Rotordynamics Analysis Overview

Featuring Analysis Capability of RAPPID™

Prepared by

Rotordynamics-Seal Research

Website: www.rda.guru

Email: rsr@rda.guru

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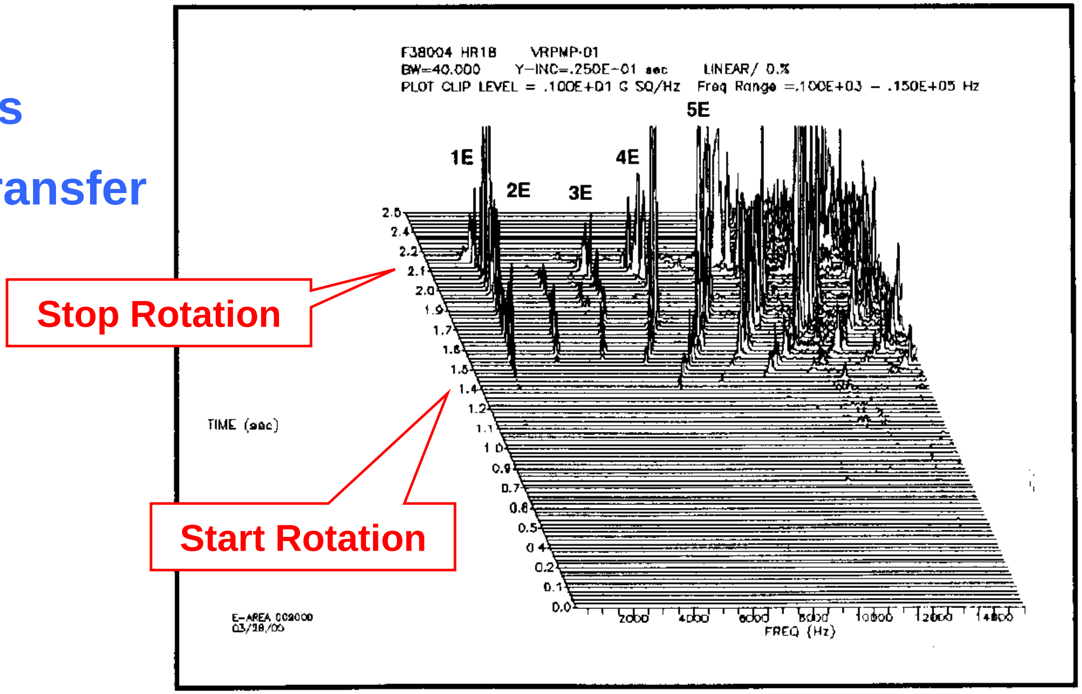
Vibration of Rotating Systems

- **Vibration Signature can be Quite Complex in Nature**
- **Vibration Modeling is Frequently used to Aid Design & Development**
- **Vibration Model**
    - **Structural Characteristics**
    - **Structure-to-Structure Transfer Functions**
    - **Forcing Functions**
- **Vibration Signature**
    - **Frequency**
    - **Magnitude**
    - **Phase**



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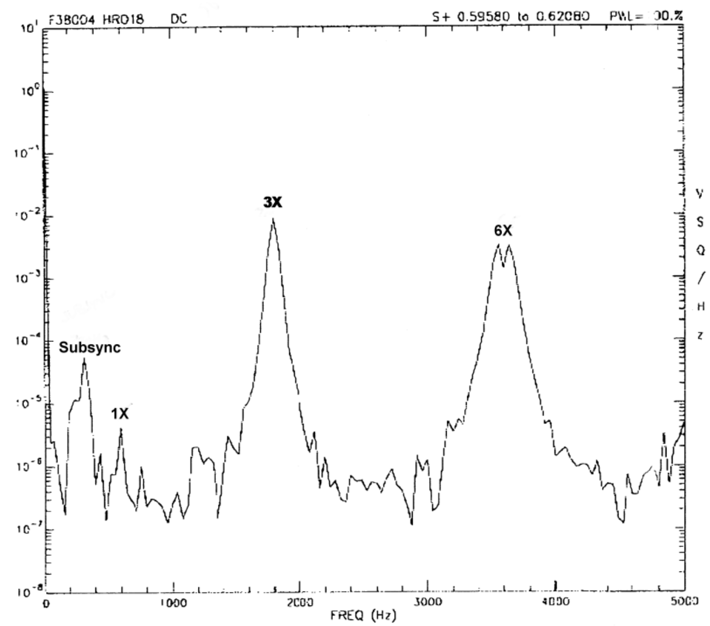
Vibration Signature Contributors

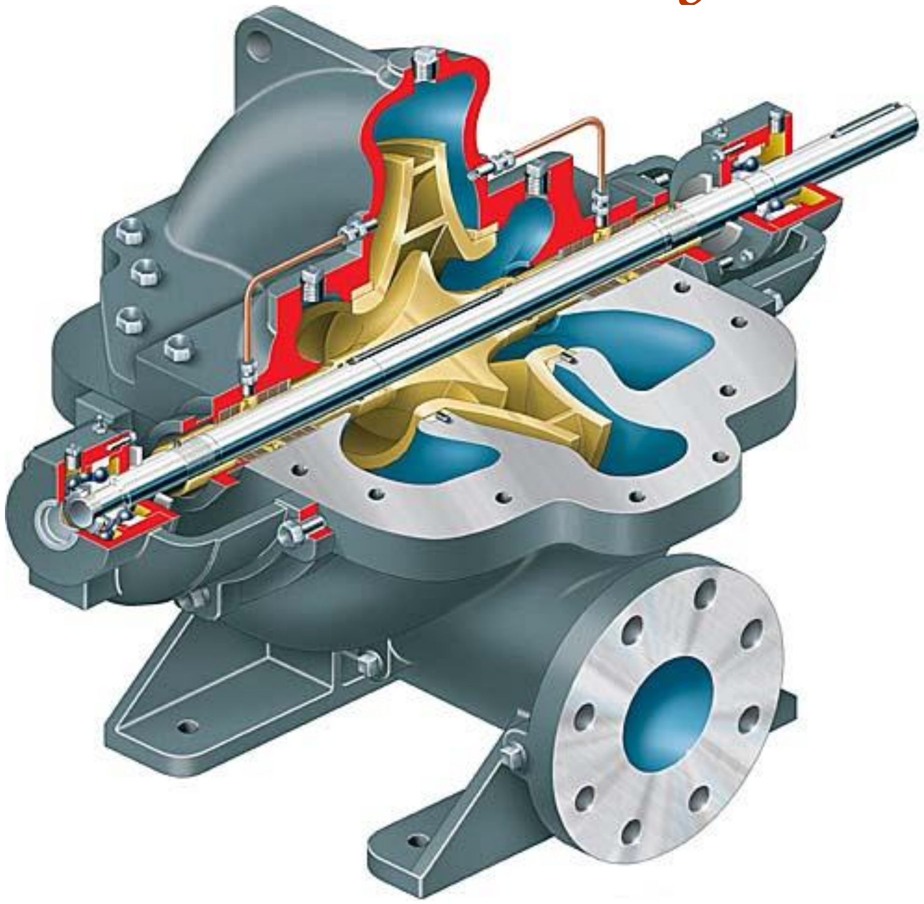
- **Major Peak Sources**
  - Structural Harmonics
  - Impacts/Rubs
  - Misalignment
  - Rotor Bow
  - Unbalance
    - Mechanical
    - Hydraulic
  - Trapped Fluids
  - Unstable Rotor Whirl
  - Large Scale Flow Effects
    - Periodic
    - Unsteady
    - Unstable

- **Noise Floor Sources**
  - Acoustics
  - Light Rubs
  - Small Scale Flows Effects
    - Turbulent eddies
    - Cavitation bubbles
    - Localized reversals



Typical Commercial Machinery

- Stationary
  - Few Weight/Volume Restrictions
    - Low speed
    - Rigid housing
    - Sub-critical rotors
    - Compartmentalized designs
  - Oil Lubrication Systems
    - Incompressible lubricant
      - Stiffness, damping, mass coef.
    - Viscous lubricant
      - High rotor damping
- Low Energy Density
  - Pump: 0.5 Hp/lb
  - Gas Turbine: 3 Hp/lb
- Continuous Operation
  - Steady State
  - Thermal Equilibrium
  - Constant Power Levels



Minimal Unsteady Effects

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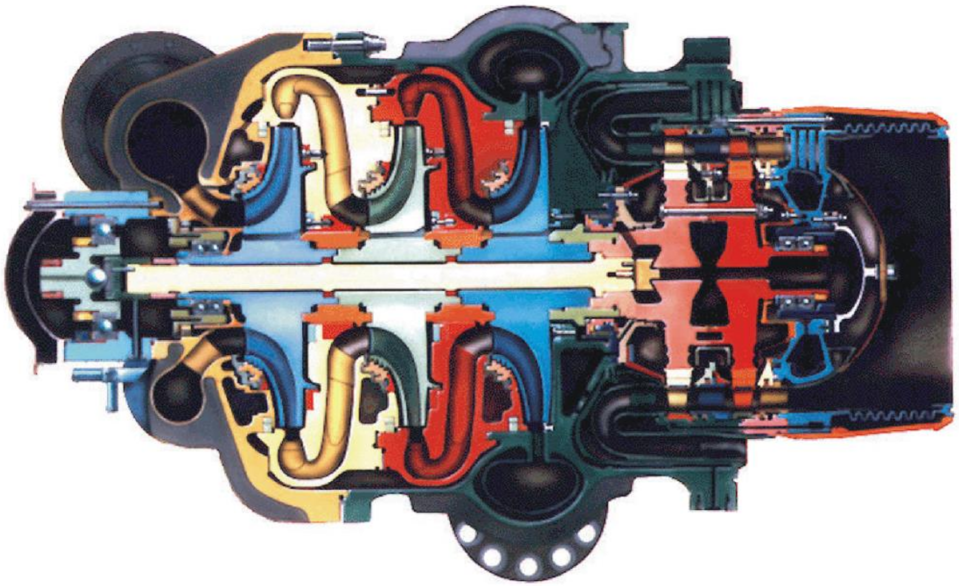
Typical Rocket Engine Turbopump

