Condition Based Maintenance Modeling for Availability Analysis of a Repairable Mechanical System

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Abstract- This paper deals with the condition based maintenance modeling for availability analysis of repairable mechanical systems using MARKOV analysis. Maintenance actions are selected out of four actions namely no repair, minor maintenance, imperfect maintenance and major maintenance. The various probabilities of selecting the maintenance depend upon the level of degradation. Thus system MARKOV model is developed incorporating these aspects, i.e. multi-state degradation, periodic inspection, condition based maintenance actions and random failures. The solution of the model is obtained analytically by solving system of ordinary differential equations by Ranga-Kutta method using MATLAB software. The proposed methodology is implemented for centrifugal pump. The suggested approach helps in gauging and assessing availability and hence is useful for the engineers in enhancing the overall availability of the system. It is also helpful for maintenance engineers in deciding suitable maintenance and replacement policies. We are optimizing the condition monitoring interval to maximize the system availability.

Keywords – Markov, CBM, Ranga-Kutta

I. INTRODUCTION

Reliability has always been an important aspect in the assessment of industrial products and/or equipment. Good product design is of course essential for products with high reliability. However, no matter how good the product design is, products deteriorate over time since they are operating under certain stress or load in the real environment, often involving randomness. Maintenance has, thus, been introduced as an efficient way to assure a satisfactory level of reliability during the useful life of a physical asset.

The earliest maintenance technique is basically breakdown maintenance (also called unplanned maintenance, or run-to-failure maintenance), which takes place only at breakdowns. A later maintenance technique is time-based preventive maintenance (also called planned maintenance), which sets a periodic interval to perform preventive maintenance regardless of the health status of a physical asset. With the rapid development of modern technology, products have become more and more complex while better quality and higher reliability are required. This makes the cost of preventive maintenance higher and higher. Eventually, preventive maintenance has become a major expense of many industrial companies. Therefore, more efficient maintenance approaches such as condition-based maintenance (CBM) are being implemented to handle the situation.

CBM is a maintenance program that recommends maintenance actions based on the information collected through condition monitoring. CBM attempts to avoid unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behaviours of a physical asset. A CBM program, if properly established and effectively implemented, can significantly reduce maintenance cost by reducing the number of unnecessary scheduled preventive maintenance operations.

A CBM program consists of three key steps (see Fig. 1):

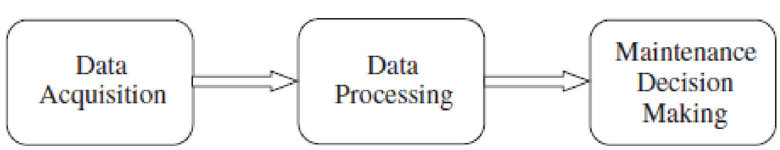

Fig.1. Three steps in a CBM program.

1. Data acquisition step (information collecting), to obtain data relevant to system health.
2. Data processing step (information handling), to handle and analyse the data or signals collected in step 1 for better understanding and interpretation of the data.
3. Maintenance decision-making step (decision-making), to recommend efficient maintenance policies.

The remaining paper is organised in the following manner:
Section II deals with system modelling. In section III the solution of the system model is obtained. In section IV results are discussed sensitive analysis is carried out to optimise the condition monitoring interval. Finally section V concludes the paper.

II. SYSTEM MODELLING

2.1 Degradation

Whenever a system or a model is in working it degrades with time. The degradation is gradual not sudden. We are trying to study a mode that follows this kind of failure.

In degradation modeling we study a system that is prone to degradation and mostly we study the systems where reliability is critical. As shown in the figure is such a system.

There are four stages shown. Fresh component is given the stage D1, then with time it degrades to a stage D2 and so on and finally it goes to a failure state. We will be studying the degradation rate from one stage to the other for all the stages.

