Prognostics & Health Management of Swing Type Check Valves

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Abstract— Prognostics and Health Management is emerging as new paradigm to address issues related to enhancing the safety as well as availability. The enabling technologies are state-of-the-art in on-line monitoring or periodic surveillance tools and availability of degradation assessment approaches that provide a framework for residual life assessment of component. Availability of physics of failure or mechanics of failure models and intelligent tools are vital for implementation of a prognostics and health management programme.

This paper presents an approach for prognostics and health management of Check valves. The results shows that this approach is promising to detect in advance the incipient failure such that maintenance programme can be initiated to improve the availability as well as safety. Even though this approach addresses modelling of swing type of check valves, the models can easily be adopted for other type of check valves also

Keywords—Check Valve, Health Monitoring, Prognostics, In-Service, RUL, Nuclear Plant, Hinge Pin Failure, Backstop Failure, Vibration, Tilt Sensing.

I. INTRODUCTION

Over the years the Nuclear and other process industries have come to realize the importance of reliable operation of passive safety devices such as Check valves. Check valves known for their passive mode of operation are often used in important process loops like the main coolant loops of Nuclear Reactors. The function of a Check Valve is to allow flow (above a minimum flow value) in the forward direction and prevent reverse flow. The inability to perform any of these functions will qualify as a failure of the check valve. Failure of these valves to operate may lead to a number of undesirable and sometimes dangerous consequences like reverse flow through pumps, over pressurization of low pressure systems, water hammer etc. (1). Conventional methods for ascertaining Check Valve health status involve manual disassembly of the valves.

Since these valves are installed in loops very central to the operation of these plants, any failure or unnecessary maintenance activities on these valves may lead to plant downtime thus affecting the availability factors of plants. In addition to the financial aspects of plant unavailability, in nuclear plants these valves may be installed in loops carrying radiation emitting process fluids, hence these maintenance jobs will involve the exposure personnel to radiation. The importance of check valve health and challenges in its maintenance has led the nuclear industry to investigate this problem in great detail.

Swing Type Check Valve internals have been shown to fail because of failure of valve internals in the hinge pin and backstop areas (2)(refer Figure 1).

![Figure 1: Swing Check Valve internals](image)

Failures are caused due to excessive wear occurring due to unstable operation. These instabilities occur due to over sizing of the valve (1) (2), improper installation (2) (3) or low flow conditions. Unstable valve operation leads to a phenomenon called as disc flutter, meaning the oscillation of the disc about a mean position. Methods to detect disc flutter include Acoustic Emission Sensing (1), (2), Magnetic Flux leakage analysis and Ultrasonic Inspection (1), (2).
Apart from these, certain methodologies to predict unstable operation based on valve design, upstream designs etc. have also been discussed (3). However all these efforts are highly specific to either condition monitoring alone or are not using any signals from the valve itself and are predicting on the basis of process parameters.

We have studied two particular failure modes in depth namely the hinge pin failure and the backstop failure. Hinge pin failure occurs when the hinge pin diameter reduces owing to the mechanical wearing of the pin (4), this will compromise the smooth working of the valve and beyond a certain limit may lead to breakage of the pin. The wearing will be exacerbated under unstable disc operation due to the increased frictional rubbing between the pin and its housing (2). Backstop failure occurs when fatigue breaking of the backstop occurs. This occurs when the disc oscillation occurs close to its fully open position and the backstop is continuously hitting against the body (4).

Keeping this in mind we have formulated a strategy to identify unstable valve operation, detect disc motion and also detect reduction in hinge pin diameter. Also we have utilized existing well proven models to provide an estimate of the Remaining Useful Life (RUL) of the valve under stated conditions. We have conceptualized a methodology to assess valve health and estimate RUL with respect to the Hinge Pin and Backstop failures. Health status is monitored by the use of vibration sensors mounted on appropriate locations (Refer Fig 2). RUL is estimated by the use of well proven mathematical models, which take an input from an Accelerometer Based Tilt Sensor (ABTS) mounted internal to the valve on the valve disc. Details regarding methodologies used in each failure mode are included in separate subsections.

A. Hinge Pin Failure

The Hinge Pin failure mode results from the reduction of the hinge pin diameter due to mechanical wearing caused by the rubbing of the Hinge Pin with the internal walls of its slot. The slot is basically the continuous groove from the valve body to the hinge arm to the valve body where the hinge pin resides. The wearing of the hinge pin would lead to increased clearances between the slot and the pin (Refer Fig 2).

Thus it is necessary to detect this reduction in pin diameter to ascertain health status of the pin. As the clearance increases, the vibration signals arising from the valve will change, this would be utilized to gauge the status of the pin.

In order to predict RUL, a well proven mathematical model known as the standard wear equation is used. The equation is as follows:

$$W = \frac{K \cdot L \cdot d}{H}$$  \hspace{1cm} (4)

This equation provides the wear volume ($W, \text{in}^3$) given the non dimensional Wear Coefficient ($W$, dimensionless), the Load ($L, \text{lb}$), the sliding distance between the two bodies ($d, \text{in}$) and the Hardness coefficient ($H, \text{psi}$). This model has been shown to conform closely to experimental trials performed by Kalsi et al (4).