- **Mobile**
  - **Extreme Weight/Volume Restrictions**
    - **High speed**
    - **Flexible rotors & housings**
    - **Highly integrated designs**
  - **Process Lubricated**
    - **Compressible lubricants**
      - **Transfer functions**
    - **Low viscosity lubricants**
      - **Lightly damped rotors**
  - **Varying Ambient Conditions**
- **High Energy Density (~ 100 Hp/lb)**
  - **Use of Cryogens**
    - **Wide pressure/temperature ranges**
  - **Steep Ramp Rates**
- **Short Run Durations**
  - **Power Level Changes**
    - **Steady state never achieved**



Major Unsteady Effects

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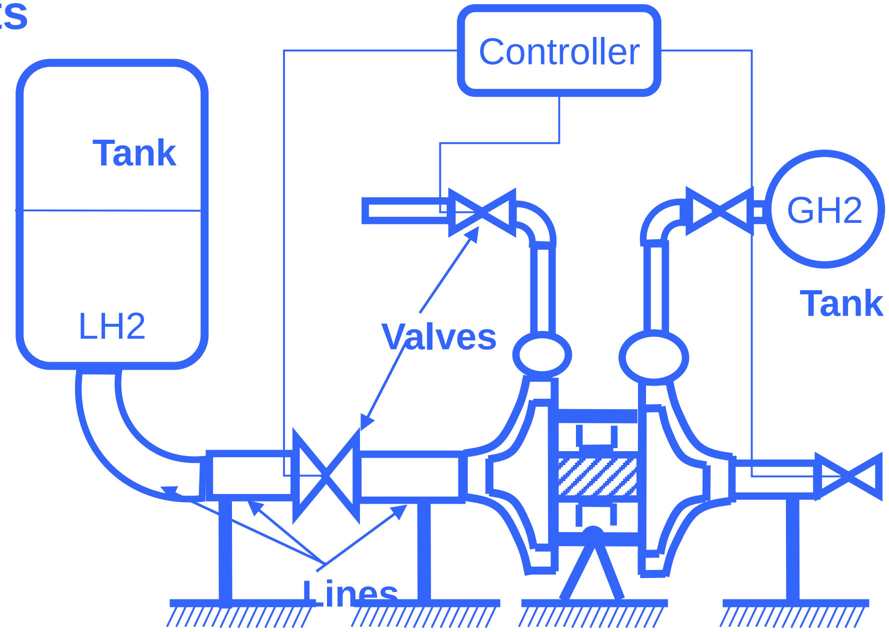
Rotordynamics Model

Elements of Vibration Model	Sub Categories
Structural Characteristics	Rotating Assemblies
	Stationary Assemblies
Structure-to-Structure Transfer Functions	Fluidic Interfaces
	Mechanical Interfaces
	Hybrid Interfaces
Forcing Functions	Flow Related
	Mechanical Related
	Electrical/Magnetic Related
	Controls Related
	Rotor/Stator Interactions
Operating Geometry Changes	Distortions
	Relative Displacements

Structural Characteristics

- **Structural Characteristics Purpose**
  - **Establish Structural Compliance and Resonance Frequencies**
- **Required for Rotating and Stationary Assemblies**
  - **Includes Facility/Engine Effects**
- **Critical Phenomena**
  - **Mass**
  - **Inertia**
  - **Load Path**
  - **Material Properties**
    - **Temperature dependent**



Accurate structural characterization is critical for establishing natural frequency locations

Transfer Functions

- **Transfer Function Purpose**
  - **Translate the Motion of One Structure into Forces on Another Structure**
    - **Motion measured in displacements, velocities, accelerations**

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \begin{bmatrix} H_{xx}(\omega) & H_{xy}(\omega) \\ H_{yx}(\omega) & H_{yy}(\omega) \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix}$$

- **Required for all Rotating and Stationary Structure Interfaces**
  - **Typical Interfaces Include**
    - **Bearings, seals, dampers**
    - **Pump, turbine, inducer wheels**
    - **Splines/couplings**
    - **Pump out vanes**
    - **Rub surfaces**

Accurate transfer functions characterization is critical for establishing orbit stability and natural frequency locations

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Transfer Functions

- **General Form of Transfer Function (H matrix)**
  - **H Matrix Elements are Complex**
  - **H Matrix Elements May Vary Non-Linearly with Frequency**

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \begin{bmatrix} H_{xx}(\omega) & H_{xy}(\omega) \\ H_{yx}(\omega) & H_{yy}(\omega) \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix}$$

– **Assuming an Interface Adheres to the Linearized Model Leads To:**

$$H_{xx}(\omega) = K_{xx} + iC_{xx}\omega - M_{xx}\omega^2$$

$$H_{xy}(\omega) = K_{xy} + iC_{xy}\omega - M_{xy}\omega^2$$

$$H_{yx}(\omega) = K_{yx} + iC_{yx}\omega - M_{yx}\omega^2$$

$$H_{yy}(\omega) = K_{yy} + iC_{yy}\omega - M_{yy}\omega^2$$

Forcing Functions

- **Forcing Function Purpose**
  - **Excite the Rotating and Stationary Assemblies**
    - **Defined by magnitude, frequency, and phase**

- **Required for Excitation Forces Acting on the Rotating and Stationary Structures**
  - **Typical Excitation Forces Include**
    - **Rotor unbalance**
    - **Impacts/rubs**
    - **Misalignment, shaft bow, loose press fits**
    - **Hydraulic unbalance**
    - **Trapped fluid in a rotating structure**
    - **Steady and unsteady flow fluctuations**
      - **Valve induced**
      - **Controller induced**
    - **Controller imperfections**
    - **Rotor/stator interactions**
      - **Jet, vane pass, vortex shedding**

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Rotordynamic Analysis

- **Available Analysis Types**

  - **Eigenvalue**
    - **Free-Free**
    - **Undamped Critical Speed**
    - **Damped Eivenvalue (Stability)**

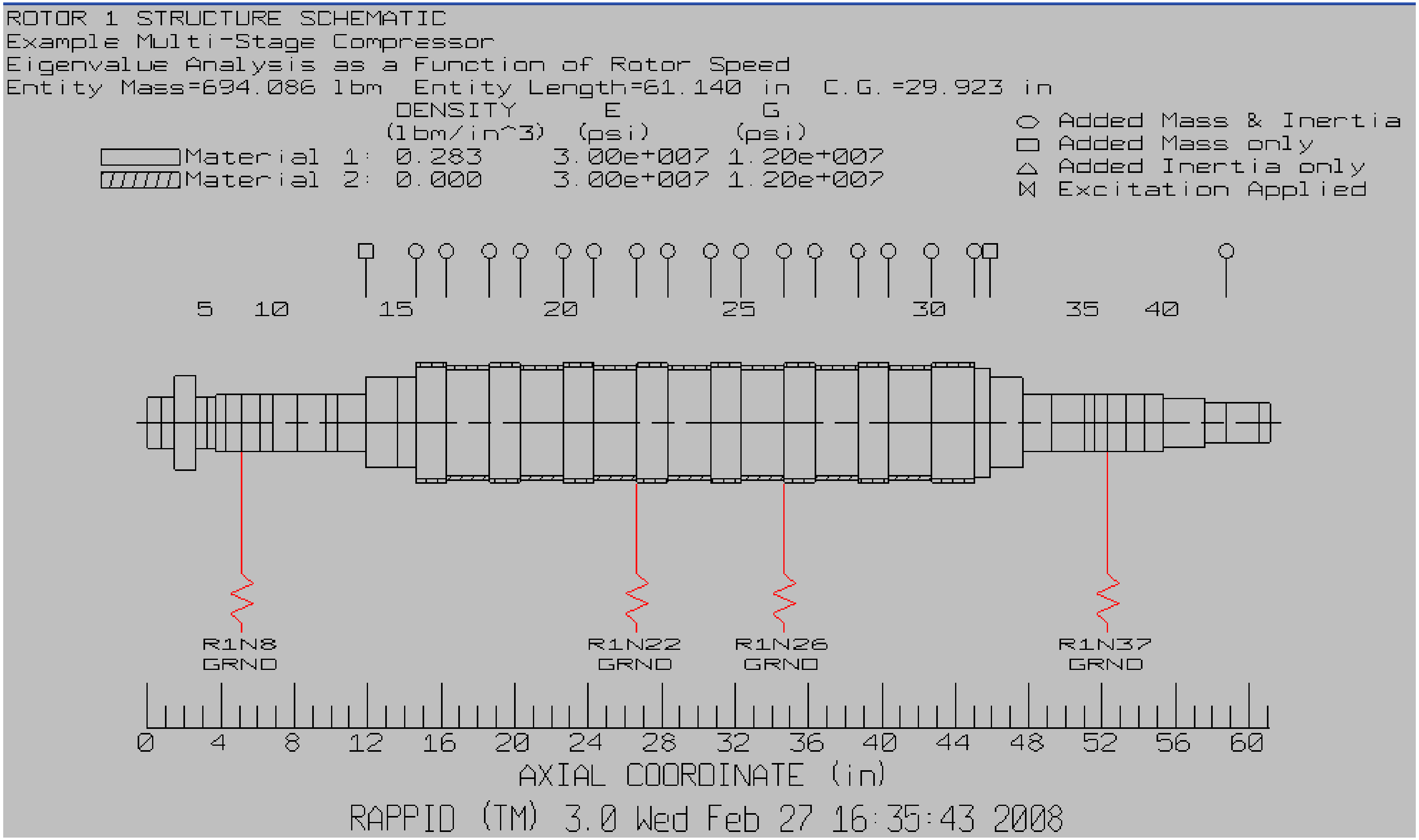
  - **Forced Response (Linear)**
    - **Steady State**

  - **Forced Response (Non-Linear)**
    - **Transient (not covered in this information package)**

Free-Free Analysis

- **Required Information**
  - **Structural Model**
- **Analysis Assumptions**
  - **No Rotation**
  - **No Interconnection Forces**
  - **No Forcing Functions**
- **Analysis Results**
  - **Natural Frequencies**
  - **Mode Shapes (planar)**
- **Why Perform Free-Free Analysis?**
  - **Verify Structural Model by Comparing to Rap Test Data**

