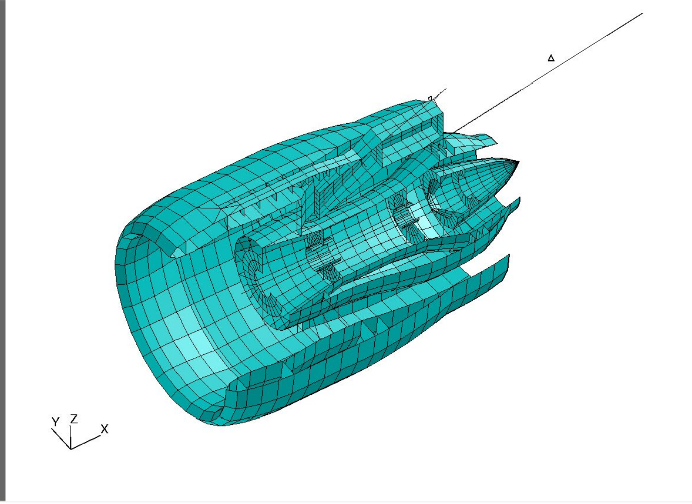

Section 5

Rotordynamics

Table of Content

Table of Content (cont.)

Overview

Introduction

- Main Focus: Jet Engines
- Three phase implementation

Overview of Rotordynamics

- **Types of analyses**
  - Static analysis
  - Complex Eigenvalue
    - Whirl modes, Campbell diagrams
    - Critical speed prediction
  - Frequency response
  - Transient (Linear and Nonlinear) response
- **Dynamic solution usually needed for most rotordynamic analyses, e.g., unbalance rotor response, critical speed analysis.**
- **Special cases solved with static analysis, e.g., aircraft in a steady turn**

Overview (cont.)

- **Assumptions and Limitations**
  - Analysis performed in a stationary (inertial) coordinate system, i.e., non-rotating
  - Models must be axisymmetric, e.g, cyclic symmetric with 3 or more segments
  - Center-line model, boundary grids must be on the center-line
    - Use SE Guyan reduction for 3D models
  - Connect rotor models to support structure by rigid elements only, elastic coupling at the g-set is not allowed

Overview (cont.)

- **Assumptions and Limitations**
  - Rotor axis is flexible, disks are rigid
- **Critical speeds and modes only available for the reference rotor**
- **Modes valid between SPDLOW and SPDHIGH specified on RGYRO entry**

Theory: Basic Equations – Time Domain

- **With Damping and Circulation**

$$
\begin{aligned}
M\,\ddot{u}(t) &+ \left(B_s + \left(\frac{g}{W3}\right) K_s + \left(\frac{1}{W4}\right) K4_s + B_r + \left(\frac{g_r}{WR3}\right) K_r + \left(\frac{1}{WR4}\right) K4_r + \Omega B^G \right) \dot{u}(t) \\
&+ \left(K_s + K_r + \Omega \left(K^{C\nu} + \left(\frac{g_r}{WR3}\right) K^{Cgr} + \left(\frac{1}{WR4}\right) K^{Cge} \right) \right) u(t) = F(t)
\end{aligned}
$$

Where

M = Total Mass Matrix

B_s = Support viscous damping matrix

Theory: Basic Equations (cont.)

$\left(\frac{g}{W3}\right)K_s$ = support viscous damping equivalent to structural damping, (PARAM,G)

$\left(\frac{1}{W4}\right)K4_s$ = support viscous damping equivalent to material structural damping (GE on MATi)

B_r = rotor viscous damping matrix (CVISC, CDAMPi)

$\left(\frac{g_r}{WR3}\right)K_r$ = rotor viscous damping equivalent to structural damping (GR on RSPINT)

$\left(\frac{1}{WR4}\right)K4_r$ = rotor viscous damping equivalent to material structural damping (GE on MATi)

Theory: Basic Equations (cont.)

B^G = gyroscopic force matrix (dependent on moment of inertia)

K_s = support stiffness matrix

K_r = rotor stiffness matrix

$K4_s$ = support material damping matrix (GE on MATi)

$K4_r$ = rotor material damping matrix (GE on MATi)

Ω = rotor spin rate

K^{Cv} = “circulation” matrix due to B_r

$g_r K_r^{Cg}$ = “circulation” matrix due to $g_r K_r$

K^{Cge} = “circulation” matrix due to $K4_r$

G, WR3, and WR4 are user parameters

Theory: Basic Equations – Frequency Domain

- **Asynchronous Condition -** $\omega \neq \Omega$
- **With Damping and Circulation**

$$\left(\begin{array}{l} -\omega^2 M + i\omega\left(B_s + B_r + \Omega B^G\right) \\ + (1+ig)K_s + iK4_s + (1+ig_r)K_r + iK4_r \\ + \Omega\left(K^{C\nu} + \left(\dfrac{g_r}{\omega}\right)K^{Cgr} + \left(\dfrac{1}{\omega}\right)K^{Cge}\right) \end{array} \right) u(\omega) = F(\omega)$$

Theory: Basic Equations – Frequency Domain

- **Synchronous Condition – $\omega = \Omega$**

$$\begin{pmatrix} -\Omega^2\left(M - iB^G\right) + i\Omega\left(B_s + B_r + iK^{C\nu}\right) \\ +\left(1+ig\right)K_s + iK4_s + \left(1+ig_r\right)K_r \\ + iK4_r + g_r K^{Cgr} + K^{Cge} \end{pmatrix} u(\Omega) = F(\Omega)$$

Theory: Multiple and Reference Rotors

- For multiple rotors, prior equations are modified to include gyroscopic and spin rate terms for individual rotors
- For frequency response and static analysis a reference rotor must be specified
- Analyses are performed with the reference rotor spinning at a specified speed
- Spin rates of other rotors are determined by means of user specified relationships between the rotor spin rates (RSPINR)

Theory: Multiple and Reference Rotors

- Synchronous frequency-domain (complex modes and frequency response) analyses are performed relative to the reference rotor
- The reference rotor spins at the excitation frequency, or for complex modes, at the eigenfrequency
- Results are interpreted in terms of the reference rotor

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Rotordynamic Input
Versions 2004 & 2005

Rotordynamics Bulk Data Entries

Table of Rotordynamic Entries versus Analysis Discipline

Entry	Static	Complex Eigenvalue	Frequency response	Transient
ROTORG	x	x	x	x
RGYRO	x	x	x	
RSPINR	x	x	x	
RSPINT				x
UNBALNC				x (optional)

Rotordynamics Bulk Data Entries

- **RGYRO—specifies synchronous or asynchronous analysis, and rotation speed of the reference rotor and reference rotor ID**

Format:

RGYRO	RID	SYNCFLG	REFROTR	SPDUNIT	SPDLOW	SPDHIGH	SPEED		

Example:

RGYRO	100	ASYNC	1	RPM			2000.		

RGYRO Contents

RID Identification number selected by Case Control command, RGYRO

SYNCFLG Specification of synchronous (SYNC) or asynchronous (ASYNC) analysis for frequency response and complex modes analysis,otherwise blank

REFROTR Specifies the reference rotor ID

SPDUNIT Specifies whether the fields SPDLOW, SPDHIGH and SPEED are given in terms of RPM (revolutions per minute) or frequency (cycles per second).

SPDLOW Specifies the low speed for synchronous analysis

SPDHIGH Specifies the high speed for synchronous analysis

SPEED Specifies reference rotor speed for asynchronous analysis

Rotordynamics Bulk Data Entries(cont.)

- ROTORG—specifies grid points that compose the rotor line model

Format:

ROTORG	ROTORID	GRID1	GRID2	GRID3	…	GRIDn			

or

ROTORG	ROTORID	GRID1	THRU	GRID2	BY	Inc			

Example:

ROTORG	1	1	THRU	101	BY	10			

ROTORG Contents

ROTORID	Identification number for rotor
GRIDi	Grids comprising the rotor
THRU	Specifies a range of identification numbers
BY	Specifies an increment for a THRU specification
INC	Increment for THRU range

Rotordynamics Bulk Data Entries (cont.)

- **RSPINR—specifies the relative spin rates between rotors for complex eigenvalue, frequency response, and static analysis**
  - Also defines positive rotor spin direction (GA to GB)

Format:

*

RSPINR	ROTORID	GRIDA	GRIDB	GR	SPDUNT	SPEED1	…	SPEEDn	

* Format for 2004 to 2005r2, changed 2005r3

Example:

RSPINR	1	1	2		FREQ	1000.	2000.	3000.	

RSPINR Contents

ROTORID Identification number of rotor

GRIDA/GRIDB Positive rotor spin direction defined from GRIDA to GRIDB

GR Rotor structural damping factor

SPDUNIT Specifies whether the listing of relative spin rates is given in terms of RPM or frequency

SPEED List of relative spin rates, entries for reference rotor must be in ascending or descending order

Rotordynamics Bulk Data Entries (cont.)

- **RSPINT—specifies rotor spin rates for transient analysis**
  - Also defines positive rotor spin direction (GA to GB)

Format:

RSPINT	ROTORID	GRIDA	GRIDB	GR	SPDUNT	TID			

Example:

RSPINT	1	1	2		RPM	10			

RSPINT Contents

ROTORID Identification number of rotor

GRIDA/GRIDB Positive rotor spin direction is defined from GRIDA to GRIDB

GR Rotor structural damping factor

SPDUNIT Specifies whether the spin rates are given in terms of RPM or frequency

TID Identification of TABLEDi entry specifying spin rate versus time

Rotordynamics Bulk Data Entries (cont.)