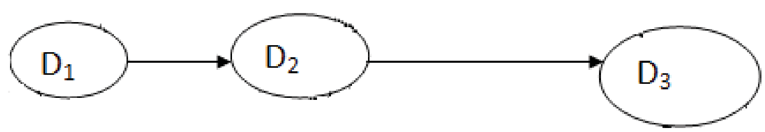

Fig.2. Multi State degradation

2.2 Inspection

Inspection is a way to see the health of the system and deciding whether the system requires repair/maintenance or not. Now there are two types of inspections:

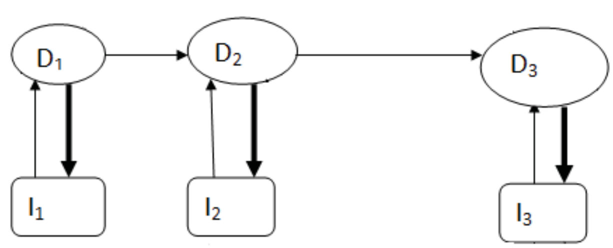

Fig 3. Periodic Inspection at every stage

Online: In this we need not to stop the system for inspection so the availability of the system is more, and

Offline: In this we need to stop the system for inspection.

As described in the above figure we take the system further and do periodic inspections at each state defined. These inspections help us in maintain the system by doing timely repairs and maintenance.

2.3 Condition Based Maintenance

Condition based maintenance (CBM), shortly described, is maintenance when need arises. This maintenance is performed after one or more indicator shows the equipment is going to fail or that equipment performance is deteriorating.

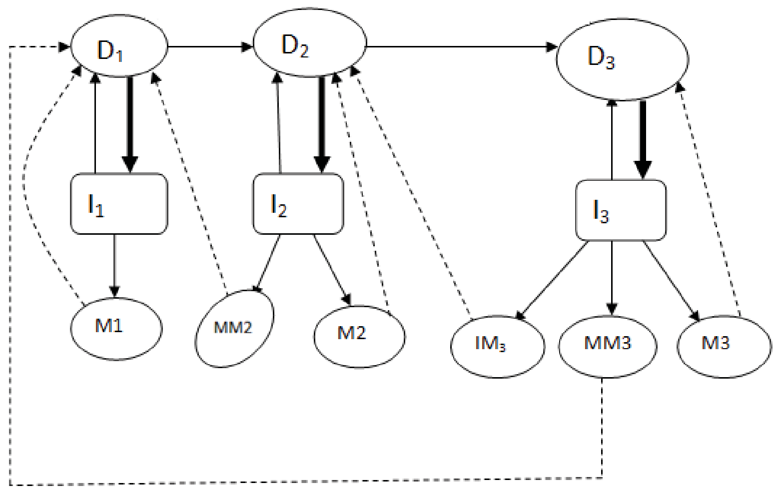

Fig 4. Condition based maintenance

In our system model, we have described three types of maintenance on the basis of the requirement of the system. The three types of maintenance are: Minor maintenance, intermediate maintenance and major maintenance.

In stage D1, our system is new, thus , we need not require much maintenance for it. Therefore we have kept the probability for our system to undergo minor maintenance to be 0.1 and the probability that system would go back to the stage D1 without any maintenance to be 0.9.

Similarly in stage D2 as our system is in continuous working state, it deteriorates and thus its efficiency decreases and the need to repair it or maintain it increases as compared to the system in stage D1. Due to this reason we have decreased the probability that the system would go back to stage D2 without any repair from 0.9 to 0.7 and the probability that the system would require maintenance has been increased from 0.1 to 0.3.

Finally, when our system moves from stage D2 to D3, it deteriorates further giving rise to the need to repair it in order to increase its availability. Therefore the probability is that he system requires minor repair or intermediate repair or major repair or no repair has been altered again the probability that the system would require major maintenance has been changed to 0.2.The probability that the system would require intermediate repair has been changed to 0.4. The probability that the system would require minor maintenance has been change to 0.2 and finally the probability that the system would go back to stage D3 without any repair has been changed to 0.2.

2.4 Random Failure

Random failure is defined as the situation Condition in which the system fails due to some random causes. These random causes can be anything from natural calamity to human error. Random failures can also occur due to voltage fluctuations, manufacturing defects, problem in system components, etc.

