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FAULT DIAGNOSIS OF RECIPROCATING COMPRESSOR USING PRESSURE PULSATIONS

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ABSTRACT:

The major problems encountered in a reciprocating compressor are because of the valve failure .The other problem of leakage past the piston because of the worn out piston rings has also been placed in the reciprocating compressor. Pressure pulsations generated inside the piping of a reciprocating compressor may be taken as one of the tool for diagnosing the nature of fault inside the compressor. In this paper the common type of faults are simulated in the complete thermodynamics process of a healthy reciprocating compressor. The fault like discharge valves and leakage past piston rings have been considered for formulation. . The change in nature of pressure pulsation can be used for condition monitoring of reciprocating compressor.

1. INTRODUCTION

Pressure pulsations of considerable magnitude are present in a reciprocating compressor system. The discharge valves are subjected to most severe service, experiencing high heat and pressure. It is felt that the pressure pulsations might change with defects like the valve failures, the piston ring wear/failure etc and may be used as signatures for the condition monitoring of the compressor.

Preliminary some work has been done by Chlumsky V (1965) on the effect of compressor faults like leaking suction and discharge valves, leakage past piston rings, vibration of valve springs, delayed closing of discharge valve and excessive clearance volume on indicator diagram of the compressor then detailed studied have been carried out on allowable vibration level and maximum allowable pulsation level at compressor valves and the piping system as observed by Wilson et. al (1969) and Nimitz W.W.V.(1974,1982).Some experimental work on pressure pulsation in reciprocating compressor system by Yadav G.S. et. al (1985), on source pressure pulsation by Zhou W and Kim(1999) and on structure oriented pulsation by Li W.S. (2002) had also be done. Guidelines for allowable pressure pulsation level in reciprocating compressor for its smooth operation have been provided in API standard 618 (1974). With these guidelines, pressure pulsation monitoring look to be a promising method for conditioning monitoring and fault detection in a reciprocating compressor.

In the present work a simulation program is prepared for obtaining signature of pressure pulsation in time domain in case of compressor having a fault like defective discharge valve and piston rings, so that these signature can be used for condition monitoring purpose.

2. PRESSURE PULSATION EQUATION FOR HEALTHY COMPRESSOR

Fig. 1 shows the system comprising of the pipe and a reservoir connected to a compressor. The system is divided into three parts, compressor cylinder, pipe & reservoir. The flow through, compressor discharge valve and the pipe, have been analyzed individually. Fig. 2 shows the outline of the physical model of a single stage reciprocating compressor for which the mathematical equations for cylinder pressure and pressure pulsations in piping have been determined..

The magnitude of pressure pulsation generated inside the piping as shown in Fig No.3 in case of a healthy compressor is given by Tiwari A. (2004)

$$P_{d2x} = (\cosh\alpha x \cos kx + jSinh\alpha x Sinkx)\frac{P_{d1x}}{dt} - \frac{dm}{dt}\frac{a}{s^2}(Sinh\alpha x \cos kx + j\cosh\alpha x Sinkx) \qquad (1)$$

3. PRESSURE PULSATION FOR DEFECTIVE COMPRESSOR

The formulation for the thermodynamic processes & pressure pulsation in pipe in case of a healthy reciprocating compressor has been given in the previous section. In this section theoretical simulation of compressor defects like the leaking discharge and leakage past piston rings have been carried out. The parameters affected by these defects have been identified considering the earlier studies on the pressure pulsations in compressor piping. The faults have been simulated by varying the leakage percentage parameters and the trend of variation in nature of pressure pulsations is studied.

In case of leakages, because of the constant area of opening in the form of leaking area, the mass flow takes place across the cylinder via leaking valve or piston rings throughout the complete cycle. The differential equation for instantaneous pressure and the continuity equation had been derived by Manepatil S.(1996) for the cylinder control volume have therefore to be modified incorporating the mass flow rates across valve due to leakage.

