Mechanical Behavior of a 9.7 MW Induction Motor Under Fault Conditions – A Case History

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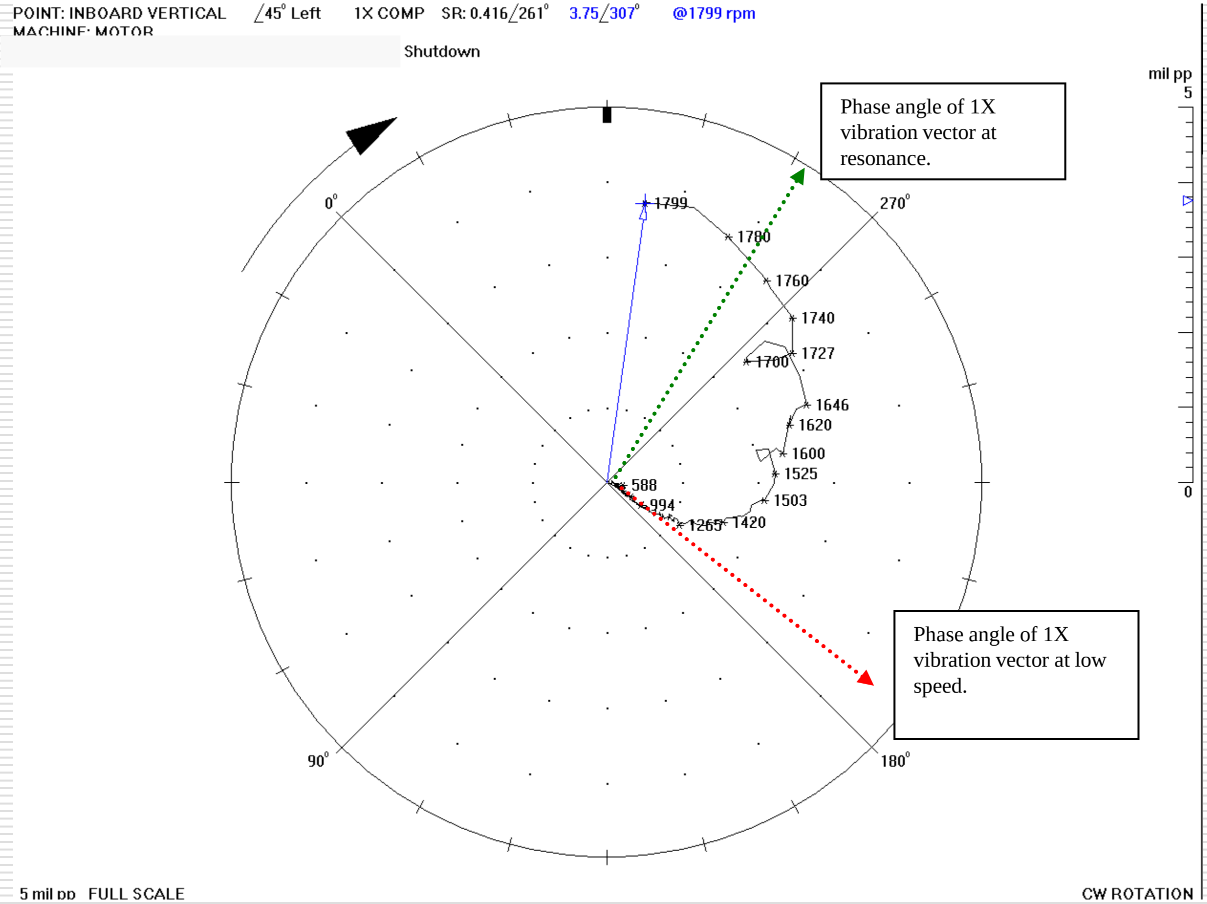
1X Polar Plot – Shutdown – 45L

