degree-of-freedom (DOFs); anisotropic composite material couplings (using full 6×6 mass and stiffness matrices, including bend-twist coupling); and a reference axis that permits blades that are not straight (supporting built-in curve, sweep, and sectional offsets). The GEBT beam equations are discretized in space with Legendre spectral finite elements (LSFEs). LSFEs are p -type elements that combine the accuracy of global spectral methods with the geometric modeling flexibility of the h -type finite elements (FEs) Patera (1984). For smooth solutions, LSFEs have exponential convergence rates compared to low-order elements that have algebraic convergence Sprague and Geers (2003); Wang and Sprague (2013). Two spatial numerical integration schemes are implemented for the finite element inner products: reduced Gauss quadrature and trapezoidal-rule integration. Trapezoidal-rule integration is appropriate when a large number of sectional properties are specified along the beam axis, for example, in a long wind turbine blade with material properties that vary dramatically over the length. Time integration of the BeamDyn equations of motion is achieved through the implicit generalized- α solver, with user-specified numerical damping. The combined GEBT-LSFE approach permits users to model a long, flexible, composite wind turbine blade with a single high-order element. Given the theoretical foundation and powerful numerical tools introduced above, BeamDyn can solve the complicated nonlinear composite beam problem in an efficient manner. For example, it was recently shown that a grid-independent dynamic solution of a 50-m composite wind turbine blade and with dozens of cross-section stations could be achieved with a single 7th-order LSFE Wang et al. (2016).

When coupled with FAST, loads and responses are transferred between BeamDyn, ElastoDyn, ServoDyn, and AeroDyn via the FAST driver program (glue code) to enable aero-elasto-servo interaction at each coupling time step. There is a separate instance of BeamDyn for each blade. At the root node, the inputs to BeamDyn are the six displacements (three translations and three rotations), six velocities, and six accelerations; the root node outputs from BeamDyn are the six reaction loads (three translational forces and three moments). BeamDyn also outputs the blade displacements, velocities, and accelerations along the beam length, which are used by AeroDyn to calculate the local aerodynamic loads (distributed along the length) that are used as inputs for BeamDyn. In addition, BeamDyn can calculate member internal reaction loads, as requested by the user. Please refers to Figure 1 for the coupled interactions between BeamDyn and other modules in FAST. When coupled to FAST, BeamDyn replaces the more simplified blade structural model of ElastoDyn that is still available as an option, but is only applicable to straight isotropic blades dominated by bending. When uncoupled from FAST, the root motion (boundary condition) and applied loads are specified via a stand-alone BeamDyn driver code.

The BeamDyn input file defines the blade geometry; cross-sectional material mass, stiffness, and damping properties; FE resolution; and other simulation- and output-control parameters. The blade geometry is defined through a curvilinear blade reference axis by a series of key points in three-dimensional (3D) space along with the initial twist angles at these points. Each *member* contains at least three key points for the cubic spline fit implemented in BeamDyn; each member is discretized with a single LSFE with a parameter defining the order of the element. Note that the number of key points defining the member and the order (N) of the LSFE are independent. LSFE nodes, which



Figure 1. Coupled interaction between BeamDyn and FAST

are located at the $N + 1$ Gauss-Legendre-Lobatto points, are not evenly spaced along the element; node locations are generated by the module based on the mesh information. Blade properties are specified in a non-dimensional coordinate ranging from 0.0 to 1.0 along the blade reference axis and are linearly interpolated between two stations if needed by the spatial integration method. The BeamDyn applied loads can be either distributed loads specified at quadrature points, concentrated loads specified at FE nodes, or a combination of the two. When BeamDyn is coupled to FAST, the blade analysis node discretization may be independent between BeamDyn and AeroDyn.

This document is organized as follows. Section 2 details how to obtain the BeamDyn and FAST software archives and run either the stand-alone version of BeamDyn or BeamDyn coupled to FAST. Section 3 describes the BeamDyn input files. Section 4 discusses the output files generated by BeamDyn. Section 5 summarizes the BeamDyn theory. Section 6 outlines potential future work. Example input files are shown in Appendix A, B, and C. A summary of available output channels is found in Appendix D.

2 Running BeamDyn

This section discusses how to obtain and execute BeamDyn from a personal computer. Both the stand-alone version and the FAST-coupled version of the software are considered.

2.1 Downloading the BeamDyn Software

There are two forms of the BeamDyn software to choose from: stand-alone and coupled to the FAST simulator. Although the user may not necessarily need both forms, he/she would likely need to be familiar with and run the stand-alone model if building a model of the blade from scratch. The stand-alone version is also helpful for model troubleshooting, even if the goal is to conduct aero-hydro-servo-elastic simulations of onshore/offshore wind turbines within FAST.

2.1.1 Stand-Alone BeamDyn Archive

Users can download the stand-alone BeamDyn archive from our Web server at <https://nwtc.nrel.gov/BeamDyn>. The file has a name similar to *BD_v1.00.00a.exe*, but may have a different version number. The user can then download the self-extracting archive (.exe) to expand the archive into a folder he/she specifies.

The archive contains the *bin*, *CertTest*, *Compiling*, *Docs*, and *Source* folders. The *bin* folder includes the main executable file, *BeamDyn_Driver.exe*, which is used to execute the stand-alone BeamDyn program. The *CertTest* folder contains a collection of sample BeamDyn input files and driver input files that can be used as templates for the user's own models. This document may be found in the *Docs* folder. The *Compiling* folder contains files for compiling the stand-alone *BeamDyn_v1.00.00.exe* file with either Visual Studio or gFortran. The Fortran source code is located in the *Source* folder.

2.1.2 FAST Archive

Download the FAST archive, which includes BeamDyn, from our Web server at <https://nwtc.nrel.gov/FAST8>. The file has a name similar to *FAST_v8.12.00.exe*, but may have a different version number. Run the downloaded self-extracting archive (.exe) to expand the archive into a user-specified folder. The FAST executable file is located in the archive's *bin* folder. An example model using the NREL 5-MW reference turbine is located in the *CertTest* folder.

2.2 Running BeamDyn

2.2.1 Running the Stand-Alone BeamDyn Program

The stand-alone BeamDyn program, *BeamDyn_Driver.exe*, simulates static and dynamic responses of the user's input model, without coupling to FAST. Unlike the coupled version, the stand-alone software requires the use of a driver file in addition to the primary and blade BeamDyn input files. This driver file specifies inputs normally provided to BeamDyn by FAST, including motions of the blade root and externally applied loads. Both the BeamDyn summary file and the results output file are available when using the stand-alone BeamDyn (see Section 4 for more information regarding the BeamDyn output files).

Run the stand-alone BeamDyn software from a DOS command prompt by typing, for example:

```
>BeamDyn_Driver.exe Dvr_5MW_Dynamic.inp
```

where, *Dvr_5MW_Dynamic.inp* is the name of the BeamDyn driver input file, as described in Section 3.2.

2.2.2 Running BeamDyn Coupled to FAST

Run the coupled FAST software from a DOS command prompt by typing, for example:

```
>FAST_Win32.exe Test26.fst
```

where *Test26.fst* is the name of the primary FAST input file. This input file has a feature switch to enable or disable the BeamDyn capabilities within FAST, and a corresponding reference to the BeamDyn input file. See the documentation supplied with FAST for further information.

3 Input Files

Users specify the blade model parameters; including its geometry, cross-sectional properties, and FE and output control parameters; via a primary BeamDyn input file and a blade property input file. When used in stand-alone mode, an additional driver input file is required. This driver file specifies inputs normally provided to BeamDyn by FAST, including simulation range, root motions, and externally applied loads.

No lines should be added or removed from the input files, except in tables where the number of rows is specified.

3.1 Units

BeamDyn uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

3.2 BeamDyn Driver Input File

The driver input file is only needed for the stand-alone version of BeamDyn and contains inputs that are normally set by FAST, and that are necessary to control the simulation for uncoupled models.

The driver input file begins with two lines of header information, which is for the user but is not used by the software. If BeamDyn is run in the stand-alone mode, the results output file will be prefixed with the same name of this driver input file.

A sample BeamDyn driver input file is given in Appendix A

3.2.1 Simulation Control Parameters

$t_{initial}$ and t_{final} specify the starting time of the simulation and ending time of the simulation, respectively. dt specifies the time step size.

3.2.2 Gravity Parameters

G_x , G_y , and G_z specify the components of gravity vector along X , Y , and Z directions in the global coordinate system, respectively. In FAST, this is normally 0, 0, and -9.80665.

3.2.3 Inertial Frame Parameters

This section defines the relation between two inertial frames, the global coordinate system and initial blade reference coordinate system. $GlbPos(1)$, $GlbPos(2)$, $GlbPos(3)$ specifies three components of the initial global position vector along X , Y , and Z directions resolved in the global coordinate system, see Figure 2. And the following 3×3 direction cosine matrix ($GlbDCM$) relates the rotations from the global coordinate system to the initial blade reference coordinate system.

3.2.4 Blade Floating Reference Frame Parameters

This section specifies the parameters that defines the blade floating reference frame, which is a body-attached floating frame; the blade root is cantilevered at the origin of this frame. Based on the driver input file, the floating blade reference frame is assumed to be in a constant rigid-body rotation mode about the origin of the global coordinate system, that is,

$$v_{rt} = \omega_r \times r_t \quad (3.1)$$

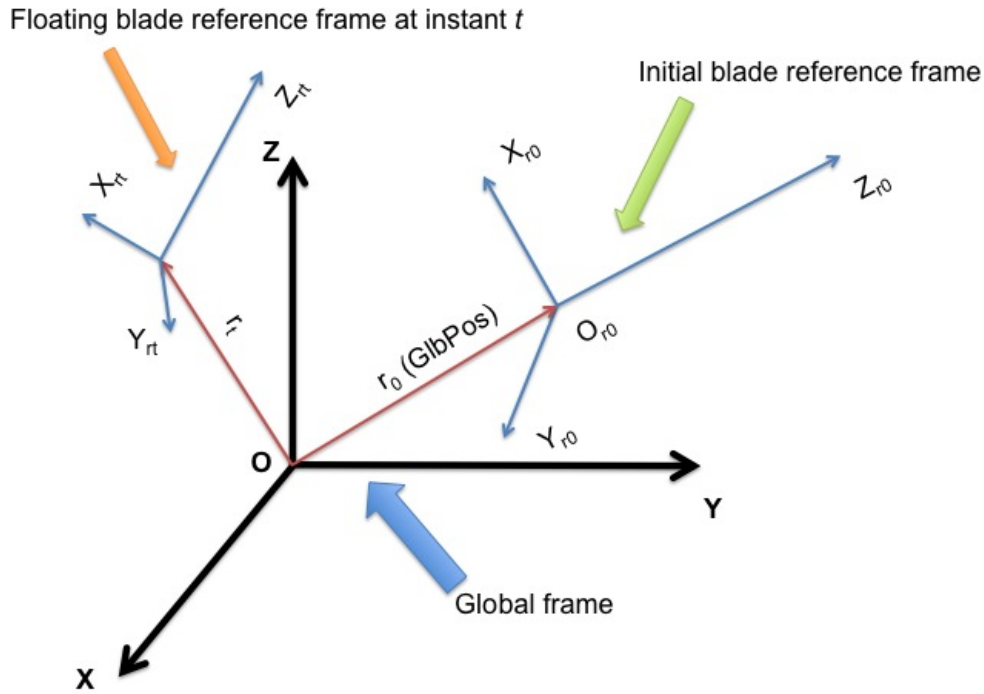


Figure 2. Global and blade coordinate systems in BeamDyn

where v_{rt} is the root (origin of the floating blade reference frame) translational velocity vector; ω_r is the constant root (origin of the floating blade reference frame) angular velocity vector; and r_t is the global position vector introduced in the previous section at instant t , see Figure 2. The floating blade reference frame coincides with the initial floating blade reference frame at the beginning $t = 0$. **RootVel(4)**, **RootVel(5)**, and **RootVel(6)** specify the three components of the constant root angular velocity vector about X , Y , and Z axes in global coordinate system, respectively. **RootVel(1)**, **RootVel(2)**, and **RootVel(3)**, which are the three components of the root translational velocity vector along X , Y , and Z directions in global coordinate system, respectively, are calculated based on Eq. 3.1.

