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Research Article

CABLE STRESS IS AN INFLUENCING FACTOR IN AN INDUCTION MOTOR VIBRATION-A CASE STUDY

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ABSTRACT

Monitoring motor vibration is an important function in an industry as motors being the prime mover of the machineries, which either can drive a single unit like a gear box or a complex machinery like a centrifugal pipe casting machine, failure of the motors, in both type of equipments, can lead to the complete stoppage and loss of production. Abnormal high vibration in a motor is an effect caused by various factors, both electrical and mechanical such as electrical unbalance, mechanical unbalance of rotor, internal effects like looseness, rubbing, bearing problems and external effects like weak or cracked base, misalignment, resonance, critical speeds. etc. With proper knowledge and diagnostics procedures it is normally possible to quickly pinpoint the cause of vibration if the root cause is limited within one or few of the usual causes as listed but if another uncommon cause compounds with few of the common causes and leads to the high vibration of the motor then erroneous conclusions are reached as a consequence of not understanding the root cause of the abnormal vibration which results in trying to fix an incorrectly diagnosed problem. In this paper it has been shown, with a case study, how laying of the motor's power supply cables, which is normally assumed not being a cause of motor vibration, played a significant role in contributing as one of the causes of abnormal vibration in a blower unit motor of a gas booster station and the same was finally detected after initial diagnosing & eliminating the usual causes for the abnormal vibrations and this resulted in spending a significant amount of time and money in the process.

INTRODUCTION

Outgoing gases of two 60 MT steel melting shop converters are sent to a gas holder of capacity 50,000 cum through ID fans as shown in the below schematic diagram. (Figure:1)

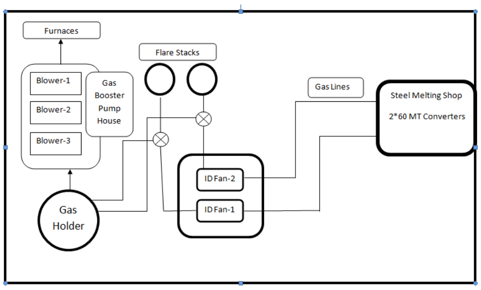

Figure 1 Schematic Layout of the Gas Lines and the Location of the Gas Booster House with the Blowers.

From the gas holder unit the gas is drawn in the gas booster house, as shown in the above figure from where 3 numbers of blowers boost up the gas pressure for supplying it to the burner units in various departments for process heating. All blower units are identical but only 2 blower units operates at a time and 1 unit is kept as standby.

All the three blower units are identical and the specification of the motor and the blower are given in Table:1

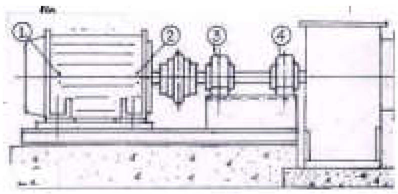

Figure 2 Schematic layout of the blower & motor unit

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The blower is coupled to the motor with a flexible coupling as shown in the Figure:2 . The measuring points for vibrations monitoring have been numbered.

vibration signature analysis and countermeasures to take on specific causes to reduce the overall vibration amplitude to the acceptable limit.

Table 1 Motor & Blower Specification

Motor Rating	Rated Current	Motor RPM	Suction Capacity	Motor Bearings Type	Booster Fan Bearing Type	Suction Pressure	Discharge Pressure	Gas Medium
200 kW	324.7 A	2974	330NM^3/min	Deep groove ball	Journal Bearing Lubrication Pressure 0.8KPA	4 KPA	20KPA	LD Gas (N_2:20.6%,O_2:0.4%,CO_2:18.5%,CO:59%H_2:1.5%)

During commissioning of the No: 1 blower unit, without any gas intake, the vibration of the motor's & blower's drive end & non-drive end bearings at the measuring points were high as shown below. (Table:2)

Table 2 Vibration Reading of the No:1 Blower after commissioning. (Abnormal vibrations marked *)