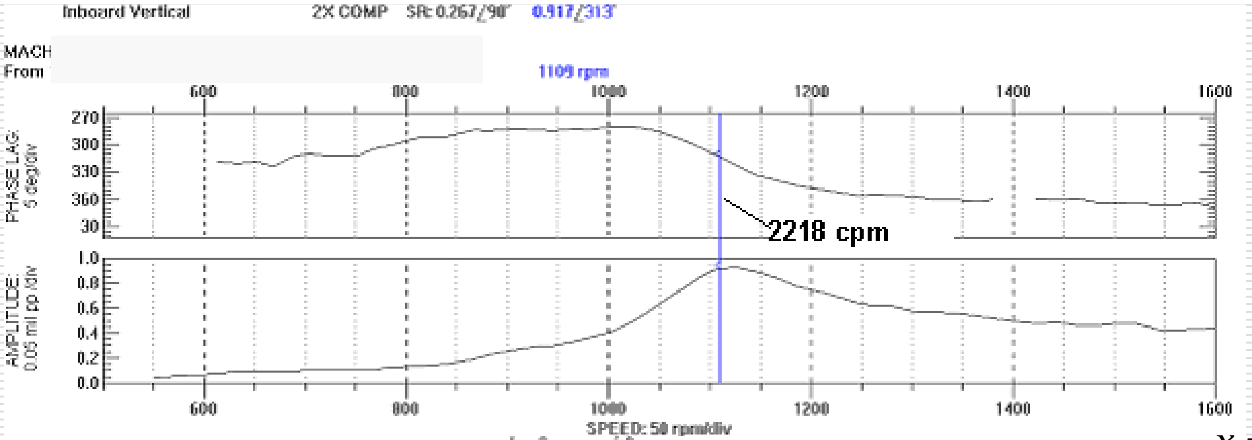


Phase angle of 1X vibration vector at resonance.

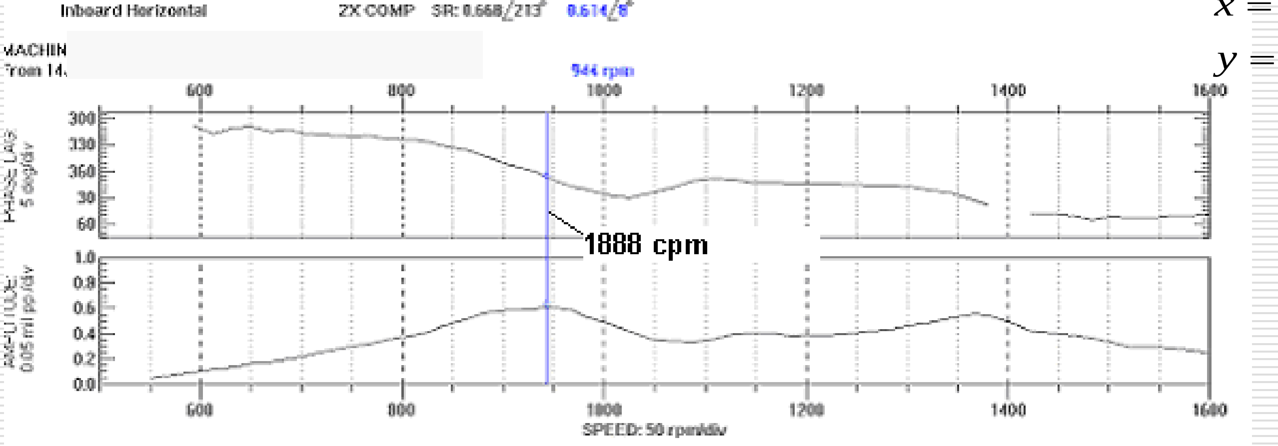
Phase angle of 1X vibration vector at low speed.

