

Implementation of Predictive Maintenance and Dynamic Analysis in Paper Industries

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Abstract

Increasing the 'operating speed' of existing Paper machines, has become an essential requirement in today's Industrial scenario. Maintenance of such machines especially after increasing the operating speed; has to be done with adequate preparation, monitoring, diagnostics and systematic implementation of maintenance corrections. This paper deals with the methodology of machinery problem identification including the critical assessment of the system natural frequency/ frequencies, before and after increasing the operating speeds. The dynamic behaviour of machinery systems including the structures, dryer frames, etc. plays a very vital role on machines, before increasing the operating speed.

INTRODUCTION

Effective Maintenance of machines in a Paper plant, is very complex; due to the various combinations of machines with respect to type, speed, feed, and functions. Apart from various combinations of utilities, auxiliaries, and preparatory machines, the Paper machine itself is a combination of several drives, very many roles, transmissions, supports, structures etc. The operating speeds of various sections/parts of Paper machines are also widely varying from the 'Wire part' up to the 'reel'.

The implementation of an effective dynamic predictive maintenance needs careful diagnostics of the existing problems of all critical sections, sub assemblies and parts through systematic implementation of Condition Monitoring methods. Even though, many monitoring and diagnostic methods are existing; one of the most effective methods is the implementation of 'Vibration Analysis and Diagnostics' on Paper machines.

Normally the machine speeds are increased without giving considerations to the system natural frequencies and the associated changes-in the resonance conditions at the increased speeds. In such cases, new problems are encountered, during the operations at increased speeds. The methodology of implementing initial diagnostics, identification of corrections, assessment of system dynamic stability, implementation of dynamic analysis and systematic methodology of Condition Monitoring on Paper machines are covered in this paper, along with specific case studies.

Steps of implementing DPM

Implementation of DPM involves

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1. Selecting all critical machines. This should include all drives, Dryer Sections, Press Sections and Felt Rolls.
2. Establishing programme and methods specifying the parts to be examined.
3. Establishing for each part of the machine the severity limits of the machine condition parameter (Vibration, Sound, Temperature, Contamination etc.) to be measured.
4. Selecting proper examination frequencies to arrive at the best frequency of examination, we must consider for each machine.
 - * Its criticality in the process flow chart.
 - * The availability of the standby machines.
 - * The standardisation of items.
 - * The operating conditions
 - * The failure statistics (MTBF-MTTR)
 - * The cost of examination
 - * The overall cost of failure
 - * The cost of maintenance
 - * Recording data
 - * Training examiners

The examiners must have a high standard of experience, a deep knowledge of machinery and particularly endowed with analytical skill.

The complex paper machine system

The first stage of implementing predictive maintenance and dynamic analysis is the identification of machine sections / parts for monitoring. In a Complex Paper machine the main groups / parts requiring careful assessment, analysis, diagnostics and identification of dynamic behaviour are the following :

All drive units from wire part to reel

- Suction couch roll drive
- Pick up roll drive
- Drier groups
- Calender roll drive
- Line shafts, Gear boxes & drives (as applicable)
- Forward drive roll drive
- Press drives
- Size press drive
- Pope reel drive
- All auxiliary drives etc.

All drier sections including drive gears

Drier frames, structures & sole plates

All rolls

- Breast roll
- Suction couch roll
- Pick up roll
- Calender rolls
- Paper lead rolls
- Wire return rolls
- Forward drive roll
- Press rolls
- Pope reel
- Felt rolls

Condition monitoring methods

Condition monitoring includes three steps

- * DETECTION (when) of the developing fault at an early stage
- * DIAGNOSIS (what) of its origin so that spare parts and other preparations can be made well in advance.
- * PROGNOSIS (FORECAST) - to help, to establish maintenance intervals and to extrapolate the behaviour at different feed, speed and other operating conditions.

Vibration analysis as an effective monitoring parameter

Machinery Vibrations are effective parameters to identify the health condition, diagnose machinery problems, pinpoint defective locations and to finalise corrective actions on Paper machines. Depending on the machine construction, capacity and speeds, the safe permissible vibration limits can be established. Based on the measured parameters like Vibration displacement, velocity, acceleration, frequency and phase; effective interpretation is possible.