Measuring Points	Measuring Axis		
	Horizontal (H) (Unit: RMS value mm/sec)	Vertical(V) (Unit: RMS value mm/sec)	Axial(H) (Unit: RMS value mm/sec)
Point No:1(Motor NDE)	3.88	1.63	4.57*
Point No:2(Motor DE)	6.48*	5.42*	4.47
Point no:3(Blower NDE)	1.97	1.11	4.68*
Point No:4(Blower DE)	1.33	4.78*	5.21*

It was observed from the above readings that the motor drive end vibrations in all the axes were much above the accepted vibration level as per ISO -10816-3.[1] as compared to the blower unit vibration. As stated earlier that the equipment is a gas booster blower and the intake gas is converter outgoing gas which, as seen from Table:1, has high percentage of Carbon Mono Oxide(CO) which being an extreme toxic gas all rectification job to reduce vibration have to be done while operating the blower unit in dry condition i.e. without any gas intake.

The first step was to analyze the reason for each high vibrations in the motor and as William R Finley *et al*. [2] had observed that to solve a vibration problem in an induction motor one must differentiate between cause and effect and in order to get this happen one has to first find the root cause of each abnormal vibration. Glenn H Bate [3] had observed that the vibration problems of the induction motor can be the combination of two groups which can be called '*magnetic'* and '*mechanical'*. Vibrations due to *magnetic* phenomenon can also be due to two reasons (a) air gap variation (b) current variation. In (a) air gap variations typical magnetic vibration has been listed as (i) static eccentricity (ii) weakness of stator support (iii) dynamic eccentricity and (iv) loose rotor bars. In (b) current variation typical magnetic vibration has been listed as (i) stator winding faults (ii) broken and cracked rotor bars (iii) shorted rotor laminations. Glenn H Bate [3] also described a simple test called 'power trip test' wherein in the test the *magnetic* components of vibration will disappear immediately once the power is removed. This test was carried out and it was observed after power switch off the vibrations remained but gradually minimized with the drop in the motor speed. It was now confirmed that the components of the vibration were *mechanical* in nature so it became evident that the specific components of *mechanical* vibrations have to be sorted through

Mikhail Tsypkin [4] had observed that major vibration sources of mechanical origin in induction motors are: shaft bow, rotor imbalance, misalignment, discrepancies in bearing operations as well as in the couplings, sheaves, and other mechanical rotating elements of the assembly. Mechanical looseness, foundation problems and/or structural resonances also may significantly changes vibration signal amplitudes and configurations.

From the initial vibration reading (Table:2) as the motor's drive end horizontal vibration amplitude(RMS mm/sec) was dominant vibration signature analysis of the same was done to analyze the cause of high vibration. (Figure:3)

Vibration Signature Analysis-1

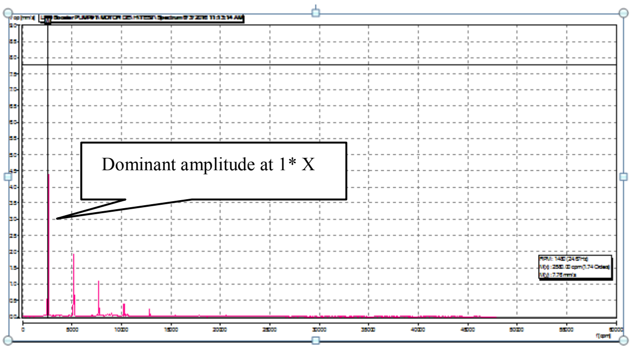

Figure 3 Signature Analysis Report of the Motor DE Horizontal Vibration

In the vibration signature analysis it was observed that the highest amplitude was at 1* running speed(X). Troy D Feese & Phillip E Grazier [5] had observed that generally when machinery experiences high vibration at 1 x running speed the first cause can be of unbalance of the rotor and the same to be checked first. So the motor was decoupled and run on full rpm of 2974 rpm to check whether the high vibration was contributed by the blower unit or it was motor specific. The vibrations readings of the motor's drive end and non-drive end bearing is given below. (Table:3)

Table 3 Motor Vibration Readings in Decoupled Condition (high vibrations are marked*).