Sample Rotor Model



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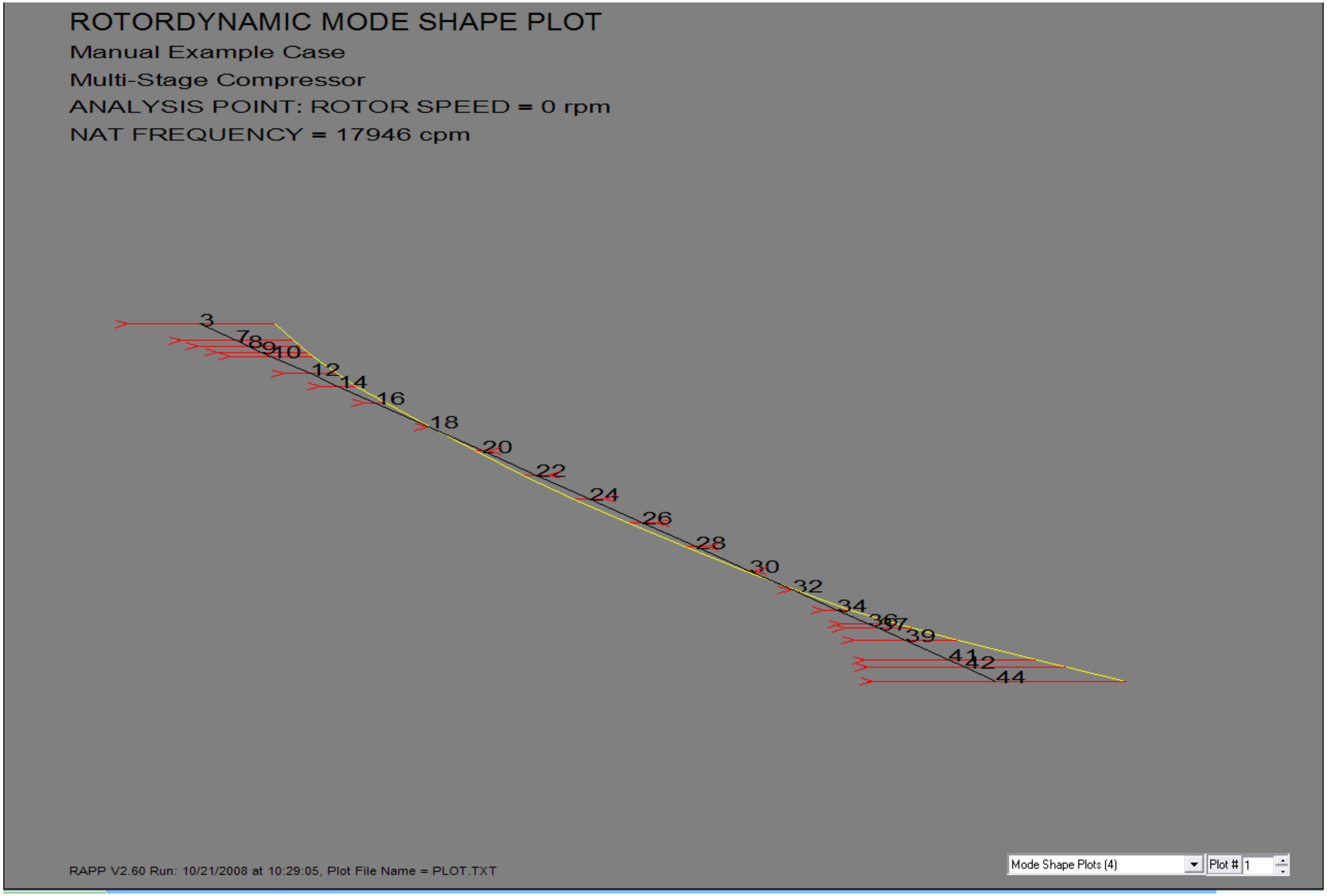
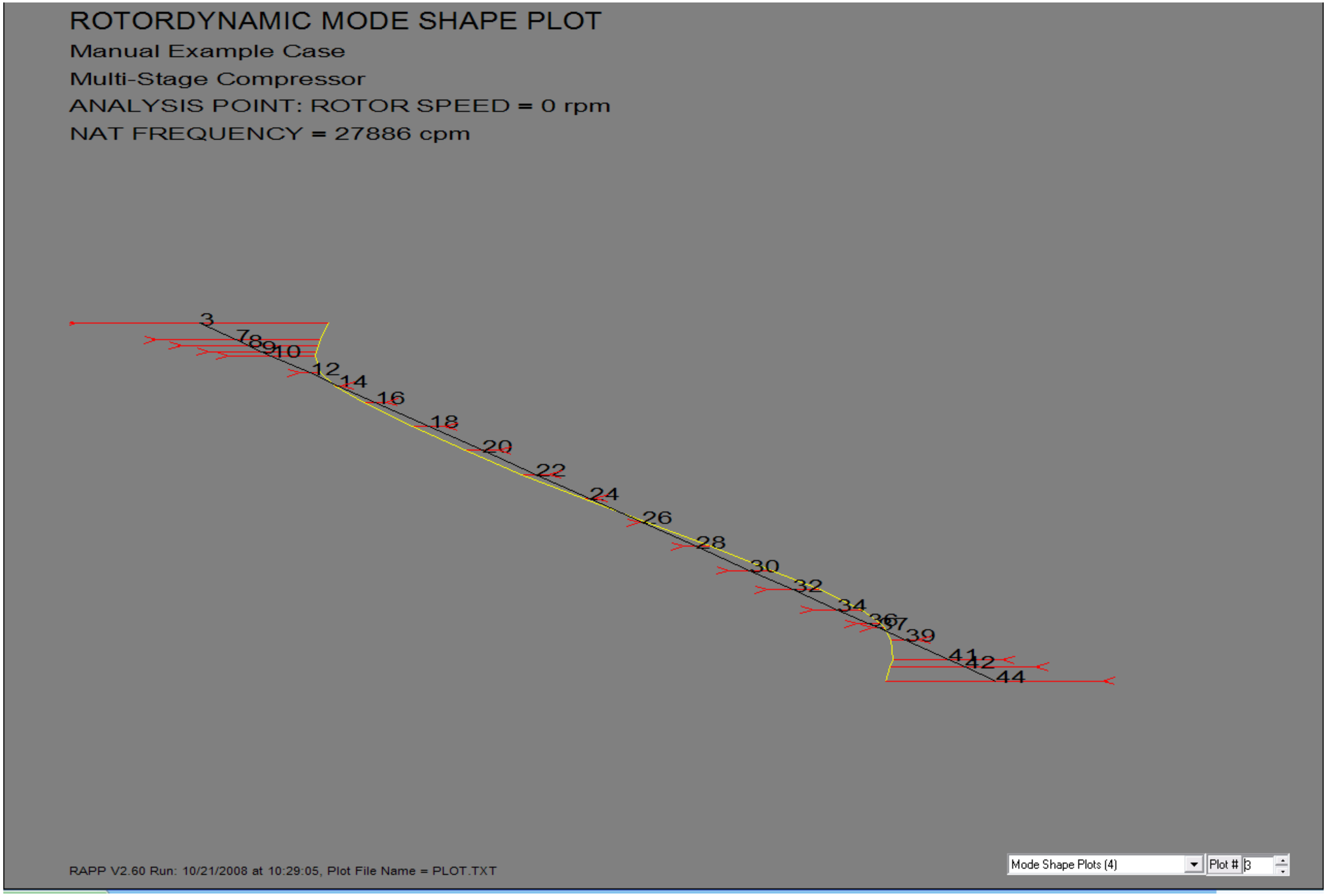
1st Free-Free Bending Mode



2nd Free-Free Bending Mode



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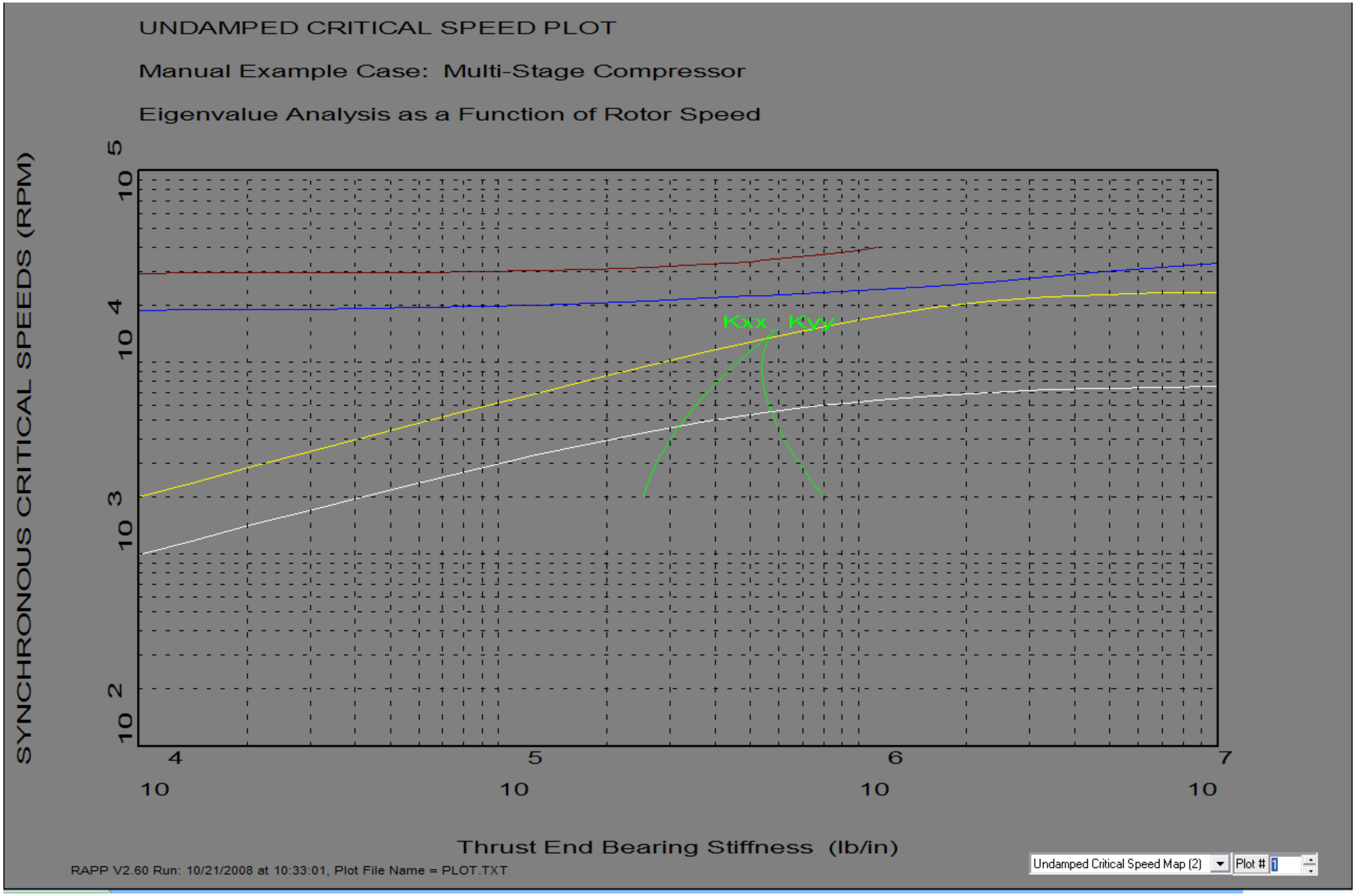
Undamped Critical Speed Analysis

