Development of an MSC.Nastran Add-On Module to Calculate Vibration of Rotating Machine with Arbitrary Geometry

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Abstract

Recently, MSC.Software and the University of Washington have joined forces to develop an add-on capacity for MSC.Nastran. Based on a patent pending algorithm developed at the University of Washington, the add-on capacity will allow MSC.Nastran users to calculate vibration of rotating machines with arbitrary geometry and complexity. The add-on capacity will be a powerful addition to the current ROTORDYNAMICS option, and can have wide applications in many sectors, such as aerospace and disk drive industry.

The add-on capacity treats a rotating machine as three major elements: a rotating part (rotor), a stationary part (stator or housing), and multiple bearings connecting the rotor and the housing. The rotors can be axisymmetric, cyclic symmetric, or asymmetric. The add-on capacity performs two major calculations: finite element analysis (FEA) and recovery of gyroscopic effects. In the first step, we conduct a finite element analysis of the rotating part and the stationary part separately using MSC.Nastran. In the FEA, we extract the following parameters using DMAP ALTER: natural frequencies, mode shapes, nodal mass, strain components, reaction force and moment at the boundary of the stationary part. In the second step, we exit MSC.Nastran temporarily using ISHELL command. Using a MATLAB script, we recover the gyroscopic effects of the rotating part in terms of the parameters extracted in the first step. A modal reduction procedure leads to a set of ordinary differential equations, whose solutions predict the vibrational response of the rotating machines. Finally, we reenter MSC.Nastran to finish all the postprocessing work.

Presentation Outline

Motivation

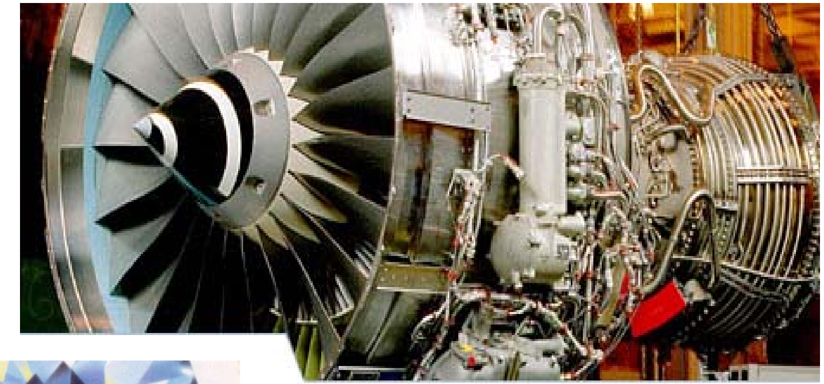
The Unified Approach

MSC-UW Collaboration

Summary

Applications

Turbine Engines



Helicopters

Disk Drives

Significance

Vibration affects performance, reliability, and service life of rotation machines.

The industry lacks a general-purpose commercial software tool to analyze vibration in designing rotating machines.

The industry now relies heavily on prototype testing.

- Expensive
- Long design cycles

Traditional Assumptions

Rotor models have simplified geometry.

- Disk drives (flexible disks, rigid hub)
- Turbines (flexible shaft, rigid/flexible disks)
- Models for disk drives will not work for turbines, and vice versa.
- May lead to inaccurate predictions.

Cannot treat rotor asymmetry effectively.

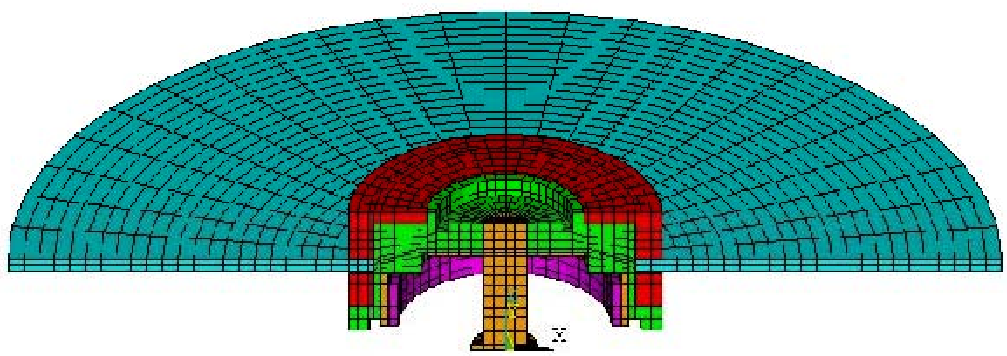
Innovation at UW

Develop several patent-pending algorithms to predict vibration of rotating machines.

Key features:

- Arbitrary geometry of rotors and stators
- Axisymmetric & Asymmetric rotors
- Fully compatible with existing finite element software packages
- Proven accuracy through experiments

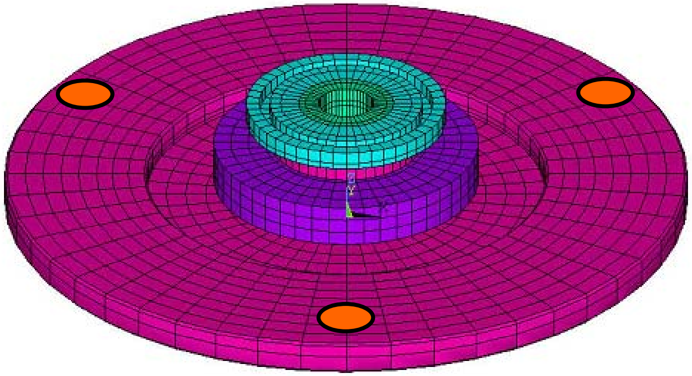
Basic Idea (1)



Use FEM to discretize the rotating part.

Export key parameters, such as mode shapes, natural frequencies, nodal mass, and nodal strains.

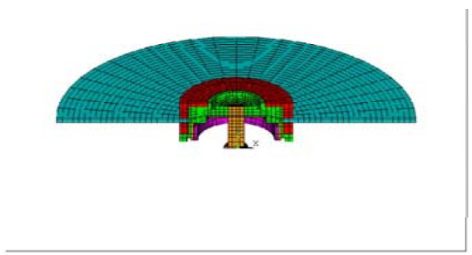
Basic Idea (2)



Use FEM to discretize the stationary part.

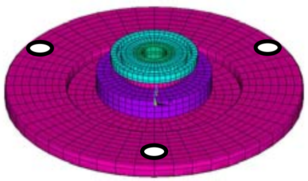
Export key parameters, such as mode shapes, natural frequencies, reactions at boundaries.

Basic Idea (3)

