A Different Perspective of Synchronous Thermal Instability of Rotating Equipment (STIR)

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3/15/2017

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Introduction

As compression technology development is driven by the market need for higher pressure & higher power units for the upstream oil and gas industry, the need to better understand this thermally induced phenomena to **identify high risk units** requiring higher level of analytical work becomes important.

- Physics behind **STIR (Synchronous Thermal Instability of Rotating Equipment)**
- Governing equation for Morton & Newkirk Effects
- Using rotor orbits to observe the effect from unbalance, misalignment and rub on STIR

Even though most published cases have been around units running at high speed (above 1st and or 2nd bending critical speeds), this phenomena can also happen in rigid rotor units. Also contrary to most of all cases observed, where a higher lubrication oil temperature triggers the instability, one unit that had been retrofitted due to known STIR tendency experienced elevated vibration which led to a trip when the oil temperature drops.

- **Case Review #1:** Compressor running below 1st critical speed experienced with thermal instability
- **Case Review #2**: Cold lubrication temperature caused thermal Instability

Several key factors need be considered when screening for high potential STIR units. Base on these observations, a experience chart built with available published STIR cases with be presented herein.

STIR – Physics Behind

Morton Effect

- Thermally induced
- Heat generated by bearing “hot spot” without rub
- The phase of the thermally induced unbalance is slightly different from the “high spot” due to heat flux from lubrication circumferential flow
- The thermally induced unbalance phase will change in time, as the heat flux moves the “hot spot” circumferentially and causes rotor spiral motion of the rotor.
- The unbalance induced will grow in time but remain at 1X frequency.

Newkirk Effect

- Thermally induced
- Heat generated by rubbing of seals and bearings at the “high spot”
- The phase of the thermally induced unbalance is in phase with the “high spot”
- The thermally induced unbalance will also change phase as friction generated heat moves the thermally induced unbalance force in a direction counter to shaft rotation.
- The unbalance induced will grow in time but remain at 1X frequency

Morton Effect Governing Equations

$$\frac{\partial}{\partial\beta}\left(H^{3}\frac{\partial P}{\partial\beta}\right)+\frac{1}{\epsilon_{\mathrm{L}}}\frac{\partial}{\partial\xi}\left(H^{3}\frac{\partial P}{\partial\xi}\right)=\frac{\partial H}{\partial\beta}+2\frac{\partial H}{\partial\tau},$$

Incompressible isoviscous flow

$$\rho_{\mathrm{L}}c_{\mathrm{L}}\left(u\frac{\partial\Theta}{\partial x}+v\frac{\partial\Theta}{\partial y}+w\frac{\partial\Theta}{\partial z}+\frac{\partial\Theta}{\partial t}\right)=k_{\mathrm{L}}\left(\frac{\partial^{2}\Theta}{\partial x^{2}}+\frac{\partial^{2}\Theta}{\partial y^{2}}+\frac{\partial^{2}\Theta}{\partial z^{2}}\right)+\Phi$$

Thermal energy transport equation

$$H=H_{0}+\epsilon_{1}H_{1}+\epsilon_{2}H_{2},$$

Film thickness with forward and backward whirl

Assumptions includes short length bearing, temperature change is minimum to use a perturbation theory. Shaft thermal induced bend and resulting unbalance force are calculated. **The predicted instability happens at a speed slightly higher than the rotor critical speed.**

Ref: P. G. Morton, 2015

Newkirk Effect Governing Equations

$$\underline{F}_R(t) = -(k_{Pr}\underline{r} + c_R\dot{\underline{r}} + m_R\ddot{\underline{r}}) \qquad d(\ )/dt = (\dot{\ }),\ \text{etc.}$$