Out of the required inputs for this equation, $K$, $H$ can be determined from valve material data. $L$ is ascertained by using the following equation:

$$L = W_{\text{disc}} + 0.5W_{\text{arm}}$$  \hspace{1cm} (4)

Where $W_{\text{disc}}$ and $W_{\text{arm}}$ are the weights of the disc and arm respectively.
The sliding distance or D is calculated by using the ABTS. The ABTS is mounted as shown in (Fig 3).

![Mounting of the Accelerometer Based Tilt Sensor (ABTS) on the Hinge Arm.](image)

The ABTS is basically an MMA6361L accelerometer which is potted in waterproof epoxy material. It is mounted using clamps on the Hinge Arm. Accelerometers can be used to measure the angle of the plane it is mounted on with respect to the normal (5). This angle is also basically the angular position of the disc-hinge arm arrangement as shown in Fig 4. The output voltage of the sensor will be representative of the tilt angle θ. The curve of tilt angle vs ABTS o/p is as follows:

![Tilt sensing using the ABTS (Schematic)](image)

By using information regarding θ, the sliding distance can be calculated by using the following methodology:

Eq. 3. \[ d = \frac{D\theta}{2} \]

Where D is the diameter of the hinge pin.

After calculating the Wear Volume, the reduction in diameter can be ascertained. This calculated by using the equation (1):

Eq. 4. \[ W = \frac{\pi Dh\delta}{4} \]

Where h is the length of the hinge pin (assuming wear occurs along the entire length) and δ is the wear depth.

Eq. 5. \[ \delta = \frac{4W}{\pi Dh} \]

Since δ is the change in hinge pin diameter, the new hinge pin diameter will be given as:

Eq. 6. \[ D' = D - \delta \]
If this wear volume $W$ is assumed to be the amount of material lost per unit time, the same Eq 1 can be rewritten as

$$W = \frac{K_{ld}}{H}$$

Here $W$ represents the Wear Rate (m$^3$/s). This is an important parameter because wear rate is the parameter that relates the wear volume with time thus enabling us to predict the RUL.

On assuming that the wear rate remains constant for a certain period of time, the total wear volume will be given by

$$W = \dot{W} \times t$$

Here $t$ is the operating time. The estimation of RUL is based on the minimum allowable Hinge Pin Diameter $D_{min}$ and total reduction in pin diameter is $\delta_{max}$. Thus the maximum allowable wear volume is given by

$$W_{max} = \frac{\pi D_{min} \delta_{max}}{4}$$

Thus combining the two equations: Eq 9 and Eq 8, we arrive at the solution

$$t_{max} = \frac{W_{max}}{W}$$

This is the RUL of the valve when considering Hinge Pin Failure.

B. Backstop Failure

Under unstable operation, backstop may continuously impact the valve body. This impacting may lead to fatigue failure of the backstop. Backstop failure refers to shearing or breakage of the backstop. This will result in variations in the travel of the disc-hinge arm arrangement when the valve goes to the fully open extreme. Any change in the maximum travel of the disc will be reflected as a change in the maximum tilt angle, this can be detected using the ABTS

The tapping frequency is detected by scanning the ABTS output for a particular value corresponding to the maximum tilt angle of the valve disc, and also noting down how many times that particular value recurs per unit time. Also the maximum oscillation angle can be determined by analyzing the trend of the ABTS signal. The Model used has been verified by experimentation (2).

The final expression for the impact force as given by (2)

$$F = V \frac{m}{\sqrt{\frac{\pi D_{min} \delta_{max}}{4}}}$$

Here $L$ is the length of the backstop, $A$ is the cross-sectional area of the backstop, $E$ is the Young’s Modulus of the material and $J$ is the moment of inertia of the backstop.

The velocity term can be found out from the ABTS signal by analyzing the total angle traversed in one second, this is the angular velocity. The angular velocity once obtained in rad/s can be used to calculate the linear velocity by using the equation.

$$V = R \omega,$$

$R$ is the distance of the backstop from the hinge point.

Once the force is calculated, the axial and bending stresses can be calculated using the expressions $\sigma_{axial} = \frac{F}{A}$; $\sigma_{bending} = \frac{F_{axial}}{Z}$, here $Z$ is the section modulus.

The total alternating stress is then given by (2):

$$\sigma_{alt} = \frac{1}{2} \times S.C. F. \times (\sigma_{axial} + \sigma_{bending})$$

Here $S.C. F.$ is the Stress Concentration Factor and $\sigma_{alt}$ is the peak alternating stress.

By knowing the alternating stress and using standard fatigue curves, the maximum no. of cycles before fatigue failure can be calculated. This maximum no. of cycles that the backstop can sustain is basically the RUL.

