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Vibration Measurement of Ball Valve at Various Ball Throat Opening Conditions

#1Jaydeep L kale, #2A. R. Suryavanshi

[1]kale_jaydeep@rediffmail.com
[2]akash.suryavanshi@zealeducation.com

#1Mechanical Department, Dnyanganga College of Engineering & Research, SavitribaiPhule Pune University,
Survey No. 39, Narhe, Pune-41

#2Dnyanganga College of Engineering & Research,
Survey No. 39, Narhe, Pune-41, India

ABSTRACT

Ball valve is the device that regulates, directs or controls the flow of fluid by opening, closing or partially obstructing various passages. The valve parameters are depending upon valve type, flow controlling mechanism and trim. It predicts the beginning of cavitation, related damage and vibration problem for a particular valve trim style. When a severe noise and vibration occurs because of cavitation across the valve throat, the valve body and pipe wall are subjected to erosion and mechanical damage of valve components. It increases possibilities of valve leakage through its stem and trim. This experimental study includes design of test bench for vibration measurement, installation of sensors, and experimental analysis for ball valve at various ball throat opening conditions. It also includes data analysis of valve vibration parameter at ambient condition with water as a media. Experimental analysis of this work will helpful for valve designer as well as process piping designer. It will help to define the acceptable vibration limit of particular valve for maintenance and process auditors in the field of power plant, oil and gas industry, food industry, marine application and many more where valves are installed for flow controlling purpose but affliction from effect of vibration.

***Keywords*— Vibration measurement, Ball valve, Cavitation**

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I. Introduction

There are many locations within a piping system where excessive, sometimes violent pipe vibration can exist. Normally pipe lines are constructed underground, on the floor and over the head. Pipe lines are designed and sized as per its flow media, travel distance and mostly system operating parameters. Vibration induced in the pipe line is due to flow characteristics and properties of media such as flow velocity, pressure, temperature, density. Another cause of vibration is operating parameter of system such as differential pressure between upstream and downstream due to pressure drop. Piping system having pipe fittings, valve, strainer, elbow etc. are one of the causes of pipe vibration. The formation of steam bubbles, which collapse to cause cavitation damage or valve body vibration which is passed on the piping system. In some cases the downstream pressure conditions are such that the steam bubbles coalesce in the downstream piping. The problem of severe pipe vibration is generally associated with start-up/shutdown and emergency bypass systems. These systems are used intermittently and thus there is a higher tolerance for the design condition. It is required to validate every newly designed valve for vibration test to ensure the operating capability of component & valve assembly under vibrating condition. For specific operating condition detail vibration measurement and analysis is required to solve the leakage problem through valve trim. Experimental results will ensure the reliability of design or input for redesign of valve component and valve trim.