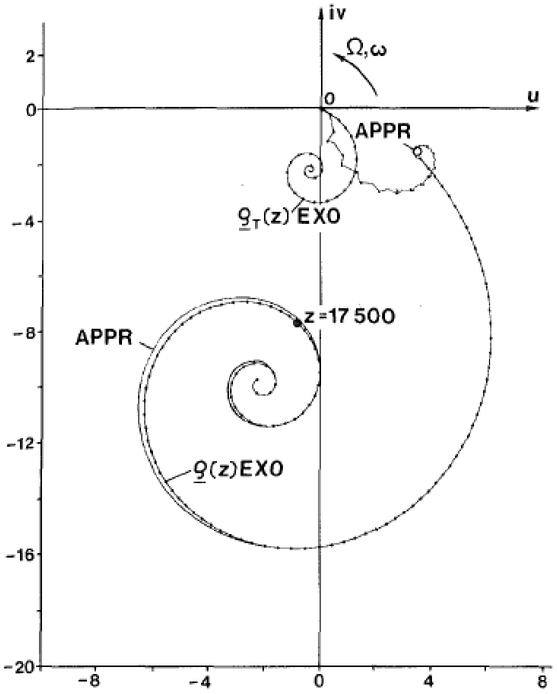
Friction Force from the seal ring

$$Q_1 = \kappa_1 W dt, \qquad W = \mu\Omega\frac{\phi}{2}F_R$$

Heat generated by the seal ring

$$\rho_T = \kappa_4 T$$

Shaft bow *(ρ_T)* is proportional to difference in temperature



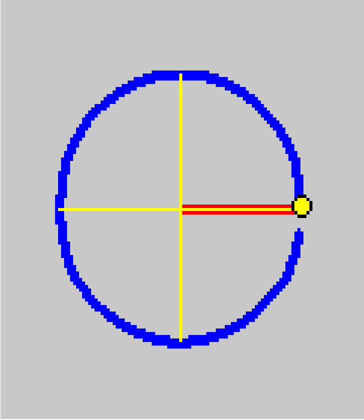
Single Degree of Freedom Model:
exact and approximated solutions both
(assume whirl amplitude is very small)

Ref: Kellenberger, ASME 1980.

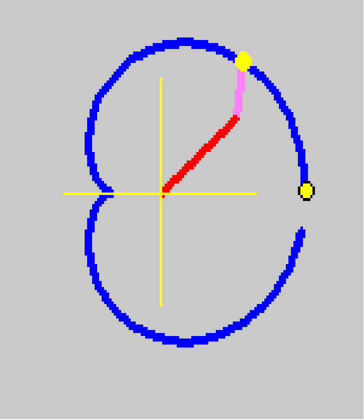
Rotor Orbits and their Effect on STIR

- Orbits shown different percentages of 1x and 2X and change of the ***hot spot*** and ***high spot***. Rubbing is usually easy to identify and happen less frequently; hence most of the *talk on the street* is about the ***Morton Effect.***

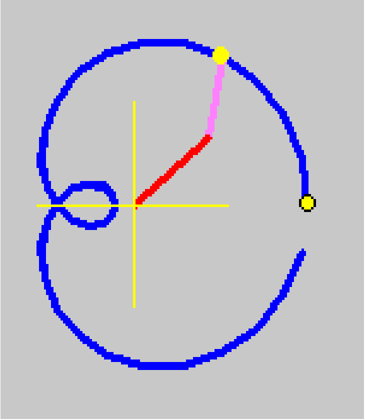
- Current analyses still have difficulty in predicting the onset condition for the Morton effect (rotor speed, oil temperature, etc.) as most simulations do not account for shaft misalignment, which actually creates **two adjacent *hot spots*.**