- **Required Information**
  - **Structural Model**
  - **Range of Bearing Stiffness**
- **Analysis Assumptions**
  - **No Damping**
  - **No Cross-Coupling**
  - **Symmetric Rotor Supports**
  - **Natural Frequency Coincides with Running Speed**
- **Analysis Results**
  - **Synchronous Critical Speed as a Function of Direct Stiffness**
  - **Mode Shapes (circular)**
- **Why Perform Undamped Critical Speed Analysis?**
  - **If Precise Transfer Functions are not Available**

Undamped Critical Speed Map



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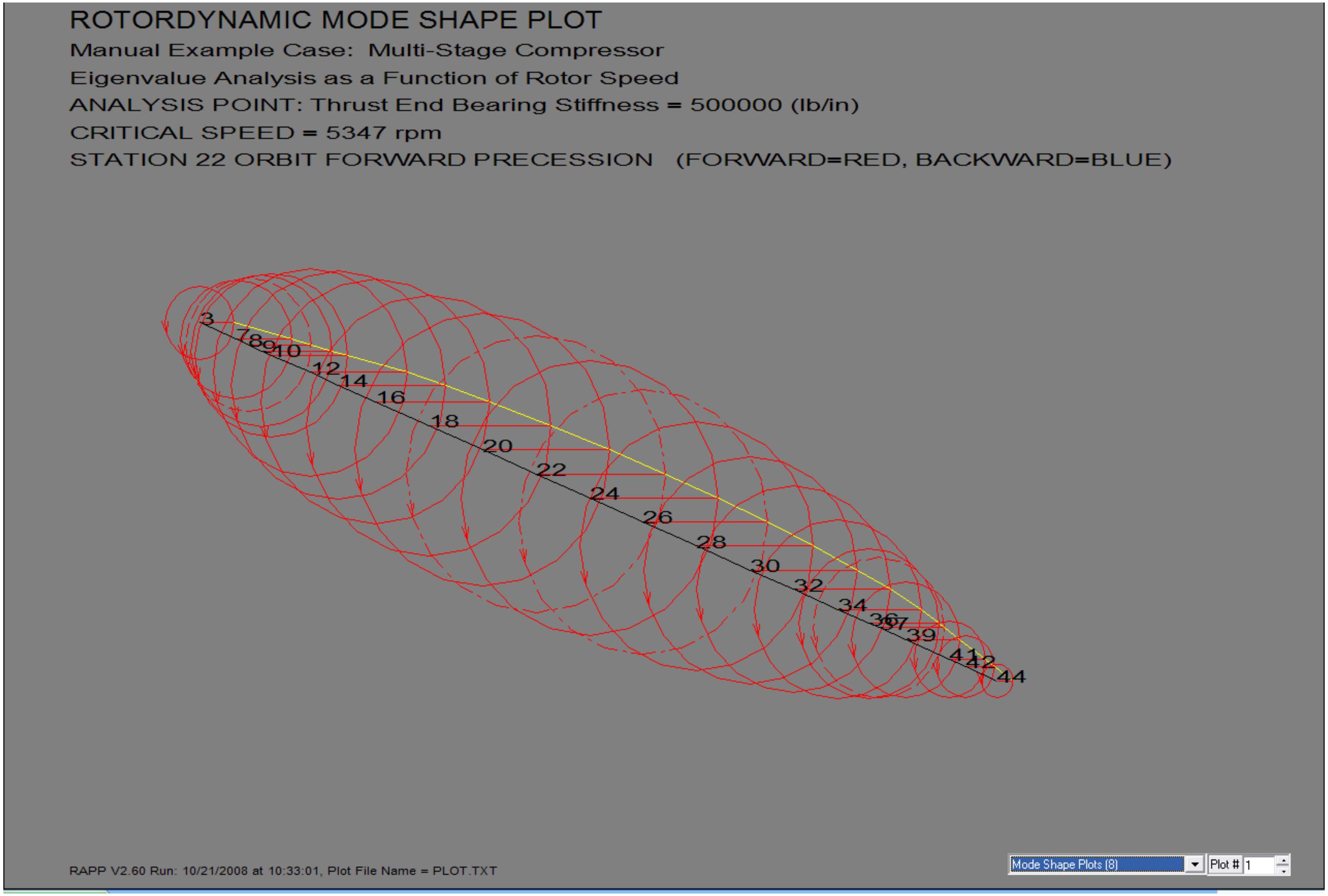
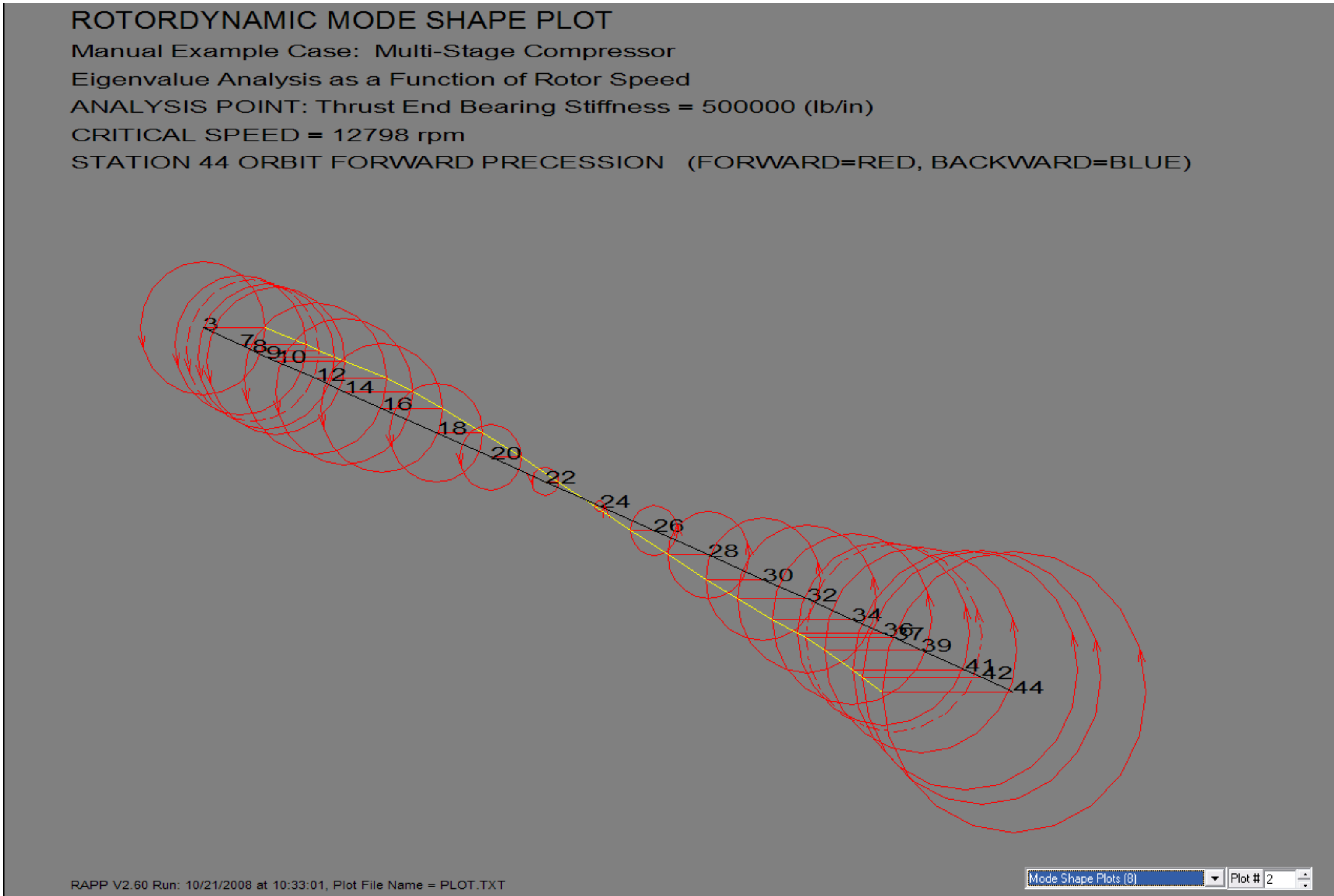
1st Synchronous Critical Speed