Measuring Points	Horizontal Vibration (Unit: RMS value mm/sec)	Vertical Vibration (Unit: RMS value mm/sec)	Axial Vibration (Unit: RMS value mm/sec)
Motor Non-Drive End Bearing	6.86*	3.42	1.77
Motor Drive end bearing	8.29*	1.83	0.96

From Table: 3 it is evident that the motor's both the bearings vibrations in the horizontal axis are extremely high as compared to the standard [1] and needs to be corrected first. In an earlier case study of motor unbalance Troy D Feese & Phillip E Grazier [5] had observed that to confirm the unbalance of a motor due to rotor a Coast Down (CD) phenomenon plot is also advisable as it can also indicate rotor unbalance. Coast Down plot, vibration Vs. rpm, at cut off rpm at 2870 rpm was also taken (Figure:4).

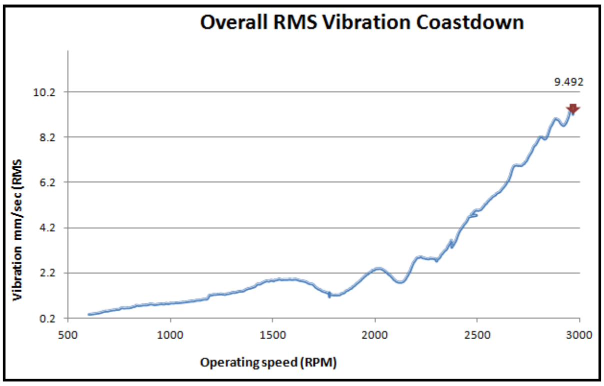

Figure 4 Coast Down Plot Vibration (RMS mm/sec) Vs Operating Speed(rpm)

A study of the Coast Down indicates there is an unbalance in the rotor shaft. Troy D Feese & Philips E Grazier[5] in one of their study on case histories of difficult balance jobs of rotors had observed that in Coast-Down monitoring in an un-balanced rotor a vibration of 0.03 mm/sec(1 mil) at 2000 rpm should have a vibration of about 0.11 mm/sec(4 mils) at 4000 rpm. In their tests an amplitude tracked with the speed, squared until 3000 rpm and then amplitude increased at a higher rate. In Fig.4 we find that at 1500 rpm amplitude was about 2.1 mm/sec (RMS) and at nearly double the rpm i.e. at 2870 rpm amplitude was 9.49 mm/sec (RMS) and this confirms the finding of above observation of unbalanced rotor.

The rotor was checked off-line for un-balance (without coupling) and the same was corrected after detection. (Table:4).

In the coupled condition the motor's drive end bearing's horizontal & vertical vibrations (marked *) again showed high vibrations level which were quite above the accepted level as per ISO Standard 10816-3 [1].

Vibration Signature Analysis-2

Vibration signature analysis of motor's non-drive end & drive end horizontal axis vibration were done (Figure:5 & 6)