BeamDyn can handle more complicated root motions by changing, for example, the *BD_InputSolve* subroutine in the *Driver_Beam.f90* (requiring a recompile of stand-alone BeamDyn):

```

u%RootMotion%RotationVel (:, :) = 0.0D0
u%RootMotion%RotationVel (1, 1) = IniVelo (5)
u%RootMotion%RotationVel (2, 1) = IniVelo (6)
u%RootMotion%RotationVel (3, 1) = IniVelo (4)
u%RootMotion%TranslationVel (:, :) = 0.0D0
u%RootMotion%TranslationVel (:, 1) = &
MATMUL(BD_Tilde( real(u%RootMotion%RotationVel (:, 1), BDKi) ), temp_rr)

```

where *IniVelo(5)*, *IniVelo(6)*, and *IniVelo(4)* are the three components of the root angular velocity vector about X , Y , and Z axising in the global coordinate system, respectively; *temp_rr* is the global position vector at instant t . The first index in the *u%RootMotion%RotationVel(:, :)* and the *u%RootMotion%TranslationVel(:, :)* arrays range from 1 to 3 for load vector components along three directions and the second index of each array are set to 1, denoting the root FE node. Note that the internal BeamDyn variables (here *IniVelo*) are based on the internal BD coordinate system described in section 5.1.

The blade is initialized in the rigid-body motion mode, i.e., based on the root velocity information defined in this section and the position information defined in the previous section, the motion of other points along the blade are initialized as

$$a_0 = \omega_r \times (\omega_r \times (r_0 + P)) \quad (3.2)$$

$$v_0 = v_{r0} + \omega_r \times P \quad (3.3)$$

$$\omega_0 = \omega_r \quad (3.4)$$

where a_0 is the initial translational acceleration vector along the blade; v_0 and ω_0 the initial translational and angular velocity vectors along the blade, respectively; and P is the position vector along the blade relative to the root.

3.2.5 Applied Load

This section defines the applied loads, including distributed and tip-concentrated loads, for the stand-alone analysis. The first six entries ***DistrLoad(i)***, $i \in [1, 6]$, specify three components of uniformly distributed force vector and three components of uniformly distributed moment vector in the global coordinate systems, respectively. The following six entries ***TipLoad(i)***, $i \in [1, 6]$, specify three components of concentrated tip force vector and three components of concentrated tip moment vector in the global coordinate system, respectively. The distributed load defined in this section is assumed to be uniform along the blade and constant throughout the simulation; the tip load is a constant concentrated load applied at the tip of a blade. It is noted that all the loads defined in this section are dead loads, i.e., they are not rotating with the blade following the rigid-body rotation defined in the previous section.

BeamDyn is capable of handling more complex loading cases, e.g., time-dependent loads, through customization of the source code (requiring a recompile of stand-alone BeamDyn). The user can define such loads in the *BD_InputSolve* subroutine in the *Driver_Beam.f90* file, which is called every time step. The following section can be modified to define the concentrated load at each FE node:

```
! Define concentrated force vector
u%PointLoad%Force (:, :) = 0.0D0
! Define concentrated moment vector
u%PointLoad%Moment (:, :) = 0.0D0
```

where the first index in each array ranges from 1 to 3 for load vector components along three global directions and the second index of each array ranges from 1 to ***node_total***, where the latter is the total number of FE nodes. For example, a time-dependent sinusoidal force acting along the X direction applied at the 2nd FE node can be defined as

```
! Define concentrated force vector
u%PointLoad%Force (:, :) = 0.0D0
u%PointLoad%Force (1, 2) = 1.0D+03*SIN((2.0* pi)* t /6.0 )
! Define concentrated moment vector
u%PointLoad%Moment (:, :) = 0.0D0
```

with 1.0D+03 being the amplitude and 6.0 being the period.

Similar to the concentrated load, the distributed loads can be defined in the same subroutine

```
IF (p%quadrature .EQ. 1) THEN
  DO i=1, p%ngp*p%elem_total+2
    u%DistrLoad%Force (1:3, i) = InitInput%DistrLoad (1:3)
    u%DistrLoad%Moment (1:3, i) = InitInput%DistrLoad (4:6)
  ENDDO
ELSEIF (p%quadrature .EQ. 2) THEN
  DO i=1, p%ngp
```

```

        u%DistrLoad%Force(1:3, i) = InitInput%DistrLoad(1:3)
        u%DistrLoad%Moment(1:3, i) = InitInput%DistrLoad(4:6)
    ENDDO
ENDIF

```

where $p\%ngp$ is the number of quadrature points, $InitInput\%DistrLoad(:)$ is the constant uniformly distributed load BeamDyn reads from the driver input file, and $p\%elem_total$ is the total number of elements. The user can modify “ $InitInput\%DistrLoad(:)$ ” to define the loads based on need.

We note that the distributed loads are defined at the quadrature points for numerical integrations. For example, if Gauss quadrature is chosen (i.e., $p\%quadrature = 1$), then the distributed loads are defined at Gauss points plus the two end points of the beam (root and tip). For trapezoidal quadrature, $p\%ngp$ stores the number of trapezoidal quadrature points.

3.2.6 Primary Input File

InputFile is the file name of the primary BeamDyn input file. This name should be in quotations and can contain an absolute path or a relative path.

3.3 BeamDyn Primary Input File

The BeamDyn primary input file defines the blade geometry, LSFE-discretization and simulation options, output channels, and name of the blade input file. The geometry of the blade is defined by key-point coordinates and initial twist angles (in units of degree) in the blade local coordinate system (IEC standard blade system where Z_r is along blade axis from root to tip, X_r directs normally toward the suction side, and Y_r directs normally toward the trailing edge).

The file is organized into several functional sections. Each section corresponds to an aspect of the BeamDyn model.

A sample BeamDyn primary input file is given in Appendix B.

The primary input file begins with two lines of header information, which are for the user but are not used by the software.

3.3.1 Simulation Controls

The user can set the *Echo* flag to “TRUE” to have BeamDyn echo the contents of the BeamDyn input file (useful for debugging errors in the input file).

Analysis_Type specifies the type of an analysis. In the current version, there are two options: 1) static analysis, and 2) dynamic analysis. If BeamDyn is run in coupled FAST mode, this entry can be only set to 2, i.e., for dynamic analysis.

rhoINF specifies the numerical damping parameter (spectral radius of the amplification matrix) in the range of $[0.0, 1.0]$ used in the generalized- α time integrator implemented in BeamDyn for dynamic analysis. For *rhoINF* = 1.0, no numerical damping is introduced and the generalized- α scheme is identical to the Newmark scheme; for *rhoINF* = 0.0, maximum numerical damping is introduced. Numerical damping may help produce numerically stable solutions.

Quadrature specifies the spatial numerical integration scheme. There are two options: 1) Gauss quadrature; and 2) Trapezoidal quadrature. We note that in the current version, Gauss quadrature is implemented in reduced form to improve efficiency and avoid shear locking. In the trapezoidal quadrature, only one member (FE element) can be

defined in the following GEOMETRY section of the primary input file. Trapezoidal quadrature is appropriate when the number of “blade input stations” (described below) is significantly greater than the order of the LSFE.

Refine specifies a refinement parameter used in trapezoidal quadrature. An integer value greater than unity will split the space between two input stations into “Refine factor” of segments. The keyword “DEFAULT” may be used to set it to 1, i.e., no refinement is needed. This entry is not used in Gauss quadrature.

N_Fact specifies a parameter used in the modified Newton-Raphson scheme. If $N_Fact = 1$ a full Newton iteration scheme is used, i.e., the global tangent stiffness matrix is computed and factorized at each iteration; if $N_Fact > 1$ a modified Newton iteration scheme is used, i.e., the global stiffness matrix is computed and factorized every N_Fact iterations within each time step. The keyword “DEFAULT” sets $N_Fact = 5$.

DTBeam specifies the constant time increment of the time-integration in seconds. The keyword “DEFAULT” may be used to indicate that the module should employ the time increment prescribed by the driver code (FAST/stand-alone driver program).

NRMax specifies the maximum number of iterations per time step in the Newton-Raphson scheme. If convergence is not reached within this number of iterations, BeamDyn returns an error message and terminates the simulation. The keyword “DEFAULT” sets $NRMax = 10$.

Stop_Tol specifies a tolerance parameter used in convergence criteria of a nonlinear solution that is used for the termination of the iteration. The keyword “DEFAULT” sets $Stop_Tol = 1.0E - 05$. Please refer to Section 5.7 for more details.

3.3.2 Geometry Parameter

The blade geometry is defined by a curvilinear local blade reference axis. The blade reference axis locates the origin and orientation of each a local coordinate system where the cross-sectional 6x6 stiffness and mass matrices are defined in the BeamDyn blade input file. It should not really matter where in the cross section the 6x6 stiffness and mass matrices are defined relative to, as long as the reference axis is consistently defined and closely follows the natural geometry of the blade.

The blade beam model is composed of several *members* in contiguous series and each member is defined by at least three key points in BeamDyn. A cubic-spline-fit pre-processor implemented in BeamDyn automatically generates the member based on the key points and then interconnects the members into a blade. There is always a shared key point at adjacent members; therefore the total number of key points is related to number of members and key points in each member.

member_total specifies the total number of beam members used in the structure. With the LSFE discretization, a single member and a sufficiently high element order, **order_elem** below, may well be sufficient.

kp_total specifies the total number of key points used to define the beam members.

The following section contains **member_total** lines. Each line has two integers providing the member number (must be 1, 2, 3, etc., sequentially) and the number of key points in this member, respectively. It is noted that the number of key points in each member is not independent of the total number of key points and they should satisfy the following equality:

$$kp_total = \sum_{i=1}^{member_total} n_i - member_total + 1 \quad (3.5)$$

where n_i is the number of key points in the i^{th} member. Because cubic splines are implemented in BeamDyn, n_i must be greater than or equal to three. Figure 3 shows two cases for member and key-point definition.

The next section defines the key-point information, preceded by two header lines. Each key point is defined by three physical coordinates (**kp_xr**, **kp_yr**, **kp_zr**) in the IEC standard blade coordinate system (the blade reference coordinate system) along with a structural twist angle (**initial_twist**) in the unit of degrees. The structural twist

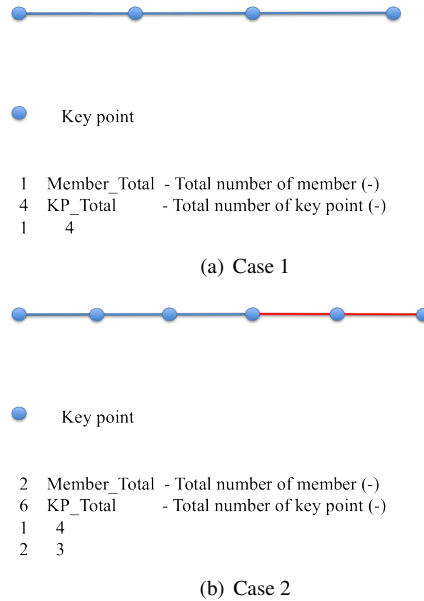


Figure 3. Member and key point definition. Case 1: one member defined by four key points; and Case 2: two members defined by six key points.

angle is also following the IEC standard which is defined as the twist about the negative Z_l axis. The key points are entered sequentially (from the root to tip) and there should be a total of *kp_total* lines for BeamDyn to read in the information, after two header lines. Please refer to Figure 4 for more details on the blade geometry definition.

3.3.3 Mesh Parameter

Order_Elem specifies the order of shape functions for each finite element. Each LSFE will have *Order_Elem*+1 nodes located at the GLL quadrature points. All LSFEs will have the same order. With the LSFE discretization, an increase in accuracy will, in general, be better achieved by increasing *Order_Elem* (i.e., *p*-refinement) rather than increasing the number of members (i.e., *h*-refinement). For Gauss quadrature, *Order_Elem* should be greater than one.

3.3.4 Material Parameter

BldFile is the file name of the blade input file. This name should be in quotations and can contain an absolute path or a relative path.

3.3.5 Pitch Actuator Parameter

In this release, the pitch actuator implemented in BeamDyn is not available. The *UsePitchAct* should be set to "FALSE" in this version, whereby the input blade-pitch angle prescribed by the driver code is used to orient the blade directly. *PitchJ*, *PitchK*, and *PitchC* specify the pitch actuator inertial, stiffness, and damping coefficient, respectively. In future releases, specifying *UsePitchAct* = TRUE will enable a second-order pitch actuator, whereby the pitch angular orientation, velocity, and acceleration are determined by the actuator based on the input blade-pitch angle prescribed by the driver code.