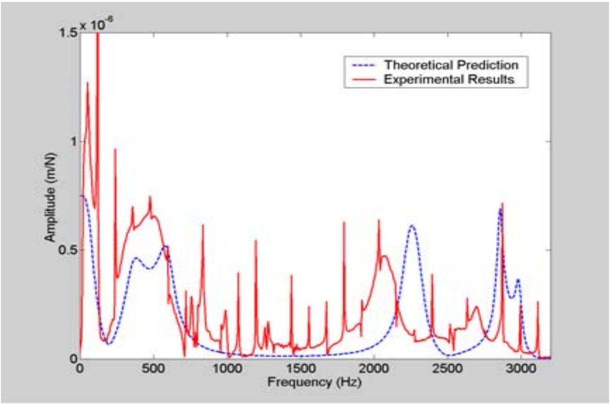


FEA from Rotor

FEA from Stator

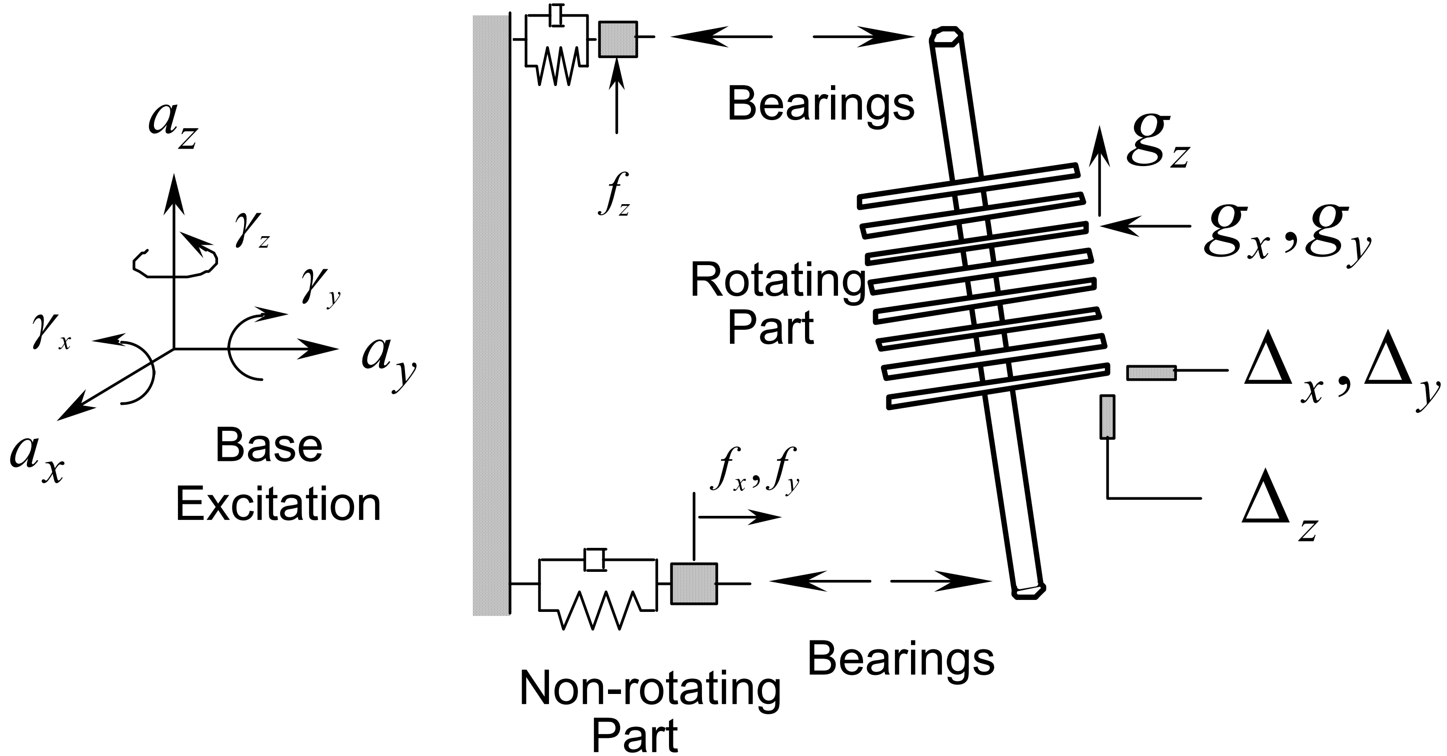


Unified Algorithm



- Gyroscopic Effects
- Equation of Motion
- Matlab Simulation

Mathematical Model (1)



Mathematical Model (2)

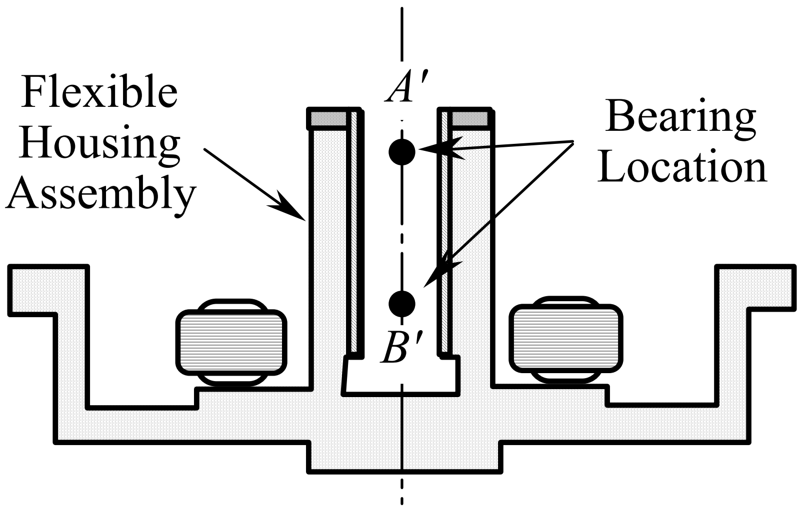
Consist of rotating part, non-rotating part, and bearings separately.

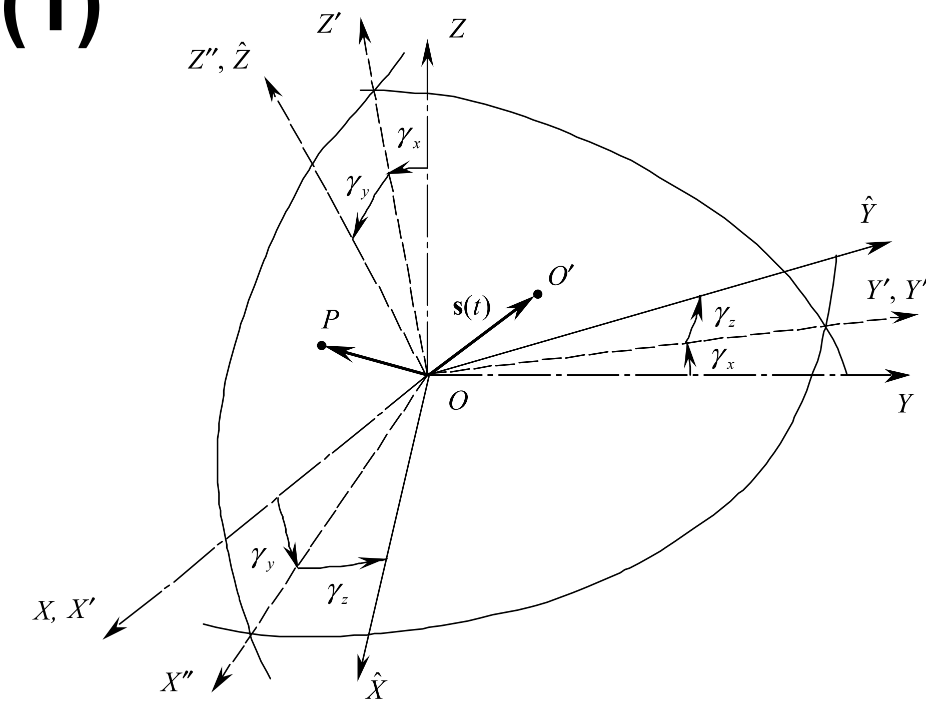
The rotating part & non-rotating part can have arbitrary geometry.

Subjected to

- Prescribed forces to rotating part and non-rotating part
- Prescribed linear and angular accelerations of the non-rotating part

Non-Rotating Part (1)





Displacement, discretized in terms of vibration modes $\mathbf{W}_n^{(S)}(\mathbf{r})$, is given by

$$\mathbf{R}_P = \mathbf{s}(t) + \left(\hat{\mathbf{r}} - \mathbf{r}\right) + \Sigma \mathbf{W}_n^{(S)}(\hat{\mathbf{r}})\, q_n^{(S)}(t)$$

Non-Rotating Part (2)

Velocity:

$$\dot{\mathbf{R}}_P = \dot{\mathbf{s}}(t) + \omega_{\hat{X}\hat{Y}\hat{Z}} \times \hat{\mathbf{r}} + \Sigma \mathbf{W}_n^{(S)}(\hat{\mathbf{r}})\dot{q}_n^{(S)}(t)$$
$$+ \Sigma\left[\omega_{\hat{X}\hat{Y}\hat{Z}} \times \mathbf{W}_n^{(S)}(\hat{\mathbf{r}})\right] q_n^{(S)}(t)$$