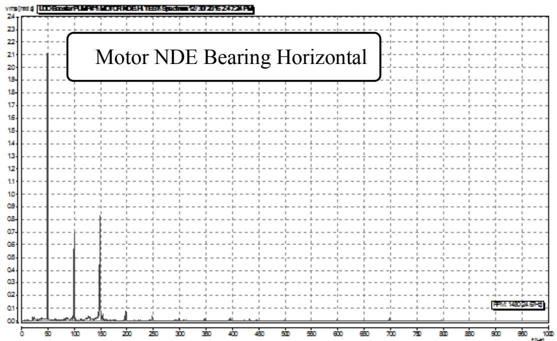

Figure 5 Signature Analysis of Motor NDE Bearing Hor.Axis

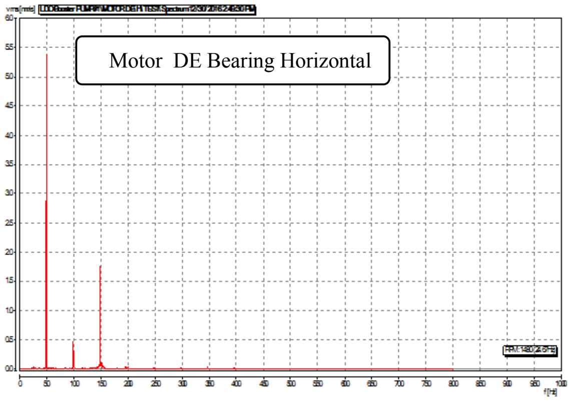

Figure 6 Signature Analysis of Motor DE Hor. Axis

Table 4 The Dynamic Balance Report of the Rotor without Coupling

Dynamic Balancing Machine	Accuracy of Balancing	Balancing Speed	Permissible residual Un-Balance	Original Un-Balance Found		Residual Un-Balance Left	
				Plane-1	Plane-2	Plane-1	Plane-2
ABRO Model JE-3K SI, No1138	2.5 grade as per IS-1123,ISO 1940/1	500 rpm	47.6 gm	80 gms.	50 gms.	10 gms.	10 gms.

After balancing the rotor the motor was run solo and the following vibration was observed.(Table:5)

Table 5 Vibration Reading Observed After Solo Run of the Motor Without Coupling

Measuring Points	Horizontal Vibration (Unit: RMS value mm/sec)	Vertical Vibration (Unit: RMS value mm/sec)	Axial Vibration (Unit: RMS value mm/sec)
Motor Non-Drive End Bearing	0.9	0.9	0.7
Motor Drive end bearing	0.7	0.7	1.0

As the motor vibrations were well within the accepted limit as per ISO Standard 10816-3[1] it was coupled with the blower unit and vibration readings were again taken (Table:6)

Table 6 Motor Vibration with Blower Unit after Rotor Balance (high vibration marked *).

Measuring Points	Horizontal Vibration (Unit: RMS value mm/sec)	Vertical Vibration (Unit: RMS value mm/sec)	Axial Vibration (Unit: RMS value mm/sec)
Motor Non-Drive End Bearing	5.35*	3.55	5.36*
Motor Drive end bearing	7.58*	7.64*	4.38

Above study of the signature analysis (Figure:5) & (Figure:6) indicates that amplitude is dominant in 1* shaft running speed and the next dominant peaks are the 2nd.&3rd.*shaft running speed. S P Nogal & D L Lalwani [7] in an elaborate experiment had observed in an unbalance situation overall

RMS value in horizontal direction is high compared to vertical direction and first order amplitude is predominant. In a similar experiment V.Hariharan & PSS Srinivasan [6] had experimentally proved that in a spectrum dominant peak at 2* shaft running speed indicates shaft misalignment. Based on the above two studies the two spectrums clearly indicated that there is still remains residual unbalance in the motor and it is compounded with misalignment between the motor and the blower unit.

Till this stage the cause of abnormal vibrations were detected by using the diagnostic tool vibration signature analysis but though the overall high vibrations had reduced it had not totally come to satisfactory level as per the ISO Standard [1]. The 2nd vibration spectrum analysis still now shows unbalance of the motor and also misalignment

K.Satyanarayana *et al*.[9] in one of their research article on detection of unbalance forces using vibration signature analysis had observed that phase analysis also gives us a clear idea of the transmission of vibration through the machines and the exact location of the faults and it is a great help while confirming the problems of unbalance, misalignment , bent shaft which cannot be easily done through spectrum analysis. It was decided to go for a phase angle analysis first to confirm the observation of the 2nd vibration signature analysis report and also for further analysis of the residual unbalance forces.

Phase Analysis

A phase analysis was carried out of the motor's both end bearings and the blower units drive end bearing and the results are given in Table :7. Figure: 7 shows the points were the phase analysis was done and in the same figure the amplitude (RMS mm/sec) is shown in the top half of the ellipse and the phase angle in the bottom half of the ellipse for the same measuring point.