Normal problems of paper machines

- * Inadequate structural rigidity
- * Roll Distortion
- * Gear Inaccuracies and problems associated with Gear Boxes

- * Rubs
- * Piping Forces
- * Problems associated with Drives, Line Shafts etc.
- * Bearing Defects
- * Unequal Bearing Stiffness
- * Unbalance
- * Defective Belt Driven System
- * Misalignment
- * Flow induced problems
- * Mechanical Looseness
- * Spring Back
- * Increased Clearances
- * Coupling Inaccuracies
- * Foundation Distortion
- * Electrical Defects in Drive Motor
- * Critical Speed and Resonance

Natural frequency, critical speed and resonance conditions

Every mechanical system has a series of natural frequencies, each of which has its own damping characteristics. These natural frequencies will lie "dormant" in a system until they are excited by some external influence or forcing function. The vibration can be greatly amplified if a forcing function, such as unbalance or a blade pass frequency happens to be within the range of a natural frequency. When such forcing frequencies coincide with or nearer to a natural frequency is known as resonance. In some machines which are subject to impact, several such natural frequencies can be excited. The effect will be significant if the frequency is sustained over a longer time. Some of the effects of this amplified vibration can range from premature wear and excessive maintenance to fatigue failure or complete structural damage.

Solving vibration problems due to resonance can increase the operating life and decrease maintenance, replacement and operating costs.

Frequencies need to be identified and compared to the operating speeds of the equipment. Second, to resolve the problem, a choice has to be made between changing the operating speed or changing the resonant frequencies. When Paper machine speed is being increased, the only choice is to change the resonance frequencies and hence such Paper machines need very careful analysis.

Understanding dynamic analysis in relation to natural frequency, critical speed & resonance conditions

Natural frequency

Table 1: Machinery problem diagnostic chart

Cause	Vibration Level	Frequency	Remarks
Unbalance	Proportional to unbalance Largest in radial direction	1 x rpm	Most common cause of vibrations
Bent shaft	Large in axial direction	1 x rpm	-
Misalignment (couplings or bearings)	Large in Axial Direction (50% or more of radial vibrations)	1 x rpm, 2 x rpm most common 3n sometimes	Best found by appearance of large axial vibrations. Positive diagnosis can be obtained using dial indicators. If sleeve-bearing machine and no coupling misalignment problem is probably unbalanced of the rotor
Eccentric Journals	Usually not large	1 x rpm	If on gears, largest vibrations in line with gear centres.
Rubs	No particular characteristic if continuous	Mainly 1x rpm plus 2 x rpm	Can excite high natural frequencies of machine. Amplitude at same speed may vary between different runs.
Mechanical Looseness	Variable	2n	Usually accompanied by misalignment and/or unbalance. Not a loose bearing assembly.
Loose Bearing Assembly	Variable	0.5 rpm	Sometimes manifest at rotor critical speed. Quite a common problem.
Oil Whirl	Severe, radial motion	0.43-0.47rpm	Only in high speed or vertical rotor machines with pressure lubricated sleeve bearings.
Friction Induced Whirl	Can be severe radial vibrations	Usually less than 0.4xrpm and equal to first critical speed of rotor	Rare can be caused by loose rotor components.
Rolling- Element Bearing Distortion	Depends upon amount of distortion	1 x rpm	Large component in either horizontal or vertical planes. Taper roller bearings will also have axial components of vibration.
Rolling Element Bearing Damage	Unsteady	High frequencies	See later discussion.
Bad Gears or Gear Noise	Low	Very high Txrpm (T number of teeth)	See later discussion.
Faults in Belt Drives	Erratic or Pulsing	1,2,3 and 4 times rotational frequency of belt	Stroboscope can be used to diagnose belt defects.
Electrical	Low, Disappears when power is turned off	1xrpm or 1 or 2 times synchronous frequency	See later notes on electrical machines

Flow Induced Problems	Variable	1 x rpm or b,n (where b is number of blades or lobes)	Rare as a cause of trouble, except in cases of resonances. See later notes on bladed machinery
Reciprocating Forces	-	1 x rpm , 2 x rpm and higher orders	Inherent in reciprocating machinery.
Faulty Combustion in Diesels	High	0.5 x rpm	Faults with injectors, fuel pumps, calibration or timing show unbalance. Resiliently mounted unit rocks at 0.5n which is close to natural frequency of mounted unit, and causes large amplitudes.
Foundation Faults	Random and can be high	Low and erratic	Check foundation bolts.
Resonance related problems	Rotational Speed Components, harmonics, natural frequencies, critical speeds, etc etc.	Can cause dangerous situations	Most complex for diagnostics as well as for corrections Dynamic analysis is recommended.

