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Rotordynamics Analysis using Abaqus/Standard

Abaqus Technology Brief

Acknowledgements

Dassault Systèmes SIMULIA would like to thank the students and faculty in the ROMAC Laboratory at the University of Virginia.

Summary

A wide variety of industrial machines employ rotating structures supported by bearings. Turbines, jet engines, computer disk drives and electric motors typify the use of spinning, shaft mounted, rotor-bearing structural systems. Any unbalance in such a system can introduce unwanted vibration; the area of engineering analysis that quantifies the dynamic behavior of such systems is known as rotordynamics.

While the vibration in a rotor-bearing system includes axial, lateral, and torsional components, the lateral vibration is the most critical because it is generally the principal cause of structural failures in rotor-bearing systems.

In this Technology Brief, a typical workflow for rotordynamics analysis using Abaqus is demonstrated. The results compare favorably with those from industry-standard codes from the University of Virginia's Rotating Machinery and Controls Laboratory (commonly known as ROMAC). A substructuring application is also discussed.

Introduction

The lateral vibration of a rotating system can be analyzed by stability analysis and unbalanced frequency response analysis. In Abaqus/Standard, the stability analysis is based on a complex frequency extraction to identify the resonance, or critical, spin speed. In order to consider the rotational or spin speed of the rotor, the stability analysis must include gyroscopic effects. In the frequency response analysis, the principal item of interest is the unbalanced load, generally introduced by the unbalanced mass of the structure. Both the stability analysis and the unbalanced frequency response analysis can be performed in Abaqus/Standard using beam elements or three dimensional (3-D) solid elements.

A rotordynamics model typically consists of the rotor, disks, and bearings. The rotor and disks are normally modeled with beam and point mass/inertia elements. When the rotor geometry is very complex, 3-D models can achieve more accurate results; however, this comes at the expense of increased compute time. Figure 1 shows a beam model and a 3-D solid model for a rotor.

Finite Element Analysis Approach

For the present analysis, beam elements are used for the structure. Connector elements are used to model the stiffness and damping of the bearings, since they support frequency dependent cross-coupling properties.

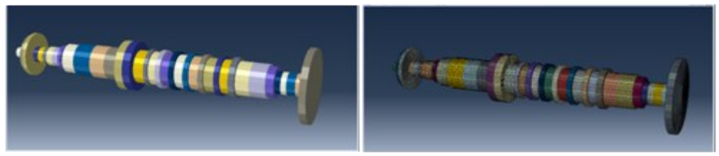

Figure 1: Beam (left) and 3-D solid (right) representations of a rotor-bearing system

Key Abaqus Features and Benefits

- Special rotordynamics loading to capture the centrifugal load effects and load stiffness terms associated with spinning bodies
- Connector elements for modeling the frequency dependent stiffness and damping behavior of rotor bearings
- Substructuring capabilities for improved computational efficiency

A stability analysis is first performed with a rotor and bearing model. Then an unbalanced frequency analysis is performed to identify the response of the rotor. Even though a rotordynamics model can be modeled directly in Abaqus/CAE, SIMULIA has developed a spreadsheet tool [1] using Excel and Visual Basic (VBA) that simplifies the development and post processing of rotor-bearing models in Abaqus (see Figure 2). Finally, examples using substructures are introduced and the results are discussed.

Rotor and Bearings

The analysis described in this Technology Brief is performed using the rotor shown in Figure 1, with section data taken from an API 684 [2] reference rotor model for a 12 MW steam turbine. A beam element model is created using the VBA spreadsheet tool. The bearing properties [3] in Tables 1 and 2 are used to represent the fre-

Speed (RPM)	K11	K12	K21	K22
2000	3.86E+01	3.61E+01	8.19E+01	5.26E+04
6000	5.78E+04	-1.28E+02	1.02E+02	6.80E+04
12000	7.56E+04	-2.74E+02	2.58E+02	8.38E+04
16000	9.19E+04	-4.83E+02	4.75E+02	9.91E+04
20000	1.06E+05	-7.55E+02	7.53E+02	1.12E+05
24000	1.18E+05	-1.09E+03	1.09E+03	1.24E+05

