Effects of Structural Forces on the Dynamic Performance of High Speed Rotating Impellers.

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Abstract: Vibration and Dynamic performances of the rotating machinery are conventionally evaluated based on the dominant structural forces such as the centrifugal forces. The increase in rotational speed, miniaturization and performance, demands for improved and accurate evaluation of the vibration performance. In this paper, the effect of stress stiffening, stress softening, Coriolis forces and damping on rotor vibration characteristics of rotor are investigated. A Single disk rotor, micro single disk rotor, double disk rotor and counter rotating rotor are considered for vibration and dynamics performance evaluation. The vibration characteristics and mode shapes are extracted and reported. The results are compared for all the four cases with and without the Coriolis forces as Campbell diagram format for further investigations. In future work, the multiphysics effects, the coupled structural, fluid and thermal forces will be included.

Keywords: Vibration, dynamics, turbines, impellers, rotating machinery, coupled fluid structure interaction, centrifugal forces, fluid forces, natural frequency, and vibration performance.

1. Introduction

Rotor dynamics are critical for safe and efficient performance of rotating machinery. Turbine, pump, computer hard disk are used in fluidic (aerodynamic or hydrodynamic) and or electromagnetic environment [1-7]. Concepts such as counter rotating turbines and micro turbines are under research for increasing the power density and efficiency. Rotor dynamics includes structural centrifugal, fluidic and thermal forces. Traditionally rotor dynamics is based on the dominant structural dynamic loads. The fluidic and thermal forces contributions are increasing in the new micro and high performance turbines. The inclusion of coupled effects of fluid and centrifugal forces can contribute significantly to the accurate performance prediction. A brief overview of multiphysics rotor dynamics is given. The governing equation related to equation of motion is given. The effect of additional structural forces and implementation in COMSOL are detailed. Four configurations, a Single disk rotor, micro single disk rotor, double disk rotor and counter rotating rotor are considered for vibration and dynamics performance evaluation. The vibration and dynamics characterization results, the modes shapes and frequency response are extracted and reported.

2. Multiphysics Rotor Dynamics

Rankine in 1869 developed a simple rotor model. Later, Laval built an impulse turbine in 1883. Jeffcott in 1919 formulated the basic rotor problem which is in use even today. Holzer and Myklestad further extend the analytical formulation for torsional and flexural mode shape extraction [1]. Recent trend is to use finite element method for rotor dynamics. One dimensional Timoshenko beam theory based formulation and lumped mass approach and solution is used for traditional rotor dynamics. This traditional one dimensional method limits the potential of simulations and does not leverage the CAD based iterative virtual design environment. The approximation of mass and inertia location and distribution leads to inaccurate results. Most common rotor dynamics software use beam and shell elements. For complex geometry 3D rotor dynamics are being used for improved accuracy. The recent developments in computing power and solution methodology allow us to do 3D rotor dynamics for complex geometry for accurate results. The stress stiffness and softening effects, coupling effects of shaft and rotor, actual and accurate geometry based modeling can be leveraged in 3D rotor dynamics. The three dimensional CAD geometry based multi body rotor dynamics for accurate performance prediction is the leading method adopted by industrial leaders. This enables virtual product development for faster and first time right product development.

Three dimensional rotator dynamics use dominant structural forces for dynamic performance evaluation. The structural, fluidic and thermal forces also influence the dynamic performances especially for micro, high speed and hydrokinetic rotors. Multiphysics modeling with sequentially and or directly coupled models are under development for improved accuracy of prediction.

3. Governing Equations

The fundamental physical law governing vibration phenomena is Newton's second law. The differential equation of motion governs the force balance equation of a linear dynamic system based on first principle motion equations, linking the inertial, damping, elastic and external forces, along with mass, damping and stiffness properties, as given below [1].

$$m\ddot{x} + c\dot{x} + kx = f(t)$$

The above differential equation for Finite element procedure for multi degree of freedom system in matrix notation is formulated as follows,

$$[M][\ddot{x}] + [C][\dot{x}] + [K][x] = [R]$$

Where,

[K], Global stiffness matrix

[x], Displacement vector of all the nodes

[C], Global Damping matrix

$[\dot{x}]$, Velocity vector

[M], Global Mass matrix

$[\ddot{x}]$, Acceleration vector

[R], Global force or load vector, where, R is f(t)

The commercial tools use the above formulation to solve for natural frequency or Eigen value extraction, forced and unforced vibration and dynamic problems. The effects of gyroscopic, Coriolis force and other forces are added to the above equation for improved performance prediction. The fluidic forces calculated from CFD or analytical models are also added to the above differential equation of motion, in a simplified multiphysics coupled analysis.