2nd Synchronous Critical Speed



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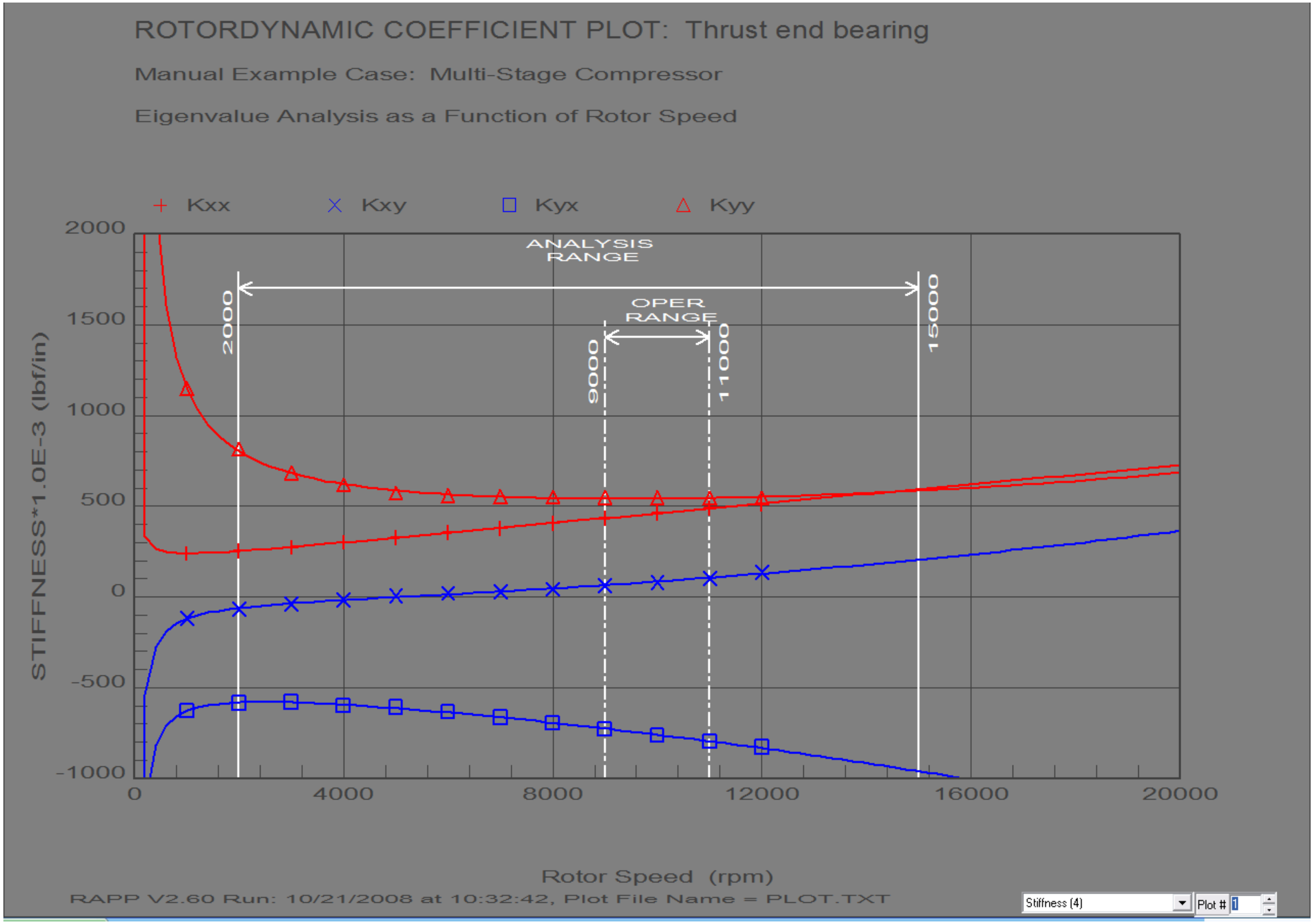
Damped Eigenvalue Analysis

- **Required Information**
  - Structural Model
  - Transfer Functions
- **Analysis Assumptions**
  - No External Excitation
- **Analysis Results**
  - Natural Frequency Map
  - Stability Map
  - Mode Shapes (elliptical)
- **Why Perform Damped Eigenvalue Analysis?**
  - Provides Essential Frequency Survey to Locate Potential Synchronous and Non-Synchronous Critical Speeds
  - Provides only Steady State Assessment of Stability

Bearing Stiffness Values



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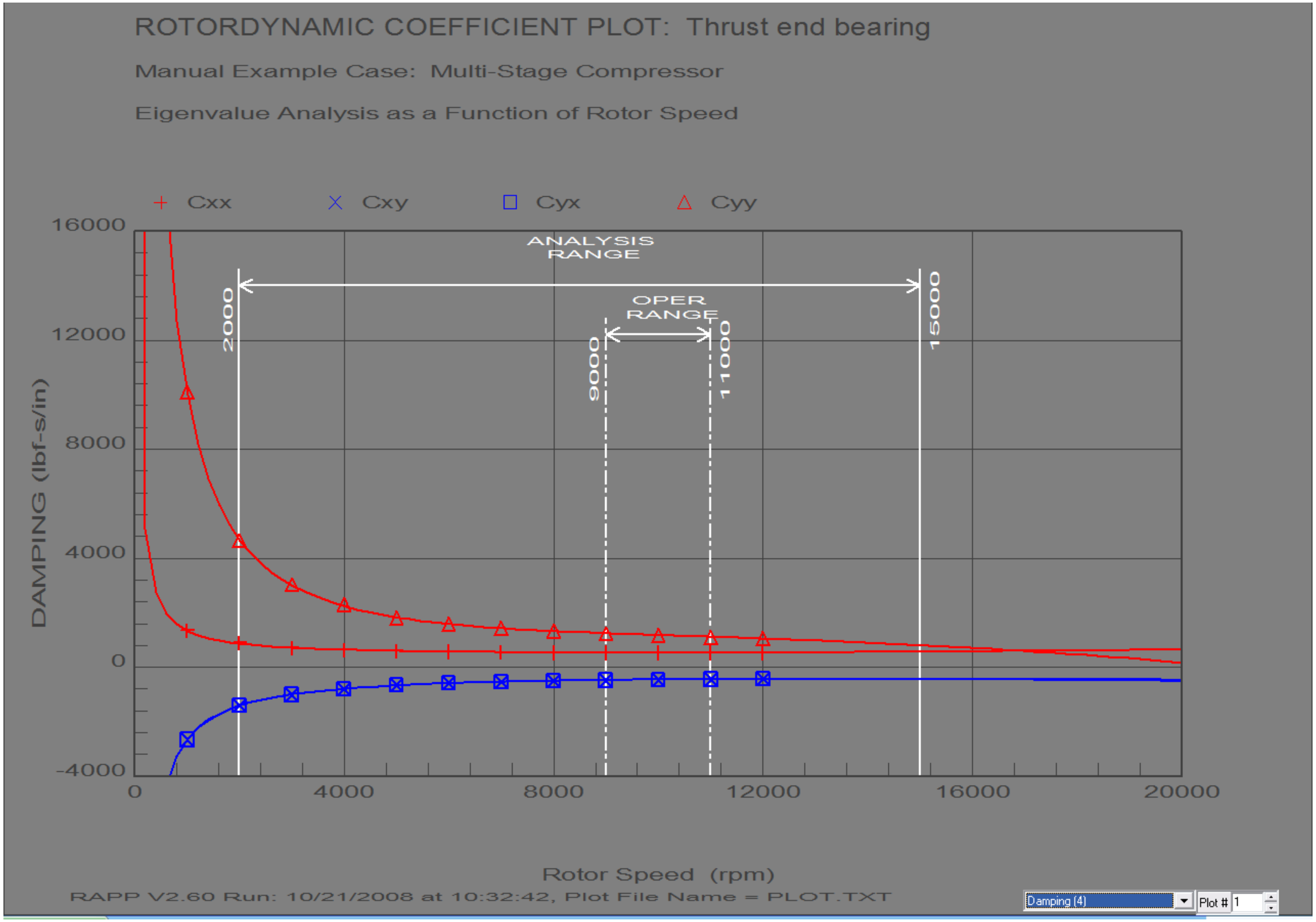
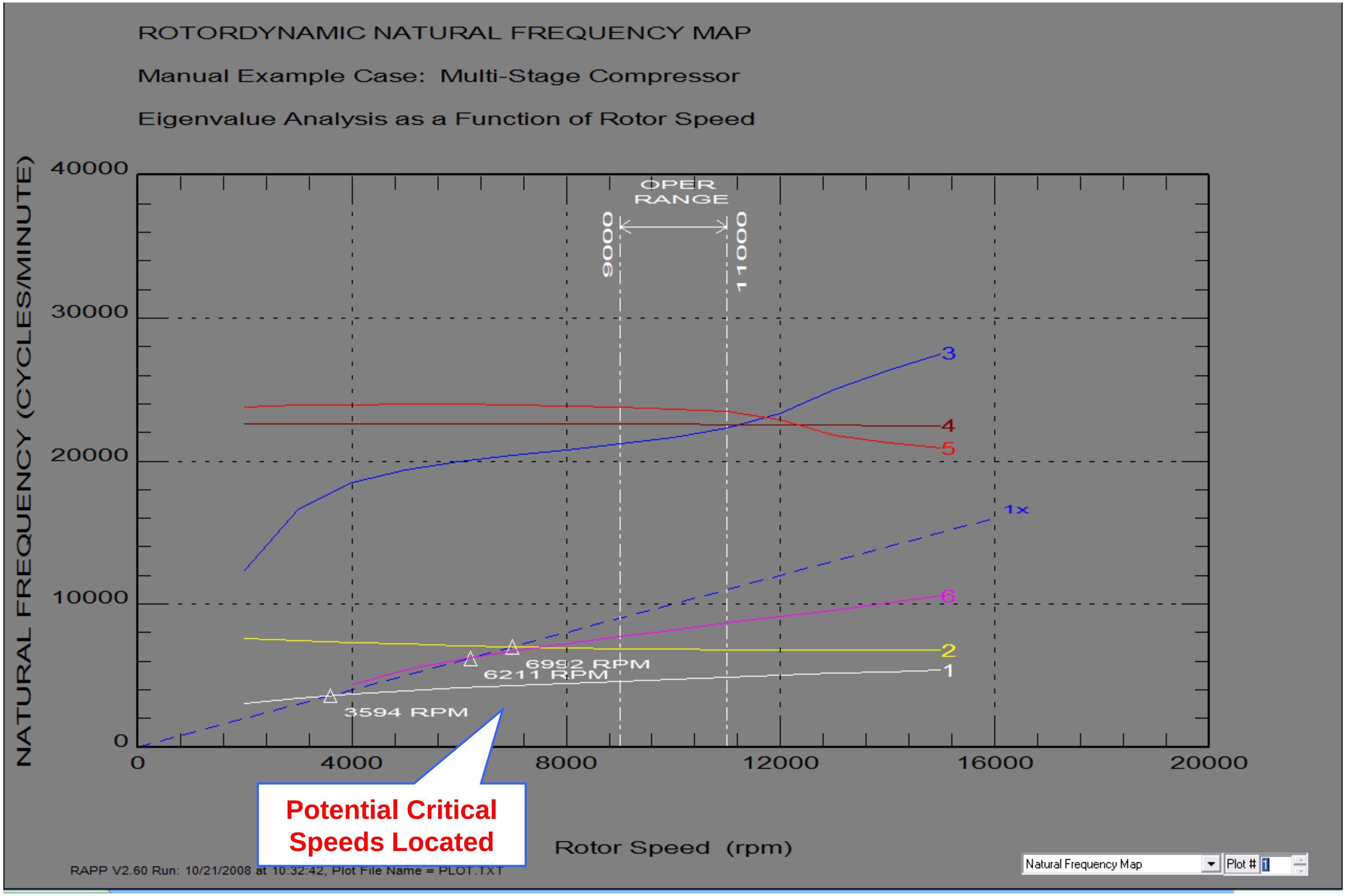
Bearing Damping Values