Table 1: Bearing stiffness (lbf/in)

Speed (RPM)	C11	C12	C21	C22
2000	5.45E+02	0.00E+00	0.0E+00	4.96E+02
6000	54.50E+02	0.00E+00	0.0E+00	4.75E+02
12000	3.92E+02	0.00E+00	0.0E+00	4.05E+02
16000	3.50E+02	0.00E+00	0.0E+00	3.58E+02
20000	3.15E+02	0.00E+00	0.0E+00	3.21E+02
24000	2.87E+02	7.56E-01	-1.01E+00	2.91E+02

Table 2: Bearing damping coefficients (lbf•s/in)

quency dependent stiffness and damping characteristics. The stiffness and damping coefficients K11 and C11 are the respective properties in the X-direction on the bearing plane (the spin axis is the Y-axis). K12 and C12 are the cross-coupling terms of the bearing stiffness and damping coefficients. Typically, the bearing coefficients are defined in two orthogonal directions on the plane.

Figure 2 shows a screen capture of the VBA spreadsheet used to set up the rotor section and bearing property data. The VBA tool streamlines model development by automatically creating an input file for a beam element model or a Python script to generate the input file for a 3-D solid model.

Stability Analysis

A stability analysis can be performed with Abaqus using a complex frequency extraction. Since the subspace projection method is used for this procedure, a real frequency extraction is required prior to the complex frequency extraction in order to create the modal space for the projection.

The effect of the rotor spin speed can be considered by applying the rotordynamic load ROTDYNF in a general static step prior to the frequency extraction step. There are two ways to consider the spin effect, which is gyroscopic: 1) in the stationary reference frame, and 2) in the moving reference frame. When the gyroscopic effect is considered in a fixed (stationary) reference frame, the complex frequency calculated in the stationary reference system represents a complex frequency in the real world. However, when the gyroscopic effect is considered in a reference frame which moves with the rotating body, the complex frequency calculated in the moving reference system does not include the effect of the spin speed of

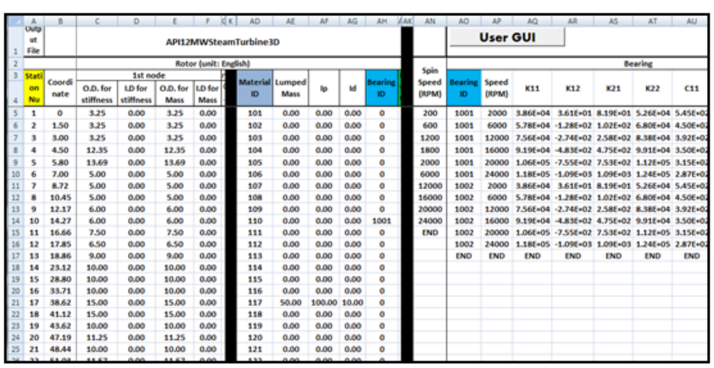

Figure 2: Screen capture of the spreadsheet tool for rotor section and bearing property data definition

Mode (non-zero only)	2000 RPM					
	ROMAC		Abaqus			
	Hz	Log Dec	Hz	Diff	Log Dec	Diff
1	5.38	1.55	5.38	0.02%	1.55	0.01%
2	6.33	1.18	6.33	0.10%	1.18	0.02%
3	13.70	12.27	13.71	0.10%	12.26	0.10%
4	171.15	1.19	171.10	0.03%	1.19	0.04%
5	172.98	1.15	172.96	0.01%	1.15	0.05%
6	334.20	0.06	334.17	0.01%	0.06	0.14%

Table 3: Comparison of Abaqus and ROMAC stability analysis results

the rotating body. Hence, the complex frequency calculated in a moving reference frame must be adjusted by adding or subtracting the spin speed in order to represent the complex frequency in the stationary reference frame.