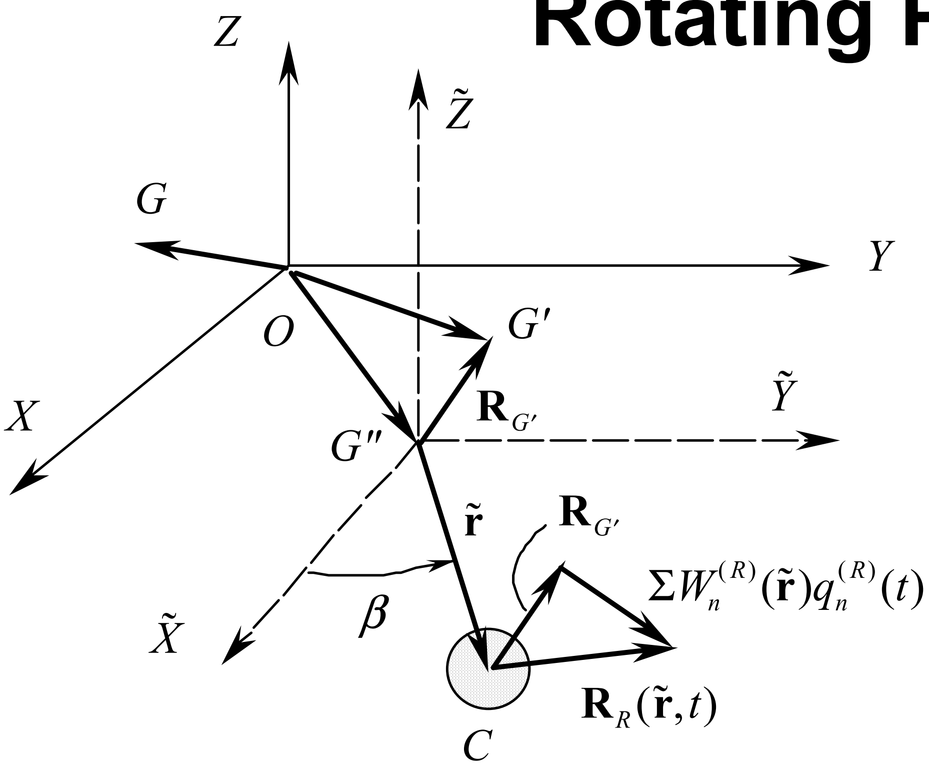
Kinetic Energy:

$$T_S = \frac{1}{2} m_S \left(\dot{s}_x^2 + \dot{s}_y^2 + \dot{s}_z^2\right) + \frac{1}{2} \omega_{\hat{X}\hat{Y}\hat{Z}} \cdot \mathbf{I}_S \cdot \omega_{\hat{X}\hat{Y}\hat{Z}}$$
$$+ \frac{1}{2} \Sigma\left[\dot{q}_n^{(S)}\right]^2 + \Sigma\left(\dot{\mathbf{s}} \cdot \mathbf{J}_{an}^{(S)}\right)\dot{q}_n^{(S)} + \Sigma\left(\omega_{\hat{X}\hat{Y}\hat{Z}} \cdot \mathbf{J}_{bn}^{(S)}\right)\dot{q}_n^{(S)} + \dot{\mathbf{s}} \cdot \omega_{\hat{X}\hat{Y}\hat{Z}} \times \mathbf{J}_{s1}^{(S)}$$

Potential Energy:

$$V_S = \frac{1}{2} \Sigma\left[\omega_n^{(S)} q_n^{(S)}\right]^2$$

Rotating Part (1)



Use concept of control volume.

Discretize displacement in terms of normal modes of the free rotor

Displacement: $$\mathbf{R}_R(\tilde{\mathbf{r}},t) = \mathbf{R}_{G'} + \Sigma \mathbf{W}_n^{(R)}(\tilde{\mathbf{r}})q_n^{(R)}(t)$$

Velocity: $$\mathbf{v}_R(\tilde{\mathbf{r}},t) = \omega \times \tilde{\mathbf{r}} + \frac{D}{Dt}\mathbf{R}_R(\tilde{\mathbf{r}},t)$$

Rotating Part (2)

$$\mathbf{v}_R(\tilde{\mathbf{r}},t) = \omega \times \tilde{\mathbf{r}} + \dot{\mathbf{R}}_{G'} + \Sigma \mathbf{W}_n^{(R)}(\tilde{\mathbf{r}})\dot{q}_n^{(R)}(t)$$
$$+ \omega_3 \Sigma \Lambda_n^{(R)}(\tilde{\mathbf{r}}) q_n^{(R)}(t)$$

Where

$$\Lambda_n^{(R)}(\tilde{\mathbf{r}}) \equiv \left(-\tilde{y}\frac{\partial}{\partial \tilde{x}} + \tilde{x}\frac{\partial}{\partial \tilde{y}} \right) \mathbf{W}_n^{(R)}(\tilde{\mathbf{r}})$$

Derive kinetic energy and potential energies as in the non-rotating part.

Equations of Motion

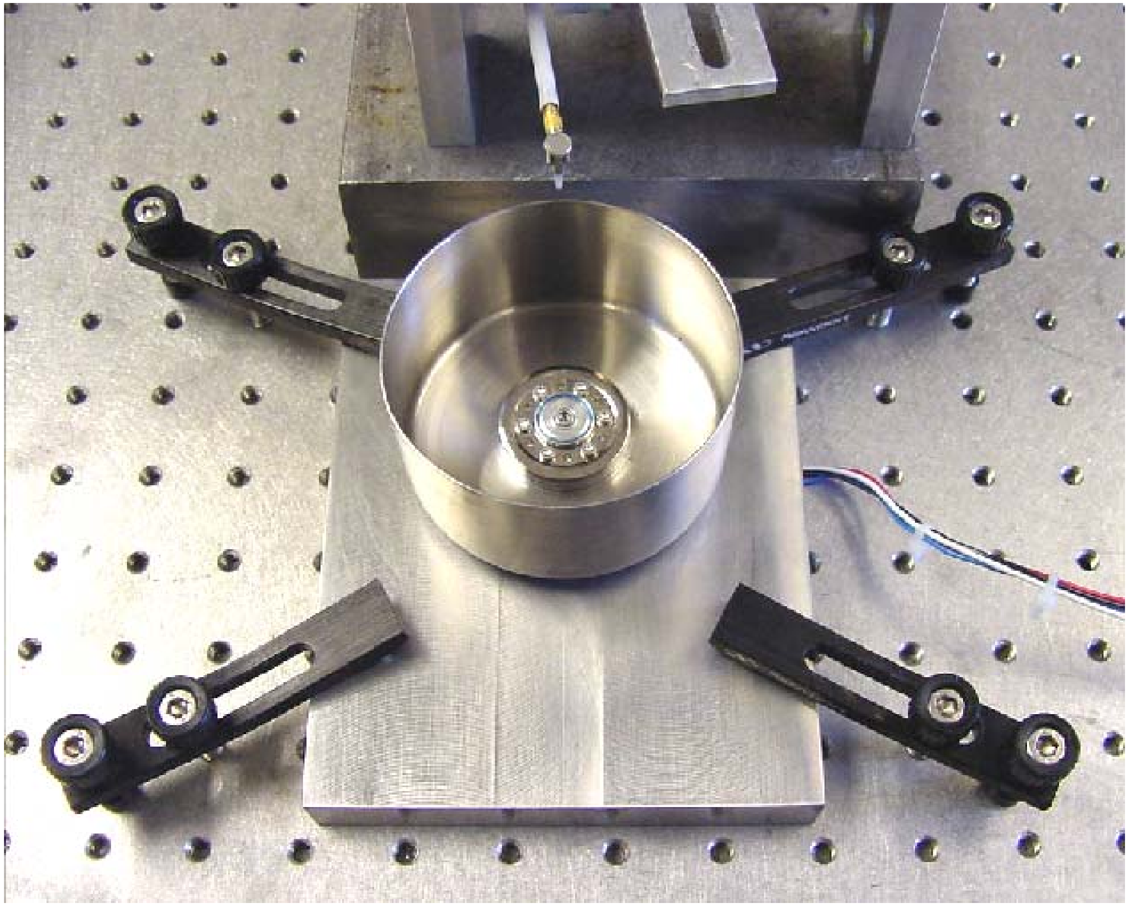
Bearing deformation and forces can be determine from the displacement and velocity fields.