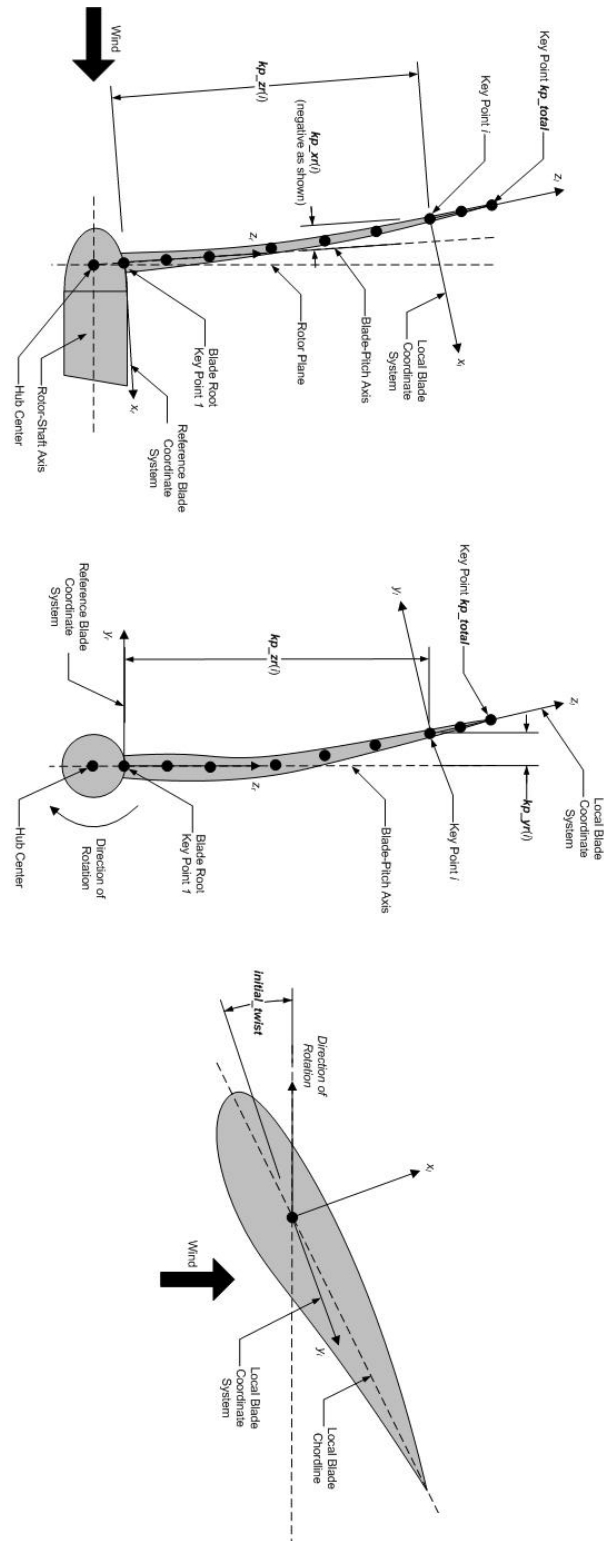


Figure 4. BeamDyn Blade Geometry - Top: Side View; Middle: Front View (Looking Downwind); Bottom: Cross Section View (Looking Toward the Tip, from the Root)

3.3.6 Outputs

In this section of the primary input file, the user sets flags and switches for the desired output behavior.

Specifying *SumPrint* = TRUE causes BeamDyn to generate a summary file with name *InputFile.sum*. See Section 4.2 for summary file details.

OutFmt parameter controls the formatting of the results within the stand-alone BeamDyn output file. It needs to be a valid Fortran format string, but BeamDyn currently does not check the validity. This input is unused when BeamDyn is used coupled to FAST.

NNodeOuts specifies the number of nodes where output can be written to a file. Currently, BeamDyn can output quantities at a maximum of nine nodes.

OutNd is a list *NNodeOuts* long of node numbers between 1 and *node_total* (total number of FE nodes), separated by any combination of commas, semicolons, spaces, and/or tabs. The nodal positions are given in the summary file, if output.

The *OutList* block contains a list of output parameters. Enter one or more lines containing quoted strings that in turn contain one or more output parameter names. Separate output parameter names by any combination of commas, semicolons, spaces, and/or tabs. If you prefix a parameter name with a minus sign, "-", underscore, "_", or the characters "m" or "M", BeamDyn will multiply the value for that channel by -1 before writing the data. The parameters are written in the order they are listed in the input file. BeamDyn allows you to use multiple lines so that you can break your list into meaningful groups and so the lines can be shorter. You may enter comments after the closing quote on any of the lines. Entering a line with the string "END" at the beginning of the line or at the beginning of a quoted string found at the beginning of the line will cause BeamDyn to quit scanning for more lines of channel names. Node-related quantities are generated for the requested nodes identified through the *OutNd* list above. If BeamDyn encounters an unknown/invalid channel name, it warns the users but will remove the suspect channel from the output file. Please refer to Appendix D for a complete list of possible output parameters and their names.

3.4 Blade Input File

The blade input file defines the cross-sectional properties at various stations along a blade and six damping coefficient for the whole blade. A sample BeamDyn blade input file is given in Appendix C. The blade input file begins with two lines of header information, which is for the user but is not used by the software.

3.4.1 Blade Parameters

Station_Total specifies the number cross-sectional stations along the blade axis used in the analysis.

Damp_Type specifies if structural damping is considered in the analysis. If *Damp_Type* = 0, then no damping is considered in the analysis and the six damping coefficient in the next section will be ignored. If *Damp_Type* = 1, structural damping will be included in the analysis.

3.4.2 Damping Coefficient

This section specifies six damping coefficients, μ_{ii} with $i \in [1, 6]$, for six DOFs (three translations and three rotations). Viscous damping is implemented in BeamDyn where the damping forces are proportional to the strain rate. These are stiffness-proportional damping coefficients, whereby the 6×6 damping matrix at each cross section is scaled from the 6×6 stiffness matrix by these diagonal entries of a 6×6 scaling matrix:

$$\underline{\mathcal{F}}^{Damp} = \underline{\underline{\mu}} \underline{\underline{S}} \underline{\underline{\dot{\epsilon}}} \quad (3.6)$$

where $\underline{\mathcal{F}}^{Damp}$ is the damping force, \underline{S} is the 6×6 cross-sectional stiffness matrix, $\underline{\dot{\epsilon}}$ is the strain rate, and $\underline{\mu}$ is the damping coefficient matrix defined as

$$\underline{\mu} = \begin{bmatrix} \mu_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \mu_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \mu_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu_{66} \end{bmatrix} \quad (3.7)$$

3.4.3 Distributed Properties

This section specifies the cross-sectional properties at each of the *Station_Total* stations. For each station, a non-dimensional parameter η specifies the station location along the local blade reference axis ranging from [0.0, 1.0]. The first and last station parameters must be set to 0.0 (for the blade root) and 1.0 (for the blade tip), respectively.

Following the station location parameter η , there are two 6×6 matrices providing the structural and inertial properties for this cross-section. First is the stiffness matrix and then the mass matrix. We note that these matrices are defined in a local coordinate system along the blade axis with Z_l directing toward the unit tangent vector of the blade reference axis. For a cross-section without coupling effects, for example, the stiffness matrix is given as follows:

$$\begin{bmatrix} K_{ShrFlp} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{ShrEdg} & 0 & 0 & 0 & 0 \\ 0 & 0 & EA & 0 & 0 & 0 \\ 0 & 0 & 0 & EI_{Edg} & 0 & 0 \\ 0 & 0 & 0 & 0 & EI_{Flp} & 0 \\ 0 & 0 & 0 & 0 & 0 & GJ \end{bmatrix} \quad (3.8)$$

where K_{ShrEdg} and K_{ShrFlp} are the edge and flap shear stiffnesses, respectively; EA is the extension stiffness; EI_{Edg} and EI_{Flp} are the edge and flap stiffnesses, respectively; and GJ is the torsional stiffness. It is pointed out that for a generic cross-section, the sectional property matrices can be derived from a sectional analysis tool, e.g. VABS, BECAS, or NuMAD/BPE.

A generalized sectional mass matrix is given by:

$$\begin{bmatrix} m & 0 & 0 & 0 & 0 & -mY_{cm} \\ 0 & m & 0 & 0 & 0 & mX_{cm} \\ 0 & 0 & m & mY_{cm} & -mX_{cm} & 0 \\ 0 & 0 & mY_{cm} & i_{Edg} & -i_{cp} & 0 \\ 0 & 0 & -mX_{cm} & -i_{cp} & i_{Flp} & 0 \\ -mY_{cm} & mX_{cm} & 0 & 0 & 0 & i_{plr} \end{bmatrix} \quad (3.9)$$

where m is the mass density per unit span; X_{cm} and Y_{cm} are the local coordinates of the sectional center of mass, respectively; i_{Edg} and i_{Flp} are the edge and flap mass moments of inertia per unit span, respectively; i_{plr} is the polar moment of inertia per unit span; and i_{cp} is the sectional cross-product of inertia per unit span. We note that for beam structure, the i_{plr} is given as (although this relationship is not checked by BeamDyn)

$$i_{plr} = i_{Edg} + i_{Flp} \quad (3.10)$$

4 Output Files

BeamDyn produces three types of output files, depending on the options selected: an echo file, a summary file, and a time-series results file. The following sections detail the purpose and contents of these files.

4.1 Echo File

If the user sets the *Echo* flag to TRUE in the BeamDyn primary input file, the contents of this file will be echoed to a file with the naming convention *InputFile.ech*. The echo file is helpful for debugging the input files. The contents of an echo file will be truncated if BeamDyn encounters an error while parsing an input file. The error usually corresponds to the line after the last successfully echoed line.

4.2 Summary File

In stand-alone mode, BeamDyn generates a summary file with the naming convention, *InputFile.sum* if the *SumPrint* parameter is set to TRUE. When coupled to FAST, the summary file is named *InputFile.BD.sum*. This file summarizes key information about the simulation, including:

- Blade mass.
- Blade length.
- Blade center of mass.
- Initial global position vector in BD coordinate system.
- Initial global rotation tensor in BD coordinate system.
- Analysis type.
- Numerical damping coefficients.
- Time step size.
- Maximum number of iterations in the Newton-Raphson solution.
- Convergence parameter in the stopping criterion.
- Factorization frequency in the Newton-Raphson solution.
- Numerical integration (quadrature) method.
- FE mesh refinement factor used in trapezoidal quadrature.
- Number of elements.
- Number of FE nodes.
- Initial position vectors of FE nodes in BD coordinate system.
- Initial rotation vectors of FE nodes in BD coordinate system.
- Quadrature point position vectors in BD coordinate system. For Gauss quadrature, the physical coordinates of Gauss points are listed. For trapezoidal quadrature, the physical coordinates of the quadrature points are listed.
- Sectional stiffness and mass matrices at quadrature points in local blade reference coordinate system. These are the data being used in calculations at quadrature points and they can be different from the section in Blade Input File since BeamDyn linearly interpolates the sectional properties into quadrature points based on need.

- Initial displacement vectors of FE nodes in BD coordinate system.
- Initial rotational displacement vectors of FE nodes in BD coordinate system.
- Initial translational velocity vectors of FE nodes in BD coordinate system.
- Initial angular velocity vectors of FE nodes in BD coordinate system.
- Requested output information.

All of these quantities are output in this file in the BD coordinate system, the one being used internally in BeamDyn calculations. The initial blade reference coordinate system, denoted by a subscript $r0$ that follows the IEC standard, is related to the internal BD coordinate system by Table 1 in Chapter 5.

4.3 Results File

The BeamDyn time-series results are written to a text-based file with the naming convention *DriverInputFile.out* where *DriverInputFile* is the name of the driver input file when BeamDyn is run in the stand-alone mode. If BeamDyn is coupled to FAST, then FAST will generate a master results file that includes the BeamDyn results. The results in *DriverInputFile.out* are in table format, where each column is a data channel (the first column always being the simulation time), and each row corresponds to a simulation time step. The data channel are specified in the OUTPUT section of the primary input file. The column format of the BeamDyn-generated file is specified using the *OutFmt* parameters of the primary input file.