Typically, the stationary reference frame approach is used in a rotordynamics analysis when considering the gyroscopic effect since it provides the correct whirl frequency; i.e., the complex frequency that shows the whirling mode shape. However, the stationary reference frame approach is limited in that it can only be applied to a body of revolution. The rotordynamic load in Abaqus, ROTDYNF, is calculated based on the stationary reference frame.

Since the stability analysis should be performed for several spin speeds, a step definition for each desired speed is necessary; these steps can be easily created using the VBA spreadsheet. Once the rotor section data and spin speeds are entered as shown in Figure 2, the spreadsheet tool creates the analysis input file automatically.

Stability analysis results for a spin speed of 2000 RPM are shown in Table 3 and compared to those obtained with the ROMAC codes. The difference between the results is less than 0.2%. Figure 3 shows an orbit plot at the 6th non-zero mode for the 2000 RPM spin speed case.

One of the most important results obtained from a stability analysis is the Campbell diagram. The Campbell diagram is a plot of the whirl frequency versus spin speed, with each whirl frequency having the same whirl mode connected with a line. It is used to identify operating conditions that could lead to damaging excitation of natural frequencies in the rotor-bearing system.

The VBA spreadsheet can also be used as a postprocessing tool to generate Campbell diagrams from Abaqus results. Figure 4 shows an example Campbell diagram and semi-minor plot. The whirl direction can be identified by the sign of the semi-minor value. A positive value denotes the forward whirl direction and a negative value denotes the backward whirl direction. The reference line in the Campbell diagram represents the excitation or "per rev" line, and any intersection point between the reference line and the same whirl mode line indicates a reso-