3.1 EQUATION FOR LEAKING MASS FLOW

The faults like, leakage across discharge valves and leakage past piston rings have been simulated as the flow taking place across and orifice having area equal to leaking area. Also the flow through such an orifice has been considered one dimensional and incompressible as in the healthy condition. The mass flow rate of gas through the orifice area may be given by the following equation;

$$\frac{dm}{dt} = C_d . A_o \sqrt{\frac{2\rho \ \Delta P}{1-\beta^4}} \qquad (2)$$

Where β is the square root of the ratio of orifice area to the inlet area, i.e. $\sqrt{A_o / A_i}$, ρ is the density of fluid and ΔP denotes the pressure difference across the orifice. If X denotes the amount of leakage in terms of percentage of maximum area of flow through a healthy valve then the leaking area across the valve plate is expressed as

$A_0 = \pi Db \ ymax \ X/100$

Where the term π.Db.ymax is the area of flow if the valve would have been fully open for healthy condition. For a given leakage 'X', the terms ymax.X/100 can be replaced by 'ye' and called as the "equivalent valve lift" by which the valve is assumed to remain open throughout the cycle resulting in the area of orifice equal to the leaking area. Thus,

$A_0 = \pi \ Db \ ye$

The inlet area A_i to be used for β, in equation (2) shall depend on the direction of flow of leaking mass. In case of different types of leakages the appropriate valves of A_0 and A_i have to be used in the mass flow rate equations for determining the leaking mass flow rates depending on the nature of leakages. The different relations for A_0 and A_i which have been used in case of different leakages are discussed below.

(i) LEAKING DISCHARGE VALVE

As mentioned earlier the mass flow rate through a leaking valve shall depend upon the leaking area and the pressure difference across the valve. The leaking area remains constant (Ao_{min}), as long as the discharge valve is closed or the valve lift is less than the equivalent valve lift, i.e. when the calculated valve lift

$y_s(t) \le ye_d$.

In the case of leaking discharge valve, the leaking area of valve can be expressed as

$A_0 = \pi Db_d \ ymax_d \ X_d/100$

$\quad = \pi \ Db_d \ ye_d$, If $y_d(t) \le ye_d$

and

$A_0 = \pi \ Db_d \ y_d(t)$, If $y_d(t) > ye_d$ (3)

where, Db_d is equivalent diameter of discharge valve, $ymax_d$ is maximum discharge valve lift; X_d being percentag leak of discharge valve and y_{ed} is equivalent valve lift. , the inlet area A, from which the flow enters into the orifice of area A_0 shall be given by

$A_i = \pi\, Dc^2/4$ if $P(t)>P_d$

$A_i = \pi\, Dp_d^2/4$ if $P(t)<P_d$

where, Dp_d is discharge plenum diameter and D_c is cylinder diameter.

(ii) LEAKAGE PAST PISTON RINGS

An ideal piston ring should be a perfect seal for the compressed gas and the ring itself should not allow any leakage past it. However in practical applications, the cylinder gas may leak through the f possible paths.

In practice, the gas flow conditions through the piston seal are constantly changing since the conditions for the formation of the oil wedge between the seal's contacting surfaces and the cylinder's mirror surfaces are changing. If we consider that the major amount of leakage occurs when the pressure drop across the seal rises and the oil wedge is more likely to break away to form a gap between the ring and the cylinder, the area of leakage may be expressed as

$$A_o = \frac{\pi}{4}(D_c^2 - D_p^2).\frac{X_p}{100} \tag{4}$$

where D_P is the diameter of piston skirt and Xp is the percent leak in piston rings. The inlet area A_i is given by

$A_i = \pi D_c^2/4$

The values of A_0 and A_i as discussed have to be used in continuity equation according to appropriate leaking conditions for determining the corresponding mass flow rate in the case of faulty compressor. These values of leaking mass flow rates shall be used with proper sings indicating the mass influx or mass afflux in the continuity equation as given below -

$$\frac{dm}{dt} = \left(\frac{dm_s}{dt} + \frac{dm_p}{dt}\right) - \frac{dm_d}{dt} \tag{5}$$

3.2 EQUATION OF FOR PRESSURE PULSATION FOR DEFECTIVE COMPRESSOR

The pressure pulsating equation at any arbitrary length (1) as derived in healthy compressor condition shall be modified due to continuous leaking mass flow across the cylinder. The leaking area has been added in the mass flow terms. The Pressure pulsation equation in case of defective compressor is given by:

$$P_{d2x} = (\cosh\alpha\, x \cos kx + J \sinh \alpha x \sin kx)\frac{dP'_{d1}}{dt} - \frac{dm}{dt}\frac{a}{S^2}(\sinh\alpha\, x\cos kx + j\cosh\alpha\, x\sin kx) \tag{6}$$

where $\dfrac{dP'_{d1}}{dt}$ is the rate of change of pressure inside the cylinder incase of defective compressor which is given by

$$\frac{dP'_{d1}}{dt} = -P_{d1}\left[\frac{dV}{dt}\left(\frac{1}{V} + \frac{R}{VC_v}\right) + \frac{hA}{mc_v}\right] + \frac{hAT_wR}{VC_v} + y\frac{R}{V}\left[Ts\left(\frac{dm_s}{dt} + \frac{dm_p}{dt}\right) - T_d\frac{dm_d}{dt}\right]$$

Where dm_p/dt indicated rate of mass flow through leaking piston. For a given leakage, the area of orifice for flow is known and the rate of mass flow is a function of pressure in compressor cylinder and piping only. Thus the continuity equation (5) and pressure pulsation equation (6) are solved simultaneously to get the pressure pulsations in case of defective compressor.