Natural Frequency Map



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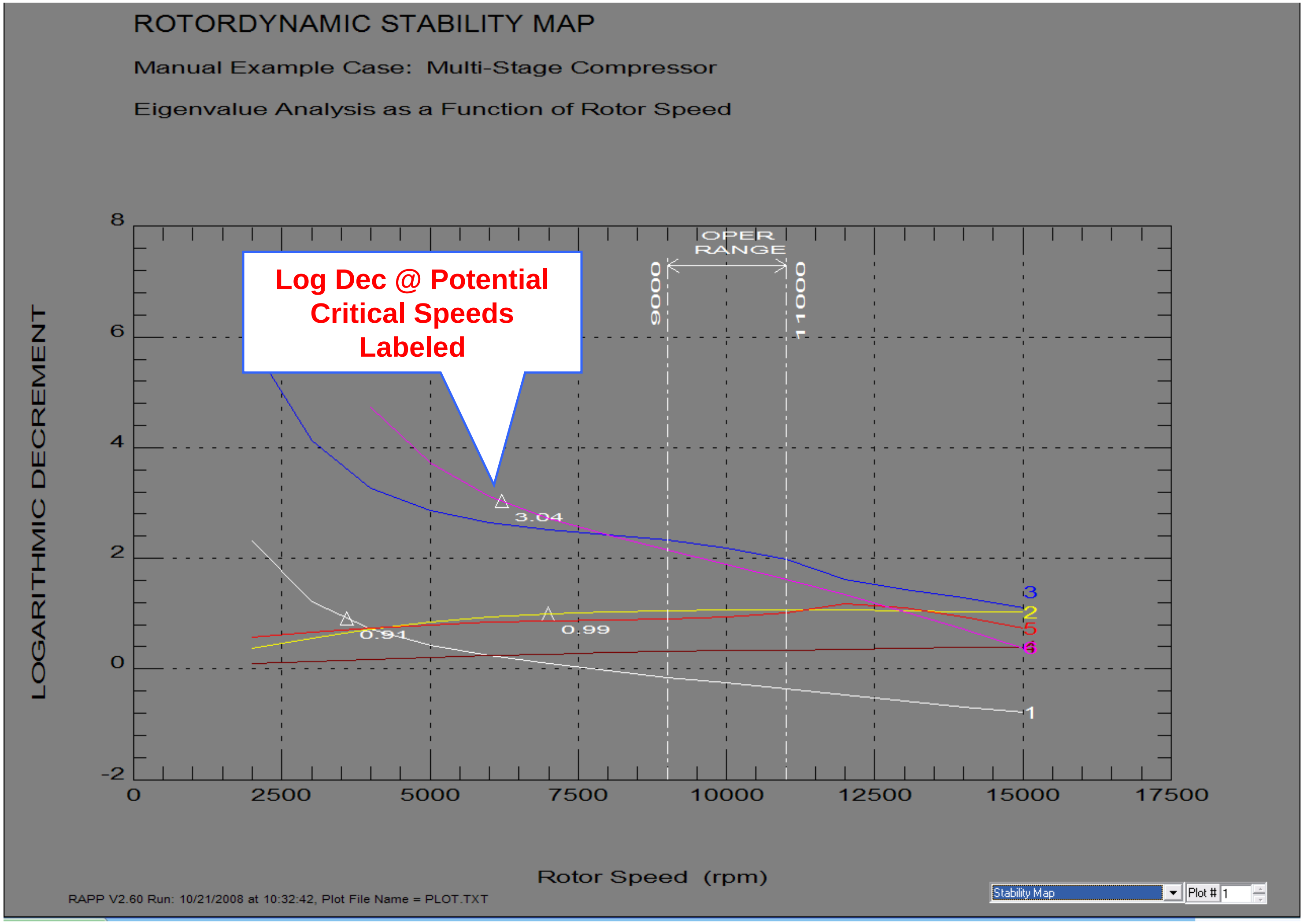
Stability Map



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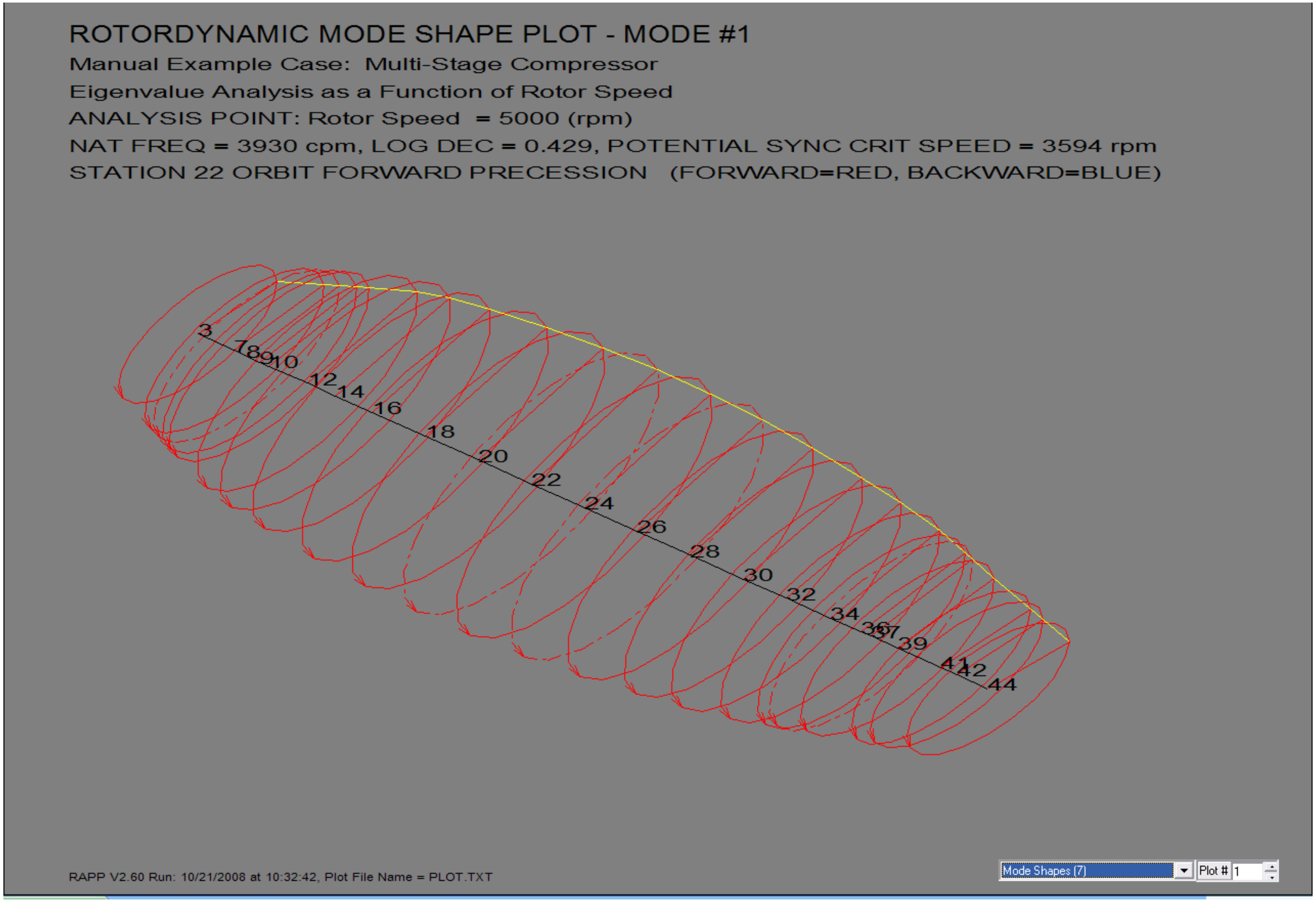
Mode Shape: Mode 1



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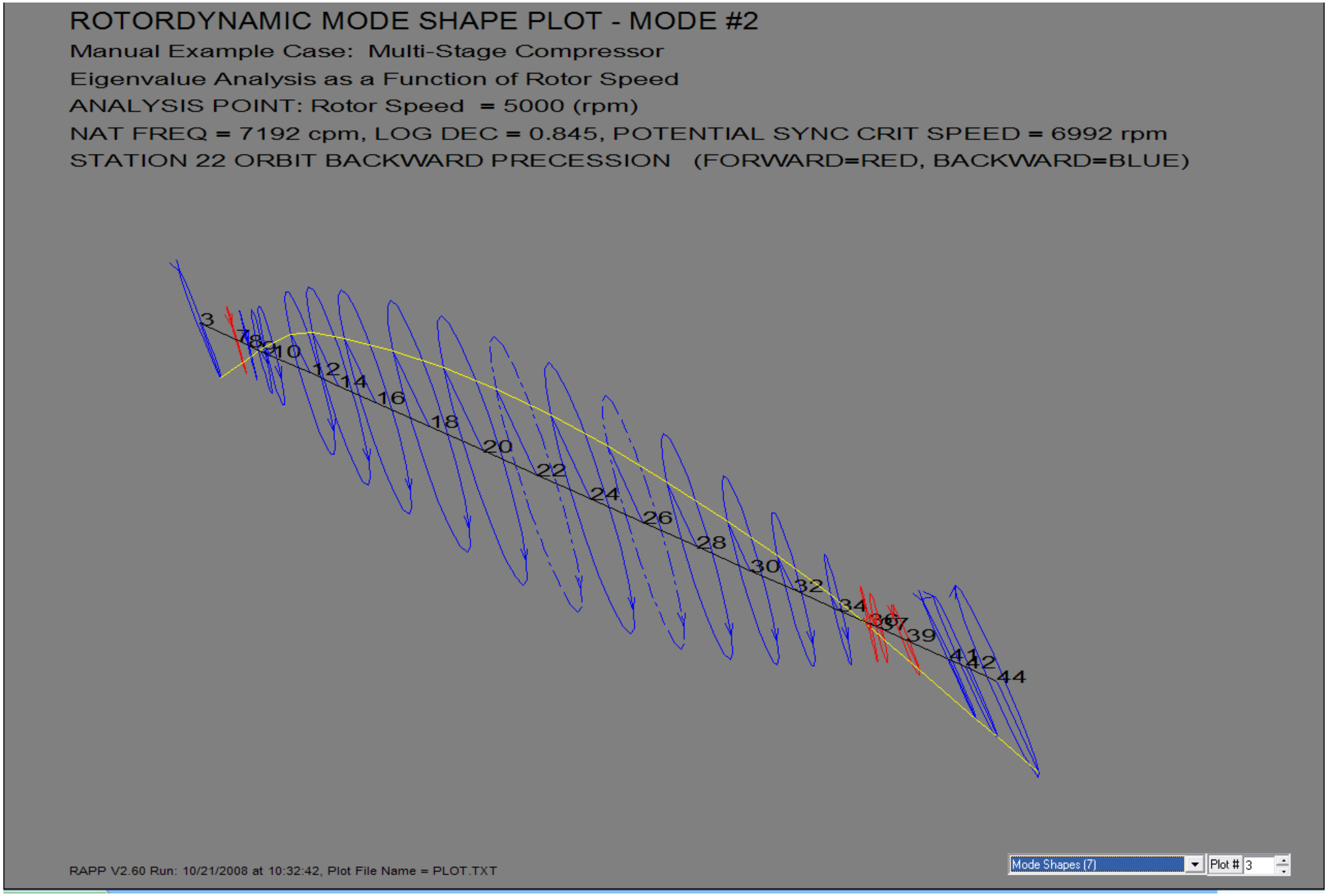
Mode Shape: Mode 2