1X only



1X/2X: 2

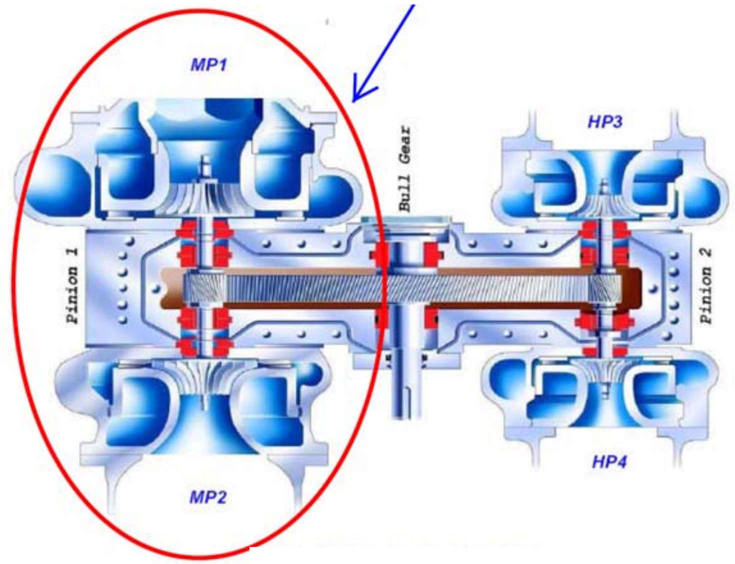


1X/2X: 1.2

Case 1: A Rotor Running Below 1st Critical Experienced Morton Effect

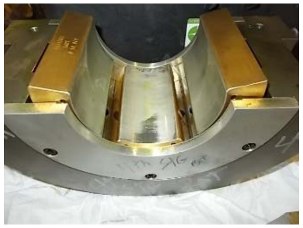
- Most published data are for units running above their first critical speed where heat generated at the "*hot spot*" is significant. Due to bearing edge loading in overhung units, a rotor operating below its 1st critical speed may still experience Morton Effect. Indeed, the issue was found out on test floor ?? and resolved with tilting pad bearing with dampers.

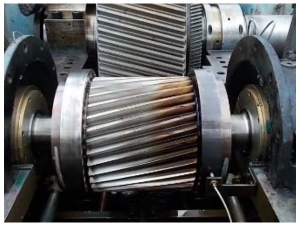
Design Power	1750	HP
1st Critical	24100	RPM
Design speed	18480	RPM
Critical Speed Ratio	0.77	
Bearing Length, *L*	2.2	
Bearing Diameter, *D*	3.5	
Bearing *L/D*	0.63	
Bearing Surface Velocity	285.7	ft/s
Babbitt Temperature	173	F
Bearing Load, Left B	1127	lbf
	147	psi
Bearing Load Right B	821	lbf
	107	psi
Overhung Shaft Length	16	in
Overhung *L/D*	4.6	
Kxx	.8E6	lbf/in
Kyy	1.2E6	lbf/in
Bearing Config	5 pad LBP, 0.55 offset	

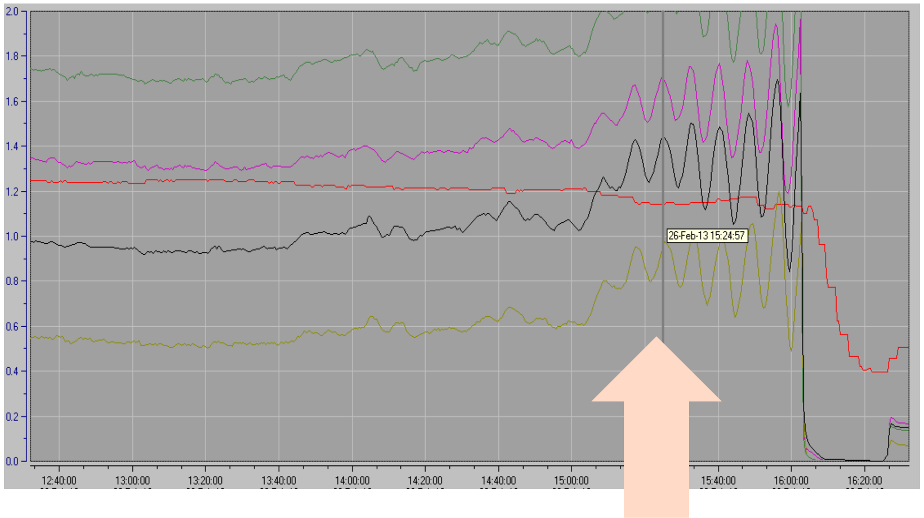


Case 2: Compressor Trip Due to Morton Effect as Lubrication Oil Temperature Drops

Design Power	7045	HP
1st Critical	11000	RPM
Design speed	15400	RPM
Critical Speed Ratio	1.40	
Bearing Length,*L*	4	in
Bearing Diameter,*D*	3.94	
Bearing *L/D*	1.02	
Bearing Surface Velocity	265	ft/s
Babbitt Temperature	194	F
Bearing Load – Left	6060	lbf
	385	psi
Bearing Load - Right	5708	lbf
	362	psi
Overhung Shaft Length	13	in
Overhung L/D	3.3	
Kxx	.2E6	lbf/in
Kyy	4.3E6	lbf/in
Bearing Config	5 tilting pad LOP, 0.5 offset	