4. COMPUTER SIMULATION FOR PRESSURE PULSATIONS OF DEFECTIVE COMPRESSOR

Now in this section computer program has been developed for defective compressor. The defects like leaking discharge valve & leaking past piston rings are incorporated in the healthy condition of a compressor. The mass flow rates through discharge valves and piston ring including the effect of leakage is calculated.

4.1 Leaking discharge valve:

In this section the simulation for leaking discharge valve condition has been carried out and it's effect on pressure pulsations has been studied. It is assumed that there is no leakage in suction valve & piston rings. The simulation process starts with the leakage percentage of 1% then it is increases in the steps of 1% which goes up to 4%. The pressure pulsation-time diagram have been shown from Fig No. 4 for different percentage of leaking discharge valve.

It has been observed that with the increase in percentage leakage the magnitude of pulsating pressure (peak to peak) have been increases. This is because as the percentage leak increases excess compressed air passes through discharge valve and it increases the pressure inside the pipe. Due to this the pressure difference between reservoir and pipe increases which causes increase in magnitude of pulsating pressure (peak to peak).

Computed value of pressure pulsation (peak to peak) due to leaking discharge valve have been shown in Table No. 2

4.2 Leaking piston rings:

The behavior of pressure pulsation for a reciprocating compressor with the leaking piston rings, has been carried out in this section. The parameter Xp is assigned different value for simulating the effect of increasing leakage past piston rings, keeping other leakages to be zero. The leak percentage varies from 1% to 4% in the steps of 1%. The pressure pulsation time diagram have been shown in Fig. No. 5 for different percentage of leaking piston rings. It has been observed that with the increase in percentage leakage in the piston ring the magnitude of pulsating pressure (peak to peak) have been decreases. This is because during expansion process the cylinder air leaks out from leaking piston rings reducing the cylinder pressure. Also during the discharge process, the high pressure air inside the cylinder leaks out from the leaking piston ring area thus reduces the pressure inside the cylinder. Thus the pressure difference, which is the factor responsible for pressure pulsation, reduces, due to which the magnitude of pulsating pressure reduces.

The predicted values of magnitude of pressure pulsation (peak to peak) due to leaking piston rings have been shown in Table No. 3

5. CONCLUSIONS

Condition monitoring is one of the methods by which we can diagnose the condition of a machine by monitoring the machine performance along with other operating parameters. A pre-indication of impending faults can be obtained by monitoring the machine condition using some specific parameters. Here it is essential to have sufficient knowledge of the effect of compressor faults on the monitoring parameters which is a matter of investigations, so that the particular fault can be diagnosed. One of the economical solutions to this problem is to develop a mathematical model of the process of a compressor and simulate the different types of the faults associated with the machine, and by solving the mathematical equations, the faults of the machine can be diagnosed. In the present study by performing simulation studies of fault on the nature of pressure pulsations, the following conclusion were occurred.

(i) With the leaking piston rings, the nature of pulsating pressure or the magnitude of pulsating pressure (peak to peak) goes on decreasing with the increase in leaking percentage. The decrease in nature is more steady in piston rings leak .

(ii) With the leaking discharge valve the nature of pulsating pressure follow different nature as compared to leaking piston ring. The magnitude of pulsating pressure (peak to peak) increases with the increase in leaking percentage.

(iii) The simulation model results may influenced by the value of the input parameters like length of pipe, diameter of pipe, damping factor of pipe a velocity of sound in the gas and RPM of compressor etc.