In this paper, the following equations are used to calculate the centrifugal and fictitious Coriolis forces using the following relation, as function of angular rotational speed, Omega. The following system of equations takes into account of the acceleration of the system in a rotating coordinate system and the associated forces of rotating machinery. In vector notation and for a system rotating with fixed angular velocity Ω about a fixed unit-length axis **e**, the centrifugal force $\mathbf{F}_{\text{cent}}$ and the Coriolis force $\mathbf{F}_{\text{cor}}$ are:

$$F_{\text{cent}} = -\rho\Omega^2\mathbf{e}\times\mathbf{e}\times(\mathbf{r}-\mathbf{r}_0)$$

$$F_{\text{cor}} = -2\rho\Omega\mathbf{e}\times\mathbf{v}$$

$$F_x = -\rho\Omega^2(e_y(e_x y' - e_y x') - e_z(e_z x' - e_x z')) - 2\rho\Omega(e_y v_z - e_z v_y)$$

$$F_y = -\rho\Omega^2(e_z(e_y z' - e_z y') - e_x(e_x y' - e_y x')) - 2\rho\Omega(e_z v_x - e_x v_z)$$

$$F_z = -\rho\Omega^2(e_x(e_z x' - e_x z') - e_y(e_y z' - e_z y')) - 2\rho\Omega(e_x v_y - e_y v_x)$$

Where, **r** and **v** are the position and velocity of a material element, respectively, ρ is its density and **r**0 is any point on the axis of rotation. The model rotational axis is z for this simulation. The above model was implemented in COMSOL [7].

4. Design of Experiments (DoE).

The first step in rotor dynamic analysis is the determination of the natural frequency and mode shapes extraction for critical speeds. A Single disk rotor, micro single disk rotor, double disk rotor and counter rotating rotor are considered for vibration and dynamics performance evaluation. The four rotor cases are schematically shown in figure 1. The vibration characteristics were investigated for a rotational speed of about 15000 RPM. For micro turbine the rotational speed was increased to about 75000 RPM. The effect of Coriolis force is also investigated. The scale effects of single disk rotor as micro single disk rotor are also considered for investigations.

A rigid bearing and flexible shaft and rotor is assumed. A density of 7861 kg/m2, modulus of elasticity of 137.9m GPa, and Poisson's ratio of 0.29 is used for rotor material. Similarly, a density of 8442 kg/m2, modulus of elasticity of 179.26 GPa, and Poisson's ratio of 0.32 is used for rotor shaft material. Appropriate mesh convergence investigations were performed prior to vibration characterization.

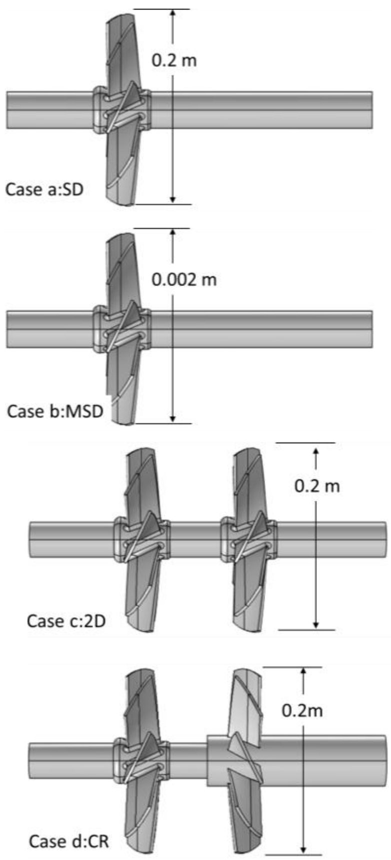

Figure 1. CAD model of the turbines considered for the vibration and dynamics performance evaluation.