Use of Lagrange equation results in

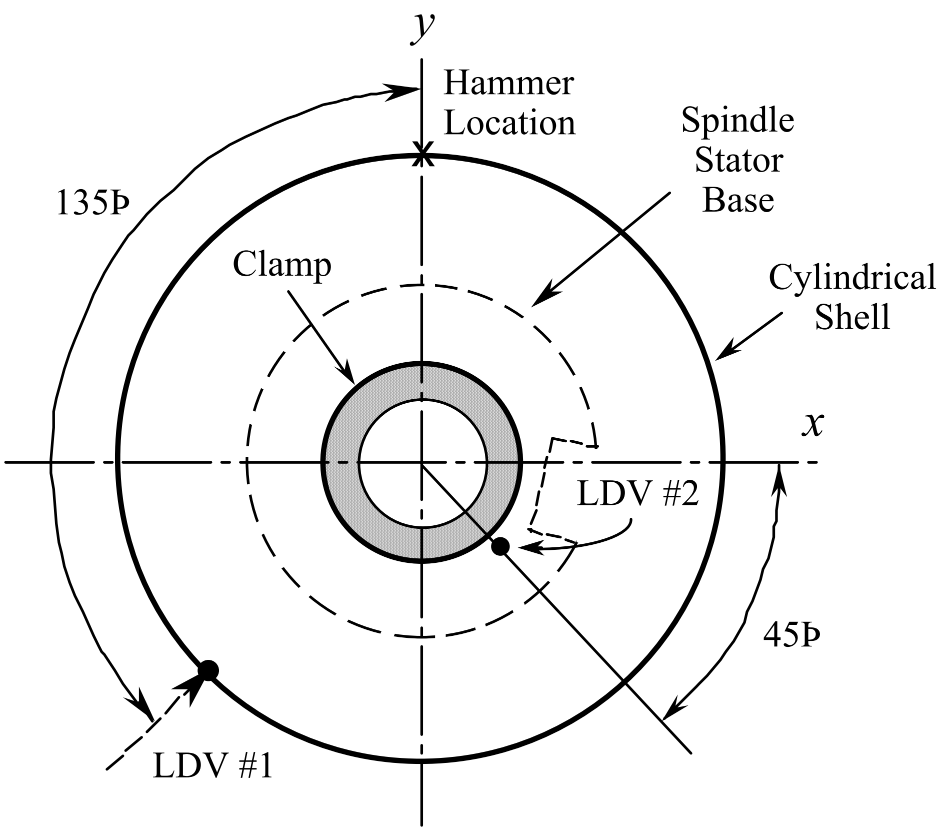
$$\ddot{\mathbf{q}} + [\mathbf{G} + \mathbf{C}_B + \mathbf{C}_m]\dot{\mathbf{q}} + [\mathbf{K} + \mathbf{K}_B + \mathbf{D}_m]\mathbf{q}$$

$$= \mathbf{B}_R^T\mathbf{f}_R + \mathbf{B}_S^T\mathbf{f}_S + \mathbf{f}_C - \mathbf{H}\ddot{\mathbf{f}} - \mathbf{G}_S\dot{\mathbf{f}} - \mathbf{H}_S\mathbf{f}$$