II. Literature Review

Lee, Park and Hur[1]had tried to reduce the vibration generated at discharge valve system in hermetic compressor for refrigerator. They used frequency measurement method for vibration measurement. They suggested tochange its thickness, because the resonance frequency is proportional to the cubic of the thickness.Ogawa[2]was clarified that the cavitation noise around a butterfly valve becomes larger when the upstream velocity distribution was different from the normal velocity distribution.Wang[3]studied vibration characteristics across duckbill valve and investigated that the vibration occurs mainly in the duckbill portion and was seen at the valve exit with largest amplitude.Pankhania1, Patel and Bhojawala[4]studied vibration analysis of a motor operated gate valve for nuclear application using finite element analysis and suggested design modification in the valve body dimension.Erdbrink, Krzhizhanovskaya, Sloot[5]conducted experiments and numerical modelling research on reducing cross-flow vibrations of underflow gates. The results show that the gate with perforated bottom profile significantly reduces cross-flow vibrations. Higher damping was appeared at high hydraulic heads.Andrew L. Lewis, Fred R. Szenasi, Daniel R. Roll[6] studied Control Valve induced Pipeline vibration in a paper pulp pumping system. The pulsation amplitude was dependent upon valve ball position and motion. It is concluded that piping system with control valve generated frequencies which excited quarter wave, standing waves. Injection of air or suitable gas into the pulp stream to lower the acoustic velocity reduced the amplitude of pulsation and their frequencies. Shan, Chao, Yulin, De, Yuejuan[7]conducted static experiment on theduel spool sleeve valve.Frequency dynamic sensor and its acquisition system were used to measure the vibration parameters, fluctuating pressure parameters at critical points of the valve. Moussou, Lafon, Potapov, Paulhiac, Tijssseling[8]has studied piping systems and valves can generate strong vibrations, transient pulses, cavitation effects and various types of flow instabilities. The described cases include water hammer, turbulence-induced vibrations, cavitation-induced vibrations, vortex shedding with acoustic lock-in, flow structure interaction and vortex shedding with lock-in, and a shallow cavity coupled to transverse acoustic modes. Miller[9]described theoretically about control valves as a source of pipe vibration at nuclear or fossil power plant pipelines which are usually handling water with fairly high pressure drop. Eilers[10]observed that the source or cause of the noise was most likely the valve trim components at refineries. A cage-guided valve design for high pressure control requirements was chosen for its more stable operating capability. Fagerlund[11]had tried to use of pipe wall vibrations to measure valve noise. Acoustic energy generated by fluid flow through a control valve propagates through the piping and creates a fluctuating pressure field which forces the pipe walls to vibrate.Rammohan,Saseendran, Kumaraswamy[12]Cavitation reduction is achieved by breaking the flow in the form of more than one liquid jet, thereby increasing the turbulence inside the valve flow path. Shouqi, Jun, Jianping, Yin,PEI Ji[13]show that at centrifugal pump the level of flow induced noise becomes smaller as the flow increment during low flow rate operations, and it is steadily close to the design point, then it increases with the growing of flow rate in high flow rate conditions. Hubballi,Sondur[14]had concludes that the techniques of prediction of cavitation can be classified into three main categories: (i) Empirical correlations with flow conditions, material properties or with electrochemical or noise measurements. (ii) Simulation techniques using special test devices to reproduce a given aggressiveness in an accelerated way (iii) Analytical methods.William,Rahmeyer, Miller, Sherikar[15]test results show the unique behaviour of flow path in its ability to minimize cavitation activity. Noise and vibration varied only slightly with size, valve trim, valve position and for flow direction. The pressure and size scale effects were found to be negligible for the valves with tortuous path. Grinis, Haslavsky,Tzadka[16]studied self-excited vibration in hydraulic ball check valve. They showed that the frequency of vibration of the ball is directly proportional to the angular velocity of its rotation. Author concluded that a criterion for rotational stability of the ball and described the main relationships that govern the rotation process. Stosiak[17]explained that pressure fluctuations cause the individual system components to vibrate. The complex problem of the transmission of vibrations can be divided into three interconnected categories, vibration sources, vibration transmission paths and its effects. The use of vibration insulator at valve housing can reduce vibration acceleration amplitude. Czop,Wszołek[18] found that the sensitivity analysis method provides major contributors and their magnitude that cause vibrations. The prototypes show frequently sensitivity to excite resonances and vibration interaction with other suspension components. Emerson Process Management of Fisher Controls International [19] sourcebook’s mentioned about cavitation and flashing of control valve. The major sources of control valve noise are mechanical vibration noise, aerodynamic noise, and hydrodynamic noise. The most prevalent source of noise resulting from mechanical vibration is the lateral movement of the valve plug relative to the guiding surfaces.Majorly the research on valve vibration has been done after the noise or vibration problem was detected in the industry. Researchers are trying to monitor the vibration in the piping system through vibration audit. Analytical and experimental research was done to calculate valve vibration for Control valve, Butterfly valve, Duckbill valve, Check valve, Dual spool sleeve valve, Hydraulic damper, Quench valve and pump also. But most of the researchers are not concentrated on Ball valve vibration. Now a day’s advanced metal seated, bubble tight ball valves are used for refinery as well as gas application. Hence it is important to study its vibration characteristics for various operating conditions and application. If we able to determine the valve vibration in design stage, then it will helpful for valve selection at particular application. It will also help to process designer for easy decision making about system structure design, piping layout design, piping or valve support requirement and location.