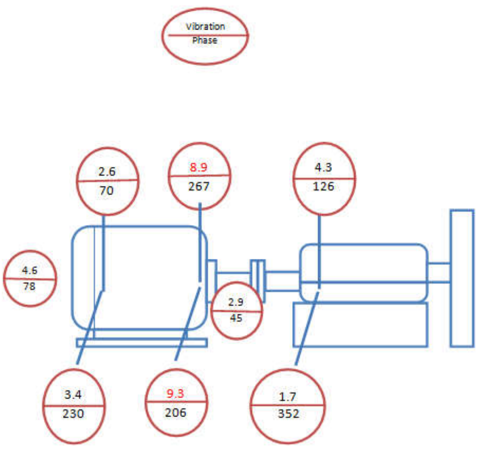

Figure 7 Phase analysis location and readings of the motor and the blower unit.

Table 7 The vibration amplitude and the phase angle of each measuring points

Points	Phase. Reading in degrees			Vibration(unit: RMS value mm/sec)		
	H	V	A	H	V	A
Motor non-drive end	230	70	78	3.4	2.6	4.6
Motor drive end	206	267	45	**9.3**	**8.9**	2.9
Blower drive end	352	126	-	1.7	4.3	-

It is evident from the above phase angle analysis that there is unbalance and also misalignment as seen from the vibration signature analysis (Fig:5) & (Fig:6). As the motor's rotor had already been balanced and the vibration severity in the solo run of the motor without the coupling was well within the accepted norms [1] so the possible cause of further unbalance in the motor could be generated from the coupling which was fitted on the motor shaft after the balancing and the same was to be investigated. As misalignment was also contributing factor to the overall vibration in the coupled condition it will also be checked and corrected but after the balancing of the rotor with the coupling has been done.

At this stage the analysis had reached a cross-road as while trying to the balance the motor with the coupling mounted in-situ it was not responding at all and the results were slitting.

Katalin Agoston[10] had observed while analyzing the various causes of motor vibration that weak base is also one of the reason for motor abnormal vibration and the standards prescribe a rigid base for electric motors which means the vibration near to the motor feet must be less than 30% of the vibration measured at the motor bearing. To check this the vibrations at the motor feet were taken and found to be just 1.2mm/sec which is much below 30% .While measuring the vibration at the base arbitrarily the power cable vibrations were measured and surprisingly it was found to be at 23mm/sec which is nearly 3 times higher than highest vibration observed at the motor bearings. Close observation of the power cables showed it was abnormally taut and in high stress and cable entry to the terminal box was not in a smooth curve but so forcefully bent that cable glands could not be even be clamped together. (Figure:8)

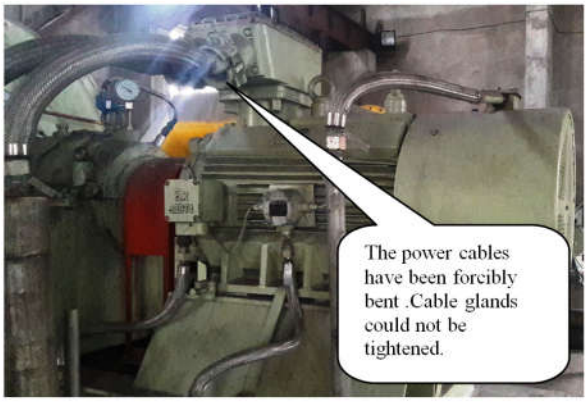

Figure 8 Actual Photograph of the Initial Cable Radius.