2X Bode Plot – Shutdown Data
Plot A = True Vertical
Plot B = True Horizontal

Plot A



Plot B

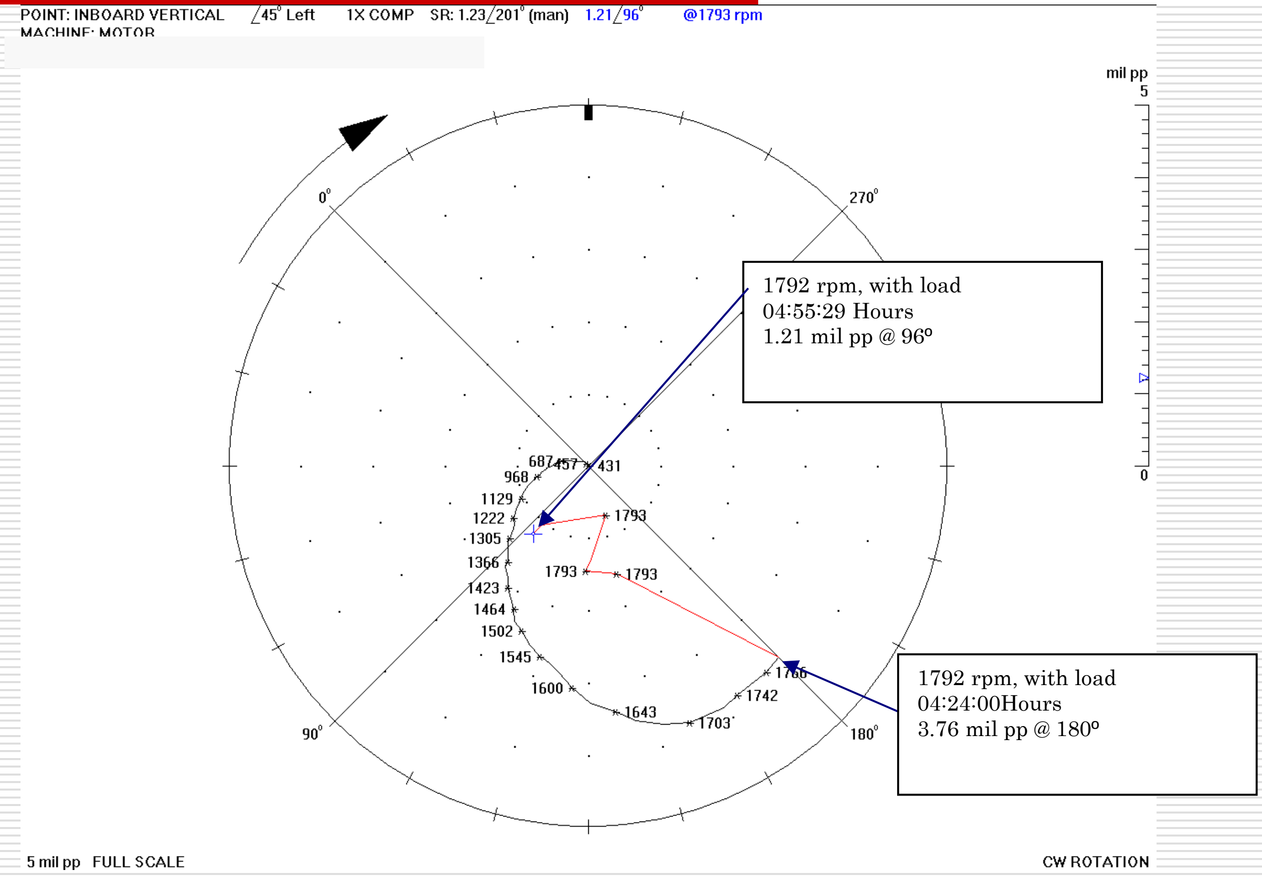


$$x = X\cos\theta + Y\sin\theta$$

$$y = -X\sin\theta + Y\cos\theta$$

A set of “virtual” transducers was created by mathematically transforming the actual vector data from two perpendicular probes at 45L and 45R via the following coordinate transform:

Typical 1X Vector Response During Startup and First 30 Minutes of Steady State Operation