- UNBALNC—specifies unbalance load for transient defined in a cylindrical coordinate system with the rotor rotational axis as the z-axis

Format:

UNBALNC	RID	MASS	GRID	X1	X2	X3			
	ROFFSET	THETA	ZOFFSET	Ton	Toff	CFLAG			

Example:

UNBALNC	100	.1	1001	0.0	1.0	0.0			
	.02	30.	.5						

UNBALNC Contents

RID Identification number of UNBALNC entry. Selected by Case Control command, RGYRO

MASS Mass imbalance

GRID Grid identification number of applying imbalance. The grid must appear on a ROTORG entry

X1, X2, X3 Components of the vector from GRID in the displacement coordinate of GRID which is used to define a cylindrical coordinate system centered at GRID

ROFFSET Offset of mass in the radial direction of the unbalance coordinate system

THETA Angular position of the mass in the unbalance coordinate system

ZOFFSET Offset of mass in the z-direction of the unbalance coordinate system

Ton Start time for applying imbalance load

Toff Time for terminating imbalance load

UNBALNC Contents (cont.)

CFLAG Correct flag to specify whether 1) the mass will be used to modify the total mass in the transient response calculations, 2) the effect of the rotor spin rate change will be included in the transient response calculation or 3) both

UFT1-3* EPOINTs to output the unbalanced forces in T1, T2 and T3 directions

UFR1-3* EPOINTs to output the unbalanced forces in R1, R2 and R3 directions

MCT1-3* EPOINTs to output the mass correction forces in T1, T2 and T3 directions

MCR1-3* EPOINTs to output the mass correction forces in R1, R2 and R3 directions

SCR1-3* EPOINTs to output the speed-correction forces for the R1, R2 and R3 directions

* Supported in 2005r3

Parameters

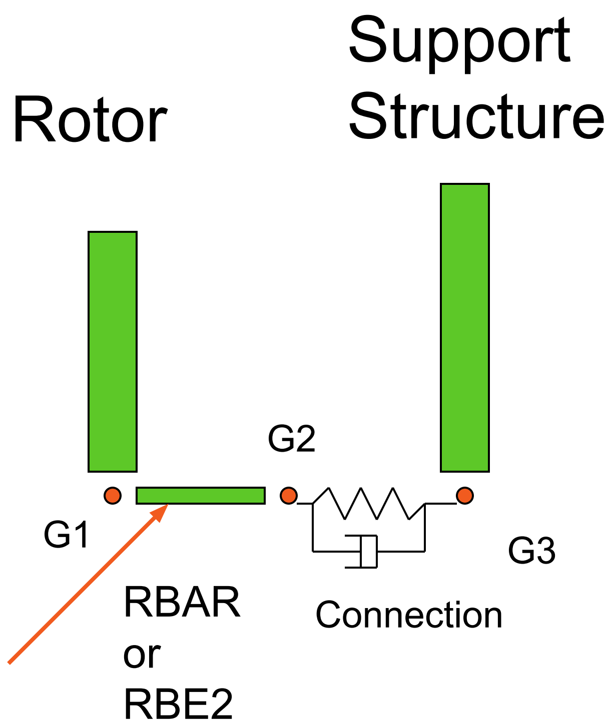
- **There are 3 new parameters added for the rotor dynamics capability**

  - PARAM,GYROAVG,x   (default=0)
    - If x=-1, the gyroscopic terms are generated using a least square fit of terms within the analysis range

  - PARAM,WR3,y   and   PARAM,WR4,z
    - Specifies “average” excitation for calculation of rotor damping and circulation terms
    - This is similar to param,w3,y and param,w4,z in transient analysis

Connection for Rotor and Support Structure

- Schematic Example of Connection



Isolates the rotor so the program computes accurate mass properties for the rotor and also indicates modeling error

G1 – centerline grid point of rotating component, i.e., boundary grid of a SE

G2 – connecting grid

G3 – attachment grid point of the nonrotating component

G1, G2 & G3 are coincident grids.

Comments

- Proper Rotor/Structure Connection avoids adding miscellaneous mass to the rotor and circulation damping terms caused by support structure stiffness.
- Note that the dependent/independent dofs of the RBAR or RBE2 does not matter since the rotor mass and circulation damping are based on the g-set dofs.

Dimentberg Example Shaft and Rigid Disk*

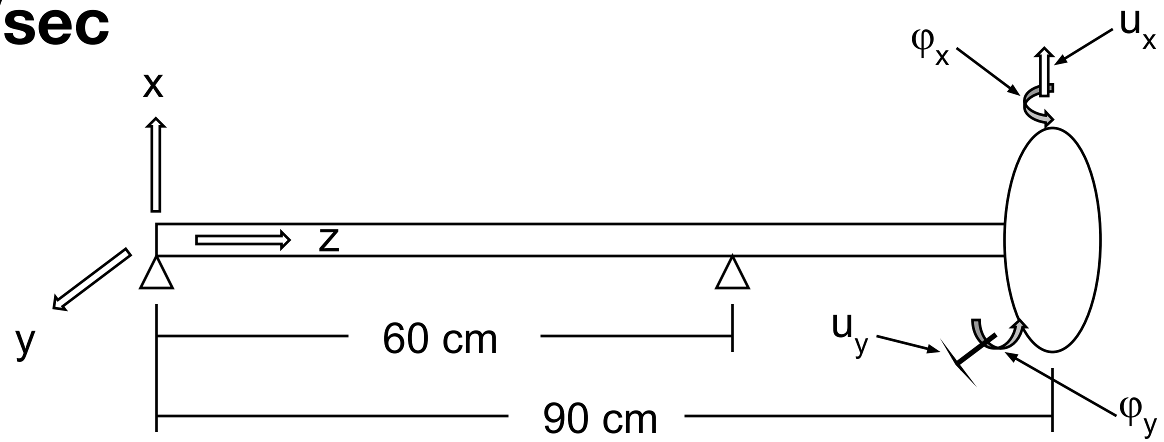
M_d = 0.0157 kg sec^2/cm

I_d = 2.45 kg/sec^2 cm

I_p = 2 I_d

EI = 1,647,700 kg cm^2

Ω = 100 rad/sec



*References: Bedrossian, H., and Viekos, N., Rotor-Disk System Gyroscopic Effects in MSC/NASTRAN Dynamics Solutions, MSC/NASTRAN User's Conf. Proc., Paper No. 12, 1982.

Dimentberg, F. M., Flexural Vibrations of Rotating Shafts, Butterworths, London, 1964

Rotordynamic Matrix Terms at One Point

- **Matrix Terms for at One Point with Constant Spin Speed, Ω, ASYNC**

6x6 Damping Matrix

$$M_{u_x u_x}\ddot{u}_x + K_{u_x u_x} u_x - K_{u_x \phi_y}\phi_y = 0$$

$$M_{u_y u_y}\ddot{u}_y + K_{u_y u_y} u_y + K_{u_y \phi_x}\phi_x = 0$$

$$I_d\,\ddot{\phi}_{\phi_x} + K_{\phi_x u_y} u_y + K_{\phi_x \phi_x}\phi_x + I_p\,\Omega\,\dot{\phi}_y = 0$$

$$I_d\,\ddot{\phi}_{\phi_y} - K_{\phi_y u_x} u_x + K_{\phi_y \phi_y}\phi_y - I_p\,\Omega\,\dot{\phi}_x = 0$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_p\Omega & 0 \\ 0 & 0 & 0 & -I_p\Omega & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Rotordynamic Matrix Terms at One Point

- **Matrix Terms for at One Point with Rotor Spin Speed, Ω, equal to the Excite or Eigenvalue Frequency, ω, (SYNC on RGYRO)**

6x6 Mass Matrix

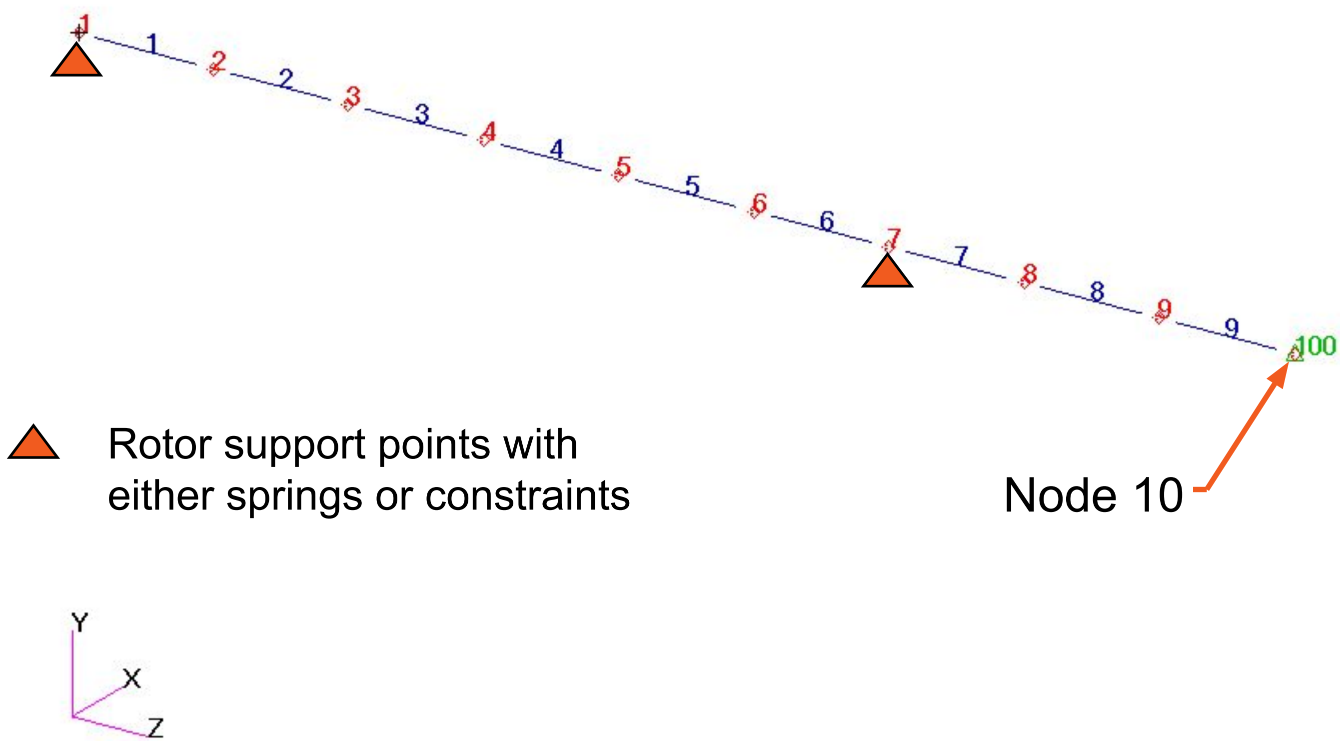
$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & iI_p & 0 \\ 0 & 0 & 0 & -iI_p & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Complex Eigenvalue Analysis

- **Whirl Frequencies**
  - Beam model setup with DMIG gyroscopic coupling
  - Beam model RGYRO setup without superelements
  - 3D model with a superelement
- **Critical Speeds**
- **Frequency Response**
- **Nonlinear Transient**

Line Model w/o Superelements

- **CBAR Elements with CONM2 100 at Node 10**



Line Model (cont.)