III. CAVITATION

Cavitation is a liquid phenomenon based on the formation and collapse of vapour cavities in the fluid passing through a valve or orifice. The vapour cavities begin to grow in low pressure regions such as areas of separation and collapse downstream of the low pressure regions. Cavitation can produce the effects of noise, vibration, and erosion or damage to a valve and downstream piping[2]. Cavitation (liquid-vapour-liquid) is a two-stage phenomenon which can greatly shorten the life of the valve trim. Certain amount of liquid passes through a restricted area such as an orifice or a valve port, the velocity of the fluid increases. As the velocity increases, the static pressure decreases. If this velocity continues to increase, the pressure at the orifice will decrease below the vapour pressure of the liquid and vapour bubbles will form in the liquid. This is the first stage of cavitation[9]. As the liquid moves downstream, the velocity decreases with a resultant increase in pressure. If the downstream pressure is maintained above the vapour pressure of the liquid, the voids or cavities will collapse or implode[12]. The second stage of cavitation is detrimental to valve. Because of the tremendous pressures created by these implosions (sometimes as high as 6894 bar), tiny shock waves are generated in the liquid. If these shock waves strike the solid portions of the valve they act as hammer blows on these surfaces. Repeated implosions on a minute surface will eventually cause fatigue of the metal surface and chip a portion of this surface off. Tests show that only those implosions close to the solid surfaces of a valve act on the valve in this manner. Modification of the valve throat geometry would improve the performance of valve with low flow resistance and pressure oscillation[14].The cavitation parameter is a dimensionless ratio of the pressure forces preventing cavitation to the pressure forces creating cavitation. The severity of cavitation in valves is generally expressed in termsthat describe physical observations of the phenomenon. Suchterms are incipient cavitation, constant cavitation, incipientdamage, and choking[15].Cavitation can arise in hydrodynamic flows when the pressure drops. This effect is, however, regarded to be a destructive phenomenon for the most part. In addition to pump rotors, control valves are particularly exposed to this problem since the static pressure at the vena contracta even at moderate operating conditions can reach levels sufficient for cavitation to start occurring in liquids.In the final phase of bubble implosion, high pressure peaks are generated inside the bubbles and in their immediate surroundings. These pressure peaks lead to mechanical vibrations, noise and material erosion of surfaces in walled areas.