(iv) Use of present simulation model shows that pressure pulsations monitoring may be used as an indication for condition monitoring and fault diagnosis of a reciprocating compressor. The model could also be used for carrying out parametric study, which could be helpful in choosing optimum parameters in compressor design

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NOMENCLATURE

a	Velocity of sound in gas.[m/sec]
Cd	Valve discharge coefficient
C_p	Specific heat of air at constant pressure [KJ/Kg K]
C_v	Specific heat of air at constant volume [KJ/Kg K]
D	Diameter of cylinder [m]
d	Diameter of pipe [m]
e	Internal energy of the system [J]
e_f	Enthalpy of flow of the system [J/Kg]
g	Acceleration due to gravity. [m/sec^2]
h	Instantaneous heat tranfer coefficient [W/m K]
L	Stroke length [m]
l	Length of Pipe [m]
m	Mass of air inside cylinder [Kg]
Pd_1	Cylinder air pressure [N/m^2}
P_d	Discharge pressure or reservoir pressure [N/m^2]
Ps	Suction pressure or ambient air pressure [N/m^2]
P*	Pressure pulsation [N/m^2]
Pd_2	Amplitude of Pressure pulsation in piping [N/m^2]
ΔP	Pressure difference across the orifice [N/m^2]
R	Specific gas constant [J/KgK]
S	Cross sectional area of pipe [m^2]
t	Time [sec]
T	Temperature of air inside cylinder [K]
t_d	Time when discharge valve is about to open [Sec]
T_d	Discharge temperature [K]
t_s	Time when suction valve is about to open [Sec]
T_s	Air temperature at suction plenum chamber [K]

V	Volume of cylinder air [m^3]
v^*	Pulsating Volumetric Velocity [m/sec]
v	Amplitude of pulsating volumetric velocity [m/sec]
X	Percent leakage
x_p	Piston displacement [m]
x	Arbitrary length of pipe [m]
y	Valve lift [m]
ye	Equivalent valve lift [m]
ymax	Maximum valve lift [m]
y_{st}	Static deflection of valve spring [m]
$\frac{dm_s}{dt}, \frac{dm_d}{dt}$	Mass flow rate through suction and discharge valves [N/sec]
$\frac{dm}{dt}$	Net mass flow rate inside the cylinder [N/sec]
$\frac{dQ}{dt}$	Heat transfer rate [J/sec]

SUFFIX

c	cylinder
d	discharge
e	equivalent
f	flow
w	cylinder wall
s	suction
i	inlet
o	orifice
p	Piston

GREEK SYMBOL

ω	Circular frequency [rad/sec]
α	Damping factor of pipe [per mtr]
μ	Absolute viscosity of air [N-Sec/m^2]
ρ	Density of air inside the cylinder [N/m^3]
ω_c	Angular velocity of crank [rad/sec]
ω_g	Swirl velocity of air inside the cylinder [rad/sec]
ξ_d	Viscous damping factor for valve springs
ξ	Eddy viscosity [N-Sec/m^2]

Table 1
Compressor cylinders, valves, piping and other system paramete value used as input for computer simulation program.

Compressor cylinder Piping and other system parameters			Values
Compressor speed,	[RPM]	rpm	750
Cylinder bore	[D_c]	m	.127
Connecting rod length/Crank radius,	l_c/r		20/5.0
Cylinder clearance	[clr]		1.4
Suction plenum chamber diameter,	[Dp_s]	m	.09
Discharge plenum chamber diameter	[Dp_d]	m	.098
Piston head diameter	[D_p]	m	.12
Density of air at NTP	[ρ]	N/m^3	10.177
Ratio of specific beats, C_p and C_v for air	[γ]		1.4
Universal gas constant (air)	[R]	J/kg K	287.1387
Specific heat at constant volume,	[C_v]	kJ/kg K	1.6747
Ambient air pressure	[P_s]	N/m^2	101000
Reservoir pressure	[P_d]	N/m^2	444000
Ambient air temperature	[T_s]	K	312
Wall temperature	[T_w]	K	373
Stroke length	L	m	.10
Length of pipe	l	m	3
Diameter of pipe	d	m	.04
Density of air at 444000 N/m^2	ρ	N/m^2	35.8

Velocity of sound in air	a	m/sec	412
Pipe damping factor	α	per meter	.000012
Time for one complete Cycle of compressor	t	sec.	.08
Specific volume of air at suction pressure	v_s	m^3/kg	.858369

Table 2

Computed result of Pressure pulsations (Peak to Peak) for different leaking discharge valve condition

Leak %	Pressure pulsation (peak to peak) $x10^5$ N/m^2
1	.626
2.0	.648
3.0	.706
4.0	.727

Table 3

Computed result of Pressure pulsations (Peak to Peak) for different leaking piston rings

Leak %	Pressure pulsation (peak to peak) $x10^5$ N/m^2
1	.837
2.0	.787
3.0	.750
4.0	.713