- Is it possible to include rotordynamics effects without the using RGYRO capability or DMAP alters?
- The answer is YES!
- But there is a price
- The next slide illustrates what is needed

Example Shaft and Disk, DMIG Setup

```
ID ROTATING DISK
SOL 107
CEND
TITLE = GYROSCOPIC INFLUENCE OF A RIGID DISK ROTATING ON A SHAFT
SUBTI = NEARLY MASSLESS SHAFT, SPIN RATE OF 100.0 RAD/SEC
B2PP          = GYROD
SPC           = 1
CMETHOD       = 1
DISP(PHASE)   = ALL
BEGIN BULK
.
$ DISK MASS AND GYRO SPECIFICATIONS
CONM2    100  10       157.0-4
          2.45         2.45
$dmig    name "0"  ifo  tin  toutpolar      ncol
DMIG GYROD    0    1    1    0
DMIG GYROD    10   4         10   5   -490.0
DMIG GYROD    10   5         10   4   490.0
$ COMPLEX EIGENVALUE EXTRACTION
EIGC 1   HESS MAX                 8
ENDDATA
```

Note: I_p is not needed on CONM2 unless torsion modes are to be calculated

Value is ΩI_p

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Whirl Modes

Example Shaft and Disk, RGYRO Setup

```
ID ROTATING DISK
SOL 107
CEND
TITLE = GYROSCOPIC INFLUENCE OF A RIGID DISK ROTATING ON A SHAFT
SUBTI = NEARLY MASSLESS SHAFT, SPIN RATE OF 100.0 RAD/SEC
   SPC          = 1
   RGYRO        = 1
   CMETHOD      = 1
   DISP(PHASE)  = ALL
BEGIN BULK
.
$ DISK MASS AND GYRO SPECIFICATIONS
CONM2    100  10        157.0-4
  2.45        2.45           4.9
$ GYROSCOPIC COUPLING AND SPEED CONTROL
$rotorg  rotorid  gid1 gid2 etc
ROTORG   1        1    thru 10   by   1
$rgyro   rid  syncflg  refrotr  spdunit  spdlow   spdhigh  speed
RGYRO    1    ASYNC    1        RPM               954.93
$rspinr  rotorid  grida    gridb    gr   spdunit  speed1   speed2   etc.
RSPINR   1        9        10            RPM      954.93
$ COMPLEX EIGENVALUE EXTRACTION
EIGC 1   HESS MAX                    8
ENDDATA
```

Note: Multiple SUBCASEs are allowed to run different speeds on the selected RGYRO entry

Note: I_p is required on the CONM2

Combined to compute ΩI_p

Keeps rotor spin speed constant

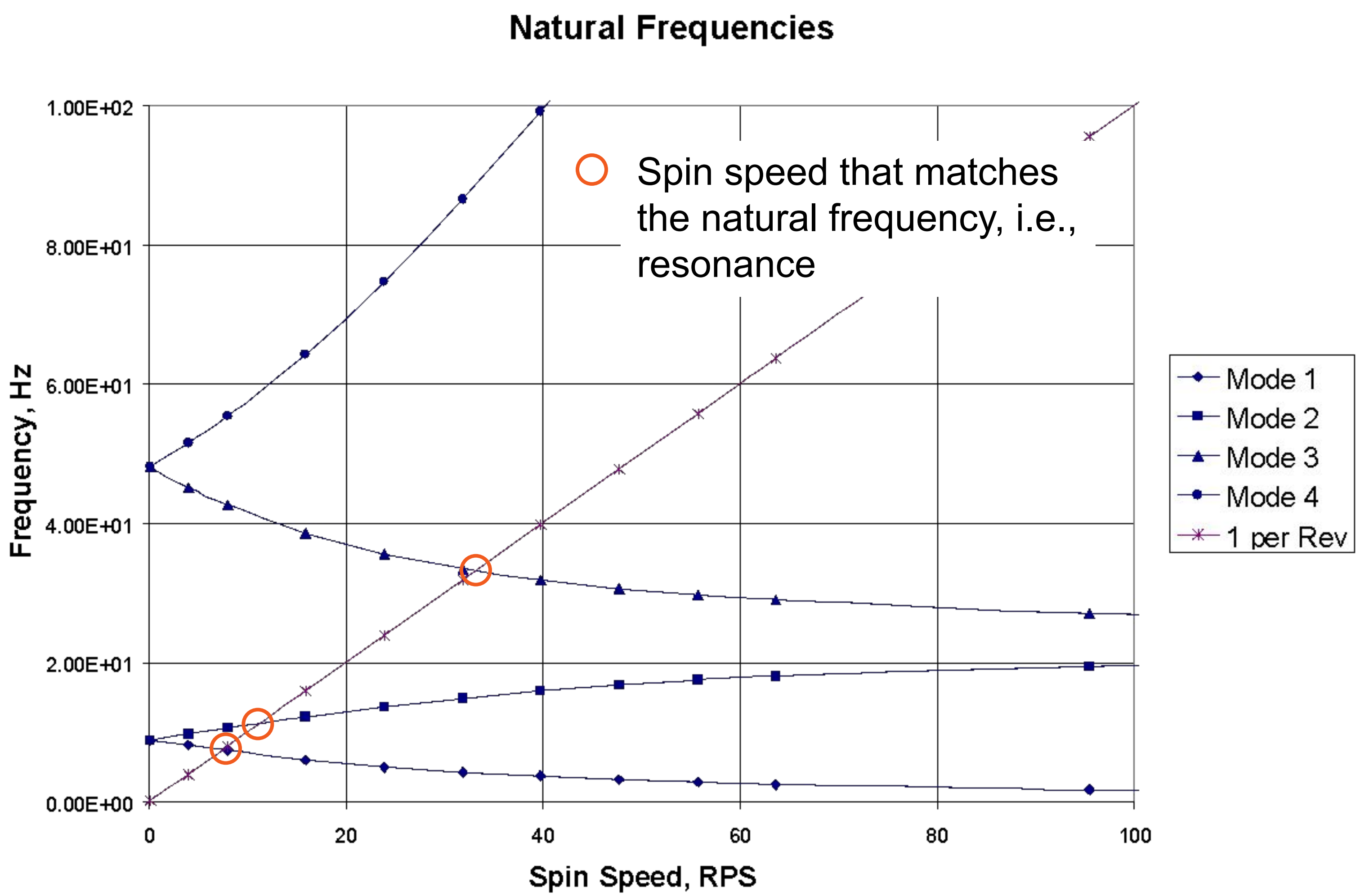
Results of Example Shaft and Disk, RGYRO or DMIG Yield Same Eigenvalues

C O M P L E X   E I G E N V A L U E   S U M M A R Y

ROOT NO.	EXTRACTION ORDER	EIGENVALUE (REAL)	EIGENVALUE (IMAG)	FREQUENCY (CYCLES)	DAMPING COEFFICIENT
1	2	7.204462E-15	-3.805280E+01	6.056291E+00	-3.786561E-16
2	1	7.204462E-15	3.805280E+01	6.056291E+00	-3.786561E-16
3	4	-2.242220E-14	-7.656962E+01	1.218643E+01	5.856683E-16
4	3	-2.242220E-14	7.656962E+01	1.218643E+01	5.856683E-16
5	6	4.939756E-14	-2.423585E+02	3.857254E+01	-4.076405E-16
6	5	4.939756E-14	2.423585E+02	3.857254E+01	-4.076405E-16
7	8	2.961827E-14	-4.038409E+02	6.427328E+01	-1.466829E-16
8	7	2.961827E-14	4.038409E+02	6.427328E+01	-1.466829E-16

- Use Eigenvectors from the Eigenvalue Table with the Positive Imaginary Part

Campbell Diagram – Non-SE Model



Critical Speed

Example Critical Speed Setup

```
ID ROTATING DISK
SOL 107
CEND
TITLE = GYROSCOPIC INFLUENCE OF A RIGID DISK ROTATING ON A SHAFT,
SUBTI = NEARLY MASSLESS SHAFT, CRITICAL SPEED ANALYSIS
SPC         = 1
  RGYRO         = 1
  CMETHOD       = 1
  DISP(PHASE) = ALL
BEGIN BULK
.
$ DISK MASS AND GYRO SPECIFICATIONS
CONM2   100 10      157.0-4
  2.45      2.45         4.9
$ GYROSCOPIC COUPLING AND SPEED CONTROL
$rotorg  rotorid  gid1 gid2 etc
ROTORG   1   1   thru 10   by   1
$rgyro   rid  syncflg  refrotr  spdunit  spdlow   spdhigh  speed
RGYRO    1    SYNC 1   RPM         954.93
$rspinr  rotorid  grida    gridb    gr   spdunit  speed1   speed2   etc.
RSPINR   1    9    10       RPM  954.93
$ COMPLEX EIGENVALUE EXTRACTION
EIGC 1   HESS MAX              8
ENDDATA
```