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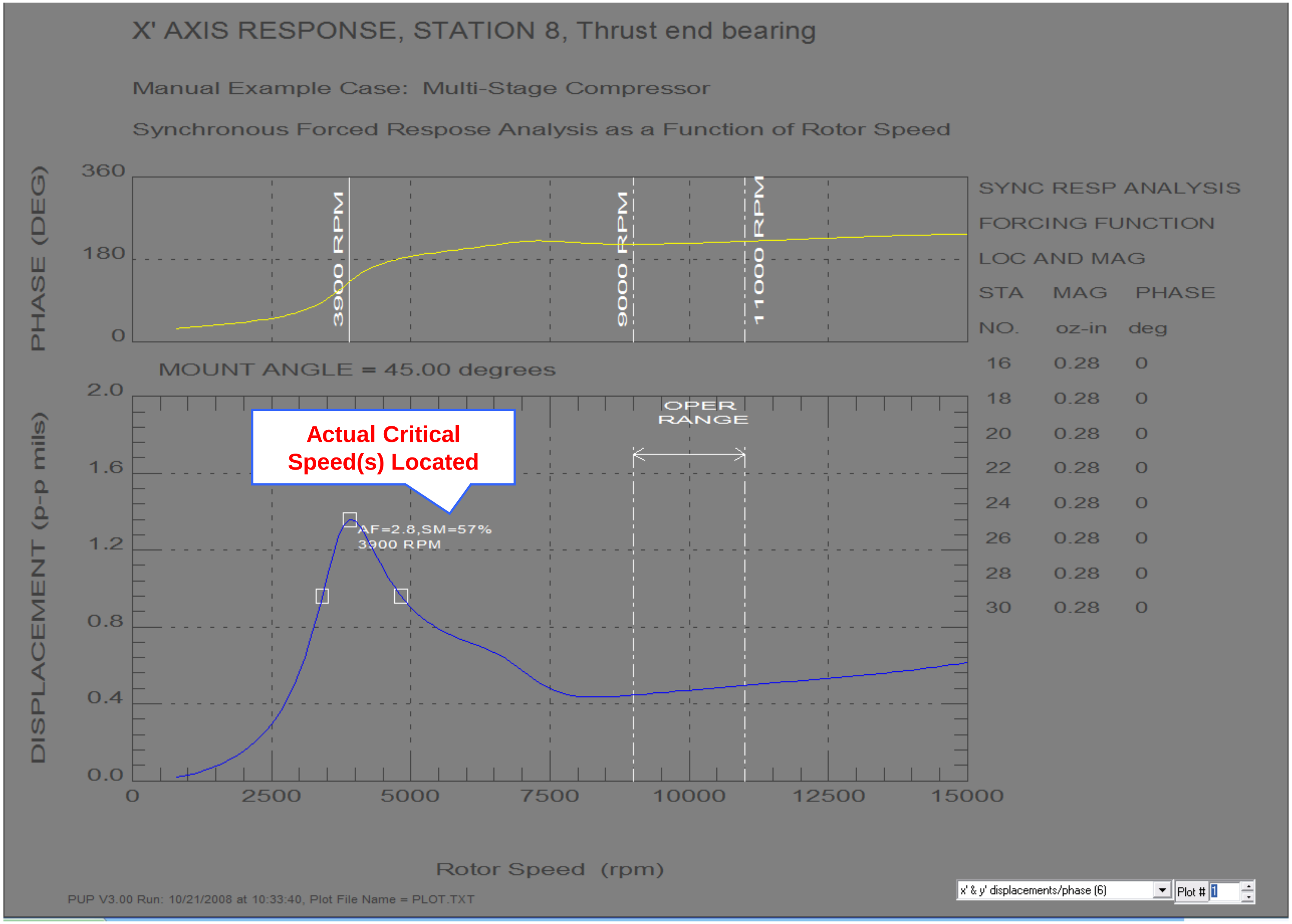
Forced Response – Steady State

- **Required Information**
  - **Structural Model**
  - **Transfer Functions**
  - **Forcing Functions**
- **Analysis Assumptions**
  - **Unbalance Always Modeled**
  - **Other Forcing Functions Modeled as Needed**
- **Analysis Results**
  - **Vibration Amplitude**
  - **Dynamic Bearing Loads**
  - **Deflected Rotor Shapes (elliptical)**
- **Why Perform Steady State Forced Response Analysis?**
  - **Locate Actual Synchronous and Non-Synchronous Critical Speeds**
  - **Determine Amplification Factors**
  - **Establish Response Shapes**

Horizontal Vibration @ Bearing



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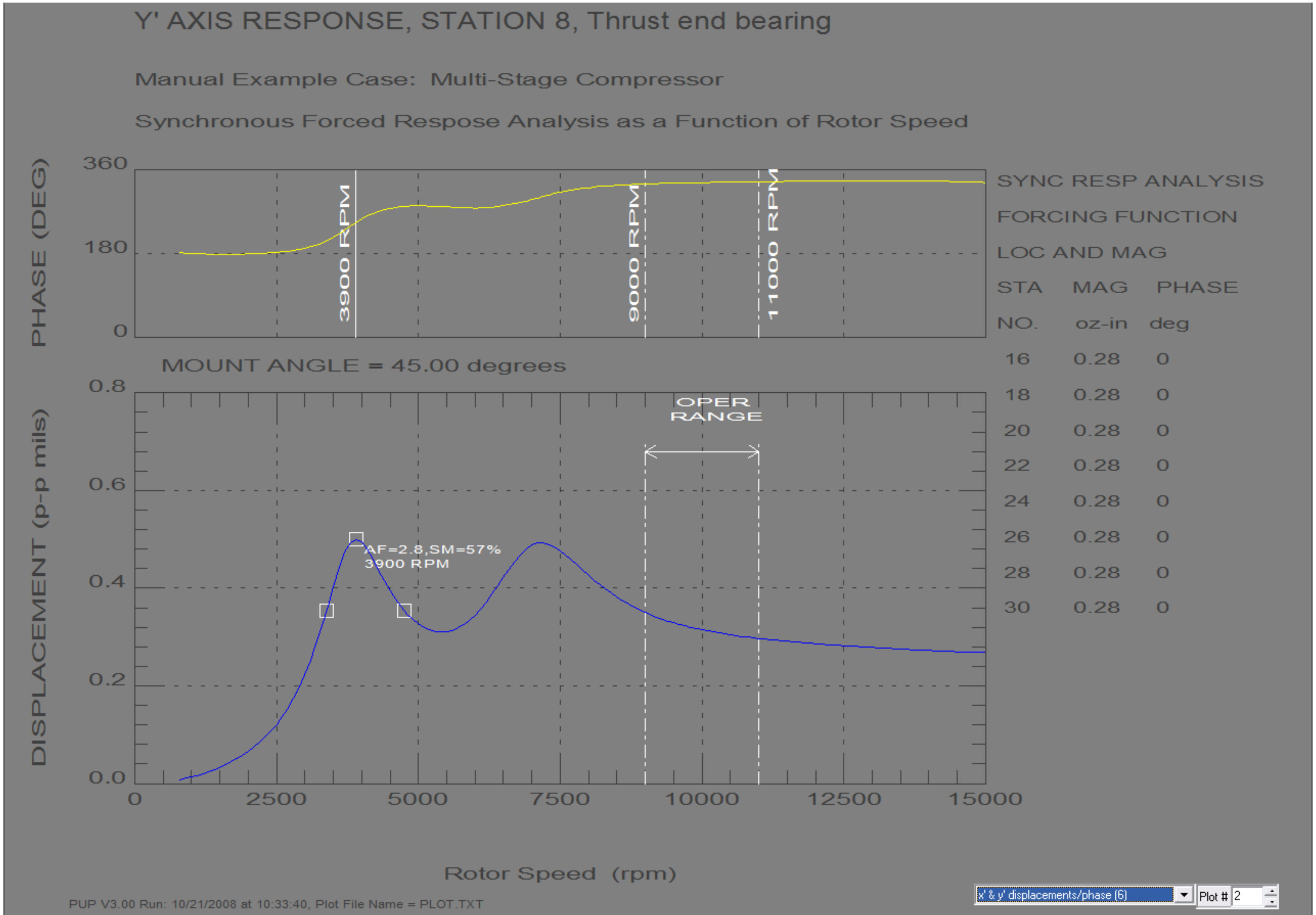
Vertical Vibration @ Bearing