Natural frequency is "the frequency of free vibration of a system. The frequency at which an undamped system with a single degree of freedom will oscillate upon momentary displacement from its rest position". In addition, for a multiple degree-of-freedom system, the natural frequencies are the frequencies of the normal modes of vibration. All machines and all structures have a number of natural frequencies. If forced to vibrate at one or more of these natural frequencies, dynamic stresses of 10 to 100 times higher than those are induced compared to those which would be generated if these same forces were input at other frequencies lower or higher than these natural frequencies.

Resonance

Resonance is the condition which occurs when such forcing frequencies do in fact coincide with one or more natural frequencies. These may be a natural frequencies of the rotor, but often can be a natural frequency of the support frame, foundation or even of drive belts. Forcing frequencies include those from sources such as unbalance, misalignment, looseness, bearing defects, gear defects, belt wear, etc. It is important to point out resonances can be encountered not only at 1X RPM, but at series of frequencies including 1X RPM, 2X RPM, 3X RPM etc.

Critical speed

"Critical speed related problems are special cases of resonance in which the vibrating forces are caused by the rotation of the rotor". "Critical speed testing is often more complicated than resonance testing

because the natural frequencies encountered are functions of stiffness and mass which may be dependent on machine speed". For example in the case of a machine with an extended overhung rotor or in the case of general sleeve bearing machines, critical speeds can change their frequency location due to changes in stiffness and/or gyroscopic motion. Unlike resonant frequencies for frames, foundations and rolling element bearing machines which have fixed natural frequencies independent of operating speed. Generally, good design practices mandate that a machine should be designed not to operate within 20% of a critical speed (not 20% of any natural frequency).

It is not recommended to operate a machine within 30% margin between any natural frequency (of the rotor, support frame, foundation and attached structure) and the excitation frequency / frequencies. Any structure has six (6) different sets of basic natural frequencies including those in the horizontal, vertical and axial directions as well as "rocking modes" in each 3 directions., Thus, the key will be to identify the locations of all resonances being excited, how severe the resonant vibration is, and what is the duration of time to which the rotating or stationary structure is subjected to resonance. Finally, if the machines and structures are fabricated from steel, cast iron, aluminum or any other lightly damped material, it may only be necessary to remain approximately 10% away from resonance in order to avoid resonant amplitude amplification.

This step alone can easily reduce vibration from 10 to as much as 30 times. The Fig.1 illustrates what

happens when a machine goes into resonance. It shows a graph of magnification factor (Q) on the vertical axis versus frequency ratio on the horizontal axis on the upper graph, while plotting phase lag (degrees) versus the same frequency ratio in the lower graph. Note that the frequency ratio is the ratio of forcing frequency to undamped natural frequency. This forcing frequency can be caused by many sources and can occur at many different frequencies. For example, it can be caused by unbalance at 1X RPM; or by misalignment possibly at 2X RPM; or by a gear mesh frequency at the number of gear teeth X RPM; or by blade pass frequency (BPF) at the number of blades (or vanes) X RPM; or even excited by a rolling element bearing defect frequency. Fig. 1 shows that the problem occurs when such a forcing frequency (f) happens to equal the system natural frequency (f_n) - ie., when $f/f_n = 1.0$. When this occurs the vibration can be amplified many times higher, often in the order of 10 or even 50 times higher depending on the amount of damping within the system (a lightly damped system will suffer a tremendous increase when vibrating at a natural frequency)