Note: I_p is required on the CONM2

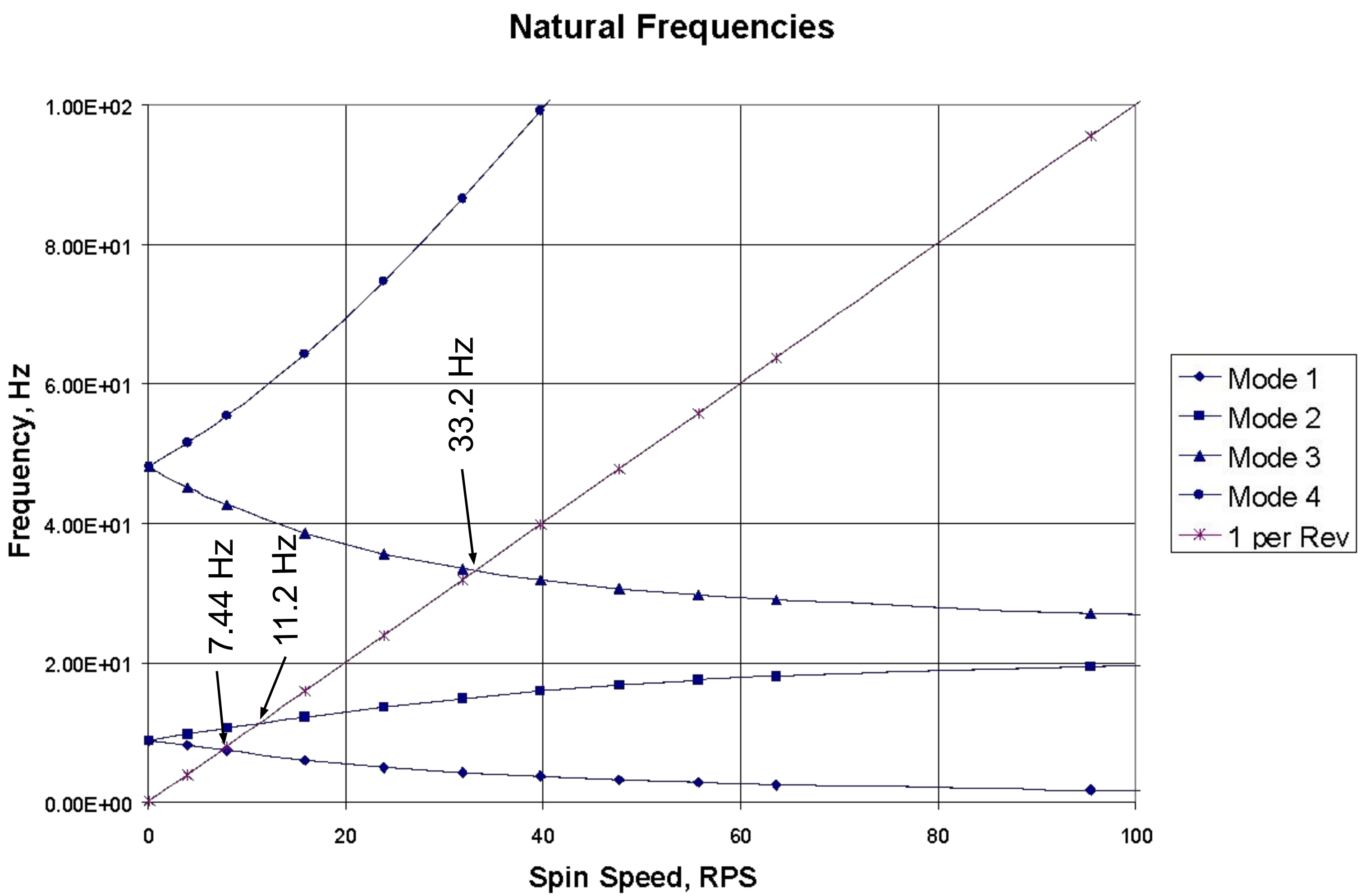
Changed from ASYNC to change spin speed with eigen frequency

Results of Critical Speed Analysis

C O M P L E X   E I G E N V A L U E   S U M M A R Y

ROOT NO.	EXTRACTION ORDER	EIGENVALUE (REAL)	EIGENVALUE (IMAG)	FREQUENCY (CYCLES)	DAMPING COEFFICIENT
1	4	-5.323785E-14	4.676258E+01	7.442496E+00	2.276942E-15
2	3	4.162563E-16	7.063671E+01	1.124218E+01	-1.178583E-17
3	2	-1.070884E-15	2.084957E+02	3.318313E+01	1.027248E-17
4	1	2.390711E+02	1.472887E-15	0.0	0.0

Campbell Diagram – Non-SE Model



Frequency Response Analysis

Example Shaft and Disk, RGYRO Setup

```
ID ROTATING DISK
SOL 108
CEND
TITLE = GYROSCOPIC INFLUENCE OF A RIGID DISK ROTATING ON A
  SHAFT
SUBTI = MASSLESS SHAFT CBAR MODEL
LABEL = FORCED RESPONSE
SPC          = 1
RGYRO        = 1
FREQ         = 1
DLOAD        = 10
DISP(PHASE)  = ALL
BEGIN BULK
$ PARAMETERS
$PARAM   ASING    1
PARAM    COUPMASS1
PARAM    GRDPNT   10
PARAM    POST 0
ASET 10  1245
.
```

RGYRO

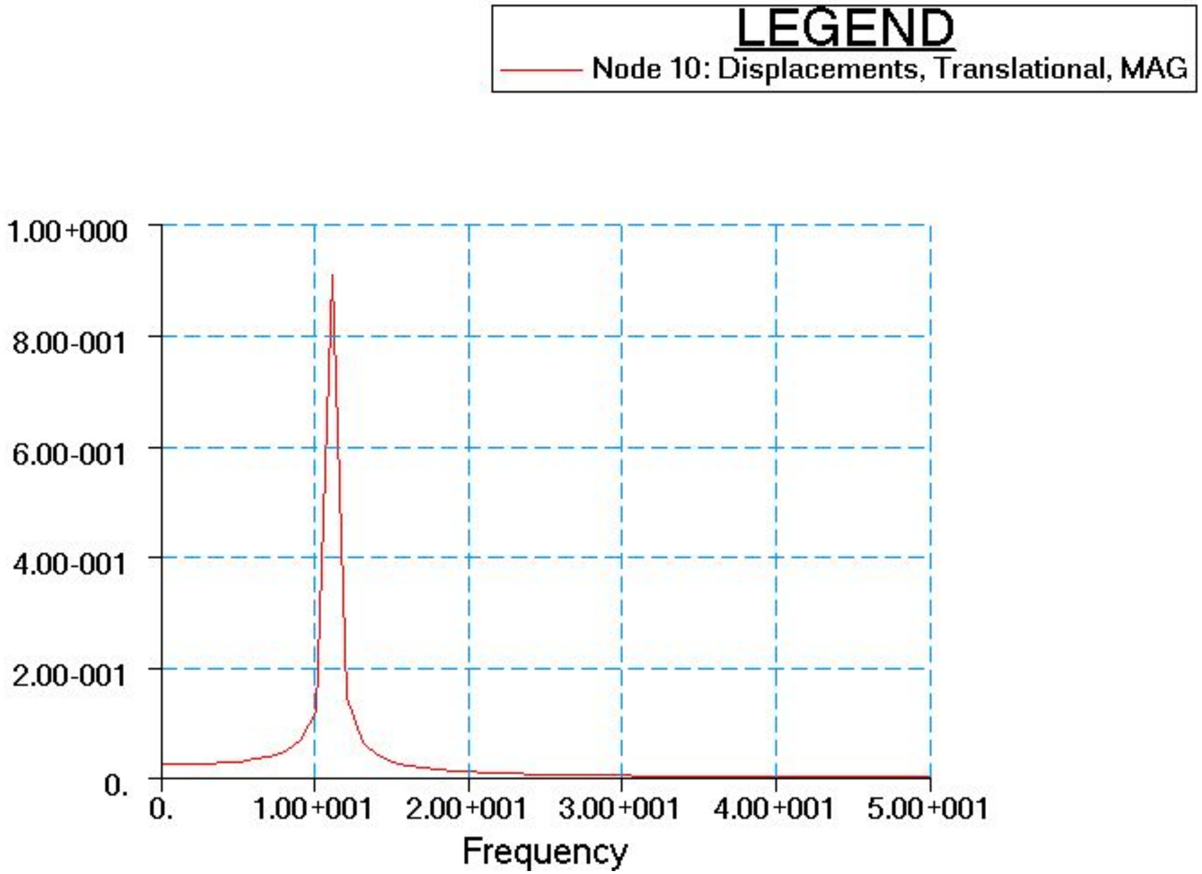
```
ASET 10     1245
$ GEOMETRY
GRID  1           0.0    0.0    0.0          6
=       *1     =      =      =      *10.0  ==
=8
$ SHAFT CONNECTIVITY SPECIFICATION
$CBAR        1      1      1      2      100
CBAR 1       1      1      2      10.0   0.0    0.0
=       *1     =      *1     *1     ==
=7
$GRID        100           10.0   0.0    100.0         123456
$ SHAFT PROPERTIES
PBAR 1       1      10.0   1.6477061.647706
MAT1  1      1.0+6         0.3    1.0-9
$ BOUNDARY CONDITIONS
SPC1  1      123    1
SPC1  1      12     7
```