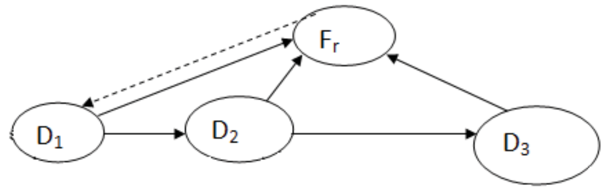

Fig 5. Random failure

Random failure causes the system to go in offline mode thereby bringing its availability to 0.

III. Solution of System Model

After developing the model as above, we will now obtain the solution using analytical approach(Markov Analysis). The set of ordinary differential equation are provided below:

1. $dP_{d1}/dt = -\lambda_{d1d2}P_{d1}(t) - \lambda_{d1i1}P_{d1}(t) - \lambda d_{1fr}P_{d1}(t) + \mu_{i1d1}P_{i1}(t) + \mu_{m1d1}P_{m1}(t) + \mu_{mm2d1}P_{mm2}(t) + \mu_{mm3}P_{mm3}(t) + \mu_{frd1}P_{fr}(t)$
2. $dP_{d2}/dt = \lambda_{d1d1}P_{d1}(t) - \lambda_{d2d3}P_{d2}(t) - \lambda_{d2fr}P_{d2}(t) - \lambda_{d2i2}P_{d2}(t) + \mu_{i2d2}P_{i2}(t) + \mu_{m2d2}P_{m2}(t) + \mu_{im3d2}P_{im3}(t)$
3. $dP_{d3}/dt = \lambda_{d2d3}P_{d2}(t) - \lambda_{d3i3}P_{d3}(t) - \lambda_{d3fr}P_{d3}(t) + \mu_{m3d3}P_{m3}(t) + \mu_{i3d3}P_{i3}(t)$
4. $dP_{i1}/dt = \lambda_{d1i1}P_{d1}(t) - \lambda_{i1m1}P_{i1}(t) - \mu_{i1d1}P_{i1}(t)$.
5. $dP_{i2}/dt = \lambda_{2i2}P_{d2}(t) - \lambda_{i2m2}P_{i2}(t) - \lambda_{i2mm2}P_{i2}(t) - \mu_{i2d2}P_{i2}(t)$
6. $dP_{i3}/dt = \lambda_{3i3}P_{d3}(t) - \lambda_{i3m3}P_{i3}(t) - \lambda_{i3mm3}P_{i3}(t) - \lambda_{i3m3}P_{i3}(t) - \mu_{i3d3}P_{i3}(t)$
7. $dP_{Fr}/dt = \lambda_{d1fr}P_{d1}(t) + \lambda_{dfr}P_{d2}(t) + \lambda_{d3fr}P_{d3}(t) - \mu_{frd1}P_{fr}(t)$
8. $dP_{m1}/dt = \lambda_{i1m1}P_{i1}(t) - \mu_{m1d1}P_{m1}(t)$
9. $dP_{m2}/dt = \lambda_{i2m2}P_{i2}(t) - \mu_{m2d2}P_{m2}(t)$
10. $dP_{mm2}/dt = \lambda_{i2mm2}P_{i2}(t) - \mu_{mm2d1}P_{mm2}(t)$
11. $dP_{m3}/dt = \lambda_{i3m3}P_{i3}(t) - \mu_{m3d3}P_{m3}(t)$
12. $dPim3/dt = \lambda_{i3m3}P_{i3}(t) - \mu_{im3}P_{i3}(t)$
13. $dP_{mm3}/dt = \lambda_{i3mm3}P_{i3}(t) - \mu_{mm3d1}P_{mm3}(t)$

IV. RESULT AND SENSITIVITY ANALYSIS

In this section results are given in tabular form and sensitivity analysis is carried out.