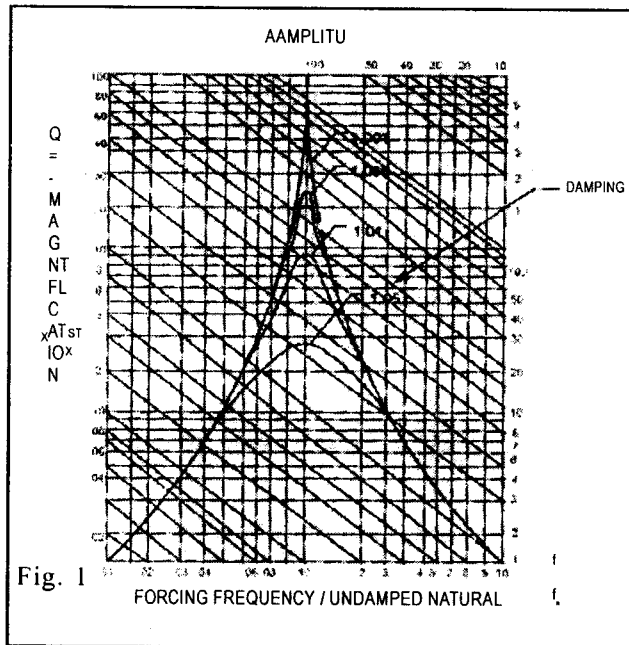


Fig. 1

Case study on a paper machine

Detailed Vibration Analysis is carried out on a paper machine which was operating at the speed of 450 mpm. This study was taken up before increasing the operating speed to 600 mpm.

The study was taken up in the following sequence

- Analysis at the present speed to identify existing defects & inaccuracies and to prepare Action Plan to improve the health condition to Satisfactory levels.

- Identify corrections to be implemented at the proposed higher speed - these corrections will include dynamic balancing of Dryer Cylinders, Felt Rolls, etc.
- Identify structural ability of the machine system.
- To identify whether dynamic analysis is required on the machine / structure, to identify solutions to eliminate possible 'nearness to resonance conditions' at the proposed higher speed of 600 mpm.
- Implementation of dynamic analysis, wherever found necessary.

The Vibration signatures plotted at the location No.37 having highest velocity are given below:

The Analysis revealed very high amplifications on many Dryer Cylinders and Frames as indicated in the Unsatisfactory category. The Dryer Cylinders and Frames of No.37 was indicating the highest vibration severity. The extrapolation of the data very close to resonance conditions. The Drive end locations are indicating very wide amplitude fluctuations with the dominance of unsteady low frequencies, rotational speed component's and meshing frequencies. Major bearing excitations are not indicated. The highest vibration velocity of 18.0 mm/sec. was measured at the Drive end bearing locations of Drier Cylinder No.37. Dominance of low frequencies and the meshing frequencies are significantly high.

Analysis

- * The axial rigidity of the Drier frame is inadequate for the increased dynamic loads at higher operating speeds. The analysis at the present low speed itself is indicating very major amplifications. Hence a detailed dynamic analysis to identify the resonance conditions and mode shapes is essential.
- * Significant meshing inaccuracies are indicated in the Gears especially those associated with Cylinders 32, 33, 35, 37, 39 & 40.
- * Looseness is indicated at the base fixing locations.
- * Bearing inaccuracies are indicated at the Drive end of Drier Cylinder No.33, 35, 37 & 40.
- * Unbalance is indicated in the Drier Cylinders 35 & 37.

Action Plan

1. Take up dynamic analysis of Dryer Groups - give priority for the Dryer Frame and Dryer Cylinder no. 37. (the simulated images of this analysis is given below).
2. All the inaccuracies indicated above are to be critically inspected and corrected.

Table : 2 Vibration analysis carried out on all the sections of the paper machine and the details on the selected Dryer Cylinders are given below.

Drier cylinders Highest amplitudes & health condition			
Location	Displacement (Microns)	Velocity (mm/sec)	Health condition
Dryer cylinders No. 31			
Drive end	120	4.0	Just satisfactory
Non drive end	30	1.6	Satisfactory
Dryer cylinder No. 32			
Drive end	65	2.8	Just satisfactory
Non drive end	100	3.5	Just satisfactory
Dryer cylinder No. 33			
Drive end	100	6.5	Unsatisfactory
Non drive end	21	1.1	Satisfactory
Dryer cylinder No. 34			
Drive end	60	3.5	Just satisfactory
Non drive end	80	2.5	Just satisfactory
Dryer cylinder No. 35			
Drive end	100	15.0	Unsatisfactory
Non drive end	19	2.1	Satisfactory
Dryer cylinder No. 36			
Drive end	60	2.5	Just satisfactory
Non drive end	80	2.5	Just satisfactory
Dryer cylinder No. 37			
Drive end	220	18.0	Unsatisfactory
Non drive end	20	1.3	Satisfactory
Dryer cylinder No. 38			
Drive end	80	2.0	Satisfactory
Non drive end	70	2.8	Just satisfactory
Dryer cylinder No. 39			
Drive end	80	6.5	Unsatisfactory

Improving the axial rigidity of the Drier frame cannot be implemented as a maintenance correction but has to be taken up after a dynamic analysis of the frame. In the meantime all other mechanical inaccuracies are to be corrected after a thorough inspection.