A total of 8 DoE runs were considered for vibration performance evaluation and comparison. These cases were selected to finalize the concept for a new turbine. The natural frequency and mode shapes were extracted. The vibration performance as function of rotating speed was investigated using Campbell diagram.

5. Results and Discussion

The vibration simulation results for the four rotors are shown in this section. Figure 2 shows the typical modes shapes for single disk rotor. Figure 3 and 4 shows Campbell diagram without and with the effect of Coriolis forces for single disk rotor, respectively. The flexural mode shapes are highlighted. The frequency increases with rotational speed for all mode shapes. The Coriolis forces increase the higher mode natural frequencies at higher rotational speed.

Micro single disk rotor has also shows mode shapes similar to single disk rotor with a higher natural frequency. The micro rotor diameter is about 2 mm. Figure 5 and 6 shows Campbell diagram without and with the effect of Coriolis forces for micro single disk rotor, respectively. The natural frequency is almost constant with lower rotational speed without the effect of Coriolis forces. The simulation results with Coriolis forces shows significant changes in pattern with increased rotational speed. At speeds comparable to macro single disk rotor, the micro single disk rotor response is almost constant. The effects are significant only at very high rotational speeds.

Figure 7 shows the typical modes shapes for double disk rotor. Figure 8 and 9 shows Campbell diagram without and with the effect of Coriolis forces for the double disk rotor, respectively. The natural frequency increases with rotation speed. The Coriolis force effects are shown only at high rotational speed.

Figure 10 shows the typical modes shapes for counter rotating double disk rotor. Figure 11 and 12 shows Campbell diagram without and with the effect of Coriolis forces for the counter rotating double disk rotor, respectively. The natural frequency increases with rotation speed for about 10000 RPM and reduction in frequency with increased RPM after 10000 is observed. The Coriolis force effects are observed at high rotational speed.

The critical speeds were determined for each case from the Campbell diagram based on the frequency curves and excitation lines. These simulation results were further used for dynamic performance evaluation of the new designs. The forward and backward whirl vibration characteristics were used for final design.

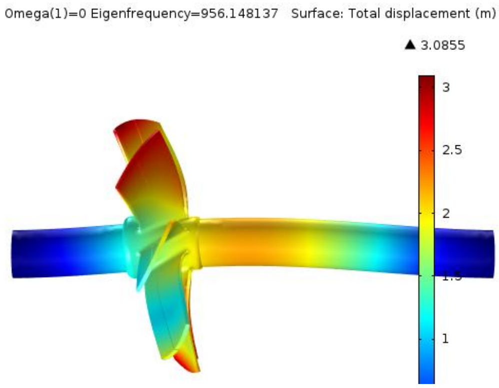

Figure 2. Typical mode shapes of single disk rotor.

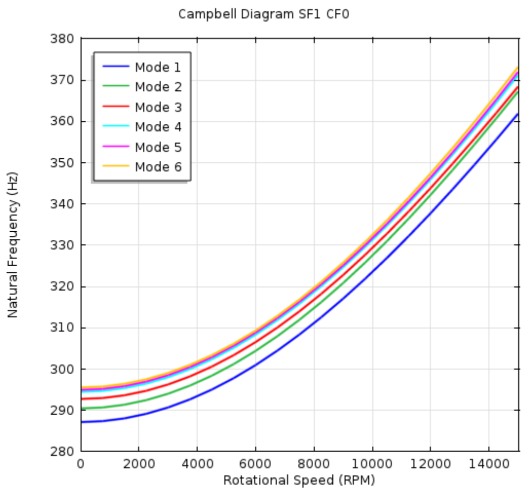

Figure 3. Vibration characteristics of single disk rotor without the effect of Coriolis forces.

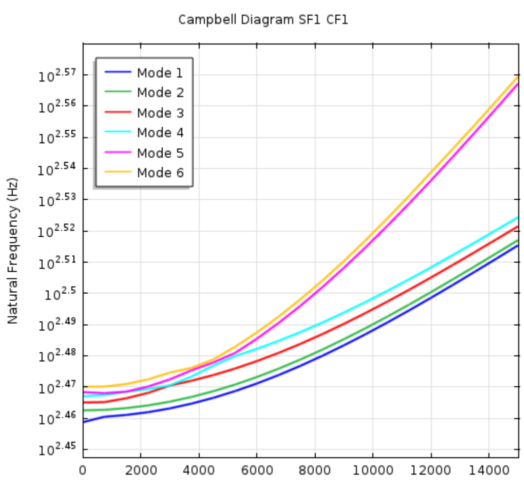

Figure 4 . Vibration characteristics of single disk rotor with the effect of Coriolis forces.