Example Shaft and Disk, RGYRO Setup

```
$ DISK MASS AND GYRO SPECIFICATIONS
CONM2    100 10     157.0-4
  2.45      2.45        4.9
$ GYROSCOPIC COUPLING AND SPEED CONTROL
$rotorg  rotorid gid1 gid2 etc
ROTORG   1   1   thru 10  by  1
$rgyro   rid syncflg refrotr spdunit spdlow  spdhigh speed
RGYRO    1   SYNC 1   RPM          954.93
$rspinr  rotorid grida   gridb   gr  spdunit speed1  speed2  etc.
RSPINR   1   9   10      RPM 954.93
$ DYNAMIC LOAD SPECIFICATION
DLOAD    10  1.  1.  1   1.  2
FREQ1    1   0.1 1.0 400
DAREA    16  10  1   1.0
DAREA    17  10  2   1.0
DPHASE   17  10  2   -90.
RLOAD1   1   16          18
RLOAD1   2   17      17  18
TABLED1  18
  0.1.   5000.   1.  ENDT
ENDDATA
```

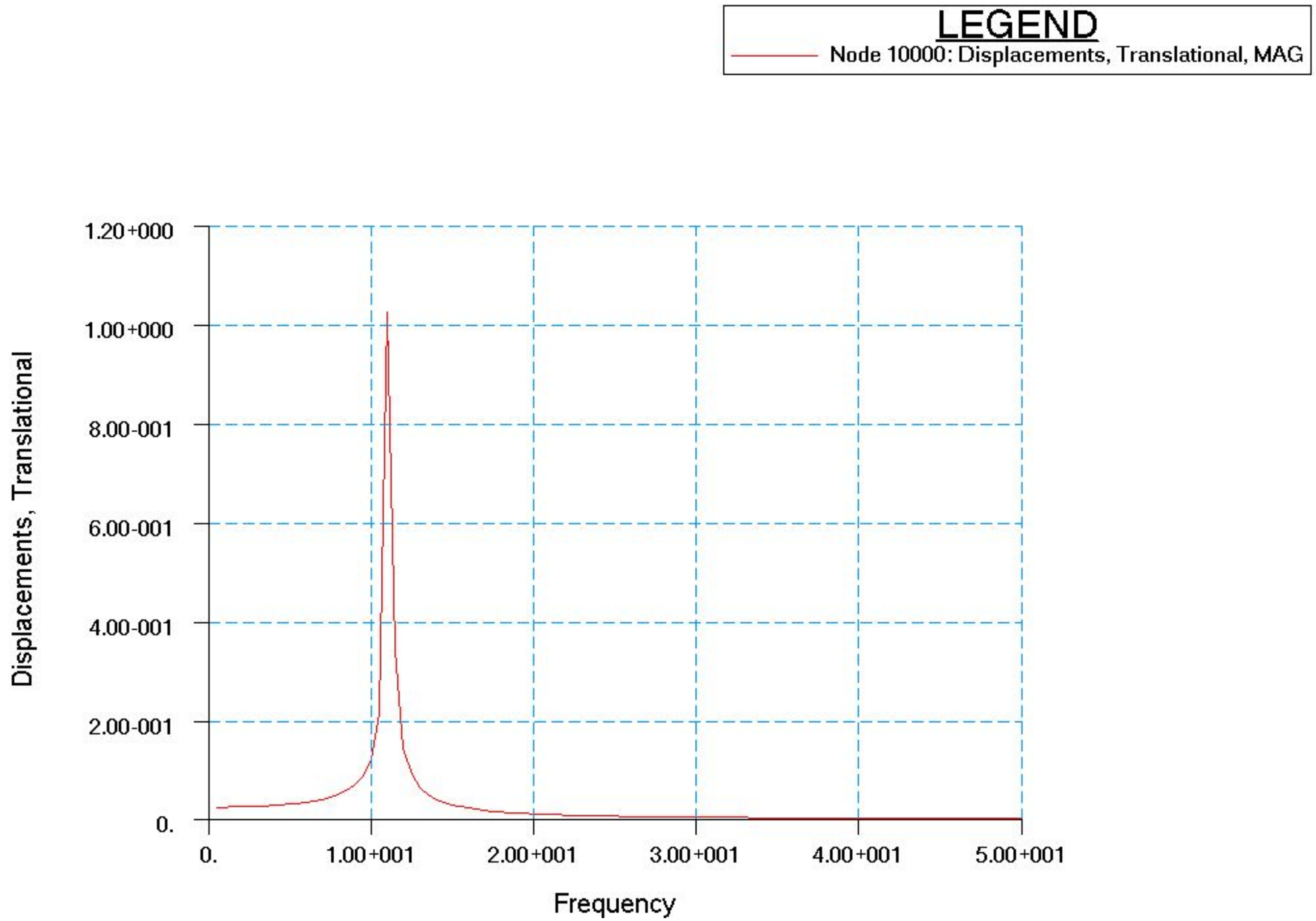
Example Shaft & Disk Frequency Response – Forward Whirl

- The CBAR model with the forward whirl mode is excitec



Example 3-D Frequency Response – Forward Whirl

- **The 3-D model with the forward whirl modes are excited**



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Nonlinear Transient Response Analysis

Transient Response Input

- Dimentberg rotor to illustrate UNBALNC input

UNBALNC	RID	MASS	GRID	X1	X2	X3			
	ROFFSET	THETA	ZOFFSET	Ton	Toff	CFLAG			

Trans. Resp. Input File – 3D Rotor

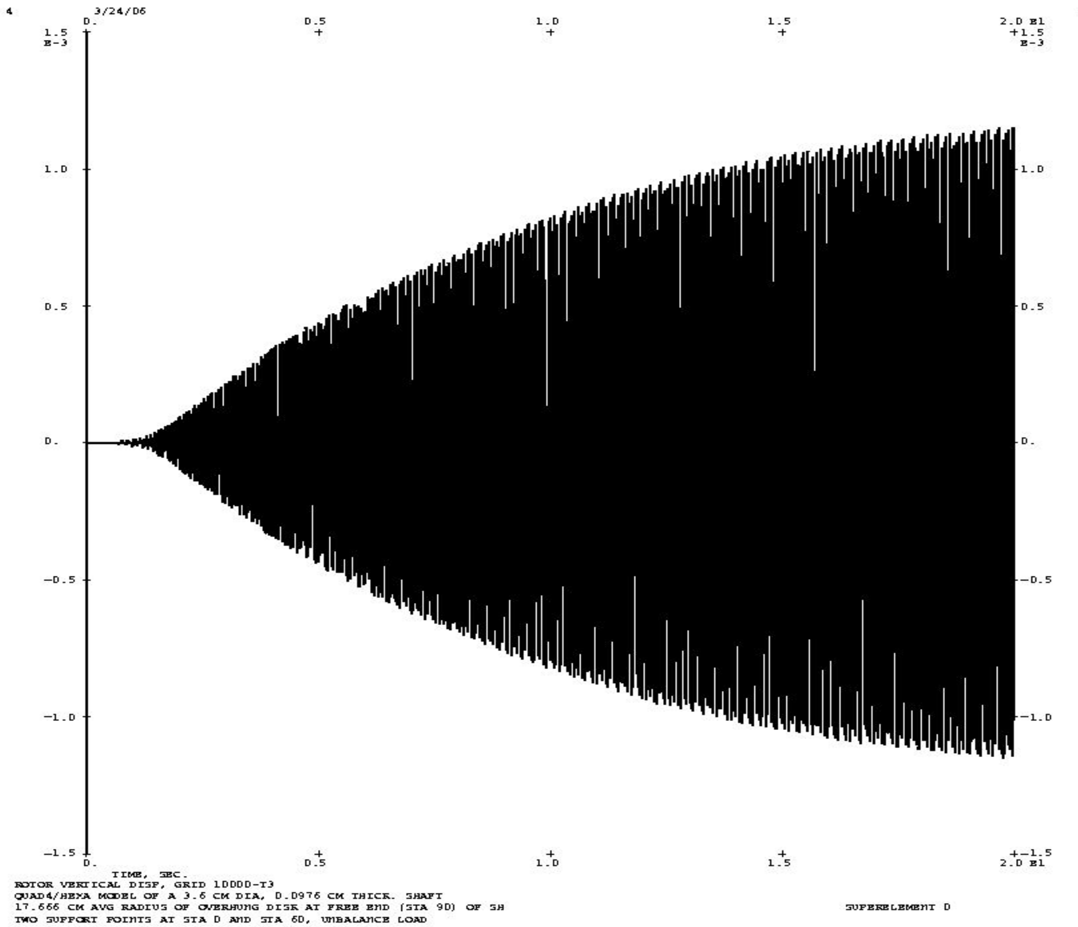
```
ID QUAD4 MODEL
TIME 1000
DIAG 8 $,15,56
SOL 129
CEND
TITLE = QUAD4 MODEL SHAFT and STIFF HEXA DISK
SUBTI = Overhung Disk SOL 129
LABEL = Two support points at sta 0 and sta 60
  echo=none
  PARAM,GRDPNT,10000
  RGYRO   = 1   $ Rotor selection
  TSTEPNL = 1   $ Time step control
  DISP(PLOT) = ALL
  OLOAD(PLOT) = ALL
  set 1 = 10000
  NLLOAD = 1
$  ESE(PLOT,PEAK)    = ALL
  STRESS(PLOT)      = ALL
  SPCFOR(PLOT)      = ALL
```

```
OUTPUT(XYPLOT)
  XAXIS=YES
  YAXIS=YES
  XTITLE=   Time, sec.
  TCURVE= RTR LAT DISP, grid 7000-T2
 XYPLOT,xyprint DISP / 7000(T2)
  TCURVE= RTR VERT DISP, grid 7000-T3
 XYPLOT,xyprint DISP / 7000(T3)
  TCURVE= RTR LAT DISP, grid 10000-T2
 XYPLOT,xyprint DISP / 10000(T2)
  TCURVE= RTR VERT DISP, grid 10000-T3
 XYPLOT,xyprint DISP / 10000(T3)
```