IV. MATHEMATICAL MODELLING

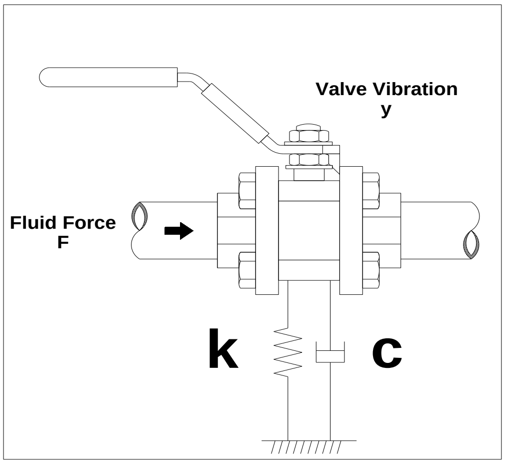

Fig. 1 Schematic of Valve Trim Vibration Model

For mathematical modelling it is shown that valve is fixed concentric with flow axis in the pipeline. Spring 'k' and damper 'c' is considered for measurement of valve trim vibration. Fluid is flowing through x direction while valve can vibrate through y direction which will be perpendicular to fluid flow axis. Valve is simply supported at both ends of valve. Hence it is obvious that self-weight of valve will act towards gravity. Fluid force is nothing but pressure of fluid flow passing through valve throat. Fluid pressure and valve throat opening angle are variables where weight of the valve is same and considered as constant for analytical calculations. Due to vibration valve deviate through its concentric position with fluid flow axis. It generated obstacle to flow. Fluid pressure and velocity hamper on ball and seat sealing. It also transfers shock to ball operating mechanism at trim. Stem is vertically perpendicular to flow axis and used to rotate ball by application of torque through lever, gear box or pneumatic actuator. Due to vibration stem is deviating its rotational axis. Hence it requires excessive torque for valve operating mechanism than predefined design torque. It also causes excessive wear at stem sealing within short span of time. It starts leaking of fluid through stem sealing. It is general tendency to replace damaged stem sealing frequently but not concentrated on exact cause of stem seal damages. From experimental analysis of fluid flow through a sphere, it is known that vortices form in the wake of the sphere and subsequently break away from it in a periodic process.The vortex shedding can produce self-excited oscillations of the ball. This oscillation is characterized by the frequency which depends on the flow conditions.Vibration Equation for Valve

$$m\ddot{y} + c\dot{y} + ky = \qquad (1)$$

Assuming that the distance between the ball and the valve seat surface is constant, we can regard this ball as a pendulum or rotor of length L and mass 'm'. The point of support of this ball is caused to vibrate with amplitude 'A' along the Y axis of the valve, as described in the following equation:Valve trim vibration

$$y = A \sin \qquad (2)$$

Fluid Force

$$F = F_o \sin(\omega t - \qquad (3)$$

$$= F_o . \cos\emptyset . \sin(\omega t) - F_o . \sin\emptyset . \cos(\omega t)$$

$$= \frac{F_O}{A}\cos\emptyset . y - \frac{F_O}{A\omega}\sin\emptyset . y$$

$$= -ky - c\dot{y}$$

Where,

$$K = -\frac{F_O}{A}\cos\emptyset$$

$$C = \frac{F_O}{A\omega}\sin\emptyset$$

Here c represents the damping present in all physical systems.Under steady state conditions, the ball will vibrate and also rotate around the central axis of the valve at an angular velocity, which is given by the following equation:

$$\omega = \frac{\mathrm{v}.\mathrm{R}_e}{2r(R+r)[\frac{\pi}{8}\left(1+\cos\frac{\pi}{4}\right)\frac{c_f}{c_v}+\frac{1}{6\sqrt{2}}\frac{c_p}{c_v}]}$$

Where v is kinematic viscosity of the water R_e represents Reynolds number and $c_f, c_p,$ are hydrodynamic friction coefficient.

V. Experimental Test Set Up

Experimental test set up for measurement of ball valve vibration is designed as shown following figure. Water is used as a test media at atmospheric temperature. Hence water reservoir is primary requirement of test set up. A booster pump is installed at reservoir to feed the pressurised fluid in the piping system. Pump is having pressure regulator arrangement to control or vary the inlet pressure during testing. Outlet of pump is connected with ball vale which will be used as a test valve for vibrations measurement. In between pump and test valve pressure gauge is mounted as a display device to indicate the upstream pressure. Acceleration sensor is mounted at valve stem. Sensor is connected with Frequency Response Function (FRF) instrument to measure and record the accelerations generated in valve under pressurised condition. One pressure gauge is mounted at downstream of test valve to display outlet pressure. Difference between the readings from two pressure gauges is a differential pressure across the test valve. Next to that one flow meter is installed to measure volumetric flow of fluid during various test conditions, parameters generated at teat valve. It will help to monitor performance of the valve under vibration condition. Outlet of the flow meter is connected to reservoir to reuse of water and to avoid the wastage of water after testing. Hence apparatus required for vibration measurement are listed as pump, pressure regulator, pressure gauge, ball valve, flow meter, FRF instrument, acceleration sensor and computer display.