5 BeamDyn Theory

This section focuses on the theory behind the BeamDyn module. The theoretical foundation, numerical tools, and some special handling in the implementation will be introduced. References will be provided in each section detailing the theories and numerical tools.

In this chapter, matrix notation is used to denote vectorial or vectorial-like quantities. For example, an underline denotes a vector \underline{u} , an over bar denotes unit vector \bar{n} , and a double underline denotes a tensor $\underline{\underline{A}}$. Note that sometimes the underlines only denote the dimension of the corresponding matrix.

5.1 Coordinate Systems

Figures 4 (in Chapter 3) and 5 show the coordinate system used in BeamDyn.

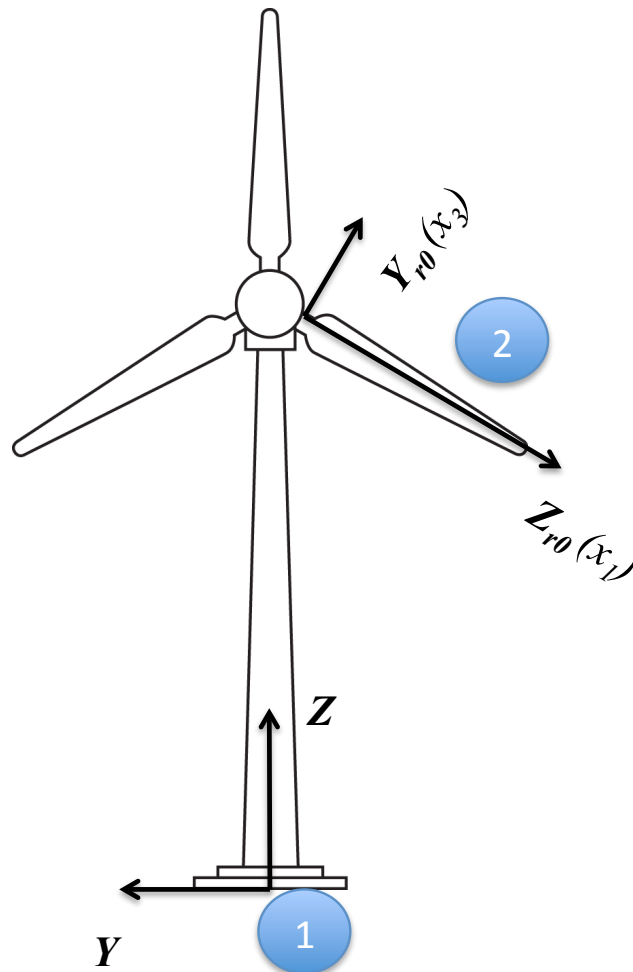


Figure 5. Global, blade reference, and internal coordinate systems in BeamDyn. Illustration by AI Hicks, NREL

Table 1. Transformation between blade coordinate system and BD coordinate system.

Blade Frame	X_{r0}	Y_{r0}	Z_{r0}
BD Frame	x_2	x_3	x_1

5.1.1 Global Coordinate System

The global coordinate system is denoted as X , Y , and Z in Figure 5. This is an inertial frame and in FAST its origin is usually placed at the bottom of the tower as shown.

5.1.2 BD Coordinate System

The BD coordinate system is denoted as x_1 , x_2 , and x_3 respectively in Figure 5. This is an inertial frame used internally in BeamDyn (i.e., doesn't rotate with the rotor) and its origin is placed at the initial position of the blade root point.

5.1.3 Blade Reference Coordinate System

The blade reference coordinate system is denoted as X_{rt} , Y_{rt} , and Z_{rt} in Figure 5 at initialization ($t = 0$). The blade reference coordinate system is a floating frame that attaches at the blade root and is rotating with the blade. Its origin is at the blade root and the directions of axes following the IEC standard, i.e., Z_r is pointing along the blade axis from root to tip; Y_r pointing nominally towards the trailing edge of the blade and parallel with the chord line at the zero-twist blade station; and X_r is orthogonal with the Y_r and Z_r axes, such that they form a right-handed coordinate system (pointing nominally downwind). We note that the initial blade reference coordinate system, denoted by subscript $r0$, coincides with the BD coordinate system, which is used internally in BeamDyn and introduced in the previous section. The axis convention relations between the initial blade reference coordinate system and the BD coordinate system can be found in Table 1.

5.1.4 Local blade coordinate system

The local blade coordinate system is used for some input and output quantities, for example, the cross-sectional mass and stiffness matrices and the sectional force and moment resultants. This coordinate system is different from the blade reference coordinate system in that its Z_l axis is always tangent to the blade axis as the blade deflects. Note that a subscript l denotes the local blade coordinate system.

5.2 Geometrically Exact Beam Theory

The theoretical foundation of BeamDyn is the geometrically exact beam theory. This theory features the capability of beams that are initially curved and twisted and subjected to large displacement and rotations. Along with a proper two-dimensional (2D) cross-sectional analysis, the coupling effects between all six DOFs, including extension, bending, shear, and torsion, can be captured by GEBT as well. The term, "geometrically exact" refer to the fact that there is no approximation made on the geometries, including both initial and deformed geometries, in formulating the equations Hodges (2006).

The governing equations of motion for geometrically exact beam theory can be written as Bauchau (2010)

$$\dot{\underline{h}} - \underline{F}' = \underline{f} \quad (5.1)$$

$$\dot{\underline{g}} + \dot{\underline{u}}\underline{h} - \underline{M}' + (\underline{x}'_0 + \underline{u}')^T \underline{F} = \underline{m} \quad (5.2)$$

where \underline{h} and \underline{g} are the linear and angular momenta resolved in the inertial coordinate system, respectively; \underline{F} and \underline{M} are the beam's sectional force and moment resultants, respectively; \underline{u} is the one-dimensional (1D) displacement of a point on the reference line; \underline{x}_0 is the position vector of a point along the beam's reference line; and \underline{f} and \underline{m} are the distributed force and moment applied to the beam structure. The notation $(\bullet)'$ indicates a derivative with respect to beam axis x_1 and $(\dot{\bullet})$ indicates a derivative with respect to time. The tilde operator $(\tilde{\bullet})$ defines a skew-symmetric tensor corresponding to the given vector. In the literature, it is also termed as "cross-product matrix". For example,

$$\tilde{\underline{n}} = \begin{bmatrix} 0 & -n_3 & n_2 \\ n_3 & 0 & -n_1 \\ -n_2 & n_1 & 0 \end{bmatrix}$$

The constitutive equations relate the velocities to the momenta and the 1D strain measures to the sectional resultants as

$$\begin{Bmatrix} \underline{h} \\ \underline{g} \end{Bmatrix} = \underline{\mathcal{M}} \begin{Bmatrix} \dot{\underline{u}} \\ \underline{\omega} \end{Bmatrix} \quad (5.3)$$

$$\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\mathcal{C}} \begin{Bmatrix} \underline{\varepsilon} \\ \underline{\kappa} \end{Bmatrix} \quad (5.4)$$

where $\underline{\mathcal{M}}$ and $\underline{\mathcal{C}}$ are the 6×6 sectional mass and stiffness matrices, respectively (note that they are not really tensors); $\underline{\varepsilon}$ and $\underline{\kappa}$ are the 1D strains and curvatures, respectively; and, $\underline{\omega}$ is the angular velocity vector that is defined by the rotation tensor \underline{R} as $\underline{\omega} = axial(\dot{\underline{R}} \underline{R}^T)$. The axial vector \underline{a} associated with a second-order tensor \underline{A} is denoted $\underline{a} = axial(\underline{A})$ and its components are defined as

$$\underline{a} = axial(\underline{A}) = \begin{Bmatrix} a_1 \\ a_2 \\ a_3 \end{Bmatrix} = \frac{1}{2} \begin{Bmatrix} A_{32} - A_{23} \\ A_{13} - A_{31} \\ A_{21} - A_{12} \end{Bmatrix} \quad (5.5)$$

The 1D strain measures are defined as

$$\begin{Bmatrix} \underline{\varepsilon} \\ \underline{\kappa} \end{Bmatrix} = \begin{Bmatrix} \underline{x}'_0 + \underline{u}' - (\underline{R} \underline{R}_0) \bar{\underline{i}}_1 \\ \underline{k} \end{Bmatrix} \quad (5.6)$$

where $\underline{k} = axial[(\underline{R} \underline{R}_0)'(\underline{R} \underline{R}_0)^T]$ is the sectional curvature vector resolved in the inertial basis; \underline{R}_0 is the initial rotation tensor; and $\bar{\underline{i}}_1$ is the unit vector along x_1 direction in the inertial basis. These three sets of equations, including equations of motion Eq. (5.1) and (5.2), constitutive equations Eq. (5.3) and (5.4), and kinematical equations Eq. (5.6), provide a full mathematical description of the beam elasticity problems.

5.3 Numerical Implementation with Legendre Spectral Finite Elements

For a displacement-based finite element implementation, there are six degree-of-freedom at each node: three displacement components and three rotation components. Here we use \underline{q} to denote the elemental displacement array as $\underline{q} = [\underline{u}^T \ \underline{c}^T]$ where \underline{u} is the displacement and \underline{c} is the rotation-parameter vector. The acceleration array can thus be defined as $\underline{a} = [\dot{\underline{u}}^T \ \dot{\underline{\omega}}^T]$. For nonlinear finite-element analysis, the discretized and incremental forms of displacement, velocity, and acceleration are written as

$$\underline{q}(x_1) = \underline{N} \hat{\underline{q}} \quad \Delta \underline{q}^T = [\Delta \underline{u}^T \ \Delta \underline{c}^T] \quad (5.7)$$

$$\underline{v}(x_1) = \underline{N} \hat{\underline{v}} \quad \Delta \underline{v}^T = [\Delta \dot{\underline{u}}^T \ \Delta \dot{\underline{\omega}}^T] \quad (5.8)$$

$$\underline{a}(x_1) = \underline{N} \hat{\underline{a}} \quad \Delta \underline{a}^T = [\Delta \ddot{\underline{u}}^T \ \Delta \ddot{\underline{\omega}}^T] \quad (5.9)$$

where \underline{N} is the shape function matrix and $(\hat{\bullet})$ denotes a column matrix of nodal values.

The displacement fields in an element are approximated as

$$\underline{u}(\xi) = h^k(\xi)\hat{\underline{u}}^k \quad (5.10)$$

$$\underline{u}'(\xi) = h^{k'}(\xi)\hat{\underline{u}}^k \quad (5.11)$$

where $h^k(\xi)$, the component of shape function matrix \underline{N} , is the p^{th} -order polynomial Lagrangian-interpolant shape function of node k , $k = \{1, 2, \dots, p+1\}$, $\hat{\underline{u}}^k$ is the k^{th} nodal value, and $\xi \in [-1, 1]$ is the element natural coordinate. However, as discussed in Bauchau et al. (2008), the 3D rotation field cannot simply be interpolated as the displacement field in the form of

$$\underline{c}(\xi) = h^k(\xi)\hat{\underline{c}}^k \quad (5.12)$$

$$\underline{c}'(\xi) = h^{k'}(\xi)\hat{\underline{c}}^k \quad (5.13)$$

where \underline{c} is the rotation field in an element and $\hat{\underline{c}}^k$ is the nodal value at the k^{th} node, for three reasons: 1) rotations do not form a linear space so that they must be ‘‘composed’’ rather than added; 2) a rescaling operation is needed to eliminate the singularity existing in the vectorial rotation parameters; 3) the rotation field lacks objectivity, which, as defined by Jelenic and Crisfield (1999), refers to the invariance of strain measures computed through interpolation to the addition of a rigid-body motion. Therefore, we adopt the more robust interpolation approach proposed by Jelenic and Crisfield (1999) to deal with the finite rotations. Our approach is described as follows

Step 1: Compute the nodal relative rotations, $\hat{\underline{r}}^k$, by removing the reference rotation, $\hat{\underline{c}}^1$, from the finite rotation at each node, $\hat{\underline{r}}^k = (\hat{\underline{c}}^{1-}) \oplus \hat{\underline{c}}^k$. It is noted that the minus sign on $\hat{\underline{c}}^1$ denotes that the relative rotation is calculated by removing the reference rotation from each node. The composition in that equation is an equivalent of $\underline{R}(\hat{\underline{r}}^k) = \underline{R}^T(\hat{\underline{c}}^1) \underline{R}(\hat{\underline{c}}^k)$.