Table -1: Distribution parameters for failure/Repair/Inspection Interval Transition

S.no.	Transition	PARAMETER	VALUE
1	D_1D_2	λ_{D1D2}	0.00025
2	D2D3	λ_{D2D3}	0.00067
3	D1I1	λ_{D1I1}	0.004
4	I1M1	Λ_{I1M1}	0.5
5	D2I2	λ_{D2I2}	0.00595
6	I2M2	λ_{I2M2}	0.25
7	I2MM2	λ_{I2MM2}	0.25
8	D3I3	λ_{D3I3}	0.01
9	I3M3	λ_{I3M3}	0.125
10	I3MM3	λ_{I3MM3}	0.125
11	I3IM3	λ_{I3IM3}	0.125
12	D1Fr	λ_{D1Fr}	0.00002

13	D2Fr	λ_{D2Fr}	0.00002
14	D3Fr	λ_{D3Fr}	0.00002
15	I1D1	μ_{I1D1}	0.005
16	I2D2	μ_{I2D2}	0.025
17	I3D3	μ_{I3D3}	0.0125
18	M1D1	μ_{M1D1}	0.05
19	M3D2	μ_{M2D2}	0.025
20	MM2D1	μ_{MM2D1}	0.0125
21	M3D3	μ_{M3D3}	0.016
22	IM3D2	μ_{IM3D2}	0.01
23	MM3D1	μ_{MM3D1}	0.0625
24	FrD1	μ_{FrD1}	0.02

*Source of data- www.barringer.com

4.1 Sensitivity Analysis

Sensitivity refers to the change in the result obtained when one or more independent parameters considered in the calculations are varied. Sensitivity Analysis is a technique to check the sensitivity of the solution obtained. For that, keeping other factors constant, one of the parameters is varied.

4.2 Varying the Inspection Interval

In the beginning we change the periodic inspection time at I1 keeping those at I2 and I3 constant. We observe that as we decrease the periodic time, the availability of the component decreases. This is so because in the beginning the component is new and the frequent inspection lead to time wastage and increases the possibility of minor repair work on the component. Thus decrease its availability. As shown in the table below:

Table -2 Sensitivity analysis for system availability varying inspection interval for degradation stage 1.

S.No.	I1(hrs)	I2(hrs)	I3(hrs)	Availability
1.	50	150	100	0.8807
2.	100	150	100	0.9194
3.	200	150	100	0.9607
4.	300	150	100	0.9731
5.	400	150	100	0.9792
6.	600	150	100	0.9859
7.	800	150	100	0.9893
8.	1000	150	100	0.9991
9.	1100	150	100	0.9922
10.	1200	150	100	0.9931
11.	1300	150	100	0.9934
12.	1500	150	100	0.9942

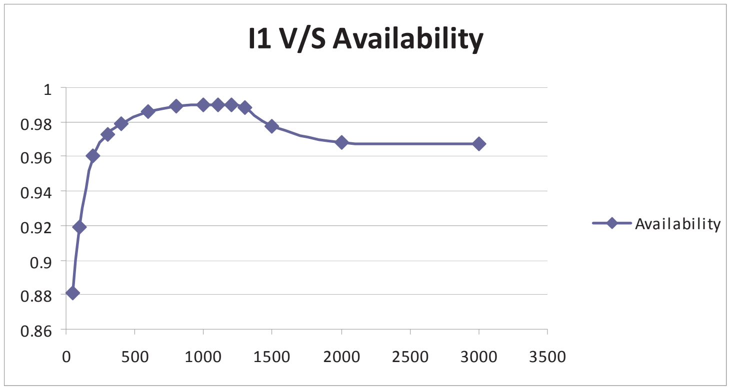

Fig 6. Inspection Interval for I1

Next, we change the periodic inspection time at I2 keeping those at I1 and I3 constant. We observe that when we increase the periodic inspection time there is very slight increase in availability of the component. This is so , because the system has degraded to an extent that it needs frequent inspection to increase the availability of the component.

Table -3 Sensitivity analysis for system availability varying inspection interval for degradation stage 2.