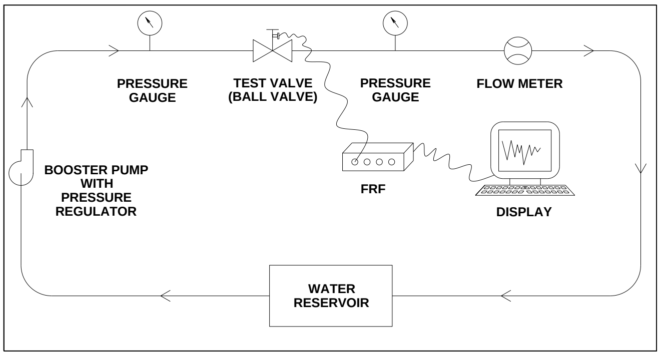

Fig. 2 Vibration Measurement Test Setup for Ball Valve

VI. Experimental Procedure

For experimental vibration measurement of valve we have input parameters such as pressure and temperature of fluid at inlet, mass of valve, percentage opening of ball throat, and rotational angle of ball. At outlet we have to record outlet pressure of fluid, acceleration induced at valve stem, volume of fluid at downstream of test valve. To obtain the first reading of acceleration we have pumped fluid to test valve with pressure P1 bar. Adjust the pressure regulator until the pressure P1 bar should display at upstream pressure gauge. Initial case ball valve should 100% open condition. Record the acceleration at FRF. Also record the pressure display at downstream pressure gauge and volume of flowing fluid through flow meter. For next measurement rotate the ball valve with lever and ensure ball throat should open only 66.6%. Keep pressure P1 bar remains same and record the pressure at downstream, volume of flow and FRF acceleration induced at valve stem. Repeat the same procedure by maintaining pressure P1 bar but reducing ball throat opening condition as 50%, 33.3% and 0%. Now increase the pumping fluid pressure through pressure regulator as P2 bar. Record the downstream pressure, volume of fluid flow and acceleration at FRF for varying ball throat opening conditions step wise from 100% to 0%. Repeat the procedure and record the output values for next pressure P3 bar.

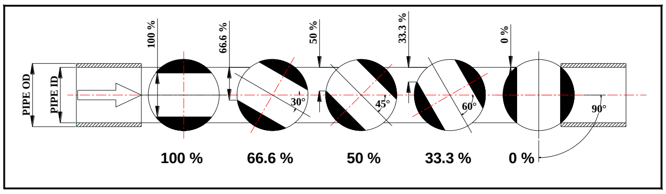

Fig. 3 Percentage Opening Conditionof Ball Throat

VII. Results and Discussion

Numerical investigation are conducted with DN80 (3”) size ball valve without support pipeline 1 meter length before and after the test valve, in order to clarify mechanism of valve trim vibrations caused by differential pressure across the ball throat for various opening conditions. Fluid force is calculated in terms of inlet pressure. At full opening condition of ball throat, valve vibration frequency is near about 100Hz and at 33.3% throat opening condition vibration frequency is 500Hz.

VIII. Conclusions

Results obtained for condition that pipe is without support;valve trim vibration shows that cavitation around the valve causes pressure fluctuations on the valve trim surface with random and impulsive wave forms. At full throat open condition of ball, the valve trim vibrates at near the natural frequency and the vibrations are excited around the operation condition where the pressure fluctuation becomes large. High valve trim vibrationsare obtained when the ball is rotated by 60^0 and throat opening is only 33.3%. The numerical result shows that vibration frequency is increasing gradually from full open throat condition to 33.3% ball throat open condition. It is achieved by ball throat opening by 30^0, 45^0, 60^0 and 90^0angleswith valve operating mechanism. Hence it is recommended to use of advanced metal seated, bubble tight ball valves for refinery as well as gas application. This study will help to process designer for easy decision making about system structure design, piping layout design, piping or valve support requirement and its location.

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