Step 2: Interpolate the relative-rotation field: $\underline{r}(\xi) = h^k(\xi)\hat{\underline{r}}^k$ and $\underline{r}'(\xi) = h^{k'}(\xi)\hat{\underline{r}}^k$. Find the curvature field $\underline{\kappa}(\xi) = \underline{R}(\hat{\underline{c}}^1)\underline{H}(\underline{r})\underline{r}'$, where \underline{H} is the tangent tensor that relates the curvature vector $\underline{\kappa}$ and rotation vector \underline{c} as

$$\underline{\kappa} = \underline{H} \underline{c}' \quad (5.14)$$

Step 3: Restore the rigid-body rotation removed in Step 1: $\underline{c}(\xi) = \hat{\underline{c}}^1 \oplus \underline{r}(\xi)$.

Note that the relative-rotation field can be computed with respect to any of the nodes of the element; we choose node 1 as the reference node for convenience. In the LSFE approach, shape functions (i.e., those composing \underline{N}) are p^{th} -order Lagrangian interpolants, where nodes are located at the $p+1$ Gauss-Lobatto-Legendre (GLL) points in the $[-1, 1]$ element natural-coordinate domain. Figure 6 shows representative LSFE basis functions for fourth- and eighth-order elements. Note that nodes are clustered near element endpoints. More details on the LSFE and its applications can be found in References Patera (1984); Ronquist and Patera (1987); Sprague and Geers (2003, 2004).

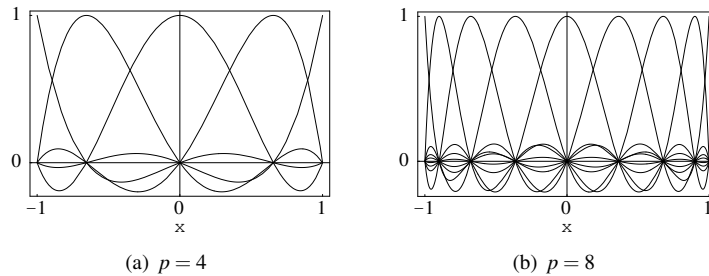


Figure 6. Representative $p+1$ Lagrangian-interpolant shape functions in the element natural coordinates for (a) fourth- and (b) eighth-order LSFEs, where nodes are located at the Gauss-Lobatto-Legendre points.

5.4 Wiener-Milenković Rotation Parameter

In BeamDyn, the 3D rotations are represented as Wiener-Milenković parameters defined in the following equation:

$$\underline{c} = 4 \tan\left(\frac{\phi}{4}\right) \bar{n} \quad (5.15)$$

where ϕ is the rotation angle and \bar{n} is the unit vector of the rotation axis. It can be observed that the valid range for this parameter is $|\phi| < 2\pi$. The singularities existing at integer multiples of $\pm 2\pi$ can be removed by a rescaling operation at π as:

$$\underline{r} = \begin{cases} 4(q_0 \underline{p} + p_0 \underline{q} + \bar{p} \underline{q}) / (\Delta_1 + \Delta_2), & \text{if } \Delta_2 \geq 0 \\ -4(q_0 \underline{p} + p_0 \underline{q} + \bar{p} \underline{q}) / (\Delta_1 - \Delta_2), & \text{if } \Delta_2 < 0 \end{cases} \quad (5.16)$$

where \underline{p} , \underline{q} , and \underline{r} are the vectorial parameterization of three finite rotations such that $\underline{R}(\underline{r}) = \underline{R}(\underline{p})\underline{R}(\underline{q})$, $p_0 = 2 - \underline{p}^T \underline{p} / 8$, $q_0 = 2 - \underline{q}^T \underline{q} / 8$, $\Delta_1 = (4 - p_0)(4 - q_0)$, and $\Delta_2 = p_0 q_0 - \underline{p}^T \underline{q}$. It is noted that the rescaling operation could cause a discontinuity of the interpolated rotation field; therefore a more robust interpolation algorithm has been introduced in Section 5.3 where the rescaling-independent relative-rotation field is interpolated.

The rotation tensor expressed in terms of Wiener-Milenković parameters is

$$\underline{R}(\underline{c}) = \frac{1}{(4 - c_0)^2} \begin{bmatrix} c_0^2 + c_1^2 - c_2^2 - c_3^2 & 2(c_1 c_2 - c_0 c_3) & 2(c_1 c_3 + c_0 c_2) \\ 2(c_1 c_2 + c_0 c_3) & c_0^2 - c_1^2 + c_2^2 - c_3^2 & 2(c_2 c_3 - c_0 c_1) \\ 2(c_1 c_3 - c_0 c_2) & 2(c_2 c_3 + c_0 c_1) & c_0^2 - c_1^2 - c_2^2 + c_3^2 \end{bmatrix} \quad (5.17)$$

where $\underline{c} = [c_1 \ c_2 \ c_3]^T$ is the Wiener-Milenković parameter and $c_0 = 2 - \frac{1}{8} \underline{c}^T \underline{c}$. The relation between rotation tensor and direction cosine matrix (DCM) is

$$\underline{R} = (\underline{DCM})^T \quad (5.18)$$

Interested users are referred to Bauchau et al. (2008) and Wang et al. (2013) for more details on the rotation parameter and its implementation with GEBT.

5.5 Linearization Process

The nonlinear governing equations introduced in the previous section are solved by Newton-Raphson method, where a linearization process is needed. The linearization of each term in the governing equations are presented in this section.

According to Bauchau (2010), the linearized governing equations in Eq. (5.1) and (5.2) are in the form of

$$\underline{\hat{M}} \Delta \hat{a} + \underline{\hat{G}} \Delta \hat{v} + \underline{\hat{K}} \Delta \hat{q} = \underline{\hat{F}}^{ext} - \underline{\hat{F}} \quad (5.19)$$

where the $\underline{\hat{M}}$, $\underline{\hat{G}}$, and $\underline{\hat{K}}$ are the elemental mass, gyroscopic, and stiffness matrices, respectively; $\underline{\hat{F}}$ and $\underline{\hat{F}}^{ext}$ are the elemental forces and externally applied loads, respectively. They are defined for an element of length l along x_1 as follows

$$\underline{\hat{M}} = \int_0^l \underline{N}^T \underline{\mathcal{M}} \underline{N} dx_1 \quad (5.20)$$

$$\underline{\hat{G}} = \int_0^l \underline{N}^T \underline{\mathcal{G}}^I \underline{N} dx_1 \quad (5.21)$$

$$\underline{\hat{K}} = \int_0^l \left[\underline{N}^T (\underline{\mathcal{K}}^I + \underline{\mathcal{Q}}) \underline{N} + \underline{N}^T \underline{\mathcal{P}} \underline{N}' + \underline{N}'^T \underline{\mathcal{C}} \underline{N}' + \underline{N}'^T \underline{\mathcal{O}} \underline{N} \right] dx_1 \quad (5.22)$$

$$\underline{\hat{F}} = \int_0^l (\underline{N}^T \underline{\mathcal{F}}^I + \underline{N}^T \underline{\mathcal{F}}^D + \underline{N}'^T \underline{\mathcal{F}}^C) dx_1 \quad (5.23)$$

$$\underline{\hat{F}}^{ext} = \int_0^l \underline{N}^T \underline{\mathcal{F}}^{ext} dx_1 \quad (5.24)$$

where $\underline{\mathcal{F}}^{ext}$ is the applied load vector. The new matrix notations in Eqs. (5.20) to (5.24) are briefly introduced here. $\underline{\mathcal{F}}^C$ and $\underline{\mathcal{F}}^D$ are elastic forces obtained from Eq. (5.1) and (5.2) as

$$\underline{\mathcal{F}}^C = \begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} = \underline{\mathcal{C}} \begin{Bmatrix} \underline{\varepsilon} \\ \underline{\kappa} \end{Bmatrix} \quad (5.25)$$

$$\underline{\mathcal{F}}^D = \begin{bmatrix} \underline{0} & \underline{0} \\ (\underline{x}'_0 + \underline{u}')^T & \underline{0} \end{bmatrix} \underline{\mathcal{F}}^C \equiv \underline{\Upsilon} \underline{\mathcal{F}}^C \quad (5.26)$$

where $\underline{0}$ denotes a 3×3 null matrix. The $\underline{\mathcal{G}}^I$, $\underline{\mathcal{K}}^I$, $\underline{\mathcal{C}}$, $\underline{\mathcal{D}}$, $\underline{\mathcal{Q}}$, and $\underline{\mathcal{F}}^I$ in Eq. (5.21), Eq. (5.22), and Eq. (5.23) are defined as

$$\underline{\mathcal{G}}^I = \begin{bmatrix} \underline{0} & (\underline{\tilde{\omega}m\eta})^T + \underline{\tilde{\omega}m\eta}^T \\ \underline{0} & \underline{\tilde{\omega}\rho} - \underline{\rho\tilde{\omega}} \end{bmatrix} \quad (5.27)$$

$$\underline{\mathcal{K}}^I = \begin{bmatrix} \underline{0} & \underline{\dot{\omega}m\eta}^T + \underline{\tilde{\omega}\tilde{\omega}m\eta}^T \\ \underline{0} & \underline{\ddot{m}\eta} + \underline{\rho\dot{\omega}} - \underline{\rho\tilde{\omega}} + \underline{\tilde{\omega}\rho\tilde{\omega}} - \underline{\tilde{\omega}\rho\tilde{\omega}} \end{bmatrix} \quad (5.28)$$

$$\underline{\mathcal{C}} = \begin{bmatrix} \underline{0} & \underline{C}_{11}\underline{\tilde{E}}_1 - \underline{\tilde{F}} \\ \underline{0} & \underline{C}_{21}\underline{\tilde{E}}_1 - \underline{\tilde{M}} \end{bmatrix} \quad (5.29)$$

$$\underline{\mathcal{D}} = \begin{bmatrix} \underline{0} & \underline{0} \\ \underline{\tilde{F}} + (\underline{C}_{11}\underline{\tilde{E}}_1)^T & (\underline{C}_{21}\underline{\tilde{E}}_1)^T \end{bmatrix} \quad (5.30)$$

$$\underline{\mathcal{Q}} = \underline{\Upsilon} \underline{\mathcal{C}} \quad (5.31)$$

$$\underline{\mathcal{F}}^I = \begin{Bmatrix} \underline{m\dot{u}} + (\underline{\dot{\omega}} + \underline{\tilde{\omega}\tilde{\omega}})m\eta \\ \underline{m\tilde{\eta}\ddot{u}} + \underline{\rho\dot{\omega}} + \underline{\tilde{\omega}\rho\tilde{\omega}} \end{Bmatrix} \quad (5.32)$$

where m is the mass density per unit length, η is the location of the sectional center of mass, ρ is the moment of inertia tensor, and the following notations were introduced to simplify the above expressions

$$\underline{E}_1 = \underline{x}'_0 + \underline{u}' \quad (5.33)$$

$$\underline{\mathcal{C}} = \begin{bmatrix} \underline{C}_{11} & \underline{C}_{12} \\ \underline{C}_{21} & \underline{C}_{22} \end{bmatrix} \quad (5.34)$$

5.6 Damping Forces and Linearization

A viscous damping model has been implemented into BeamDyn to account for the structural damping effect. The damping force is defined as

$$\underline{f}_d = \underline{\mu} \underline{\mathcal{C}} \begin{Bmatrix} \underline{\dot{\varepsilon}} \\ \underline{\dot{\kappa}} \end{Bmatrix} \quad (5.35)$$

where $\underline{\mu}$ is a user-defined damping-coefficient diagonal matrix. The damping force can be recast in two separate parts, like $\underline{\mathcal{F}}^C$ and $\underline{\mathcal{F}}^D$ in the elastic force, as

$$\underline{\mathcal{F}}_d^C = \begin{Bmatrix} \underline{F}_d \\ \underline{M}_d \end{Bmatrix} \quad (5.36)$$

$$\underline{\mathcal{F}}_d^D = \begin{Bmatrix} \underline{0} \\ (\underline{x}'_0 + \underline{u}')^T \underline{F}_d \end{Bmatrix} \quad (5.37)$$