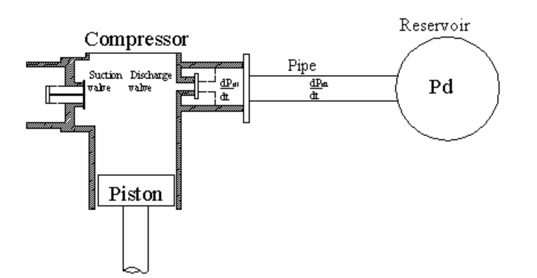

Fig No.1 Schematic diagram of a typical reciprocating compressor, piping and reservoir system

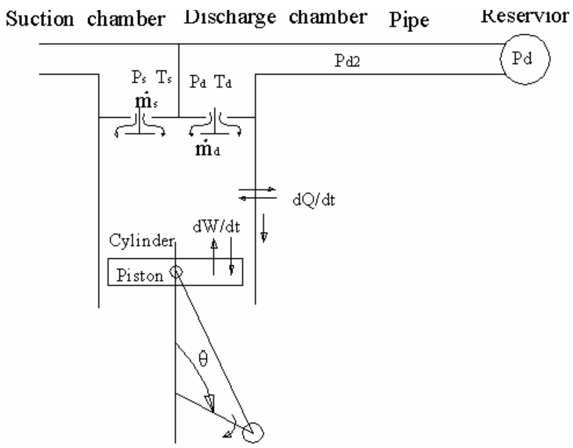

Fig No.2 Physical model of the single stage reciprocating compressor

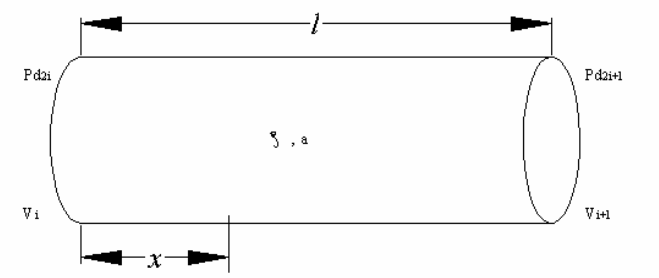