Trans. Resp. Input File – 3D Rotor (cont.)

```
BEGIN BULK
PARAM    LGDISP   1
PARAM    POST 0
PARAM    PRGPST   NO
$
$ rotor input
$
$rotorg  rotorid  gid1 gid2 etc
ROTORG   1    1000 THRU 10000    by   1000
$rspint  rotorid  grida    gridb    gr   spdunit  teid
RSPINT   1    9000 10000        FREQ 100
TABLED1  100
     0.   0.   .01  0.   2.0  15.9155  1000.    15.9155
     ENDT
$
$ DYNAMIC LOAD SPECIFICATION AND SOLUTION TIME STEP
$
TSTEPNL  1    20000    0.001    10
UNBALNC  1    1.56-4   10000    0.   1.   0.
     1.0  0.0  0.0  0.0  1000.    none
```

Rotor Nonlinear Transient Response



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MD Nastran 2006R1

Rotordynamics Bulk Data Entries

Table of Rotordynamic Entries versus Analysis Discipline

Entry	Static	Complex Eigenvalue	Frequency response	Transient
ROTORG	x	x	x	x
RGYRO	x	x	x	
RSPINR	x	x	x	
RSPINT				x
UNBALNC				x (optional)
ROTORSE	x	x	x	x

MD.Nastran 2006r1

- **Additional Damping Options**
  - Hybrid
  - Proportional (Rayleigh)
  - Note: Format change of RSPINR and RSPINT input entries
- **Squeeze Film Damper**
  - As Element CBUSH2D/PBUSH2D
  - Nonlinear Force NLRSFD
- **Rotordynamics Added to Aeroelastic Solutions**
- **Campbell Diagrams - Mode Identification/Tracking**
- **Rotor centerline as a Superelement**
- **Modified Equations of Motion**

High Lights

Damping

Additional Damping Options - RSPINR

1	2	3	4	5	6	7	8	9	10
RSPINR	ROTORID	GRIDA	GRIDB	SPDUNIT	SPTID				
	GR	ALPHAR1	ALPHAR2	HYBRID					

- **SPDUNIT and SPTID shifted left one field**
- **SPTID change**
  - It can be Real
  - Or an Integer, Selects a DDVAL entry
- **Format change, GR moved to continuation line**
- **Added Rayleigh (ALPHAR1 and ALPHAR2) and Hybrid Damping fields**

RSPINR Contents

ROTORID Identification number of rotor

GRIDA/GRIDB Positive rotor spin direction defined from GRIDA to GRIDB

SPDUNIT Specifies whether the listing of relative spin rates is given in terms of RPM or frequency

SPTID Identification number of DDVAL entry listing spin speeds

GR Rotor structural damping factor

ALPHAR1 Scale factor applied to rotor mass matrix for the Rayleigh damping

ALPHAR2 Scale factor applied to rotor stiffness matrix for the Rayleigh damping

HYBRID Identification number of of HYBDMP entry for hybrid damping

Additional Damping Options - RSPINT

1	2	3	4	5	6	7	8	9	10
RSPINT	ROTORID	GRIDA	GRIDB	SPDUNIT	SPTID	SPDOUT			
	GR	ALPHAR1	ALPHAR2	HYBRID					

- SPDUNIT,SPTID shifted left one field
- SPDOUT added to output spin speed versus time
- SPTID change
  - It can be Real
  - Or an Integer, Selects a DDVAL entry
    - For version 2005r2 and earlier, selects a TABLED1
- Continuation line added
  - Format change, GR moved to continuation line
  - Added Rayleigh (ALPHAR1 and ALPHAR2) and Hybrid Damping fields

RSPINT Contents

ROTORID Identification number of rotor

GRIDA/GRIDB Positive rotor spin direction is defined from GRIDA to GRIDB

SPDUNIT Specifies whether the spin rates are given in terms of RPM or frequency

SPTID Identification of DDVAL entry specifying spin rate versus time

SPDOUT EPOINT id to output rotor speed versus time

GR Rotor structural damping factor

ALPHAR1 Scale factor applied to rotor mass matrix for the Rayleigh damping

ALPHAR2 Scale factor applied to rotor stiffness matrix for the Rayleigh damping

HYBRID Identification number of of HYBDMP entry for hybrid damping

Additional Damping Options – HYBDAMP

1	2	3	4	5	6	7	8	9	10
HYBDAMP	ID	METHOD	SDAMP	KDAMP					

- Hybrid modal damping for direct dynamic solutions
- Specifies the modes and damping for hybrid damping calculations. Currently only on applies to rotor, support hybrid damping to be added

ID Identification number of HYBDAMP entry (Integer > 0; Required)

METHOD Identification number of METHOD entry for modes calculation (Integer > 0; Required)

SDAMP Identification number of SDAMP entry for modes calculation (Integer > 0; Required)

KDAMP Selects modal “structural” damping (Character: “YES or “NO”, see Remark 1; Default = “NO”)

Squeeze Film Damper as Nonlinear Force

1	2	3	4	5	6	7	8	9	10
NLRSFD	SID	GA	GB	PLANE	BDIA	BLEN	BDLR	SOLN	
	VISCO	PVAPCO	NPORT	PRES1	THETA1	PRES2	THETA2	NPNT	
	OFFSET1	OFFSET2							

- The squeeze film damper (SFD) was implemented as a nonlinear force similar to the NLRGAP. The SFD forces are activated from the Case Control Section using the NONLINEAR command. The NLRSFD bulk data entry has the above input format.
- See MD-Nastran 2006r1 QRG or Release Guide for details of each field. See Section 7.1 of the MSC.Nastran 2005 Release Guide for more complete description and example problem.

Squeeze Film Damper as Nonlinear Element

1	2	3	4	5	6	7	8	9	10
CBUSH2D	EID	PID	GA	GB	CID	PLANE	SPTID		

- For better accuracy and to facilitate use in other solution sequences the NLRSFD was also implemented as an element. The Squeeze Film Damper was added as an option of a more general 2-D bearing element (CBUSH2D).

EID	Element identification number (Integer > 0)
PID	Property identification number of a PBUSH2D entry. (Integer > 0).
GA	Inner grid (Integer > 0).
GB	Outer grid (Integer > 0).
PLANE	Orientation plane CID, XY,YZ, ZX (Character)
SPTID	Optional rotor speed input for use with table lookup or DEQATN generation of element properties (Integer > 0 or blank).

Squeeze Film Damper as Nonlinear Element

1	2	3	4	5	6	7	8	9	10
PBUSH2D	PID	K11	K22	B11	B22	M11	M22		
	"SQUEEZE"	BDIA	BLEN	BCLR	SOLN	VISCO	PVAPCO		
	NPORT	PRES1	THETA1	PRES2	THETA2	OFFSET1	OFFSET2		

- Defines linear and nonlinear properties of a two-dimensional element (CBUSH2D entry).
- Stiffness, damping and Mass for linear element similar to the CBUSH element except the CBUSH2D only specifies values in two directions only.
- The nonlinear element input follows the NLRSFD input.
- See MD.Nastran 2006r1 QRG and Release Guide for specific details of the input fields for the PBUSH2D entry.

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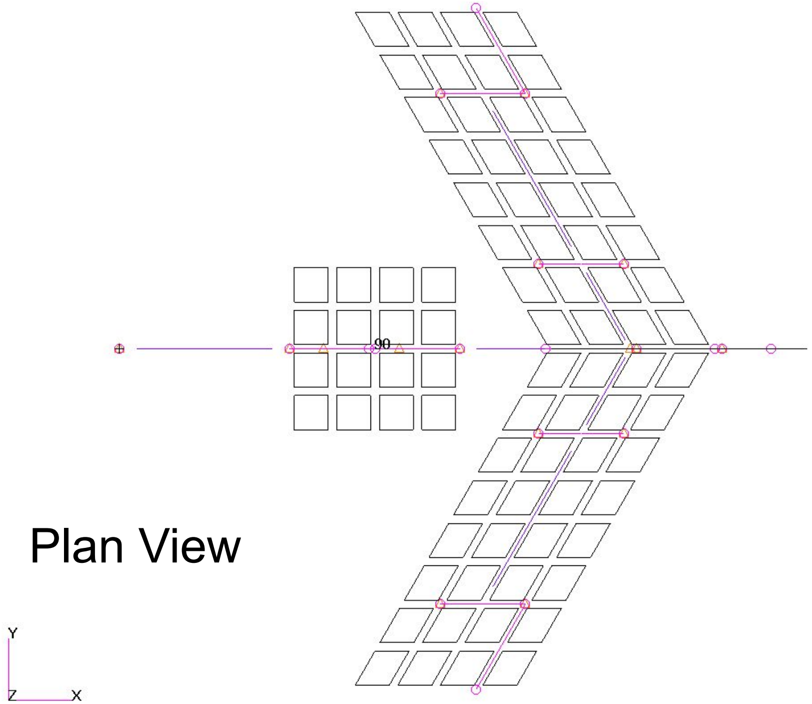
Rotors and Aeroelasticity

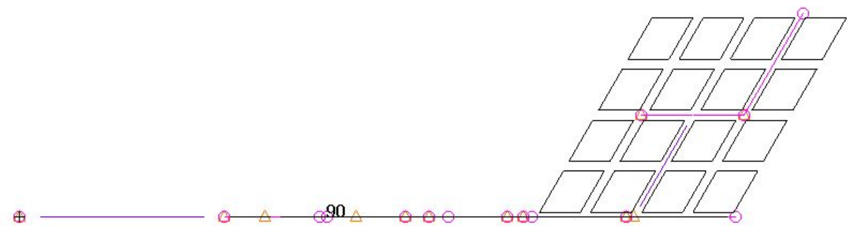
Gyroscopic Terms Added to Aeroelasticity

- **SOL 145 and 146 have the same rotordynamic equations as complex eigenvalue and frequency response analyses.**