III. CHECK VALVE TEST SETUP (CVTS) AND THE EXPERIMENTS PERFORMED

A check valve test setup was designed and erected so as to perform experiments on a swing type check valve. These experiments were to validate the methodologies that we proposed in the health monitoring strategies. The test setup consisted of a 4" stainless steel Swing Type Check Valve, a tank, a pump, isolating valves and associated piping (refer Figure 2). Process instruments that were installed in the loop include a flow metering orifice and a connected flow transmitter, pressure transmitters on the upstream and downstream of the valve. The transmitter signals were connected to a paperless recorder for data acquisition. A P and I diagram has been shown below.
In order to attenuate the vibrations that arise from other loop equipments, the nuts and bolts used for the flanged connection of the valve were fitted with neoprene washers (refer Figure 6). This was done so as to ensure that the vibration signals arising from the valve were born inside the valve itself.

The Check Valve disc was fitted with the ABTS (refer Figure 4). Also a standard vibration measuring instrument (OROS OR 24) was used to measure the vibrational frequencies that arise from the valve.

The experiments were planned such that different levels of degradation pertaining to each failure mode would be simulated in the valve and under varying conditions of flow, the vibration signatures and ABTS measurements would be measured.

A. Analysis of Backstop Failure

Vibration measurements were made with the valve in service and the pipelines full with water, but without any flow. The valve was actuated manually externally by using a tether attached to the disk.

This was done so as to ascertain the vibrational frequencies that the valve would produce when the backstop was impacting with the valve body. The vibration probes were connected to the inlet flange and the top cover as shown in the figure (Refer Figure 7). Continuous impacting or backstop tapping could eventually lead to backstop breakage and hence when detected early, this can be used to prevent backstop failure.
From amongst all the available peaks, two peaks were chosen for further analysis:
The FFT’s of the selected peaks are (Refer Figure 9):

The first spike that appears is of the vibration caused because of the valve opening and impacting of the backstop against the valve body. The middle portion shows the flow noise and when the pump is tripped, the flow noise reduces slowly, this shows the flow coast down and finally the valve closure is shown by the disc impacting against the seat. Similar experiments were repeated and similar waveforms were obtained. FFT’s of the respective zones on the waveform were taken, the resulting frequency spectrum are as shown in fig 11,12 and 13.
Fig 11: FFT of vibration measurement of ‘valve opening’. Top: Channel 1, Bottom: Channel 2.

Figure 12: FFT of vibration measurement of ‘flow noise’. Top: Channel 1, Bottom: Channel 2.
Figure 13: FFT of vibration measurement of ‘valve closure’. Top: Channel 1, Bottom: Channel 2.

After making all these measurements, coincident frequencies were identified. They have been summarized as follows.

Frequencies that are present during the pump operating cases and absent during the hand actuation cases show are basically due to flow induced noise. This flow associated noise occurs in the frequency range of 2063-2248Hz.

Frequencies that arise during the impaction of the backstop during manual actuation and process actuation lies in the range of 2360-2375 Hz. This information can be used as a means of detecting whether or not the backstop is impacting with the valve body. The ABTS signal can be used for detection of actual backstop breakage, as when the backstop breaks, the ABTS signal will show an increase in the opening angle.

B. Analysis of Hinge Pin Failure

Hinge Pin failure was simulated by fabricating undersized hinge pins. Three different hinge pins were used, the full size or healthy hinge pin with outer diameter of 10 mm, and two undersized hinge pins having outer diameters 9.09mm and 7.90 mm.

Each Hinge Pin was inserted in the hinge pin slot and mounted in the valve. The valve was then supplied with flow at three different flow rates and vibration measurements were made by mounting the vibration probe on the valve body as shown below:

Figure 15: FFTs of vibration signals obtained with 3 different sizes of hinge pin at 125 lpm flow (Top: 10.55 mm dia, Middle: 9.09 mm dia, Bottom: 7.90mm dia).
The detection of this third peak can hence be used exclusively for detecting the reduction in hinge pin diameter. The third peak has been observed to be falling in the ranges as shown in the table below:

<table>
<thead>
<tr>
<th>Hinge Pin Size</th>
<th>Third Peak Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.55 mm</td>
<td>4049-4078</td>
</tr>
<tr>
<td>9.09 mm</td>
<td>5084-5173</td>
</tr>
<tr>
<td>7.90 mm</td>
<td>5288-5768</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

Two failure modes, namely Hinge Pin failure and Backstop Failure of the Swing Type Check valve have been analyzed in detail and a strategy for the detection and RUL estimation have been formulated. Vibration measurement and analysis are seen to be a useful method for the detection of Hinge Pin Failure. The use of an accelerometer based tilt sensor has also been suggested for the purposes of model based RUL estimation for Hinge Pin failure. A vibration analysis based method was investigated for the purpose of backstop tapping detection. An accelerometer based tilt sensor has also been suggested for the purpose of detecting backstop failure and for use in the model based RUL estimation for the same failure mode.

REFERENCES