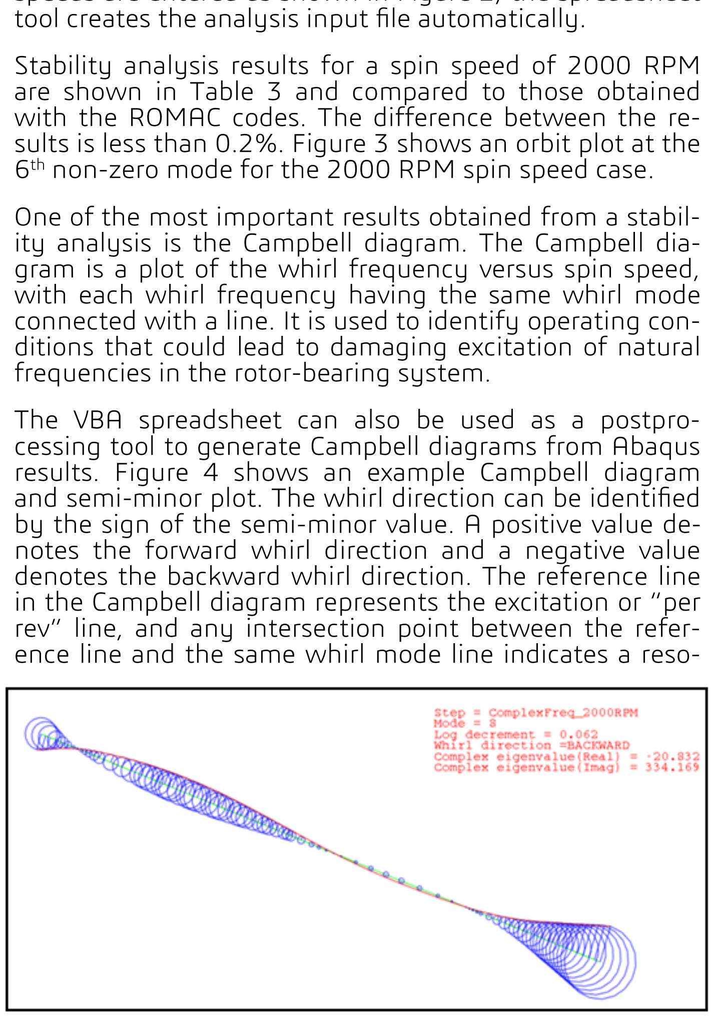

Figure 3: Orbit plot at the 6th non-zero mode, 2000 RPM case

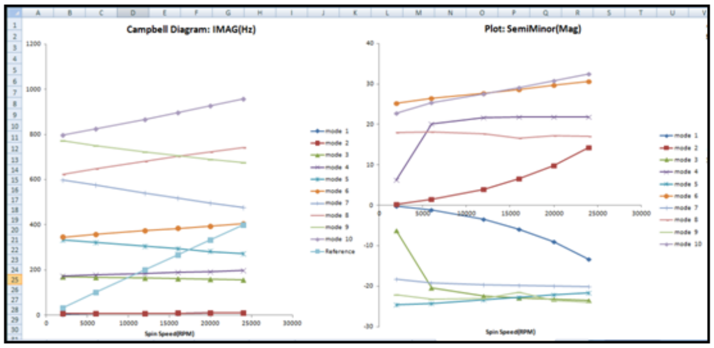

Figure 4: Campbell diagram (left) and semi-minor plot (right)

nance point. The corresponding spin speed at this point is called the critical speed. In Figure 4, we have identified three critical speeds (9,941 RPM, 11,033 RPM, and 17,374 RPM). The VBA spreadsheet also provides the critical speeds in an external text format file.

Unbalanced Frequency Response Analysis

The unbalanced frequency response analysis can be performed using the steady state dynamics procedure. Since the gyroscopic effect is treated as a damping effect in Abaqus, only a direct or subspace-based steady state dynamic analysis can be used. The unbalanced mass effect can be modeled using concentrated forces with imaginary or real options.

The VBA spreadsheet is also used to automatically create the unbalanced frequency response model. The unbalanced load can be defined using a magnitude and phase angle in the spreadsheet. The internal VBA script in the spreadsheet converts the magnitude and phase angle to the real and imaginary format used in the analysis input file.

As shown in Figure 5, the unbalanced loads are applied at three different points on the rotor with different phase angles. The response results on the 1st probe, which is marked with a circled x at the center of the rotor in Figure 5, are compared with the results from the ROMAC codes in Figure 6. The magnitudes and phase angles predicted by Abaqus correlate well with the ROMAC results.

Substructuring

Abaqus/Standard offers a substructuring capability that allows you to create a reduced model that captures the reduced modal space of the target structural model, but that can run substantially faster than the full model. Abaqus also has the unique capability to create substructures for both the stationary and rotating structures. The rotor and support plate model shown in Figure 7 illustrates the substructure capability for rotordynamics analysis. The rotor is located at the end of the cantilevered support plate, which is modeled with solid elements and the connected rotor is modeled with coupling and connector elements.

Figure 5: Unbalanced loads and probes on the rotor

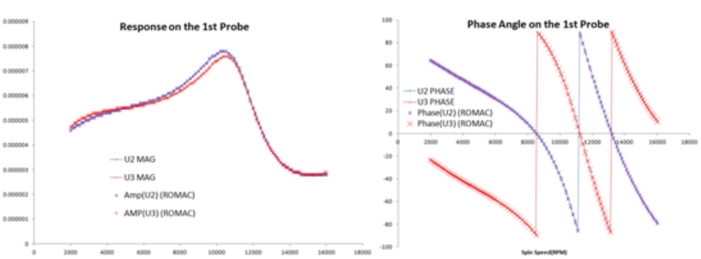

Figure 6: Response results from Abaqus and ROMAC

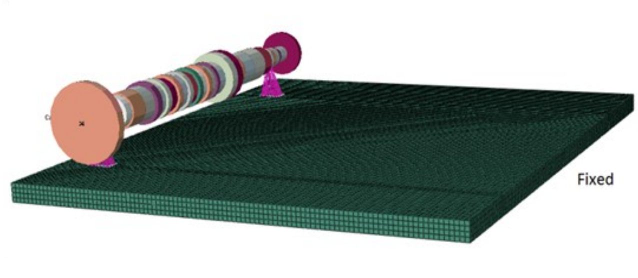

Figure 7: Example model of rotor and support plate

A complex frequency extraction analysis for a rotor spin speed of 24,000 RPM is performed for three different models: 1) full model: the rotor and support plate are modeled without substructures; 2) rotor & support substructure: the support plate is modeled as a substructure with the full rotor model; and 3) rotor substructure & support plate: the rotor at the 24,000 RPM spin speed is modeled as a substructure in the full support plate model.