FSW Full Model Transient Response



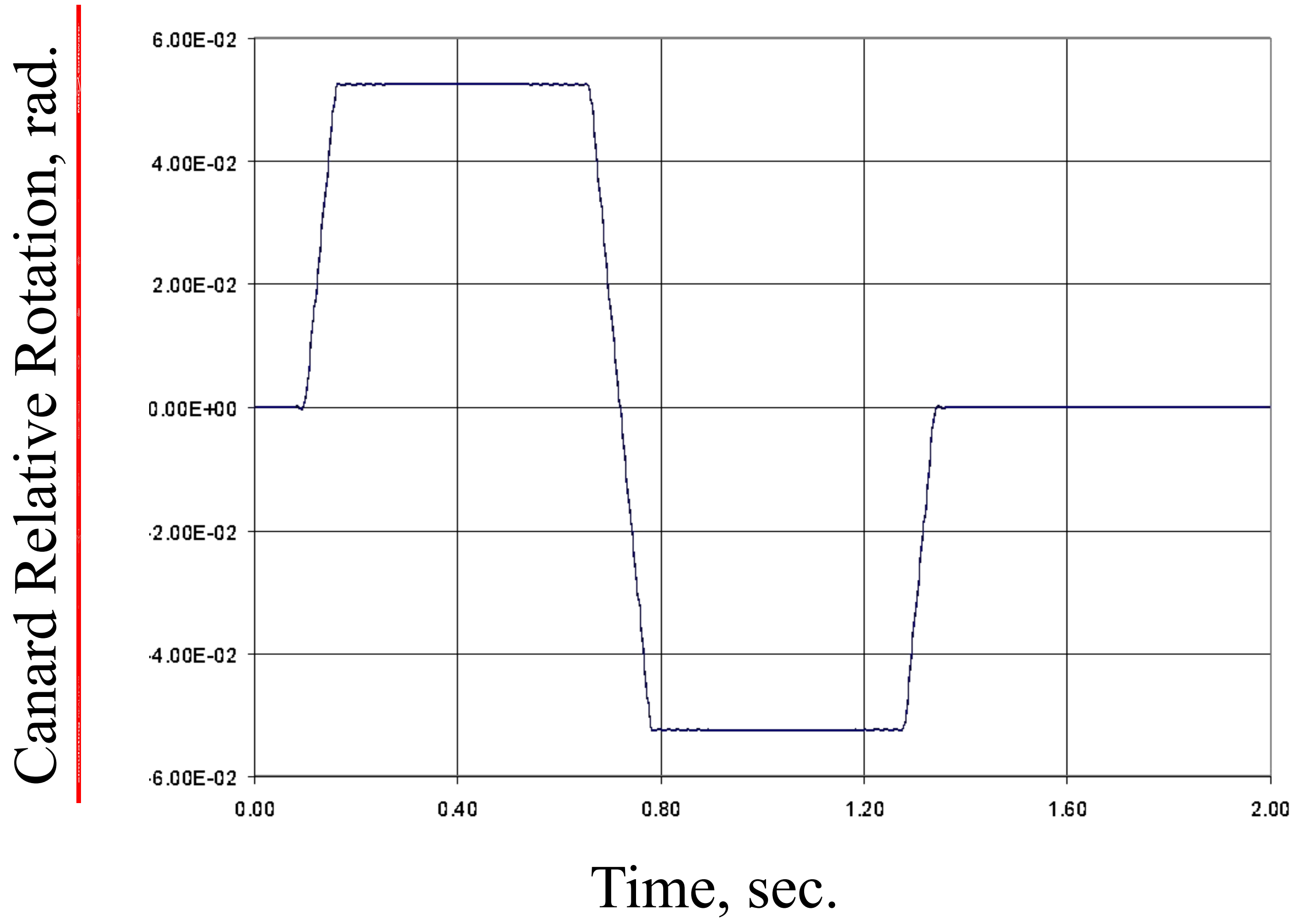
Plan View



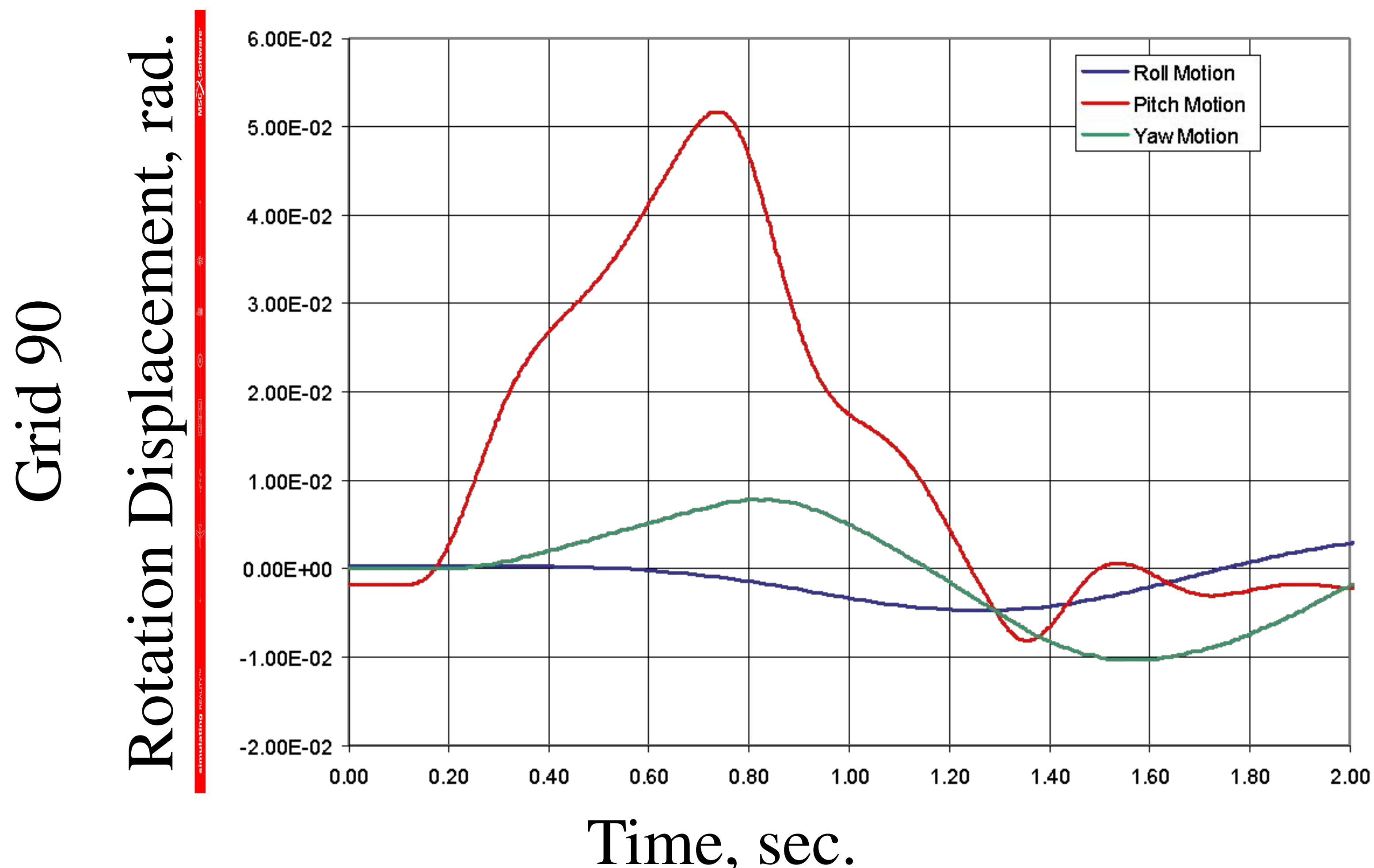
Side View

Z
Y X

Canard Control Surface Input Deflection



Pitch, Roll and Yaw Response



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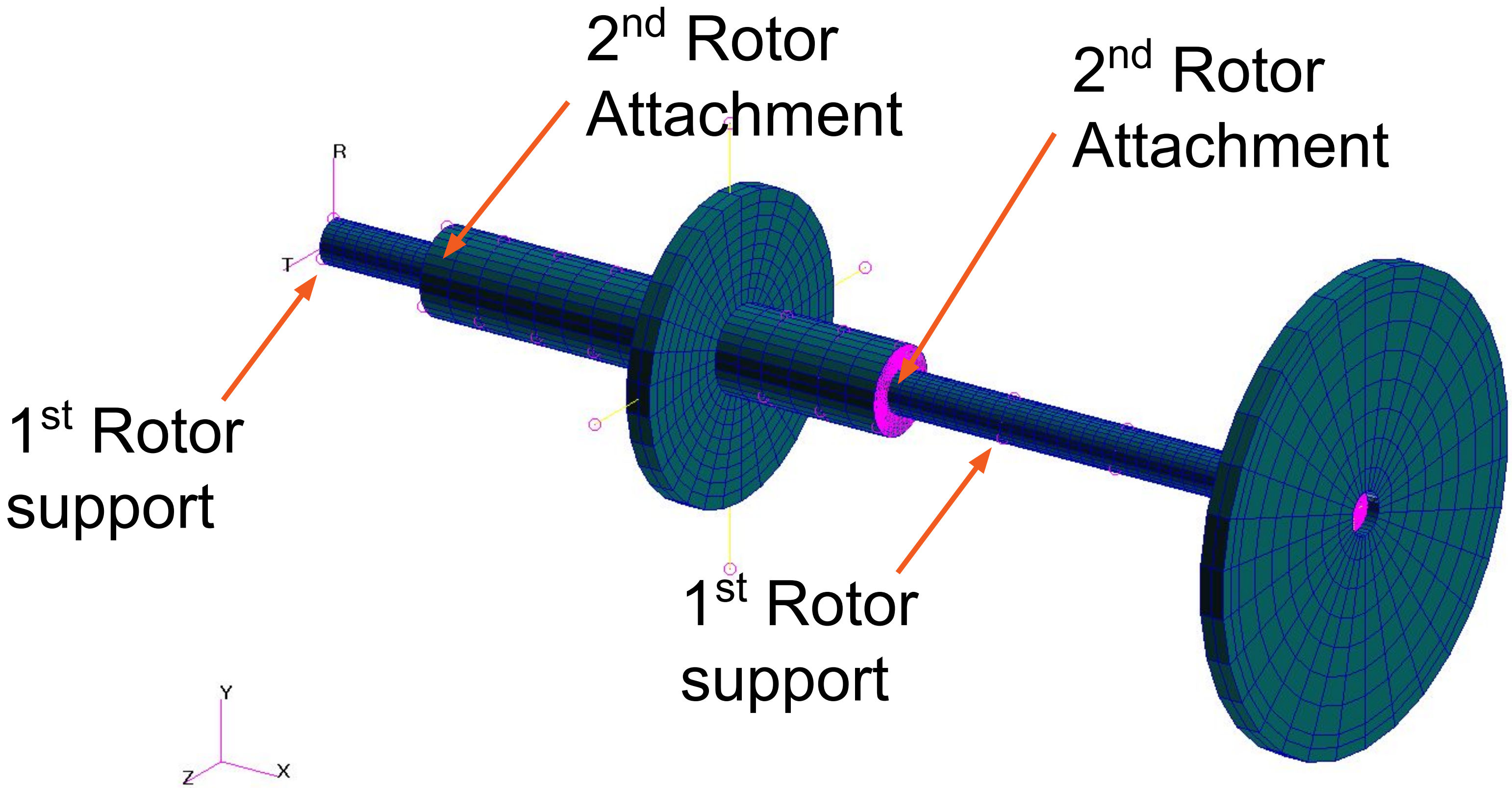
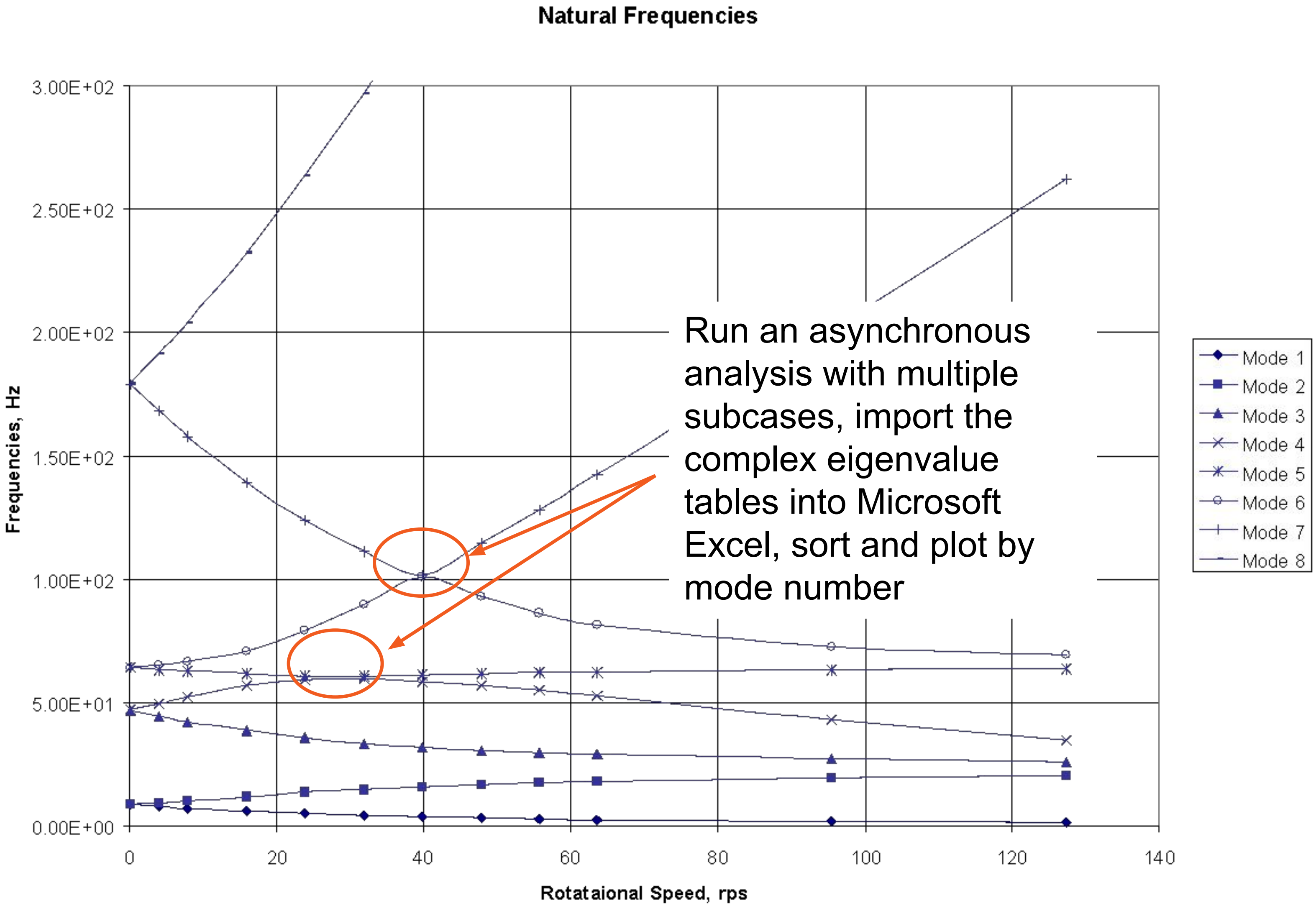
Campbell Diagrams

Campbell Diagrams

- **Let's first look as a 2 rotor model**



Campbell Diagram for the 2 Rotor Model



Run an asynchronous analysis with multiple subcases, import the complex eigenvalue tables into Microsoft Excel, sort and plot by mode number

New Input to Generate Data for Campbell Diagrams

- **Used in Complex Eigenvalue Analysis with SOL 107 or 110**

- **Case Control Command**
  - CAMPBELL=n
  - Selects CAMPBLL bulk data entry

CAMPBLL Bulk Data

1	2	3	4	5	6	7	8	9	10
CAMPBLL	CID	VPARM	DDVALID	TYPE	ID	NAME/FID			

- **Parameters for Campbell diagram generation.**

  CID Identification number of entry (Integer >0).

  VPARM Variable parameter, 'SPEED', 'PROP', 'MAT' Only SPEED is implemented, PROP and MAT are not.

  DDVALID Identification number of DDVAL entry.

  TYPE For VPARM set to 'SPEED' allowable entries are: 'FREQ' and 'RPM', others not implemented.

  ID Property or material entry identification number (Integer > 0), not required for 'SPEED'

  NAME/ID No data needed for 'SPEED'

Campbell Diagram Data Generation Require Forward and Backward Rotor Mode Identification and Tracking

- Forward and backward rotor modes are identified using proportional kinetic and strain energies of the reference rotor compared to the total structure.
- The rotor modes must be tracked in case the eigenvalues of the modes change ordering.
- Tracking the modes may require running from highest to lowest spin speeds.

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Rotor Centerline Grids Interior to a SE

Rotordynamics Bulk Data Entries

- ROTORSE—specifies grids that compose the rotor line model

Format:

ROTORSE	ROTORID	SEID	SEOPT						

Example:

ROTORSE	100	10							

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Modified Equations of Motion

Rotordynamic Basic Equations Are Modified