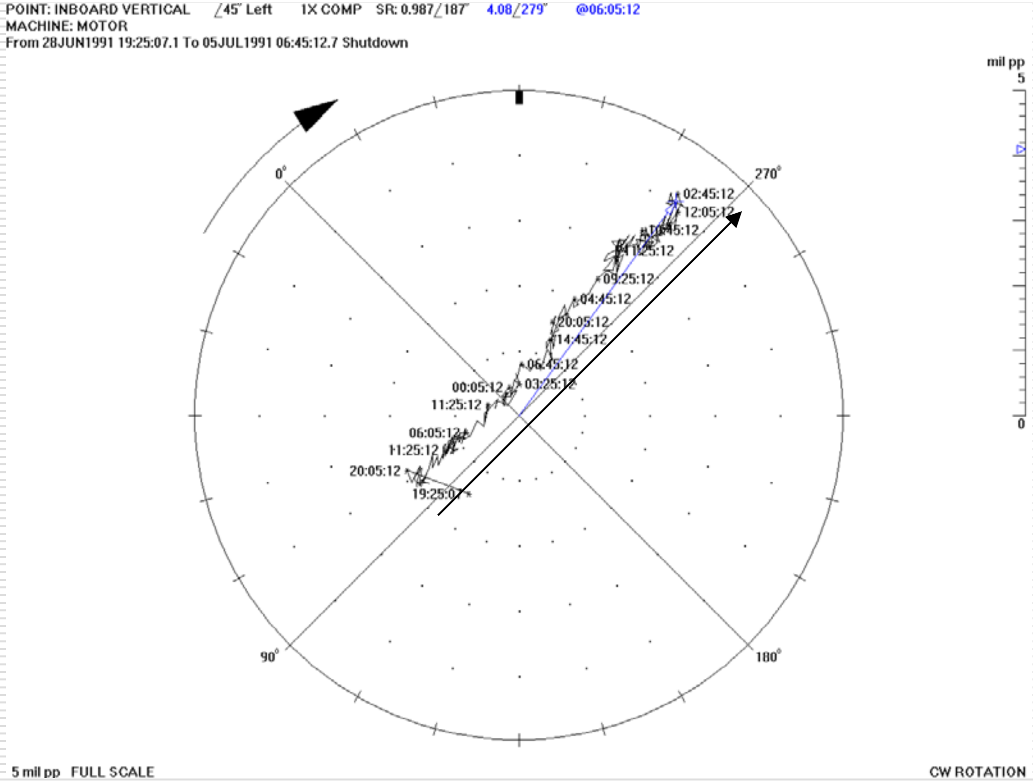


1792 rpm, with load
04:55:29 Hours
1.21 mil pp @ 96º

1792 rpm, with load
04:24:00Hours
3.76 mil pp @ 180º

Thermal Vector = 3.83 mil pp @ 18º
Motor Coupled to Gearbox/Compressor
Under Load

1X Vector Change vs. Time



❑Acceptance Region Trend Plot from 28 June – 5 July

❑Depicts the change in the 1X vibration vector vs. time

❑Similar vector changes occurred from:

- 27 April through 14 June
- 14 June through 21 June
- 21 June through 28 June
- 28 June through 5 July
- 5 July through 14 July

1X Vector Change from 28 June Through 5 July = 5.14 mil pp @ 272°

FIELD BALANCING:
27 APRIL 1991

$$\overrightarrow{Vibration} = \frac{\sum \vec{F}}{\sum \overrightarrow{K}}$$

Influence Vector / Synchronous Dynamic Stiffness Vector

$$\overrightarrow{H}_{average} = 0.015 milpp / gram \angle 101^{0}$$

$$\frac{1}{\overrightarrow{H}_{average}} = \frac{\text{mass}}{\text{displacement}} \sim \frac{force}{displacement},\ e.g.\ \text{stiffness}$$

Multiply mass by $r\Omega^2$ and divide by gravitational constant to convert from mass to force units.

Influence Vector / Synchronous Dynamic Stiffness Vector

$$\vec{K}_{DS} = \frac{1}{0.5\vec{H}} \text{ x } \frac{r\Omega^2}{g_c}$$

Where:

$\vec{H}$ = influence vector

r = calibration mass radius, 12. 5 in

Ω = Rotational speed, radians/second, 187.66 rad/sec

g_c = Gravitational Constant;

386 (in - lb_m)/(lb_f - sec^2),

or 1 (m – Kg)/(N – sec^2)

Note: The factor of 0.5 is included in the denominator in order to convert mils pp to mils peak. Stiffness is usually defined such that both the force and the displacement units are 0 to peak, not peak to peak, with typical engineering units expressed as either lb_f/in or N/m. The gravitational constant is necessary in order to ***properly*** convert from mass units to force units.

Influence Vector / Synchronous Dynamic Stiffness Vector

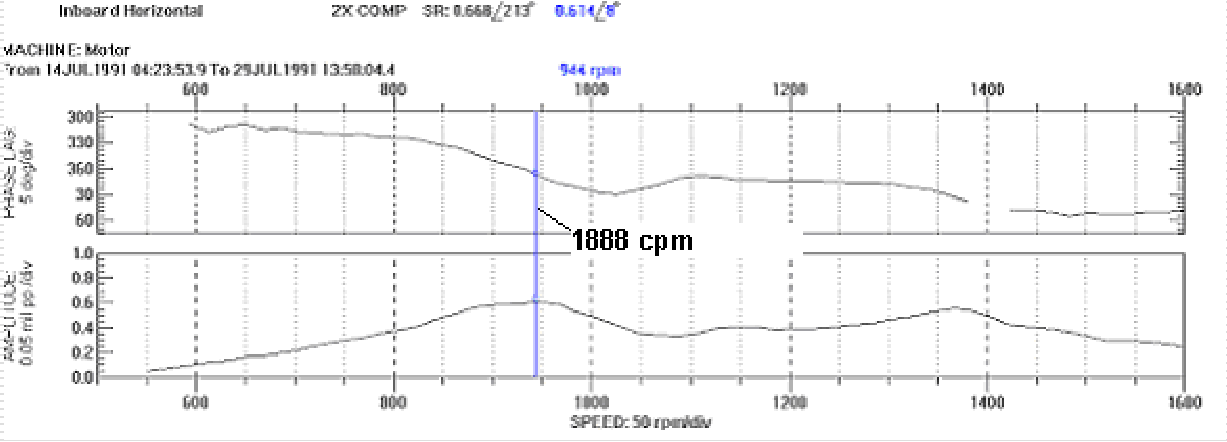
$$\vec{K}_{\mathrm{DS}} = \frac{1}{0.5\vec{\mathrm{H}}} \mathrm{x} \frac{\mathrm{r}\Omega^2}{\mathrm{g_c}}$$