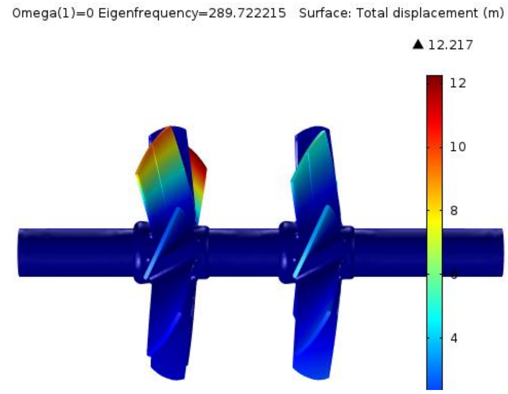

Figure 7. Typical mode shapes of double disk micro rotor

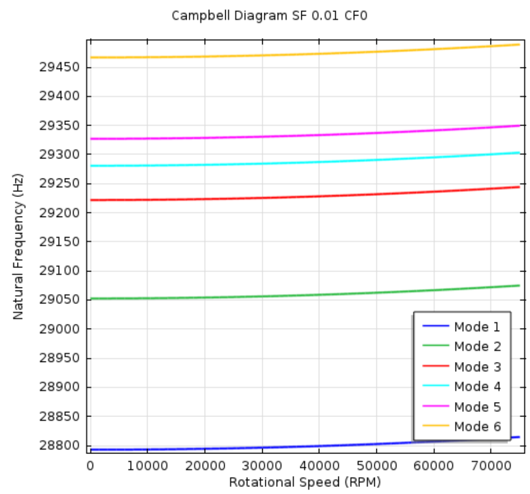

Figure 5. Vibration characteristics of single disk micro rotor without the effect of Coriolis forces.

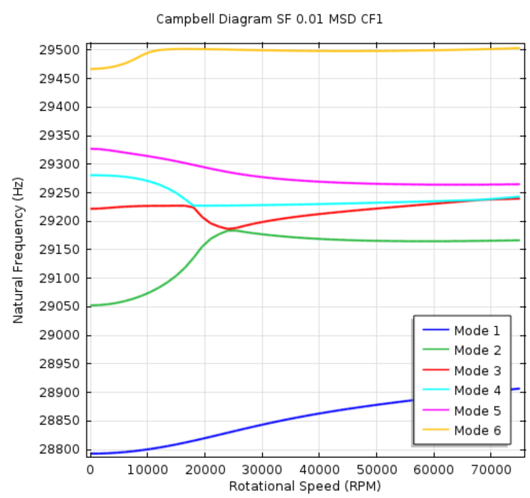

Figure 6 . Vibration characteristics of single disk micro rotor with the effect of Coriolis forces.

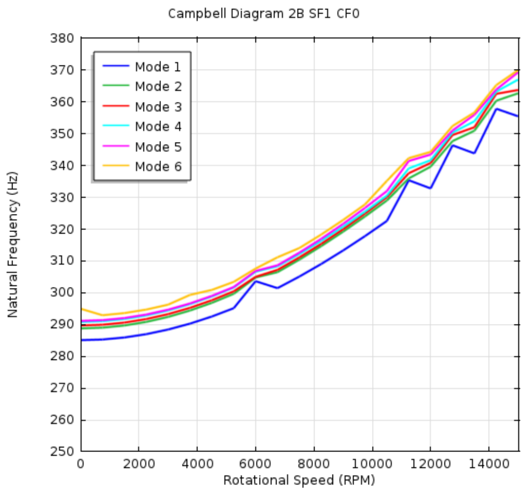

Figure 8. Vibration characteristics of double disk rotor without the effect of Coriolis forces.