S.No.	I1(hrs)	I2(hrs)	I3(hrs)	Availability
1.	250	50	100	0.9667
2.	250	100	100	0.9695
3.	250	150	100	0.9677
4.	250	200	100	0.9682
5.	250	400	100	0.9689
6.	250	600	100	0.9692
7.	250	800	100	0.9694
8.	250	1000	100	0.9694
9.	250	1500	100	0.9696
10.	250	2000	100	0.9697
11.	250	10000	100	0.9700
12.	250	20000	100	0.9697

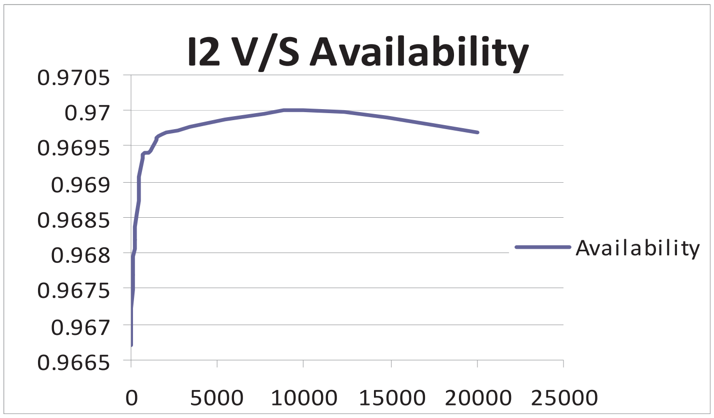

Fig 7. Inspection Interval for I2

Next, we change the periodic inspection time at I3 keeping those at I1 and I2 constant. We observe that, as we increase the periodic inspection time the availability of the component merely increases. This is so, because the component has degraded to a higher level and need frequent inspection.

Table -4 Sensitivity analysis for system availability varying inspection interval for degradation stage 3.

S.No.	I1(hrs)	I2(hrs)	I3(hrs)	Availability
1.	250	150	25	0.9676
2.	250	150	50	0.9676
3.	250	150	100	0.9677
4.	250	150	150	0.9677
5.	250	150	200	0.9677
6.	250	150	300	0.9678
7.	250	150	400	0.9678
8.	250	150	500	0.9678

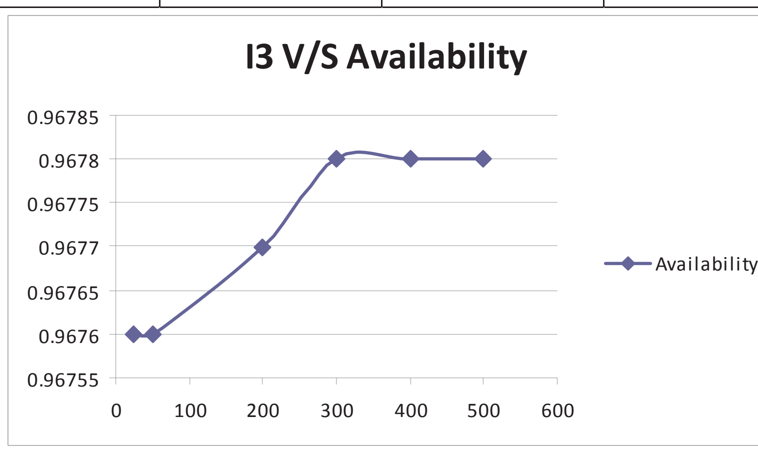

Fig.8. Inspection Interval for I3

V. CONCLUSION

In this paper availability model considering multi stage degradation, periodic inspection, and condition based maintenance and random failure is developed. The system model is solved analytically using MARKOV approach. A sensitivity analysis is conducted to see the effect of variation in probability for various maintenance decision, variation of inspection interval and final degraded states with and without failure. As far as frequency of inspection is concerned at stage D1, less frequent inspection should be done as the health of the component is very good and unnecessary inspection will only lead to time wastage and reducing our component availability.

At stage D2, the inspection should be done frequently as the health of the component is fairly good.

At stage D3, inspection work should be done quite frequently as the health of the component has deteriorated and frequent inspection would readily provide us information about its degradation so we can undertake necessary repair actions.

This model can be used by practicing maintenance engineers as it takes care of the cost involved.

This model cannot handle none exponential distribution and only Markov's Approach is used.

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