As shown in Table 4, the complex frequency results from the three models are very similar. The 5th mode shapes for the three models are shown in Figures 8, 9 and 10 respectively. The whirl mode is presented as an orbit plot along with the mode shape of the support plate. All of the 5th modes show a backward whirl mode of the rotor and the same mode shape of the plate. The rotor and support substructure model shows a 10 x speed-up in run time compared with the full model.

	Full Model	Rotor & Support Plate Substructure		Rotor Substructure & Support Plate	
Mode	Complex Frequency	Complex Frequency	Diff	Complex Frequency	Diff
1	1.71	1.71	0.00%	1.71	0.00%
2	7.33	7.33	0.02%	7.35	0.22%
3	7.85	7.86	0.03%	7.95	1.16%
4	19.00	19.14	0.73%	19.02	0.12%
5	23.97	24.20	0.93%	23.99	0.06%

Table 4: Stability analysis results for 24,000 RPM spin

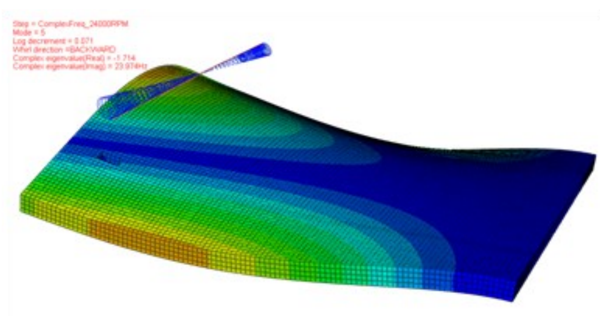

Figure 8: Full model results, 5th mode

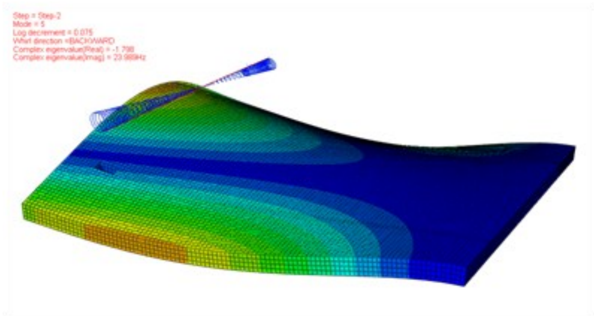

Figure 9: Model with rotor substructure, 5th mode

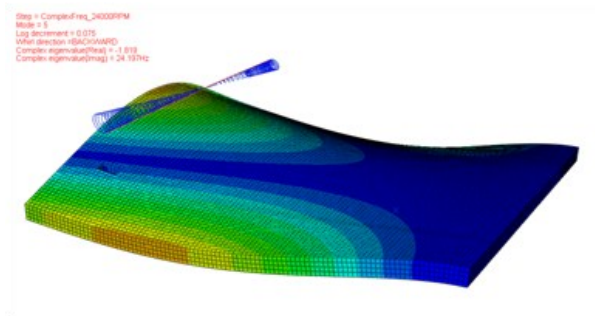

Figure 10: Model with support substructure, 5th mode

Conclusions

This Technology Brief illustrates the procedures used in Abaqus/Standard to perform stability and unbalanced response analyses for an API 684 steam turbine rotor. It also describes a new VBA spreadsheet tool that has been developed specifically to enable easy pre- and postprocessing of rotordynamics analyses with Abaqus. The results from Abaqus/Standard correlate well with the results from the well-known ROMAC rotordynamics codes. We have also shown that Abaqus has a powerful substructure capability for stationary and rotating structures that allow reduced models to be run in considerably less time, while still achieving almost the same accuracy as the full models.

References

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