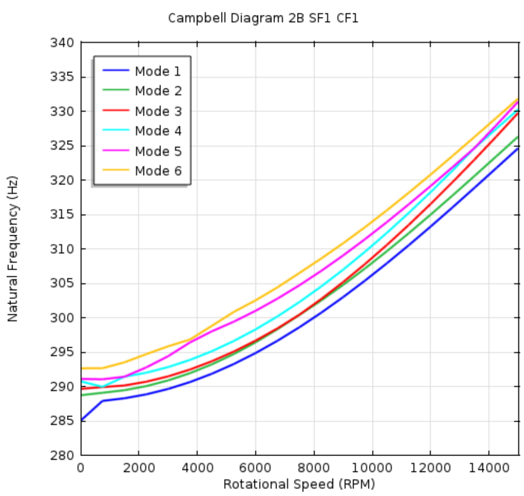

Figure 9. Vibration characteristics of double disk rotor with the effect of Coriolis forces.

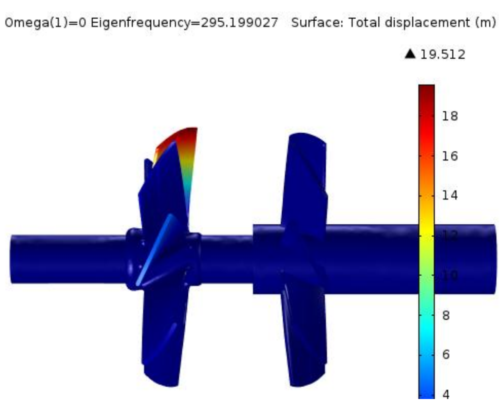

Figure 10. Typical mode shapes of counter rotating disk rotor

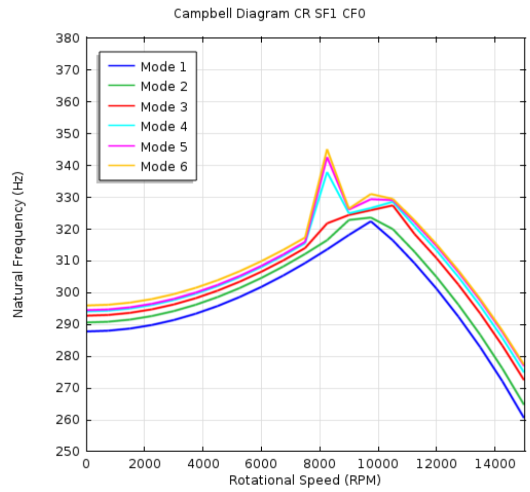

Figure 11. Vibration characteristics of counter rotating disk rotor without the effect of Coriolis forces.

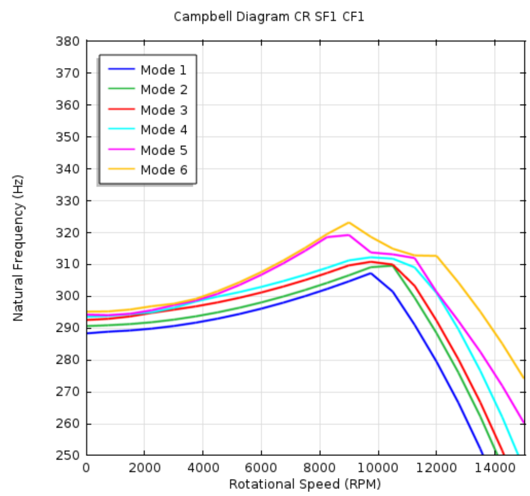

Figure 12. Vibration characteristics of counter rotating disk rotor with the effect of Coriolis forces.

5. Conclusions

A brief overview of three dimensional rotor dynamics was given. The differential governing equation of motion is detailed. The forces related to rotor dynamics were briefly discussed. Four cases, single disk rotor, micro single disk rotor, double disk rotor and counter rotating rotor were considered for vibration and dynamics performance evaluation. The Coriolis forces effects on all the four cases were investigated. The mode shapes and natural frequency Eigen modes were extracted. The results were reported as Campbell diagram for further investigations. The single disk rotor was shown to increase frequency with rotation speed. The Coriolis forces were shown to lower the frequency at higher rotational speeds. The counter rotating disk was shown a dual frequency vs rotation speed behavior. The overall vibration characteristics as a function of structural forces were investigated and reported. The effect of fluidic (aero and hydro) and thermal forces along with structural forces will be investigated in the future work.

6. References

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