The linearization of the structural damping forces are as follows:

$$\Delta \underline{\mathcal{F}}_d^C = \underline{\mathcal{L}}_d \begin{Bmatrix} \Delta \underline{u}' \\ \Delta \underline{c}' \end{Bmatrix} + \underline{\mathcal{O}}_d \begin{Bmatrix} \Delta \underline{u} \\ \Delta \underline{c} \end{Bmatrix} + \underline{\mathcal{G}}_d \begin{Bmatrix} \Delta \underline{\dot{u}} \\ \Delta \underline{\omega} \end{Bmatrix} + \underline{\mu} \underline{C} \begin{Bmatrix} \Delta \underline{\dot{u}}' \\ \Delta \underline{\omega}' \end{Bmatrix} \quad (5.38)$$

$$\Delta \underline{\mathcal{F}}_d^D = \underline{\mathcal{P}}_d \begin{Bmatrix} \Delta \underline{u}' \\ \Delta \underline{c}' \end{Bmatrix} + \underline{\mathcal{Q}}_d \begin{Bmatrix} \Delta \underline{u} \\ \Delta \underline{c} \end{Bmatrix} + \underline{\mathcal{X}}_d \begin{Bmatrix} \Delta \underline{\dot{u}} \\ \Delta \underline{\omega} \end{Bmatrix} + \underline{\mathcal{Y}}_d \begin{Bmatrix} \Delta \underline{\dot{u}}' \\ \Delta \underline{\omega}' \end{Bmatrix} \quad (5.39)$$

where the newly introduced matrices are defined as

$$\underline{\mathcal{L}}_d = \underline{\mu} \underline{\mathcal{C}} \begin{bmatrix} \underline{\tilde{\omega}}^T & \underline{0} \\ \underline{0} & \underline{\tilde{\omega}}^T \end{bmatrix} \quad (5.40)$$

$$\underline{\mathcal{O}}_d = \begin{bmatrix} \underline{0} & \underline{\mu} \underline{C}_{11} (\underline{\dot{u}}' - \underline{\tilde{\omega}} \underline{\tilde{E}}_1) - \underline{\tilde{F}}_d \\ \underline{0} & \underline{\mu} \underline{C}_{21} (\underline{\dot{u}}' - \underline{\tilde{\omega}} \underline{\tilde{E}}_1) - \underline{\tilde{M}}_d \end{bmatrix} \quad (5.41)$$

$$\underline{\mathcal{G}}_d = \begin{bmatrix} \underline{0} & \underline{C}_{11}^T \underline{\mu}^T \underline{\tilde{E}}_1 \\ \underline{0} & \underline{C}_{12}^T \underline{\mu}^T \underline{\tilde{E}}_1 \end{bmatrix} \quad (5.42)$$

$$\underline{\mathcal{P}}_d = \begin{bmatrix} \underline{0} & \underline{0} \\ \underline{\tilde{F}}_d + \underline{\tilde{E}}_1^T \underline{\mu} \underline{C}_{11} \underline{\tilde{\omega}}^T & \underline{\tilde{E}}_1^T \underline{\mu} \underline{C}_{12} \underline{\tilde{\omega}}^T \end{bmatrix} \quad (5.43)$$

$$\underline{\mathcal{Q}}_d = \begin{bmatrix} \underline{0} & \underline{0} \\ \underline{0} & \underline{\tilde{E}}_1^T \underline{O}_{12} \end{bmatrix} \quad (5.44)$$

$$\underline{\mathcal{X}}_d = \begin{bmatrix} \underline{0} & \underline{0} \\ \underline{0} & \underline{\tilde{E}}_1^T \underline{G}_{12} \end{bmatrix} \quad (5.45)$$

$$\underline{\mathcal{Y}}_d = \begin{bmatrix} \underline{0} & \underline{0} \\ \underline{\tilde{E}}_1^T \underline{\mu} \underline{C}_{11} & \underline{\tilde{E}}_1^T \underline{\mu} \underline{C}_{12} \end{bmatrix} \quad (5.46)$$

$$(5.47)$$

where \underline{O}_{12} and \underline{G}_{12} are the 3×3 sub matrices of $\underline{\mathcal{O}}$ and $\underline{\mathcal{G}}$ as \underline{C}_{12} in Eq. (5.34).

5.7 Convergence Criterion and Generalized- α Time Integrator

The system of nonlinear equations in Eqs. (5.1) and (5.2) are solved using the Newton-Raphson method with the linearized form in Eq. (5.19). In the present implementation, an energy-like stopping criterion has been chosen, which is calculated as

$$\|\Delta \mathbf{U}^{(i)T} \left({}^{t+\Delta t} \mathbf{R} - {}^{t+\Delta t} \mathbf{F}^{(i-1)} \right)\| \leq \|\epsilon_E \left(\Delta \mathbf{U}^{(1)T} \left({}^{t+\Delta t} \mathbf{R} - {}^t \mathbf{F} \right) \right)\| \quad (5.48)$$

where $\|\cdot\|$ denotes the Euclidean norm, $\Delta \mathbf{U}$ is the incremental displacement vector, \mathbf{R} is the vector of externally applied nodal point loads, \mathbf{F} is the vector of nodal point forces corresponding to the internal element stresses, and ϵ_E is the user-defined energy tolerance. The superscript on the left side of a variable denotes the time-step number (in a dynamic analysis), while the one on the right side denotes the Newton-Raphson iteration number. As pointed out by Bathe and Cimento (1980), this criterion provides a measure of when both the displacements and the forces are near their equilibrium values.

Time integration is performed using the generalized- α scheme in BeamDyn, which is an unconditionally stable (for linear systems), second-order accurate algorithm. The scheme allows for users to choose integration parameters that introduce high-frequency numerical dissipation. More details regarding the generalized- α method can be found in Bauchau (2010); Chung and Hulbert (1993).

5.8 Calculation of Reaction Loads

Since the root motion of the wind turbine blade, including displacements and rotations, translational and angular velocities, and translational and angular accelerates, are prescribed as inputs to BeamDyn either by the driver (in stand-alone mode) or by FAST glue code (in FAST-coupled mode), the reaction loads at the root are needed to satisfy equality of the governing equations. The reaction loads at the root are also the loads passing from blade to hub in a full turbine analysis.

The governing equations in Eq. 5.1 and 5.2 can be recast in a compact form

$$\underline{\mathcal{F}}^I - \underline{\mathcal{F}}^{Ct} + \underline{\mathcal{F}}^D = \underline{\mathcal{F}}^{ext} \quad (5.49)$$

with all the vectors defined in Section 5.5. At the blade root, the governing equation is revised as

$$\underline{\mathcal{F}}^I - \underline{\mathcal{F}}^{Ct} + \underline{\mathcal{F}}^D = \underline{\mathcal{F}}^{ext} + \underline{\mathcal{F}}^R \quad (5.50)$$

where $\underline{\mathcal{F}}^R = [\underline{F}^R \quad \underline{M}^R]^T$ is the reaction force vector and it can be solved from Eq. 5.50 given that the motion fields are known at this point.

5.9 Calculation of Blade Loads

BeamDyn can also calculate the blade loads at each finite element node along the blade axis. The governing equation in Eq. 5.49 are recast as

$$\underline{\mathcal{F}}^A + \underline{\mathcal{F}}^V - \underline{\mathcal{F}}^{Ct} + \underline{\mathcal{F}}^D = \underline{\mathcal{F}}^{ext} \quad (5.51)$$

where the inertial force vector $\underline{\mathcal{F}}^I$ is split into $\underline{\mathcal{F}}^A$ and $\underline{\mathcal{F}}^V$:

$$\underline{\mathcal{F}}^A = \begin{Bmatrix} m\ddot{u} + \dot{\omega}m\eta \\ m\ddot{\eta} + \underline{\rho}\dot{\omega} \end{Bmatrix} \quad (5.52)$$

$$\underline{\mathcal{F}}^V = \begin{Bmatrix} \tilde{\omega}\tilde{\omega}m\eta \\ \tilde{\omega}\underline{\rho}\omega \end{Bmatrix} \quad (5.53)$$

$$(5.54)$$

The blade loads are thus defined as

$$\underline{\mathcal{F}}^{BF} \equiv \underline{\mathcal{F}}^V - \underline{\mathcal{F}}^{Ct} + \underline{\mathcal{F}}^D \quad (5.55)$$

We note that if structural damping is considered in the analysis, the $\underline{\mathcal{F}}_d^C$ and $\underline{\mathcal{F}}_d^D$ are incorporated into the internal elastic forces, $\underline{\mathcal{F}}^C$ and $\underline{\mathcal{F}}^D$, for calculation.

6 Future Work

The following list contains future work on BeamDyn software:

- Eliminating numerical problems in single precision.
- Implementing eigenvalue analysis.
- Improving input options for stand-alone version to make it more user-friendly.
- Implementing GEBT based on modal method for computational efficiency.
- Adding more options for blade cross-sectional properties inputs. For example, for general isotropic beams, engineering parameters including sectional offsets, material properties, etc will be used to generate the 6×6 matrices needed by BeamDyn.
- Writing a general guidance on modeling composite beam structures using BeamDyn, , for example, how to select a time step, how to select the model discretization, how to define the blade reference axis, where to get 6x6 mass/stiffness matrices, etc.
- Extending applications in FAST to other slender structures in the wind turbine system, for example, tower, mooring lines, and shaft.
- Developing a simplified form of GEBT with only rotational DOFs (bending, torsion) for computational efficiency.

A BeamDyn Driver Input File

```

----- BEAMDYN V1.00.00 Driver INPUT FILE -----
Dynamic analysis of rotating NREL 5MW blade under gravity force
-----
SIMULATION CONTROL
0 t_initial - Starting time of simulation (s)
30.0 t_final - Ending time of simulation (s)
2E-03 dt - Time increment size (s)
-----
GRAVITY PARAMETER
0.0 Gx - Component of gravity vector along X direction (m/s^2)
-9.8 Gy - Component of gravity vector along Y direction (m/s^2)
0.0 Gz - Component of gravity vector along Z direction (m/s^2)
-----
FRAME PARAMETER
0.0 GLBPos(1) - Component of position vector of the initial blade reference frame along X direction (m)
0.0 GLBPos(2) - Component of position vector of the initial blade reference frame along Y direction (m)
1.0 GLBPos(3) - Component of position vector of the initial blade reference frame along Z direction (m)
---The following 3 by 3 matrix is the initial direction cosine matrix, GLBDCM(3,3),
---relates global frame to initial blade reference frame
1.000E+00 0.000E+00 0.000E+00
0.000E+00 1.000E+00 0.000E+00
0.000E+00 0.000E+00 1.000E+00
-----
ROOT VELOCITY PARAMETER
1.0006 RootVel(4) - Component of angular velocity vector of the beam root about X axis (rad/s)
0.0 RootVel(5) - Component of angular velocity vector of the beam root about Y axis (rad/s)
0.0 RootVel(6) - Component of angular velocity vector of the beam root about Z axis (rad/s)
-----
APPLIED FORCE
0.0 DistrLoad(1) - Component of distributed force vector along X direction (N/m)
0.0 DistrLoad(2) - Component of distributed force vector along Y direction (N/m)
0.0 DistrLoad(3) - Component of distributed force vector along Z direction (N/m)
0.0 DistrLoad(4) - Component of distributed moment vector along X direction (N-m/m)
0.0 DistrLoad(5) - Component of distributed moment vector along Y direction (N-m/m)
0.0 DistrLoad(6) - Component of distributed moment vector along Z direction (N-m/m)
0.0 TipLoad(1) - Component of concentrated force vector at blade tip along X direction (N)
0.0 TipLoad(2) - Component of concentrated force vector at blade tip along Y direction (N)
0.0 TipLoad(3) - Component of concentrated force vector at blade tip along Z direction (N)
0.0 TipLoad(4) - Component of concentrated moment vector at blade tip along X direction (N-m)
0.0 TipLoad(5) - Component of concentrated moment vector at blade tip along Y direction (N-m)
0.0 TipLoad(6) - Component of concentrated moment vector at blade tip along Z direction (N-m)
-----
PRIMARY INPUT FILE
"BeamDyn_Input_5MW.inp" InputFile - Name of the primary input file