- **Time-Domain Equation**

$$M\ddot{u}(t) +$$

$$\left(\begin{array}{l} B_s + \alpha 1 M_s + \alpha 2 K_s + \left(\dfrac{g}{W3}\right) K_s + \left(\dfrac{1}{W4}\right) K4_s \\ + \left(B_R + BH_R + \alpha 1_R M_R + \alpha 2_R K_R\right) + \left(\dfrac{g_r}{WR3}\right) K_R \\ + \left(\dfrac{1}{WR4}\right) K4_R + \left(\dfrac{1}{WRH}\right) KH_R + \Omega B^G \end{array}\right) \dot{u}(t) +$$

$$\left(\begin{array}{l} K_s + K_R \\ + \Omega \left(\begin{array}{l} K^{CB} + K^{CBH} + \alpha 1_R K^{CM} + \alpha 2_R K^{CK} \\ \left(\dfrac{g_r}{WR3}\right) K_R^{CK} + \left(\dfrac{1}{WR4}\right) K_R^{CK4} + \left(\dfrac{1}{WRH}\right) K^{CKH} \end{array}\right) \end{array}\right) u(t) = F(t)$$

Rotordynamic Basic Equations Are Modified

- **Time-Domain Equation (cont.) - where**

M	= total mass matrix
B_s	= support viscous damping matrix
$\alpha 1 M_s$	= support mass contribution to Rayleigh damping
$\alpha 2 K_s$	= support stiffness contribution to Rayleigh damping
$\left(\dfrac{g}{W3}\right) K_s$	= support viscous damping equivalent to structural damping
$\left(\dfrac{1}{W4}\right) K4_s$	= support viscous damping equivalent to material structural damping
B_R	= rotor viscous damping matrix
BH_R	= rotor hybrid damping matrix
$\alpha 1_R M_R$	= rotor mass contribution to Rayleigh damping
$\alpha 2_R K_R$	= rotor stiffness contribution to Rayleigh damping
$\left(\dfrac{g_r}{WR3}\right) K_R$	= rotor viscous damping equivalent to structural damping

Rotordynamic Basic Equations Are Modified

$\left(\frac{1}{WR4}\right) K4_R$ = rotor viscous damping equivalent to material structural damping

$\left(\frac{1}{WRH}\right) KH_R$ = rotor viscous damping equivalent to hybrid structural damping

B^G = gyroscopic force matrix

K_s = support stiffness matrix

K_R = rotor stiffness matrix

$K4_s$ = support material damping matrix

$K4_R$ = rotor material damping matrix

Ω = rotor rotation rate

K^{CB} = "circulation" matrix due to B_R

K^{CBH} = "circulation" matrix due to BH_R

$g_r K_R^{CK}$ = "circulation" matrix due to $g_r K_R$

K_R^{CK4} = "circulation" matrix due to $K4_R$

K^{CKH} = "circulation" matrix due to KH_R

WR3, WR4 and WRH are user parameters