Modeling dynamic analysis & simulation of dryer frame & cylinder No. 37

It is essential to take up Dynamic Analysis of the complete Paper Machines structure, all Dryer Frames with the Cylinder and other parts, whose natural frequency / frequencies are falling closer to the increased machine speed / speeds and their

harmonics. Based on the case study, it is found that Dryer Cylinder no.37 is indicating the highest severity and maximum unstabilities. The actual example of 3D modelling and simulation of this Dryer Frame and Cylinder is given below

Dryer Frame & Cylinder No. 37 - 1st Mode

Simulations in different modes are taken up to identify corrections to the Dryer Frames and supports. Simple stiffening as identified from the dynamic analysis was implemented on this machine. The vibration velocity has come down from 18.0 mm/sec to 2.1 mm/sec at the current operating speed. The extrapolation of the results indicate that at the proposed higher speed of 600 mpm, the vibration

Table : 3 Vibration Data sheet

DE - Drive End				NDE - Non Drive End			
Location		Displacement in microns	Velocity in mm/sec	Location		Displacement in microns	Velocity in mm/sec
31 DE	H	40	4.0	31 NDE	H	30	1.60
	V	40	4.0		V	20	1.20
	A	120	3.60		A	25	1.00
32 DE	H	60	2.80	32 NDE	H	40	2.00
	V	30	1.20		V	19	1.10
	A	65	2.30		A	100	3.50
33 DE	H	40	6.50	33 NDE	H	21	1.10
	V	100	4.50		V	20-	0.90
	A	100	4.00		A	19	1.10
34 DE	H	35	3.50	34 NDE	H	40	1.70
	V				V	22	1.20
	A	60	2.70		A	80	2.50
35 DE	H	100	15.0	35 NDE	H	19	2.10
	V	40	4.0		V	15	1.20
	A	90	5.0		A	80	1.20
36 DE	H	60	2.50	36 NDE	H	40	1.80
	V				V	19	1.50
	A	60	2.50		A	80	2.50
37 DE	H	200	18.0	37 NDE	H	20	1.30
	V	25	4.00		V	15	1.00
	A	40	5.00		A	16	1.00
38 DE	H	35	1.60	38 NDE	H	35	1.60
	V	13	1.20		V	17	0.90
	A	80	6.00		A	70	2.80
39 DE	H	20	6.50	39 NDE	H	22	1.40
	V	80	6.00		V	18	1.40
	A	50	4.00		A	25	1.40
40 DE	H	65	7.50	39 NDE	H	30	1.60
	V				V	16	0.90
	A	60	3.50		A	40	1.60
	(H-Horizontal, V- Vertical, A-Axial)						

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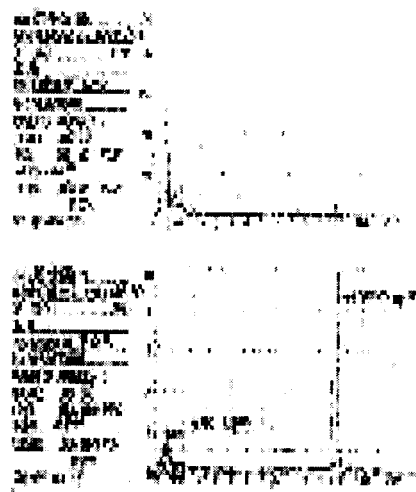
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The vibration signatures plotted at the location No. 37 having highest velocity are given below:



CONCLUSION

The case study is indicative of the effectiveness of vibration analysis and dynamic analysis on a Paper machine in pinpointing defects and inaccuracies and in evolving effective solutions. The 3D modelling dynamic analysis including mode shape analysis are being effectively implemented in Indian Paper Industry; at the time of increasing the operating speed; with proven effectiveness and significant cost benefits. These capabilities were not existing in the Indian context, till recently; but are available at present with proven expertise and experience.