$$\vec{K}_{DS_{avg}} = \left[\left(\frac{1}{0.0075\ \mathrm{mil/gram}\ @\ \angle 101^0}\right)\left(\frac{1\ \mathrm{lb_m}}{454\ \mathrm{grams}}\right) \mathrm{x}\right.$$

$$\left.\left(\frac{1000\ \mathrm{mil}}{1\ \mathrm{in}}\right)\left(\frac{12.5\ \mathrm{in}}{386\ \mathrm{in\text{-}lb_m/lb_f\text{-}sec^2}}\right)\frac{(187.66\ \mathrm{rad/sec})^2}{}\right]$$

$$\vec{K}_{DS_{avg}} = 334{,}926\ lb_f\ /\ in$$

Dynamic Stiffness / Rotor Resonance



$$\Omega_{res} = \sqrt{\mathrm{K_{DS}} / M}$$

$$\Omega_{res} = \sqrt{\frac{334{,}926\ lb_f\ / in\ \left(386\ \text{in-lb}_\text{m}/\text{lb}_\text{f}\text{-sec}^2\right)}{4200\ lb_m}}$$

$$\Omega_{res} = 175.4\ \text{rad/sec}$$

$$\Omega_{res} = 27.9\ \text{rev/sec}$$

$$\Omega_{res} = 1675\ \text{rev/min}$$

FIELD BALANCING:
14 June

- Seven weeks later, on Friday, 14 June, the Wet Gas Compressor Train was shut down due to high motor 1X vibration readings

$$\overrightarrow{H}_{1,1} = \frac{\overrightarrow{C}_A}{\overrightarrow{W}_A} \qquad ?$$

$$\textit{Increase in } \overrightarrow{\textit{Vibration}} = \frac{\sum \vec{\mathrm{F}}}{\sum \vec{K}} \quad \textit{due to:} \qquad \vec{K}_{\mathrm{DS}} = \frac{1}{0.5\vec{H}} \text{ x } \frac{r\Omega^2}{g_c} \qquad ?$$

$$\Omega_{res} = \sqrt{\mathrm{K}_{\mathrm{DS}} / M} \qquad ?$$

What Do We Know?

- Significant changes in the 1X steady state vibration response occurred from 14June through 14 July
- Five subsequent balance corrections required after the initial in situ field balancing on 27 April:
  - 14 June
  - 21 June
  - 28 June
  - 5 July
  - 14 July

Balance Summary Data: April 27 - July 14, 1991

Run No.	Data Type	Date	Day of the Week	Elapsed Time	Speed (rpm)	BP	Mass Added (gms)	Mass Angle	+ -	Outboard 45L (vertical xducer) (mil pp @ Φ)	Outboard 45R (horz xducer) (mil pp @ Φ)	Inboard 45L (vertical xducer) (mil pp @ Φ)	Inboard 45R (horz xducer) (mil pp @ Φ)
1	Initial	27-Apr-91	Saturday	0 Days	1792	A	118	300º	+	2.90 @ 225º	0.70 @ 346º	3.80 @ 211º	1.90 @ 325º
						B	118	300º	+				
	Final	27-Apr-91								0.30 @ 4º	0.50 @ 99º	0.60 @ 151º	0.40 @ 307º
2	Initial	14-Jun-91	Friday	48 Days	1792	A	130	15º	+	4.17 @ 313º	1.84 @ 69º	4.16 @ 302º	2.08 @ 46º
						B	130	15º	+				
	Final	14-Jun-91								0.52 @ 340º	0.44 @ 106º	0.56 @ 234º	0.72 @ 338º
3	Initial	21-Jun-91	Friday	7 Days	1792	A	150	0º	+	4.32 @ 289º	1.98 @ 42º	3.77 @ 280º	2.10 @ 39º
						B	150	0º	+				
	Final	21-Jun-91								0.88 @ 137º	0.22 @ 212º	1.44 @ 165º	1.36 @ 293º
4	Initial	28-Jun-91	Friday	7 Days	1792	A	179	330º	+	4.50 @ 269º	1.36 @ 15º	5.07 @ 258º	2.50 @ 350º
						B	179	330º	+				
	Final	28-Jun-91								1.11 @ 72º	0.51 @ 182º	1.14 @ 113º	1.26 @ 263º
5	Initial	5-Jul-91	Friday	7 Days	1792	A	159	345º	+	3.86 @ 281º	1.19 @ 22º	4.10 @ 266º	1.93 @ 345º
						B	159	345º	+				
	Final	5-Jul-91								0.73 @ 184º	0.45 @ 182º	1.69 @ 178º	1.93 @ 190º
6	Initial	14-Jul-91	Sunday	9 Days	1792	A	160	315º	+	3.23 @ 240º	1.25 @ 334º	3.85 @ 224º	2.39 @ 315º
						B	160	315º	+				
	Final	14-Jul-91								0.79 @ 123º	0.60 @ 245º	1.49 @ 149º	2.02 @ 268º