Fig No.3 Pipe of compressor

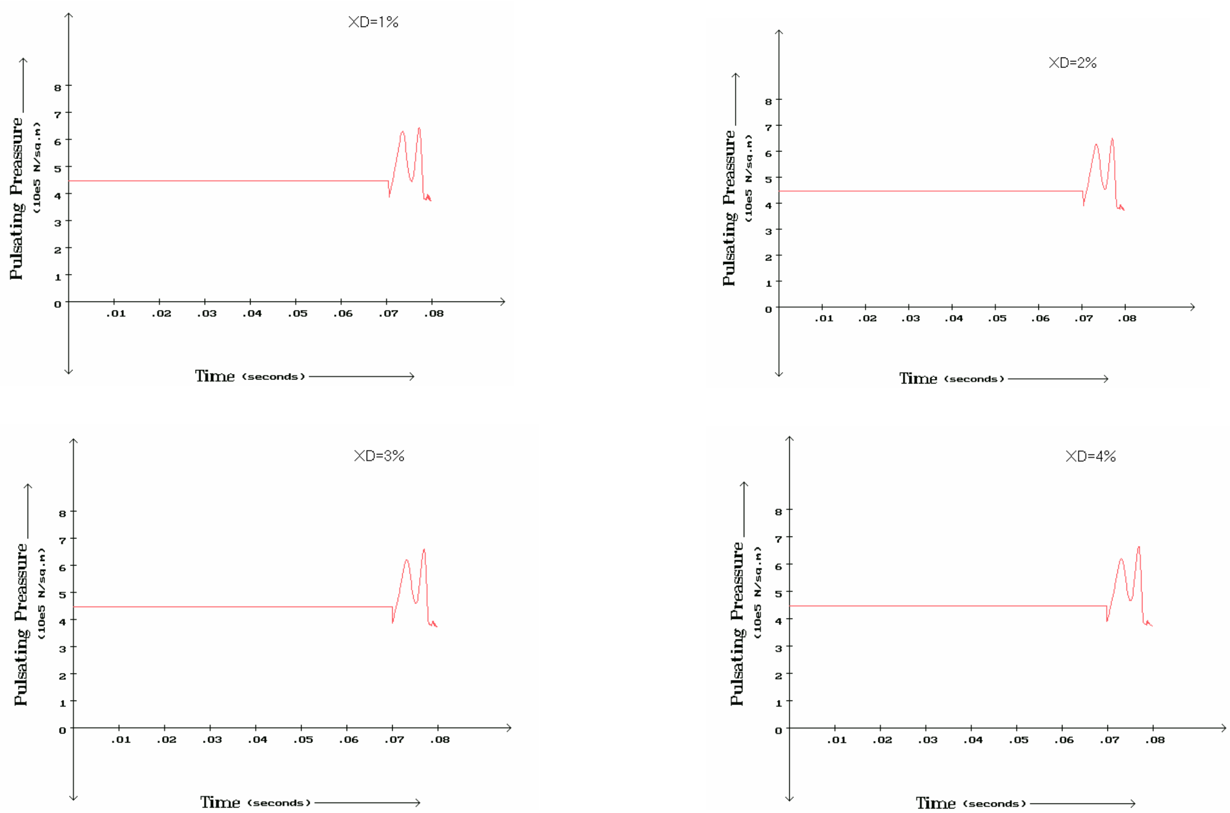

Fig No.4 Pressure pulsation time diagram for different values of leaking discharge valve

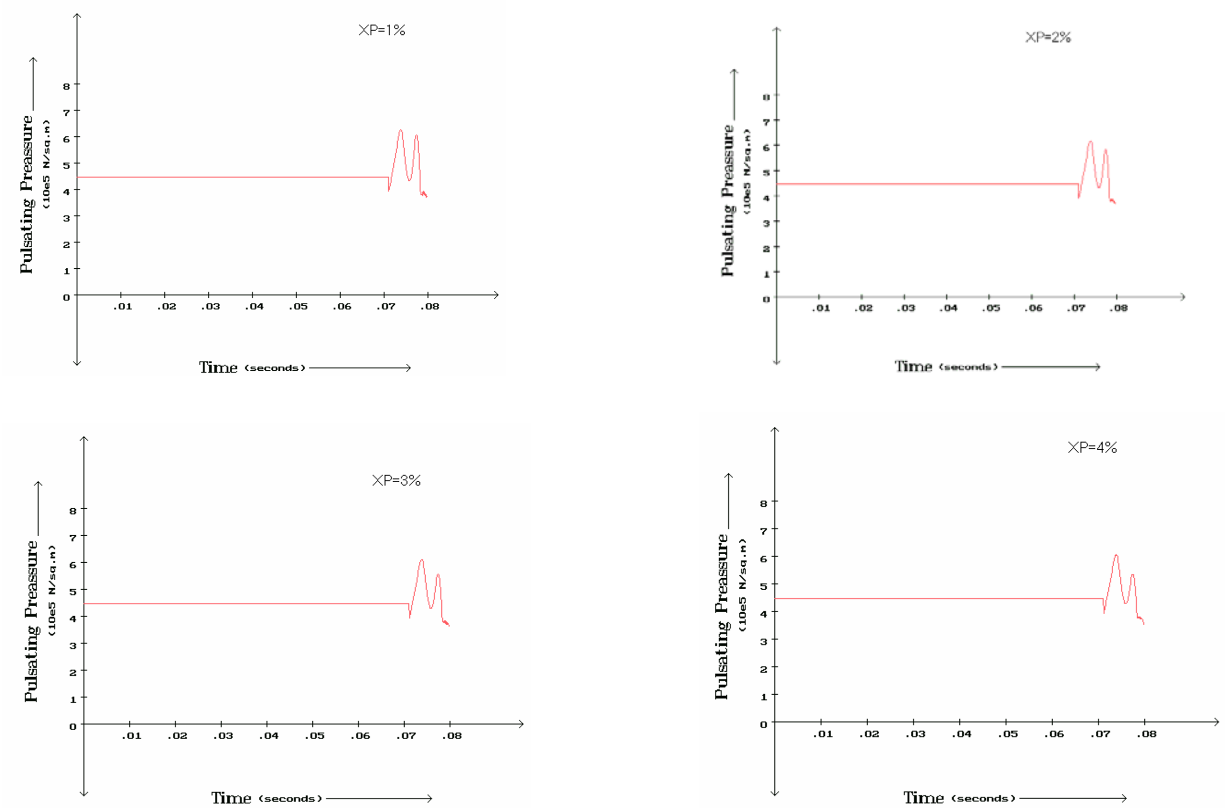

Fig No.5 Pressure pulsation time diagram for different values of leaking piston ring