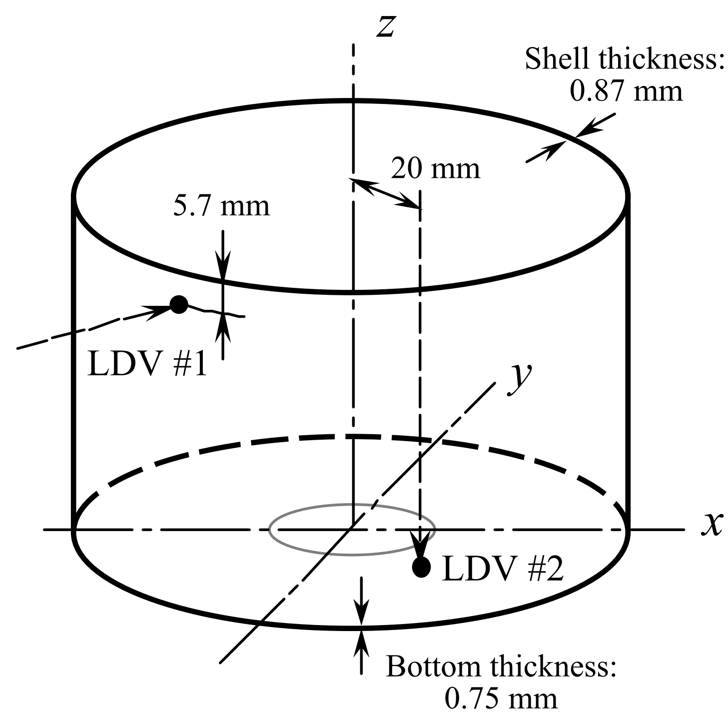
Experimental Setup



Measurement Locations

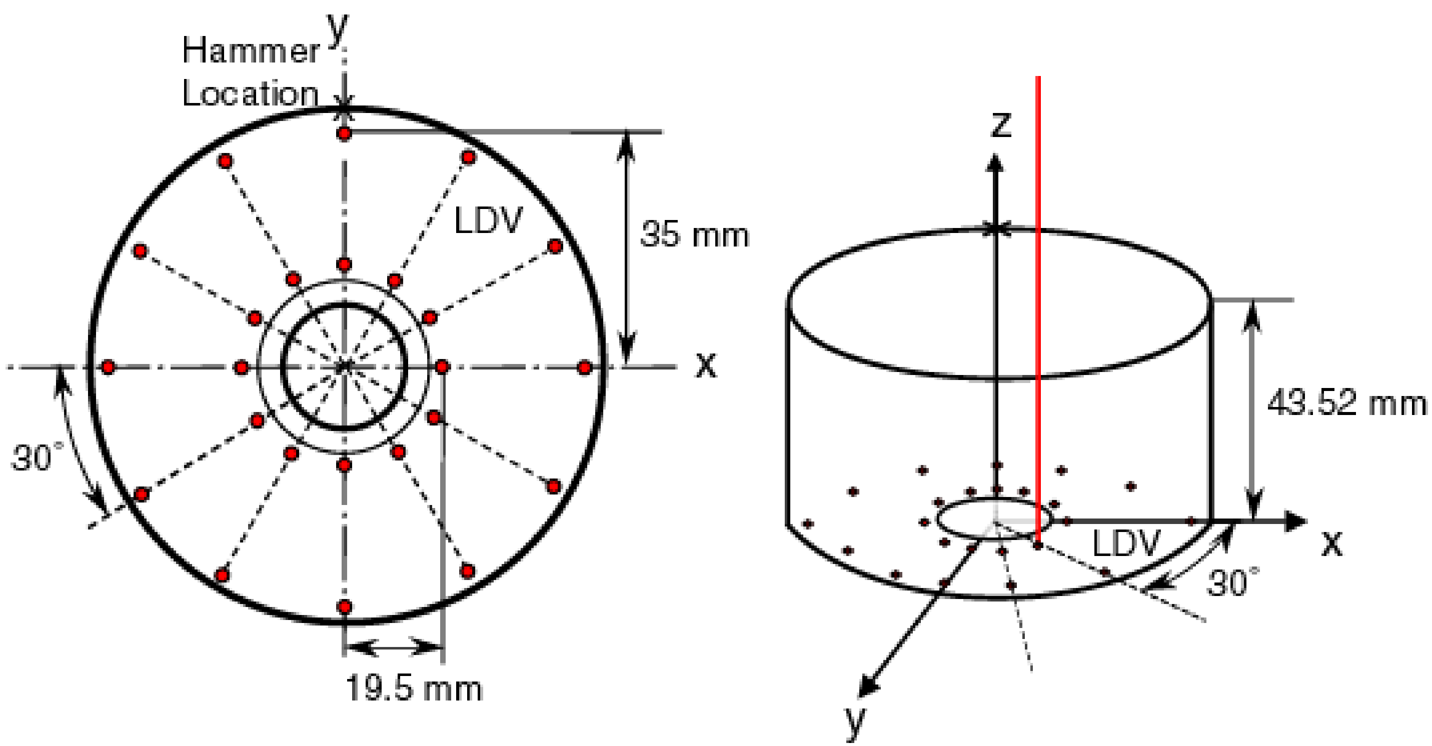


Top View



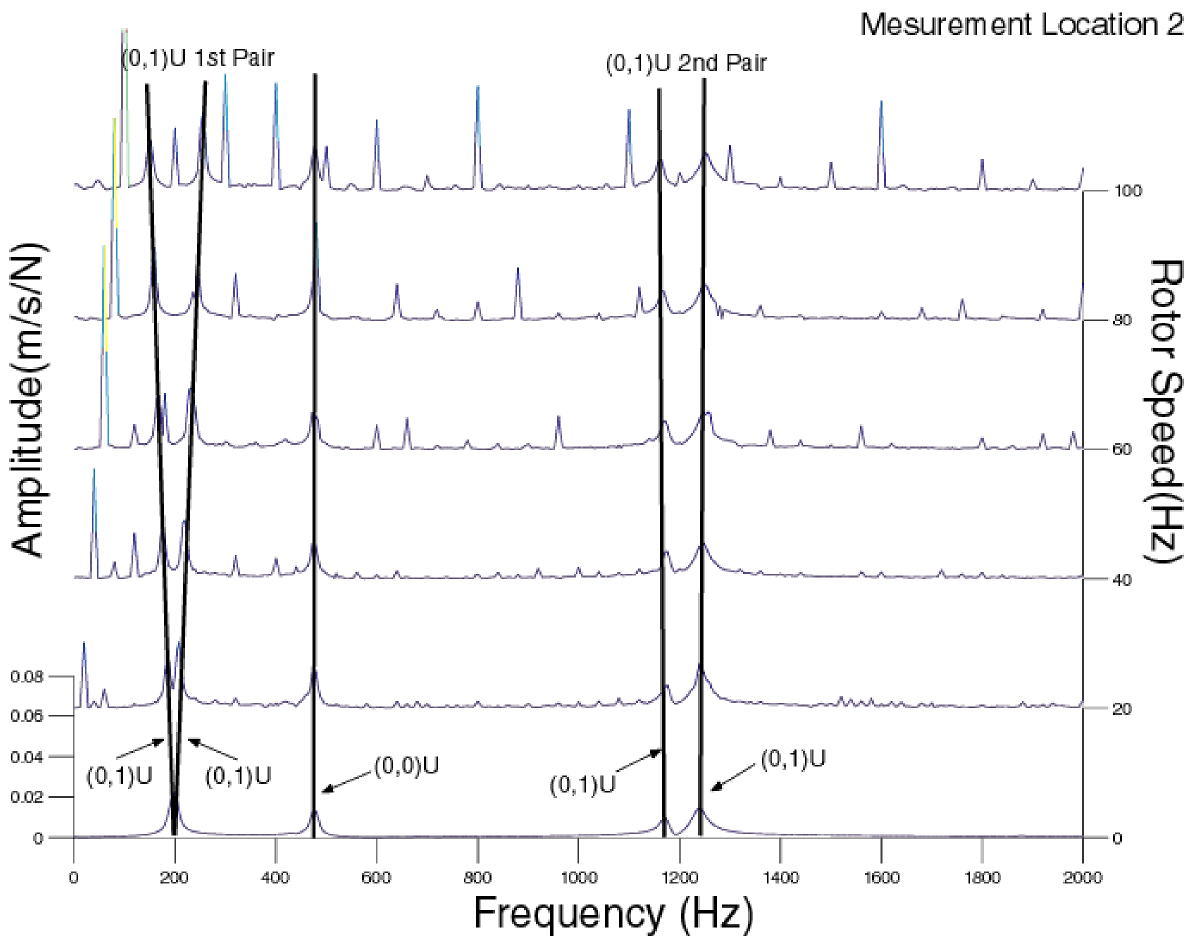
3-D Sketch

Modal Analysis Locations

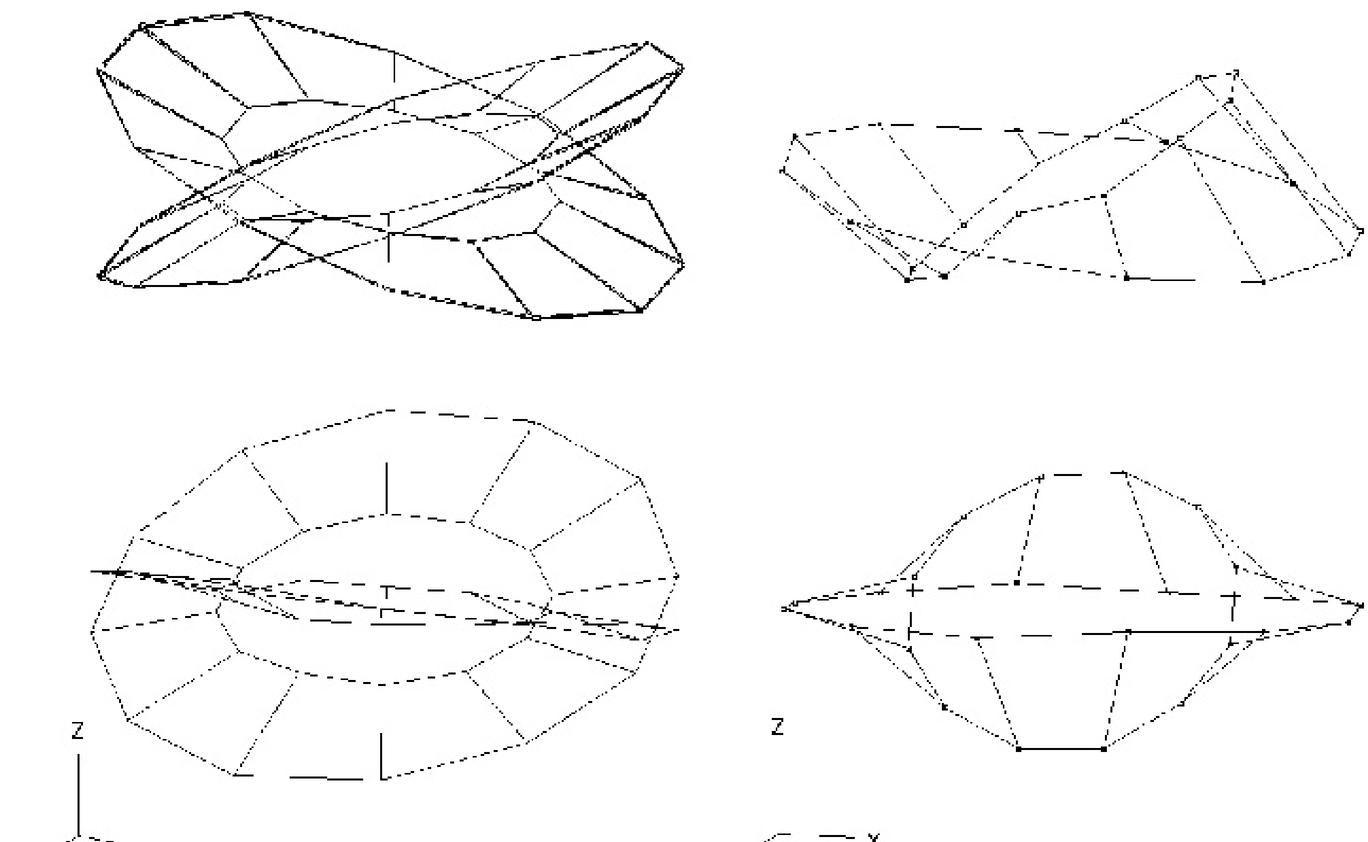


(a) Top view (b) Side view

Waterfall Plot (1)