Balance Summary Data Sheet

Notes:
BP = Balance Plane; A=Outboard; B= Inboard
The "+" sign = mass added
The "-" sign = mass removed
All vibration data is shaft relative displacement data
Mass added at a 12.5 inch balance radius
Mass angle is referenced to the 45L (vertical) transducer

Table 1

1X Vector Change vs. Time

<table>
<tr><th colspan="6">CHANGE IN 1X VIBRATION VECTOR vs TIME</th></tr>
<tr><th>From</th><th>To</th><th>Outboard 45L
(vertical xducer)
(mil pp @ Φ)</th><th>Outboard 45R
(horz xducer)
(mil pp @ Φ)</th><th>Inboard 45L
(vertical xducer)
(mil pp @ Φ)</th><th>Inboard 45R
(horz xducer)
(mil pp @ Φ)</th></tr>
<tr><td>27-Apr-91</td><td>14-Jun-91</td><td>3.99 @ 310º</td><td>1.43 @ 59º</td><td>4.69 @ 306º</td><td>2.18 @ 56º</td></tr>
<tr><td>14-Jun-91</td><td>21-Jun-91</td><td>4.01 @ 283º</td><td>1.83 @ 30º</td><td>3.40 @ 287º</td><td>1.86 @ 59º</td></tr>
<tr><td>21-Jun-91</td><td>28-Jun-91</td><td>5.13 @ 276º</td><td>1.57 @ 17º</td><td>5.34 @ 274º</td><td>2.10 @ 23º</td></tr>
<tr><td>28-Jun-91</td><td>5-Jul-91</td><td>4.86 @ 275º</td><td>1.68 @ 16º</td><td>5.14 @ 272º</td><td>2.15 @ 20º</td></tr>
<tr><td>5-Jul-91</td><td>14-Jul-91</td><td>2.89 @ 252º</td><td>1.66 @ 341º</td><td>2.94 @ 248º</td><td>3.84 @ 339º</td></tr>
<tr><th colspan="6">TOTAL 1X VECTOR CHANGE vs TIME</th></tr>
<tr><td>27-Apr-91</td><td>14-Jul-91</td><td>19.97 @ 280º</td><td>7.45 @ 20º</td><td>11.20 @ 294º</td><td>10.35 @ 20º</td></tr>
</table>

Table 2

Conclusions

- Analysis of field balancing data in order to determine the Influence and Synchronous Dynamic Stiffness properties of the rotor / bearing system provides powerful insight into the origin(s) of a change in rotor vibration.
- Coupled with other forms of direct and indirect data, operating risks are minimized and the proper machinery asset management is provided.
- Synchronous perturbation is an inherent part of every field balancing exercise.
- By synchronously perturbing the rotor system with a know centrifugal force, the response of the system to the synchronous perturbation force can be directly measured.
- Since the rotor response (vibration) is always equal to the summation of the dynamic forces that act on the rotor / bearing system divided by the complex dynamic stiffness of the system, it becomes apparent that an increase in rotor vibration may be due to:
  - An increase in the dynamic forces
  - A decrease in the complex dynamic stiffness
  - Both
- From this information, both the Synchronous Dynamic Stiffness and Influence Vectors can be determined.
- Along with other direct and indirect (calculated) forms of machinery data, both the Synchronous Dynamic Stiffness and Influence Vectors are evaluated and trended over time.