Cable Stress Analysis & Rectification

The specification of the motor cables are given below: (Table:8)

Table 8 Specification of the Power Cables of the Motor

Cable Type	No. of Cores	Outer Sheath	Inner Sheath	Core	Core Insulation	Cable Outside Diameter(mm)
Unarmored	3 1/2	XLPE	PVC wrapping	17 strands Copper	XLPE	43.9

XLPE cable manufacturer's catalogue [11] was consulted where it was indicated that the minimum bending radius of an unarmored XLPE 3 core cable of outside diameter 'D' the bend radius should be '12D' (Figure:9)

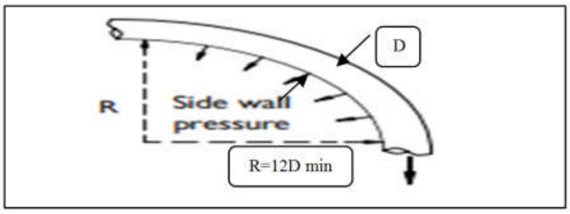

Figure 9 Minimum Bend Radius of an XLPE Cable during Installation

The cable diameter was measured to be 43.9mm so as per the catalogue the minimum bend radius should be been in the range of 500mm but it was found to be just 300mm. This extremely short bend was exerting an abnormal pressure on the termination box which in turn was transmitting the forces to the motor body. The termination box is more near to the motor drive end bearing which explains why the vibration was higher at the motor drive end and not as much at the motor non-drive end bearing. To increase the cable bend radius of the initial motor cable lay out (Figure: 10) the cable's aluminum conduit pipes were shorten to give a more bend radius to the cable and new termination was done (Figure:11).

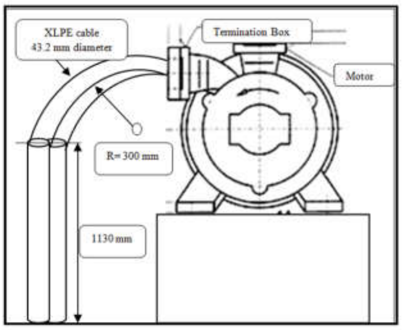

Figure 10 Initial Motor Cable Lay Out

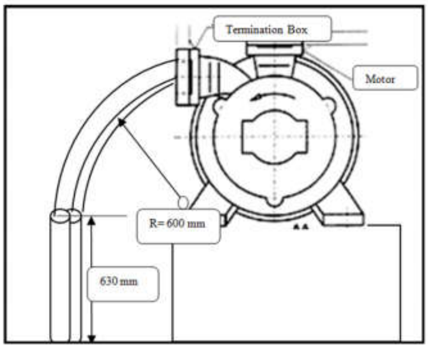

Figure 11 Modified Motor Cable Lay Out

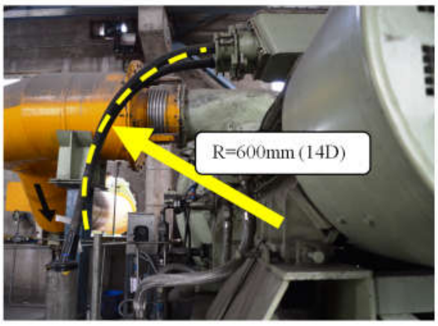

Figure 12 Actual Photograph of the Cable Radius after Modification

The cable's bending radius now measured about 600 mm which is about 14D and much above the minimum standard of 12D as noted in the catalogue[11] (Figure:12)

After the rectification of the cable bend the motor along with the coupling could be balanced as the system was responding to the trial weight that was being added to the coupling hub. (Table:9)

Table 9 Balancing Report of the Motor Shaft with the coupling

Dynamic Balancing Machine	Accuracy of Balancing	Balancing Speed	Permissible residual unbalance	Original Unbalance	Residual Unbalance left
Vib Expert-II	6.3 Grade as per ISO-1940-1	2970 rpm	20 gms.	140 gms.	5 gms.

After the successful balancing of the motor shaft with the coupling the alignment with the blower was then checked and corrected.