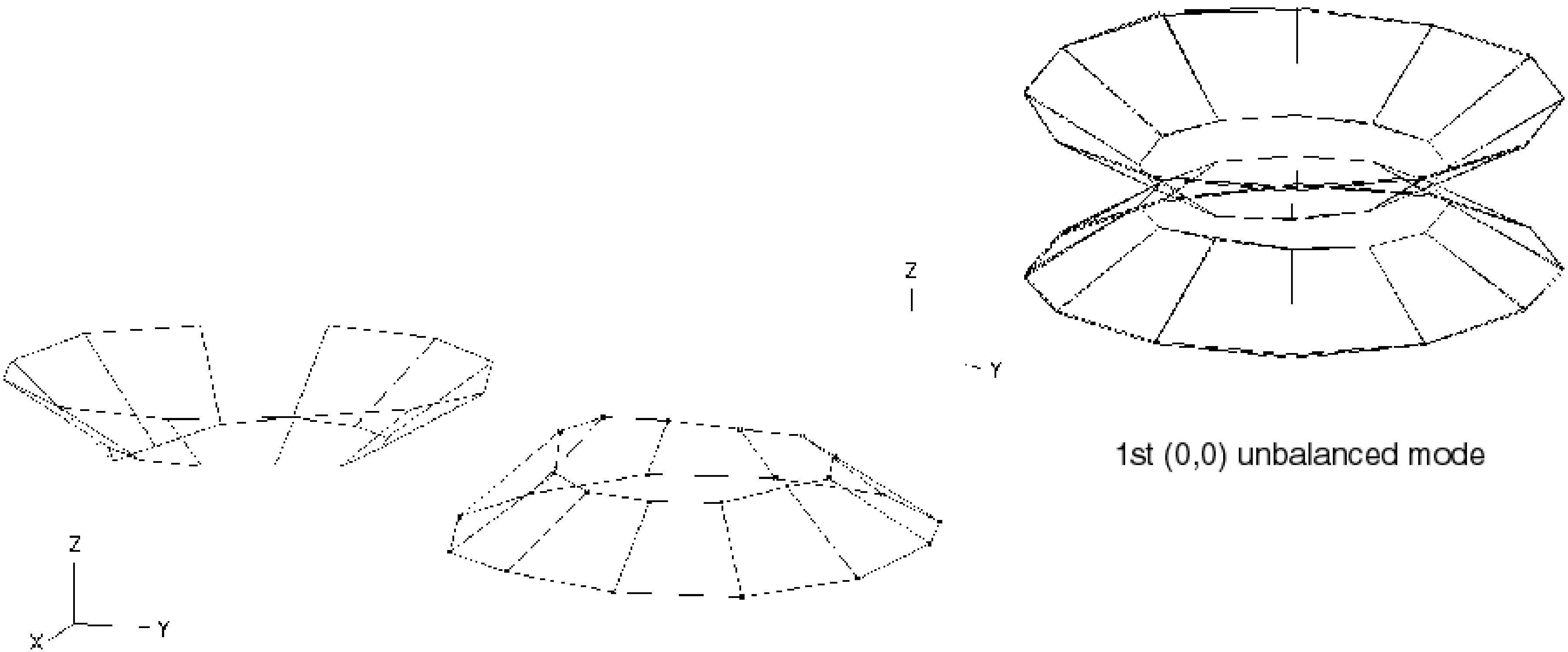
(0,1) Unbalanced Modes



1st Pair

2nd Pair

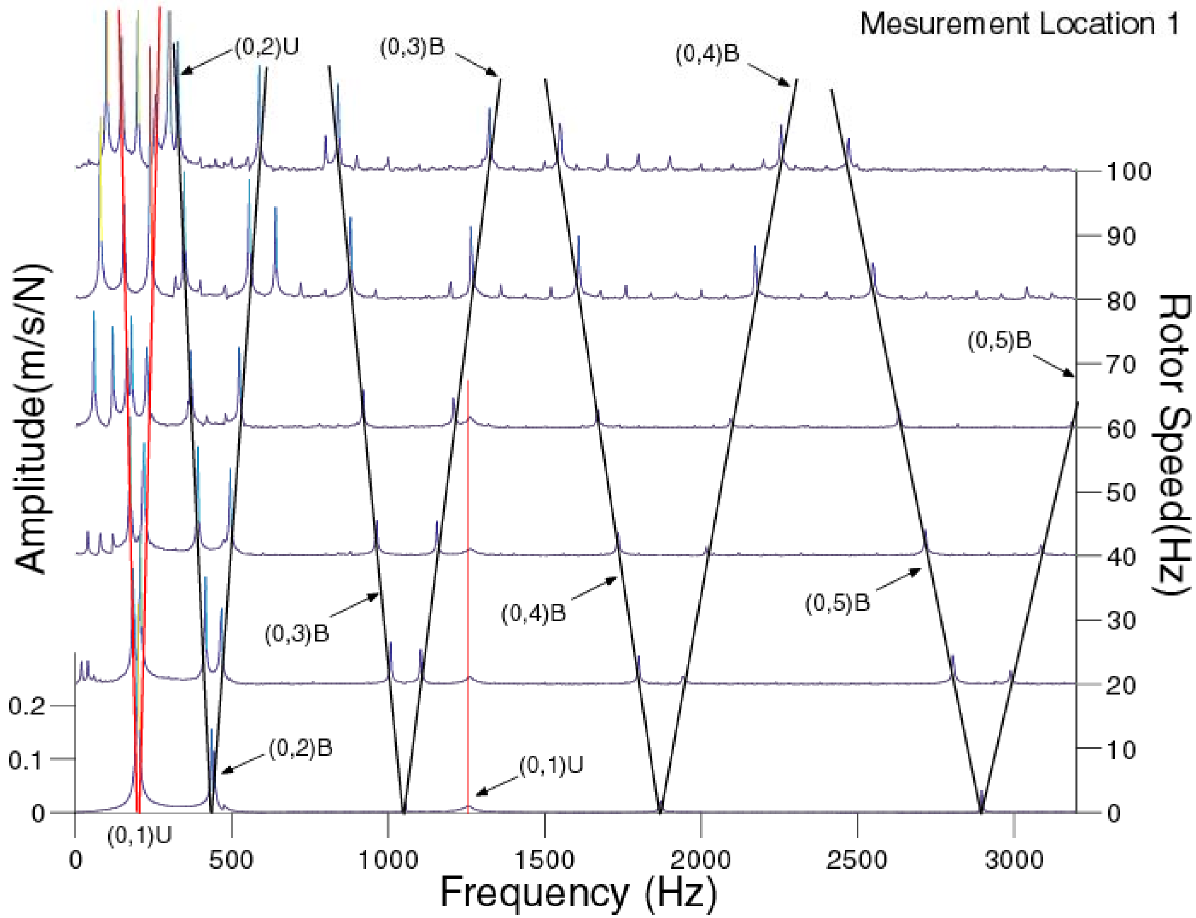
(0,0) Unbalanced Modes



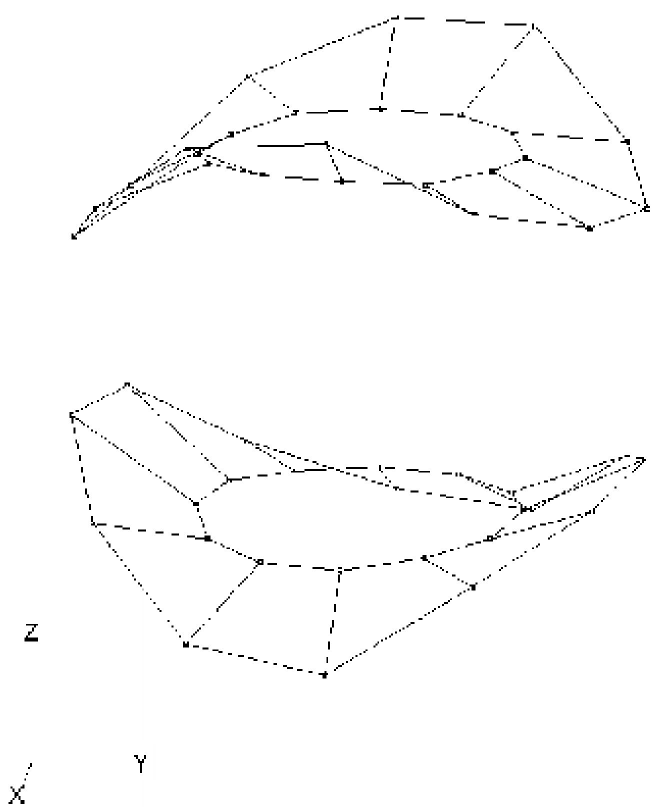
1st (0,0) unbalanced mode

2nd (0,0) unbalanced mode

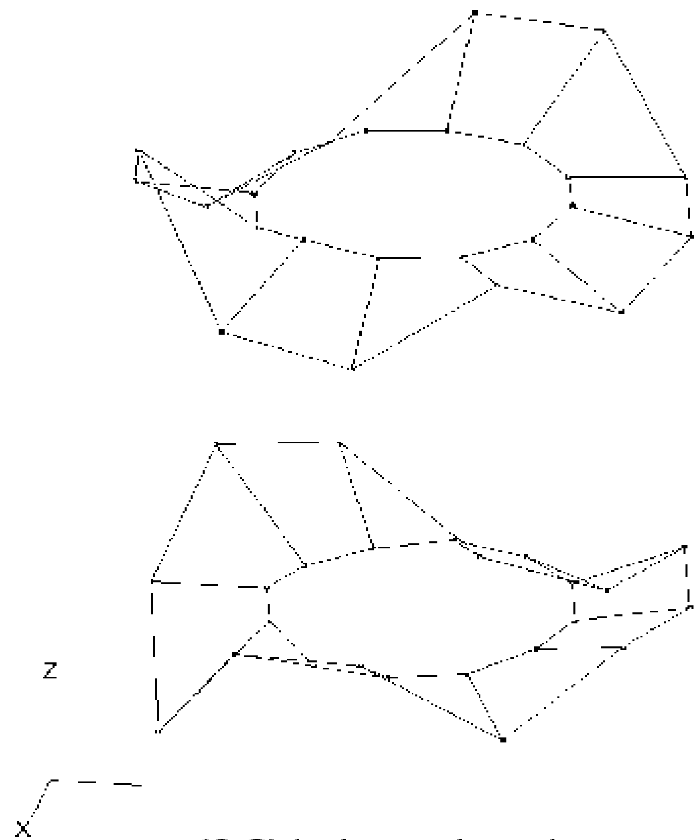
Waterfall Plot (2)