```


B BeamDyn Primary Input File: NREL 5-MW Reference Wind Turbine

```

----- BEAMDYN V1.01.* INPUT FILE -----
NREL 5MW blade primary input file
----- SIMULATION CONTROL -----
TRUE      Echo
2         analysis_type - 1: Static analysis; 2: Dynamic analysis (switch)
0.0      rhoINF
2         quadrature
          - 1: Gauss; 2: Trapezoidal (switch)
DEFAULT refine
          - Refinement factor for quadrature 2 (-). DEFAULT = 1
DEFAULT n_fact
          - Factorization frequency (-). DEFAULT = 5
DEFAULT DTBeam
          - Time step size (s). DEFAULT = glue/driver code time step
DEFAULT NRMMax
          - Max number of iterations in Newton-Ralphson algorithm (-). DEFAULT = 10
DEFAULT stop_tol
          - Tolerance for stopping criterion (-) DEFAULT = 1.0E-5
----- GEOMETRY PARAMETER -----
1 member_total - Total number of members (-)
49 kp_total - Total number of key points (-)
1 49
kp_xr kp_yr kp_zr initial_twist
(m) (m) (m) (deg)
0.000000 0.000000 0.000000 0.000000 13.308000
0.000000 0.000000 0.000000 0.199875 13.308000
0.000000 0.000000 0.000000 1.199865 13.308000
0.000000 0.000000 0.000000 2.199855 13.308000
0.000000 0.000000 0.000000 3.199845 13.308000
0.000000 0.000000 0.000000 4.199835 13.308000
0.000000 0.000000 0.000000 5.199825 13.308000
0.000000 0.000000 0.000000 6.199815 13.308000
0.000000 0.000000 0.000000 7.199805 13.308000
0.000000 0.000000 0.000000 8.201025 13.308000
0.000000 0.000000 0.000000 9.199785 13.308000
0.000000 0.000000 0.000000 10.199775 13.308000
0.000000 0.000000 0.000000 11.199765 13.181000
0.000000 0.000000 0.000000 12.199755 12.848000
0.000000 0.000000 0.000000 13.200975 12.192000
0.000000 0.000000 0.000000 14.199735 11.561000
0.000000 0.000000 0.000000 15.199725 11.072000
0.000000 0.000000 0.000000 16.199715 10.792000
0.000000 0.000000 0.000000 18.200925 10.232000
0.000000 0.000000 0.000000 20.200290 9.672000

```

```

0.000000 0.000000 22.200270 9.110000
0.000000 0.000000 24.200250 8.534000
0.000000 0.000000 26.200230 7.932000
0.000000 0.000000 28.200825 7.321000
0.000000 0.000000 30.200190 6.711000
0.000000 0.000000 32.200170 6.122000
0.000000 0.000000 34.200150 5.546000
0.000000 0.000000 36.200130 4.971000
0.000000 0.000000 38.200725 4.401000
0.000000 0.000000 40.200090 3.834000
0.000000 0.000000 42.200070 3.332000
0.000000 0.000000 44.200050 2.890000
0.000000 0.000000 46.200030 2.503000
0.000000 0.000000 48.201240 2.116000
0.000000 0.000000 50.199990 1.730000
0.000000 0.000000 52.199970 1.342000
0.000000 0.000000 54.199950 0.954000
0.000000 0.000000 55.199940 0.760000
0.000000 0.000000 56.199930 0.574000
0.000000 0.000000 57.199920 0.404000
0.000000 0.000000 57.699915 0.319000
0.000000 0.000000 58.201140 0.253000
0.000000 0.000000 58.699905 0.216000
0.000000 0.000000 59.199900 0.178000
0.000000 0.000000 59.699895 0.140000
0.000000 0.000000 60.199890 0.101000
0.000000 0.000000 60.699885 0.062000
0.000000 0.000000 61.199880 0.023000
0.000000 0.000000 61.500000 0.000000
-----
MESH PARAMETER -----
5      order_elem - Order of interpolation (basis) function (-)
-----
"5MW_Blade_IEC.inp" BldFile - Name of file containing properties for blade (quoted string)
-----
PITCH ACTUATOR PARAMETERS -----
False  UsePitchAct - Whether a pitch actuator should be used (flag)
200    PitchJ    - Pitch actuator inertia (kg-m^2) [used only when UsePitchAct is true]
2.0E+7 PitchK    - Pitch actuator stiffness (kg-m^2/s^2) [used only when UsePitchAct is true]
5.0E+5 PitchC    - Pitch actuator damping (kg-m^2/s) [used only when UsePitchAct is true]

```

```

----- OUTPUTS -----
True      SumPrint      - Print summary data to "<RootName>.sum" (flag)
"ES10.3E2" OutFmt      - Format used for text tabular output, excluding the time channel.
  2      NNodeOuts      - Number of nodes to output to file [0 - 9] (-)
  1, 3   OutNd          - Nodes whose values will be output (-)
                        - The next line(s) contains a list of output parameters. See
                        OutList
OutListParameters.xlsx.
"RootFxr, RootFyr, RootFzr"
"RootMxr, RootMyr, RootMzr"
"NlFxl, NlFyl, NlFzl"
"NlMxl, NlMy1, NlMz1"
"TipTDxr, TipTDyr, TipTDzr"
"TipRDxr, TipRDyr, TipRDzr"
END of input file (the word "END" must appear in the first 3 columns of this last OutList line)
-----

```

C BeamDyn Blade Input File: NREL 5-MW Reference Wind Turbine Blade

-1.154189E-01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.945900E+03
0.019510	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
1.078950E+09	1.078950E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.078950E+10	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.955860E+10	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.942490E+10	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	5.431590E+09
7.733630E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.785695E+01
0.000000E+00	7.733630E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	7.733630E+02	-1.785695E+01	-1.785695E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	-1.785695E+01	1.066380E+03	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.091520E+03	0.000000E+00
1.785695E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.157900E+03
0.035770	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
1.006723E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	1.006723E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.006723E+10	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.949780E+10	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.745590E+10	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.993980E+09
7.405500E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-2.547492E+00
0.000000E+00	7.405500E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	7.405500E+02	2.547492E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.547492E+00	1.047360E+03	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	9.660900E+02	0.000000E+00
-2.547492E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.013450E+03
0.052030	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
9.867780E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	9.867780E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.978880E+10	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.528740E+10	0.000000E+00

0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.666590E+09
7.400420E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.215482E+01
0.000000E+00	7.400420E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	7.400420E+02	3.215482E+01	1.099750E+03	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.738100E+02	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.973560E+03
-3.215482E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.068290						
7.607860E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	7.607860E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	7.607860E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.485850E+10	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.078240E+10	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.474710E+09
5.924960E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.491579E+01
0.000000E+00	5.924960E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.924960E+02	3.491579E+01	8.730200E+02	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.485500E+02	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.521570E+03
-3.491579E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.084550						
5.491260E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	5.491260E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.491260E+08	5.491260E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.022260E+10	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.229720E+09	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.323540E+09
4.502750E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-2.924086E+01
0.000000E+00	4.502750E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	4.502750E+02	4.502750E+02	2.924086E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.924086E+01	6.414900E+02	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.567600E+02	0.000000E+00
-2.924086E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.098250E+03


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0.100810
4.971300E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 4.971300E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.971300E+09 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 9.144700E+09 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 6.309540E+09 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 1.907870E+09 0.000000E+00

4.240540E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 -3.272849E+01
0.000000E+00 4.240540E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.240540E+02 3.272849E+01 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 5.937300E+02 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 4.005300E+02 0.000000E+00
-3.272849E+01 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 9.942600E+02

0.117070
4.493950E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 4.493950E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.493950E+09 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 8.063160E+09 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 5.528360E+09 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 1.570360E+09 0.000000E+00

4.006380E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 -3.362955E+01
0.000000E+00 4.006380E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.006380E+02 3.362955E+01 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 3.362955E+01 5.471800E+02 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 3.516100E+02 0.000000E+00
-3.362955E+01 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 8.987900E+02