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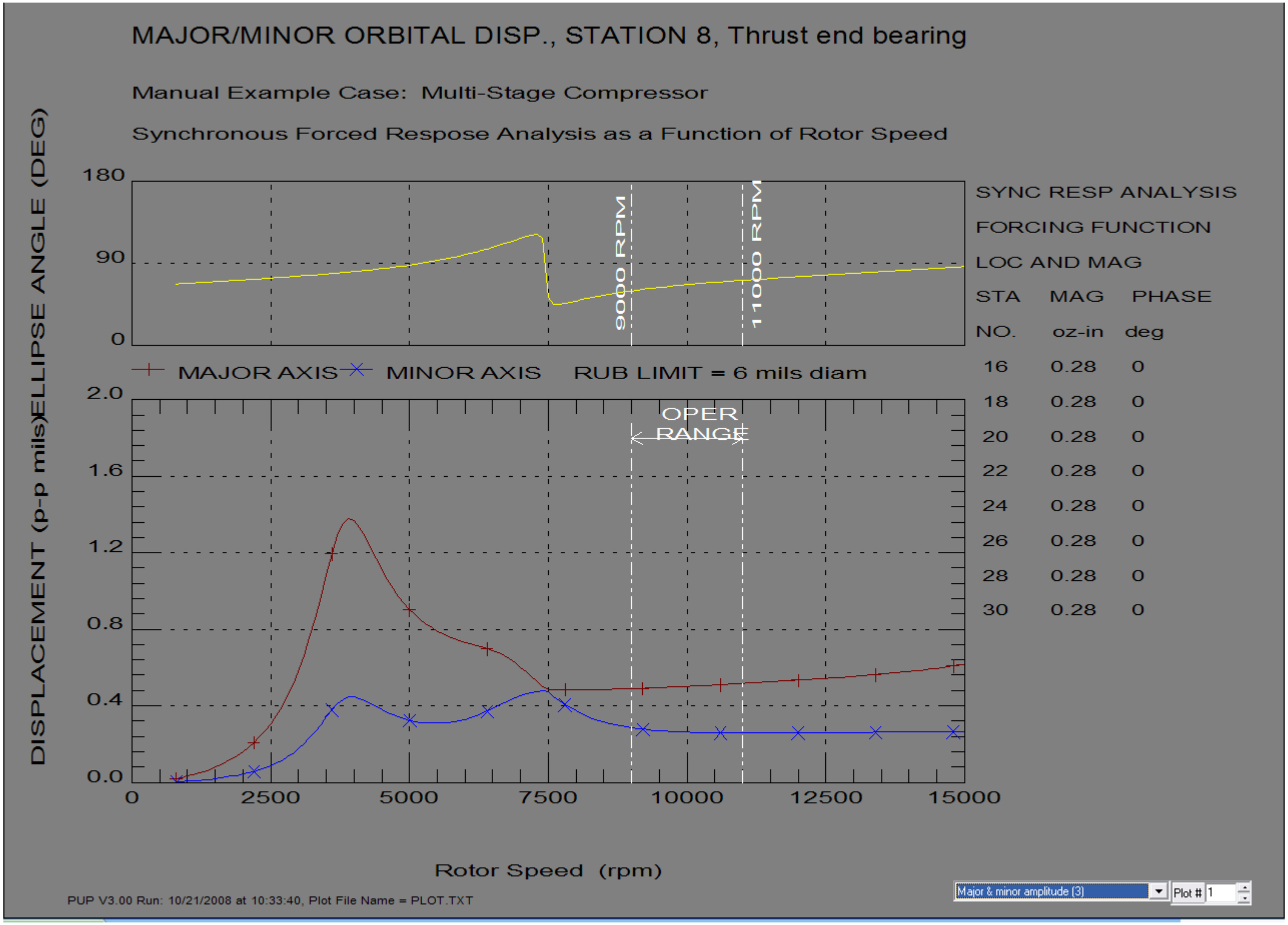
Maximum Vibration @ Bearing



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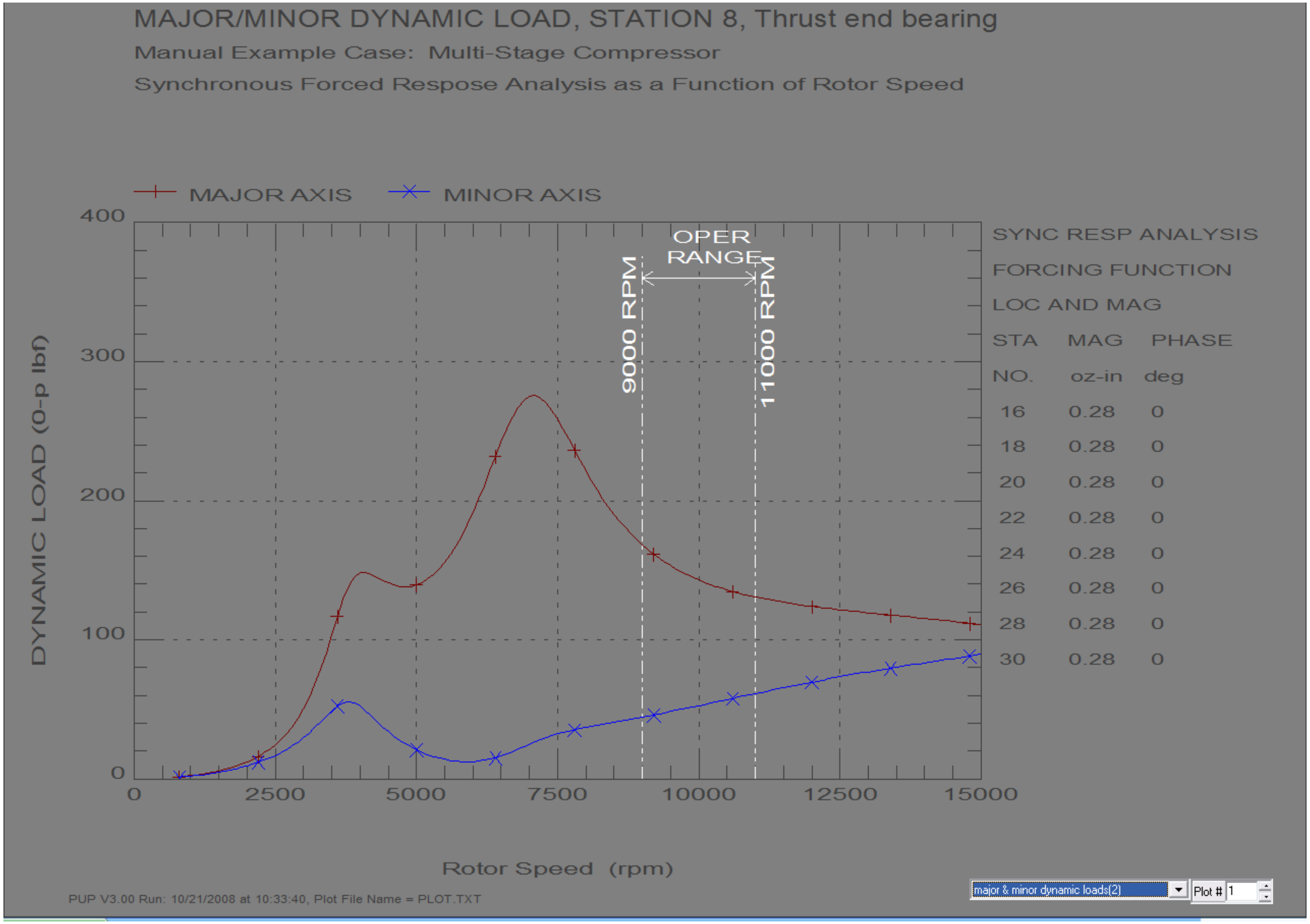
Maximum Dynamic Bearing Load



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Rotor Response Shape

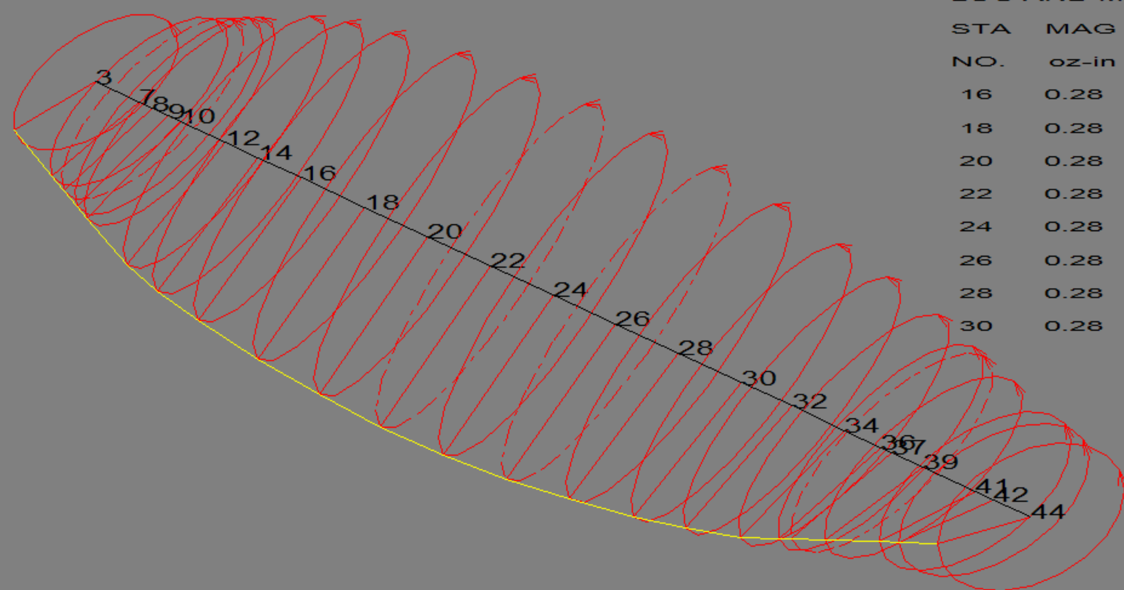
ROTOR RESPONSE SHAPE

ROTOR SPEED = 5000 rpm

Manual Example Case: Multi-Stage Compressor

Synchronous Forced Respose Analysis as a Function of Rotor Speed

STATION 22 ORBIT FORWARD PRECESSION   (FORWARD=RED, BACKWARD=BLUE)



SYNC RESP ANALYSIS

FORCING FUNCTION

LOC AND MAG

STA NO.	MAG oz-in	PHASE deg
16	0.28	0
18	0.28	0
20	0.28	0
22	0.28	0
24	0.28	0
26	0.28	0
28	0.28	0
30	0.28	0

PUP V3.00 Run: 10/21/2008 at 10:33:40, Plot File Name = PLOT.TXT

3D lateral response shapes (2)   Plot # 1

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