Balanced Modes

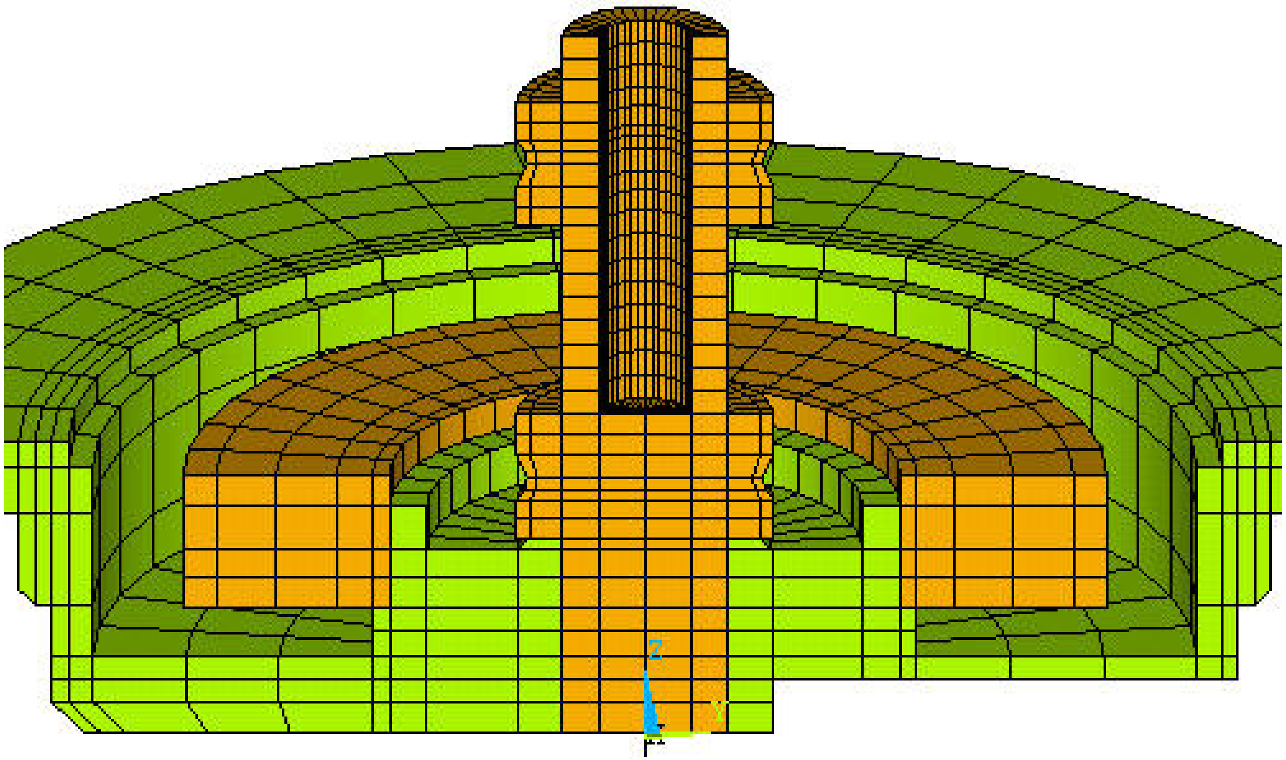


(0,2) balanced mode

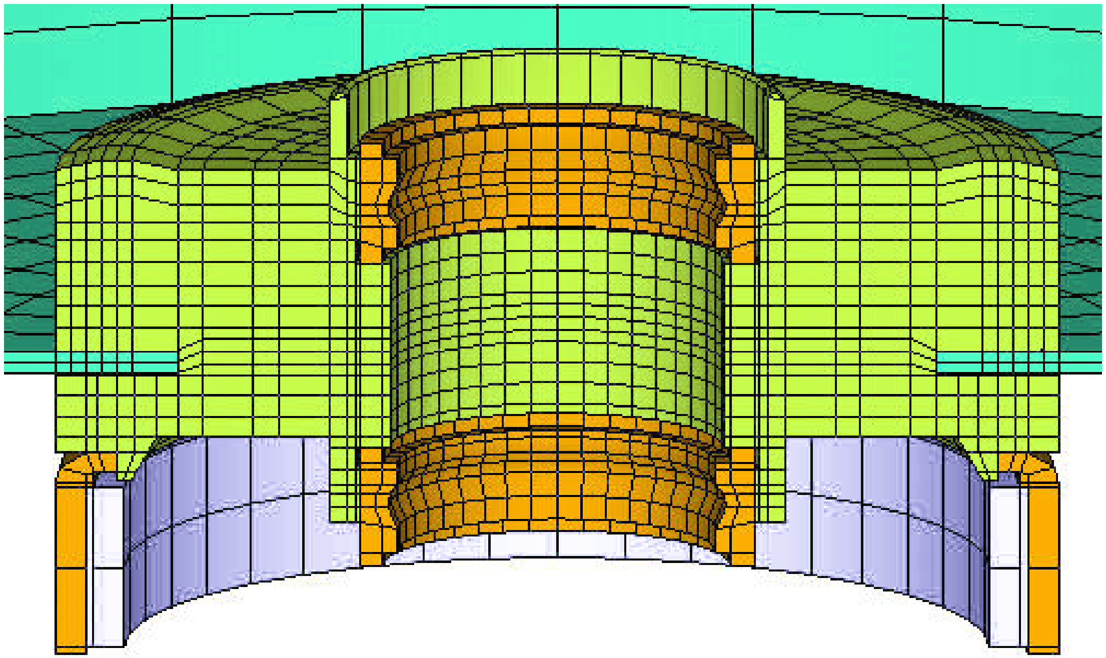


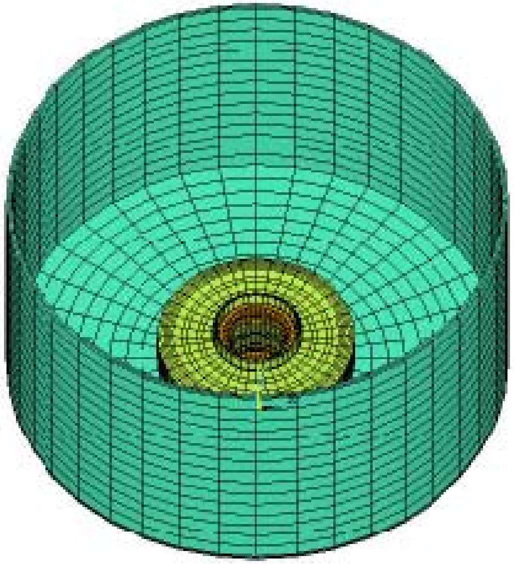
(0,3) balanced mode

FEA -- Stationary Part

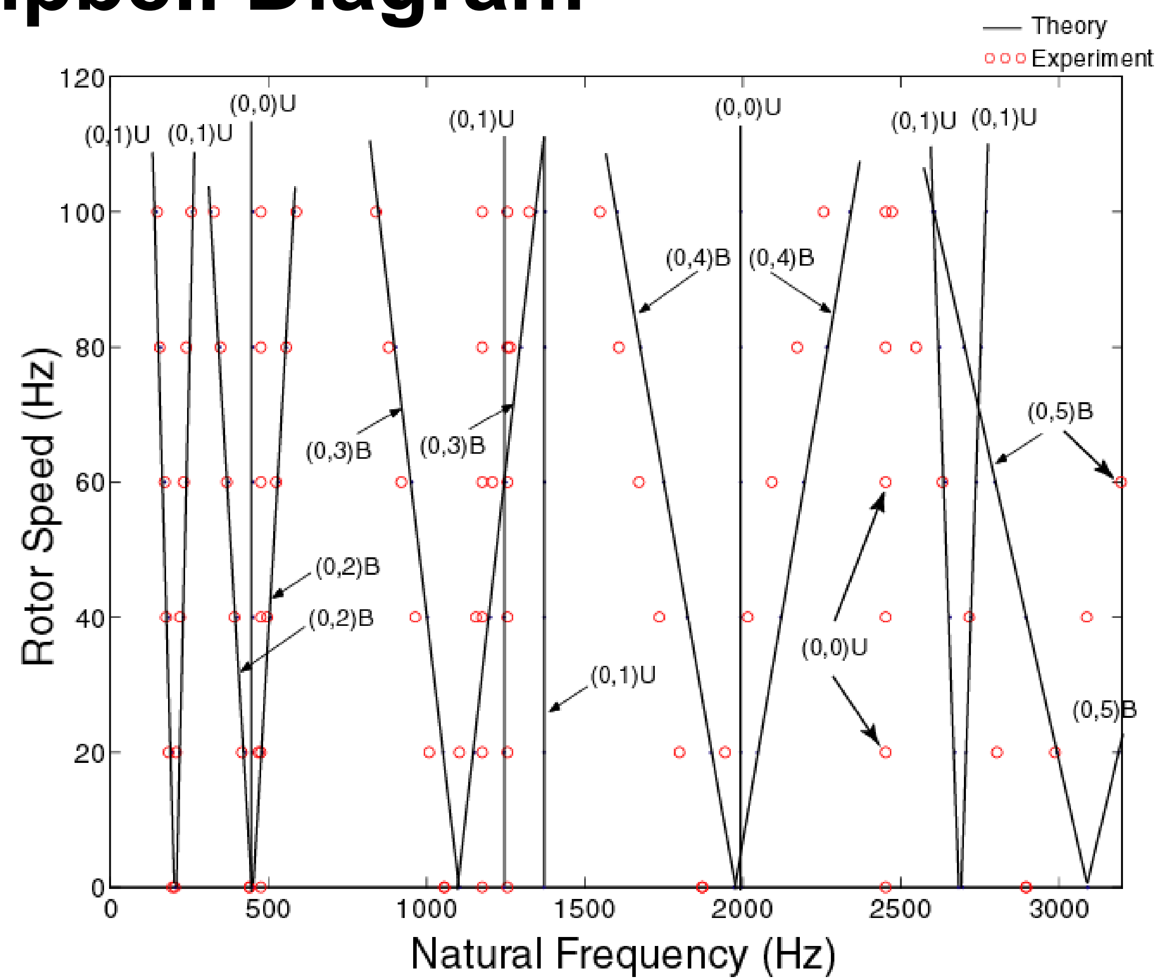


FEA -- Rotating Part

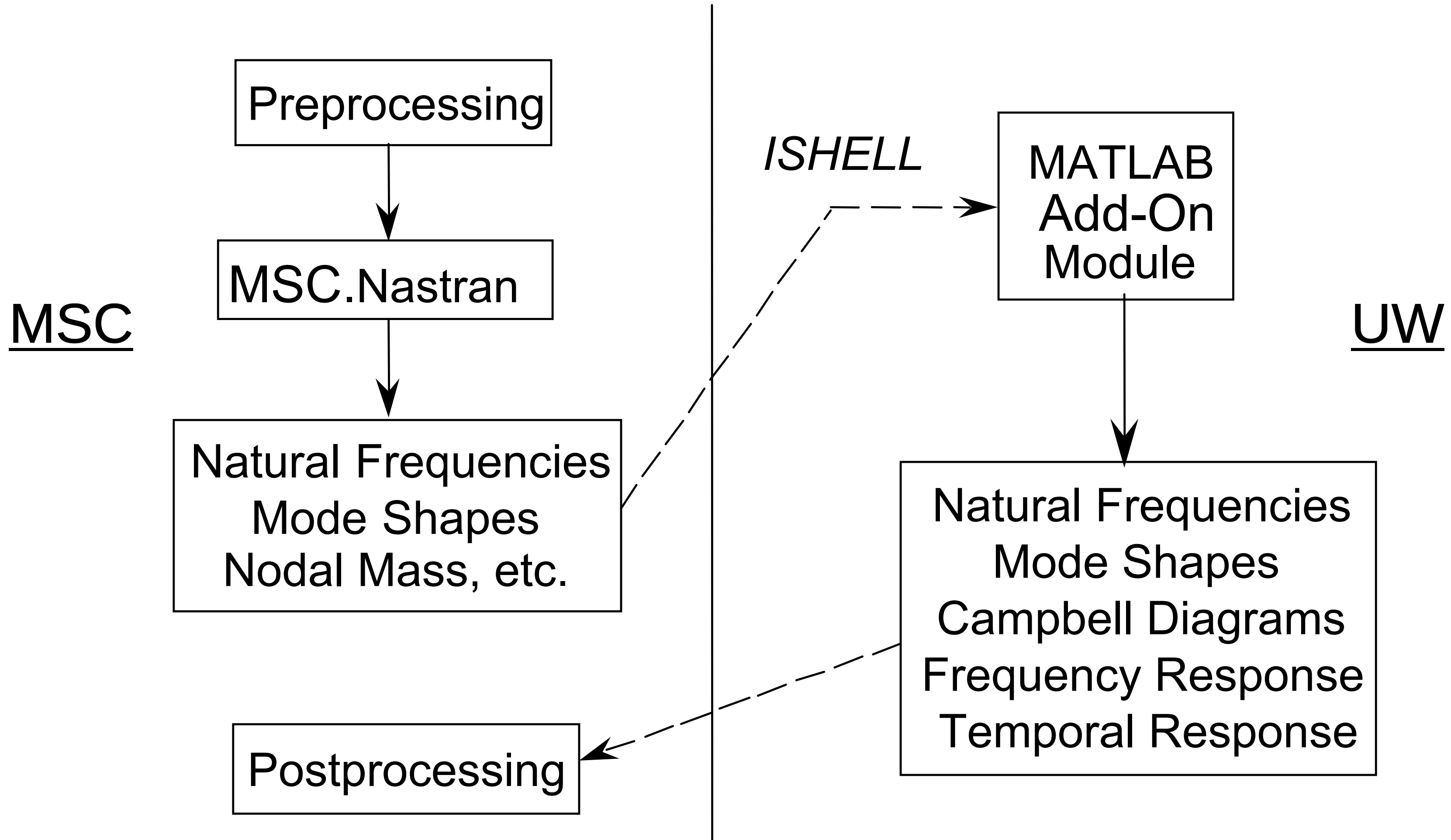




Campbell Diagram



MSC-UW Collaboration



Preliminary Time Table

2004, December: α-code (axisymmetric rotors)

2005, March: β-code (axisymmetric rotors)

2005, June: α -code (asymmetric rotors)

2005, September: β -code (asymmetric rotors)

Big Picture

Internal Solutions (MSC.Software)	External Solutions (UW)
M, **C**, **K** matrices	Modal reduction
Large DOF	Small DOF
Steady states	Steady/Transient states

Two complementary sets of solutions to solve most rotordynamics problems

Summary

Have developed a unified approach to analyze vibration of rotating machines with arbitrary rotor/stator geometry and complexity.

Preliminary experimental results agree with theoretical predictions very well for spindle motors carrying an axisymmetric shell.

Currently working with MSC.Software to commercialize this new patent-pending algorithm.