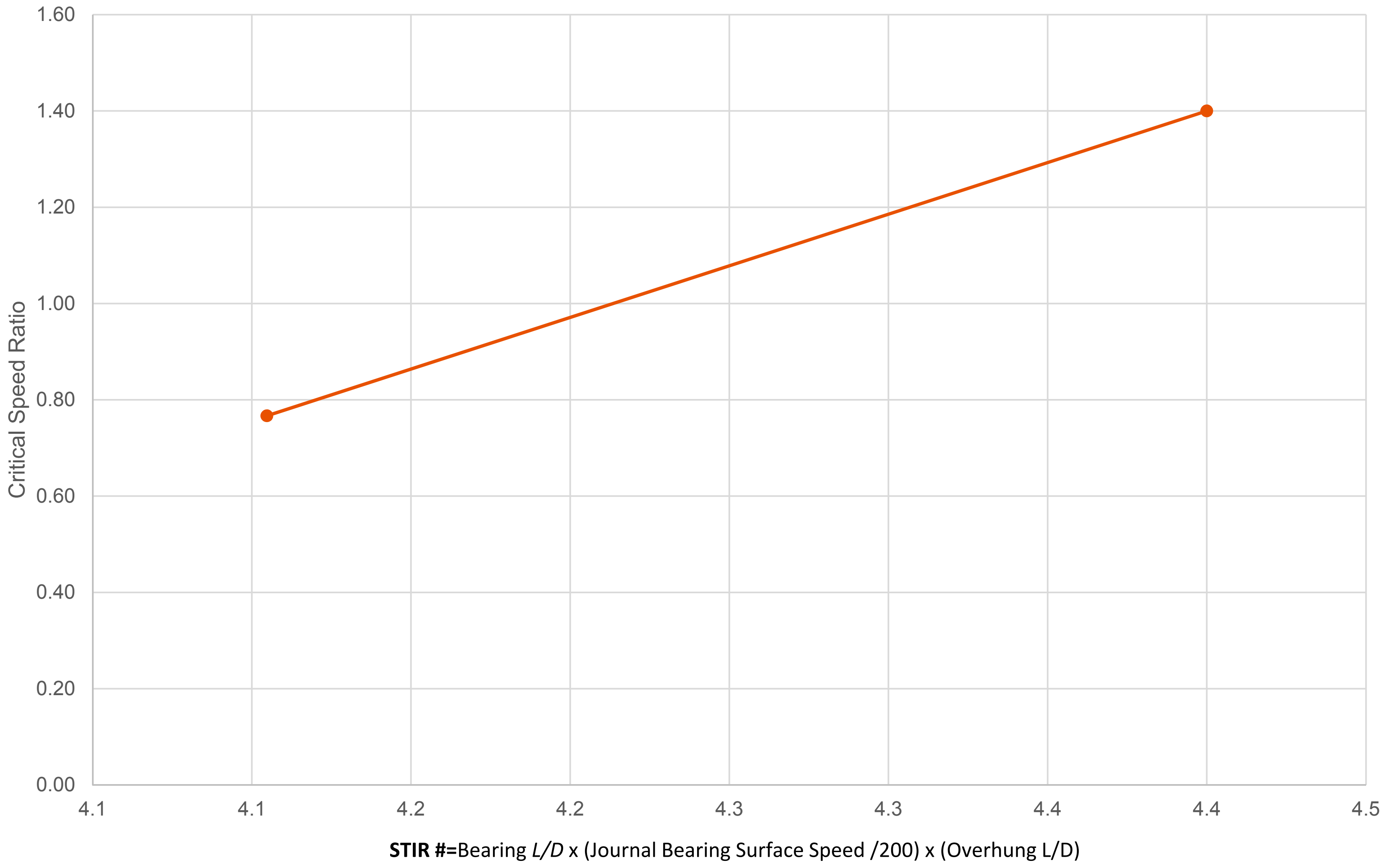




Unit tripped after 50 min, 8 cycle of vibration swings

Lubrication Temperature 110-130 F

Screening Chart – Experience Derived



Lessons Learned

- STIR can happened to unit running below first critical speed
- Lowering lube oil temperature can trigger STIR
- Misalignment will have effect on the onset speed and phase changes for unit experience STIR
- Further effort on collecting design information on units with STIR will help build a better experience chart as screening criteria

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