0.133350
4.034800E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 4.034800E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.034800E+09 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 6.884440E+09 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 4.980060E+09 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 1.158260E+09

```

3.820620E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.887099E+01
0.000000E+00	3.820620E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.820620E+02	3.887099E+01	4.908400E+02	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.161200E+02	0.000000E+00	0.000000E+00
-3.887099E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.069600E+02	
0.149590							
4.037290E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	4.037290E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	4.037290E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.009180E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.936840E+09	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.002120E+09	
3.996550E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-4.299488E+01	
0.000000E+00	3.996550E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.996550E+02	4.299488E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	4.299488E+01	5.038600E+02	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.036000E+02	0.000000E+00	0.000000E+00
-4.299488E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.074600E+02	
0.165850							
4.169720E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	4.169720E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	4.169720E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.167680E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.691660E+09	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.559000E+08	
4.263210E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-6.748235E+01	
0.000000E+00	4.263210E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	4.263210E+02	6.748235E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	6.748235E+01	5.447000E+02	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.892400E+02	0.000000E+00	0.000000E+00
-6.748235E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.339400E+02	

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0.182110
4.082350E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 4.082350E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.082350E+09 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 7.271660E+09 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 3.949460E+09 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 6.722700E+08

4.168200E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 -9.267993E+01
0.000000E+00 4.168200E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.168200E+02 4.168200E+01 9.267993E+01 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 9.267993E+01 5.699000E+02 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 2.465700E+02 0.000000E+00
-9.267993E+01 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 8.164700E+02

0.198370
4.085970E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 4.085970E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.085970E+09 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 7.081700E+09 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 3.386520E+09 0.000000E+00 5.474900E+08
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 -1.249266E+02

4.061860E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 -1.249266E+02
0.000000E+00 4.061860E+02 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 4.061860E+02 1.249266E+02 6.012800E+02 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 1.249266E+02 0.000000E+00 2.159100E+02 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 8.171900E+02

0.214650
3.668340E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 3.668340E+08 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 3.668340E+09 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 6.244530E+09 0.000000E+00 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 2.933740E+09 0.000000E+00 0.000000E+00
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 4.488400E+08

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3.814200E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-1.158983E+02
0.000000E+00	3.814200E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.814200E+02	0.000000E+00	1.158983E+02	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.158983E+02	5.465600E+02	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.871100E+02	0.000000E+00	0.000000E+00
-1.158983E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.336700E+02
0.230890							
3.147760E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.147760E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.147760E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	5.048960E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.568960E+09	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.359200E+08
3.528220E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-9.356487E+01
0.000000E+00	3.528220E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.528220E+02	9.356487E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	9.356487E+01	4.687100E+02	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.608400E+02	0.000000E+00	0.000000E+00
-9.356487E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.295500E+02
0.247150							
3.011580E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.011580E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.011580E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.948490E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.388650E+09	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.113500E+08
3.494770E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-9.065783E+01
0.000000E+00	3.494770E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.494770E+02	9.065783E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	9.065783E+01	4.537600E+02	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.485600E+02	0.000000E+00	0.000000E+00
-9.065783E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.023200E+02
0.263410							

0.000000E+00	3.300040E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.300040E+02	6.726142E+01	6.726142E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	6.726142E+01	3.620800E+02	3.620800E+02	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.094200E+02	0.000000E+00
-6.726142E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.715000E+02
0.360980						
2.146860E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	2.146860E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	2.146860E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.146860E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.995280E+09	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.588710E+09	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.007500E+08
3.219900E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-6.418549E+01
0.000000E+00	3.219900E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.219900E+02	6.418549E+01	6.418549E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	6.418549E+01	3.350100E+02	3.350100E+02	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	9.436000E+01	0.000000E+00
-6.418549E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.293700E+02
0.393500						
1.944090E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	1.944090E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.944090E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.944090E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.750760E+09	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.361930E+09	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.743800E+08
3.138200E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-6.063944E+01
0.000000E+00	3.138200E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.138200E+02	6.063944E+01	6.063944E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	6.063944E+01	3.085700E+02	3.085700E+02	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.024000E+01	0.000000E+00
-6.063944E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.888100E+02
0.426020						
1.632700E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

0.000000E+00	1.632700E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.632700E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.447140E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.102380E+09	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.444700E+08	
2.947340E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-4.419242E+01	
0.000000E+00	2.947340E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	2.947340E+02	4.419242E+01	4.419242E+01	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	4.419242E+01	2.638700E+02	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.267000E+01	0.000000E+00	
-4.419242E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.265400E+02	
0.458550							
1.432400E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	1.432400E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	1.432400E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.139070E+09	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.758000E+08	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.199800E+08	
2.871200E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-4.427678E+01	
0.000000E+00	2.871200E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	2.871200E+02	4.427678E+01	4.427678E+01	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	4.427678E+01	2.370600E+02	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.942000E+01	0.000000E+00	
-4.427678E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.864800E+02	
0.491060							
1.168760E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	1.168760E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	1.168760E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.734240E+09	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.813000E+08	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.119000E+07	
2.633430E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.489821E+01	
0.000000E+00	2.633430E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	

0.000000E+00	0.000000E+00	2.633430E+02	3.489821E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.489821E+01	1.964100E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+01	0.000000E+00	0.000000E+00
-3.489821E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.337500E+02
0.523580							
1.047430E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	1.047430E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.047430E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.554870E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	5.347200E+08	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.909000E+07	
2.532070E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.370945E+01	
0.000000E+00	2.532070E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	2.532070E+02	3.370945E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.370945E+01	1.803400E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.914000E+01	0.000000E+00	0.000000E+00
-3.370945E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.094800E+02	
0.556100							
9.229500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	9.229500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	9.229500E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.334030E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.089000E+08	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	5.745000E+07	
2.416660E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.391782E+01	
0.000000E+00	2.416660E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	2.416660E+02	3.391782E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.624300E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.216000E+01	0.000000E+00	0.000000E+00
-3.391782E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.845900E+02	
0.588620							
7.608200E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	7.608200E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

0.000000E+00	0.000000E+00	7.608200E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.828730E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.145400E+08	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.592000E+07	
2.206380E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.077900E+01	
0.000000E+00	2.206380E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	2.206380E+02	3.077900E+01	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	3.077900E+01	1.348300E+02	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.733000E+01	0.000000E+00	
-3.077900E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.521600E+02	
0.621150						
6.480300E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	6.480300E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	6.480300E+08	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	1.584100E+09	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.386300E+08	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.598000E+07	
2.002930E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.031234E+01	
0.000000E+00	2.002930E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	2.002930E+02	3.031234E+01	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	3.031234E+01	1.163000E+02	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.330000E+01	0.000000E+00	
-3.031234E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.296000E+02	
0.653660						
5.397000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	5.397000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	5.397000E+08	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	1.323360E+09	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.758800E+08	0.000000E+00	
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.744000E+07	
1.794040E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.124859E+01	
0.000000E+00	1.794040E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	
0.000000E+00	0.000000E+00	1.794040E+02	3.124859E+01	0.000000E+00	0.000000E+00	

0.000000E+00	0.000000E+00	3.124859E+01	9.798000E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
-3.124859E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.079400E+02
0.686180						
5.311500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	5.311500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.311500E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.183680E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.260100E+08	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.090000E+07
1.650940E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-4.114473E+01
0.000000E+00	1.650940E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.650940E+02	4.114473E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	4.114473E+01	9.893000E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.300000E+00	0.000000E+00	0.000000E+00
-4.114473E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.062300E+02
0.718700						
4.600100E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	4.600100E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	4.600100E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.020160E+09	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.072600E+08	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.854000E+07
1.544110E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-4.018083E+01
0.000000E+00	1.544110E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.544110E+02	4.018083E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	4.018083E+01	8.578000E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.220000E+00	0.000000E+00	0.000000E+00
-4.018083E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	9.200000E+01
0.751220						
3.757500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.757500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.757500E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00

0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
1.389350E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.133540E+01
0.000000E+00	1.389350E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.389350E+02	3.133540E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
-3.133540E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.515000E+01
0.783760	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
3.288900E+07	3.288900E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.288900E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.096100E+08	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.631000E+07	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.453000E+07
1.295550E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-2.953206E+01
0.000000E+00	1.295550E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.295550E+02	2.953206E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.141000E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.360000E+00	0.000000E+00
-2.953206E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.577000E+01
0.816260	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
2.440400E+07	2.440400E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.440400E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	5.181900E+08	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	6.105000E+07	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	9.070000E+06
1.072640E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-2.209638E+01
0.000000E+00	1.072640E+02	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.072640E+02	2.209638E+01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.209638E+01	4.544000E+01	0.000000E+00	0.000000E+00

0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
-2.209638E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.360000E+00	0.000000E+00
0.848780						4.880000E+01
2.116000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	2.116000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	2.116000E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	4.548700E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.948000E+07	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.060000E+06	
9.877600E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-2.139686E+01	
0.000000E+00	9.877600E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	9.877600E+01	2.139686E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	2.139686E+01	3.957000E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.750000E+00	0.000000E+00	0.000000E+00
-2.139686E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.232000E+01	
0.881300						
1.815200E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	1.815200E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.815200E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.951200E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.936000E+07	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.080000E+06	
9.024800E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-2.056210E+01	
0.000000E+00	9.024800E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	9.024800E+01	2.056210E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	2.056210E+01	3.409000E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.210000E+00	0.000000E+00	0.000000E+00
-2.056210E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.630000E+01	
0.897560						
1.602500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	1.602500E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.602500E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.537200E+08	0.000000E+00	0.000000E+00	0.000000E+00

-1.055375E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.002000E+01
0.938210	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
9.224000E+06	9.224000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	9.224000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	2.617100E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.384000E+07	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.940000E+06	0.000000E+00
6.626400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-1.019273E+01
0.000000E+00	6.626400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	6.626400E+01	1.019273E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.019273E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.340000E+00	0.000000E+00	0.000000E+00
-1.019273E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.845000E+01
0.946360	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
6.323000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	6.323000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	6.323000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.588100E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.963000E+07	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.240000E+06	0.000000E+00
5.934000E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-5.619498E+00
0.000000E+00	5.934000E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.934000E+01	5.619498E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.619498E+00	1.155000E+01	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.100000E+00	0.000000E+00	0.000000E+00
-5.619498E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.265000E+01	0.000000E+00
0.954470	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
5.332000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	5.332000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.332000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	1.378800E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.600000E+07	0.000000E+00	0.000000E+00

0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.660000E+06
5.591400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-5.042325E+00
0.000000E+00	5.591400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.591400E+01	0.000000E+00	5.042325E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	5.042325E+00	9.770000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.900000E-01	0.000000E+00	0.000000E+00
-5.042325E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.066000E+01
0.962600							
4.453000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	4.453000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	4.453000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.187900E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.283000E+07	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	3.130000E+06
5.248400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-4.493155E+00
0.000000E+00	5.248400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	5.248400E+01	0.000000E+00	4.493155E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	4.493155E+00	8.190000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.100000E-01	0.000000E+00	0.000000E+00
-4.493155E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	8.900000E+00
0.970730							
3.690000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.690000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.690000E+06	0.000000E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.016300E+08	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.008000E+07	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.640000E+06	
4.911400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-3.946310E+00
0.000000E+00	4.911400E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	4.911400E+01	0.000000E+00	3.946310E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	3.946310E+00	6.820000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	5.600000E-01	0.000000E+00	0.000000E+00
-3.946310E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.380000E+00

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0.978860
2.9920000E+06 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
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0.0000000E+00 0.0000000E+00 2.9920000E+07 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 8.5070000E+07 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 7.5500000E+06 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 2.1700000E+06

4.5818000E+01 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 -3.251245E+00
0.0000000E+00 4.5818000E+01 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 4.5818000E+01 3.251245E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 5.5700000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 4.2000000E-01 0.0000000E+00
-3.251245E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 5.9900000E+00

0.986990
2.1310000E+06 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 2.1310000E+06 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 2.1310000E+07 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 6.4260000E+07 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 4.6000000E+06 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 1.5800000E+06

4.1669000E+01 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 -2.260127E+00
0.0000000E+00 4.1669000E+01 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 4.1669000E+01 2.260127E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 2.260127E+00 4.0100000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 2.5000000E-01 0.0000000E+00 0.0000000E+00
-2.260127E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 4.2600000E+00

0.995120
4.8500000E+05 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
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0.0000000E+00 0.0000000E+00 4.8500000E+06 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 6.6100000E+06 0.0000000E+00 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 2.5000000E+05 0.0000000E+00 0.0000000E+00
0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 2.5000000E+05

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1.145300E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-6.169731E-01
0.000000E+00	1.145300E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.145300E+01	0.000000E+00	6.169731E-01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	6.169731E-01	9.400000E-01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.000000E-02	0.000000E+00
-6.169731E-01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	9.800000E-01
1.000000						
3.530000E+05	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.530000E+05	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	3.530000E+06	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	5.010000E+06	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.700000E+05	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.900000E+05	0.000000E+00
1.031900E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	-5.346274E-01
0.000000E+00	1.031900E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	1.031900E+01	0.000000E+00	5.346274E-01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	5.346274E-01	6.800000E-01	0.000000E+00	0.000000E+00
0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	2.000000E-02	0.000000E+00
-5.346274E-01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	7.000000E-01

D BeamDyn List of Output Channels

This is a list of all possible output parameters for the BeamDyn module. The names are grouped by meaning, but can be ordered in the OUTPUTS section of the BeamDyn primary input file as the user sees fit. $N\beta$, refers to output node β , where β is a number in the range [1,9], corresponding to entry β in the *OutNd* list. When coupled to FAST, “ $B\alpha$ ” is prefixed to each output name, where α is a number in the range [1,3], corresponding to the blade number. The outputs are expressed in one of the following three coordinate systems:

- r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system.
- l: a floating coordinate system local to the deflected beam.
- g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system.

Channel Name(s)	Units	Description
RootFxr, RootFyr, RootFzr	(N), (N), (N)	Root reaction forces expressed in r
RootMxr, RootMyr, RootMzr	(N m), (N m), (N m)	Root reaction moments expressed in r
TipTDxr, TipTDyr, TipTDzr	(m), (m), (m)	Tip translational deflection (relative to the undeflected position) expressed in r
TipRDxr, TipRDyr, TipRDzr	(-), (-), (-)	Tip angular/rotational deflection Wiener-Milenković parameter (relative to the undeflected orientation) expressed in r
TipTVXg, TipTVYg, TipTVZg	(m/s), (m/s), (m/s)	Tip translational velocities (absolute) expressed in g
TipRVXg, TipRVYg, TipRVZg	(deg/s), (deg/s), (deg/s)	Tip angular/rotational velocities (absolute) expressed in g
TipTAXg, TipTAYg, TipTAZg	(m/s ²), (m/s ²), (m/s ²)	Tip translational accelerations (absolute) expressed in g
TipRAXg, TipRAYg, TipRAZg	(deg/s ²), (deg/s ²), (deg/s ²)	Tip angular/rotational accelerations (absolute) expressed in g
NβFxl, NβFyl, NβFzl	(N), (N), (N)	Sectional force resultants at Nβ expressed in l
NβMxl, NβMyl, NβMzl	(N m), (N m), (N m)	Sectional moment resultants at Nβ expressed in l
NβTDxr, NβTDyr, NβTDzr	(m), (m), (m)	Sectional translational deflection (relative to the undeflected position) at Nβ expressed in r
NβRDxr, NβRDyr, NβRDzr	(-), (-), (-)	Sectional angular/rotational deflection Wiener-Milenković parameter (relative to the undeflected orientation) at Nβ expressed in r
NβTVXg, NβTVYg, NβTVZg	(m/s), (m/s), (m/s)	Sectional translational velocities (absolute) at Nβ expressed in g
NβRVXg, NβRVYg, NβRVZg	(deg/s), (deg/s), (deg/s)	Sectional angular/rotational velocities (absolute) at Nβ expressed in g
NβTAXg, NβTAYg, NβTAZg	(m/s ²), (m/s ²), (m/s ²)	Sectional translational accelerations (absolute) at Nβ expressed in g
NβRAXg, NβRAYg, NβRAZg	(deg/s ²), (deg/s ²), (deg/s ²)	Sectional angular/rotational accelerations (absolute) at Nβ expressed in g
NβPFxl, NβPFyl, NβPFzl	(N), (N), (N)	Applied point forces at Nβ expressed in l
NβPMxl, NβPMyl, NβPMzl	(N m), (N m), (N m)	Applied point moments at Nβ expressed in l
NβDFxl, NβDFyl, NβDFzl	(N/m), (N/m), (N/m)	Applied distributed forces at Nβ expressed in l
NβDMxl, NβDMyl, NβDMzl	(N m/m), (N m/m), (N m/m)	Applied distributed moments at Nβ expressed in l

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