Initial alignment of the blower and the motor unit in coupled condition was checked with a laser aligner and the result is given in Table:10

Table 10 Initial Alignment Reading of the Motor with the Blower Unit before Correction

Measuring Area	Gap (Dimension in mm)	Off-Set(Dimension in mm)
Vertical	0.24	-0.02
Horizontal	-0.45	-0.01

As per ISO Standard [8] for a 3000 rpm equipment accepted tolerance Gap and Offset is given below.(Table: 11)

Table 11 Alignment Tolerances for a 3000 rpm Machine

Rpm	Tolerance Excellent Gap(mm)	Tolerance Okay Gap(mm)	Tolerance Excellent Offset(mm)	Tolerance Okay Offset(mm)
3000	0.1	0.13	0.1	0.06

From the comparison of Table 10 with Table: 11 it was evident that after assembly of motor with the blower unit the machine alignment was significantly not within the standard limits and this misalignment had also added to overall high vibration which was reflected in the vibration spectrum analysis.(Figure: 5) & (Figure:6)

After correcting the misalignment by providing required size shims the alignment was re-checked.(Table:12).

Table 12 Actual Alignment Reading of the Motor with the Blower Unit After Correction.

Measuring Area	Gap (Dimension in mm)	Off-Set(Dimension in mm)
Vertical	-0.06	0
Horizontal	-0.09	-0.01

From the comparison with the standard (Table:11) the alignment is now within accepted limit. After 2nd balancing of the motor shaft and the final alignment the unit was run without intake gas and the observed vibration values of both motor and the blower are given in Table: 13.

Table 13 Vibration Reading (mm/sec) Obtained Before and After the Balancing of the Motor with the Coupling. (Abnormal vibrations marked *)

Measuring Points	Motor DE Horizontal	Motor DE Vertical	Motor DE Axial	Motor NDE Horizontal	Motor NDE Vertical	Motor NDE Axial
Before Balancing and Alignment	7.5*	7.64*	4.38	5.35*	3.55	5.36*
After Balancing and Alignment	4.19	4.91*	2.96	3.00	2.7	1.8

From the above readings it is evident that all the vibrations levels have dropped significantly. Only the motor drive end vertical vibration reading is however just 9% above the satisfactory level of 4.5mm/sec [1] but from experience we assumed that once we run the unit with the intake gas this minor deviation of the vibration reading will normalize on load.
5.0 Final Result:

Unit 1 was handed over for operation with full intake gas and after few hours of uninterrupted operation the final vibration readings of the motor were taken (Table:14)

Table 14 Final Vibration Reading (RMS mm/sec) after Cable Bend Rectification, Final Balancing & Alignment

Measuring Points	Horizontal Axis	Vertical Axis	Axial Axis
Motor non-drive end	1.31	1.06	1.33
Motor drive end	1.96	1.14	0.74

All the vibration amplitudes, measured in RMS mm/sec value are well within the norms as per the ISO Standard 10816-3[1]

DISCUSSION

From the above course of events while analyzing in a defined procedure to reduce the abnormal high vibration of a newly commissioned blower and induction motor unit it was observed

1. Even in a new motor there can be rotor unbalance but while checking and correcting the unbalance it should always be done with the coupling mounted as otherwise results can be erroneous if the coupling is fitted after the balancing of the rotor.
2. Signature analysis is the best method to do the root cause analysis of abnormal vibrations at any measuring points and the causes to be eliminated one at a time to bring the overall vibration within the accepted limits.
3. When vibration analysis gives a indication of complex causes for high vibration then phase analysis is the next best method to narrow down to the most dominant reason for the high vibration.
4. The cause for motor abnormal vibration can be also from the incorrect laying of the power cables as shown in the case study and during installation the cable bend should be as per the standard of the cable manufacturer.

CONCLUSION

In this case study we have not calculated the actual stress generated by the forcibly bending the power cables and its cascading effect on the motor body but any analysis on this aspect would have given more insight to the distribution of the forces along the motor bearings initiated by the pre-stressed cables.

During literature survey we could locate no significant work in this area by any researchers except for one study by Ai-ting Yu [12] but it was on stranded cables. Future researchers can work further on this problem and develop a standard, in similar lines done for motor base, the accepted level of cable vibration for motors of various sizes and speeds and the findings will give an extra tool to the condition monitoring engineers while analyzing the vibration levels of induction motors.

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