A Combined Practical Approach to Condition Monitoring of Industrial Machines Using Different Techniques

Mohamed Elhaj[1] Mohamed Rgeai[2], Meftah Elmrabet[3], Salem Alhashmi[4]
[1,2,4] Dept. of Mechanical and Industrial Engineering- Tripoli University
[3] Dept. of Electronic Engineering- Zawia University

Abstract:

A comparison and evaluation of the different condition monitoring (CM) techniques was applied experimentally on industrial machines (reciprocating compressor) e.g. Dynamic cylinder pressure and crankshaft Instantaneous Angular Speed (IAS), for the detection and diagnosis of valve faults in a two-stage reciprocating compressor (RC). Valve Spring Deterioration was introduced experimentally into a two-stage RC. The effect of the faults on compressor performance was monitored and the differences with the normal, healthy performance noted as a fault signature *been used. The paper concludes with what is considered to be a unique approach to condition monitoring. First, each of the two most useful techniques is used to produce a Truth Table which details the circumstances in which each method can be used to detect and diagnose a fault. The two Truth Tables are then combined into a single Decision Table to provide a unique and reliable method of detection and diagnosis of each of the individual faults introduced into the RC. This gives accurate diagnosis of RC faults.*

***Keywords** - Condition Monitoring, Dynamic Pressure, Instantaneous Angular Speed, Reciprocating Compressor.*

1.0 . Introduction:

Reciprocating compressors are one of the most popular machines in use in industry. The timely detection of faults; which may influence the performance, is expected to help in both reducing maintenance costs and increasing the plant efficiency.

Compressor valves can be the largest single cause of unscheduled RC shutdowns. The aim of this research is to develop more accurate and sensitive fault detection and diagnosis tools that can be used with two-stage RC. The paper uses; in order to compare them, CM techniques (dynamic cylinder pressure and IAS) for the study of predictive maintenance of a RC. It also introduces the measurement of IAS in order to assess its suitability for CM and predictive maintenance.

Mohamed Rgeai [1] has developed a procedure for the detection of mechanical faults in industrial machines using different techniques, Steven M.Schultheis [2] has developed different techniques for Reciprocating compressor Condition Monitoring.

Gu and Ball [3] have studied automating the diagnosis of valve faults in RC. In 1984 Imaichi [4] studied vibration sources in RC and how to minimize vibration generation. Daniel [5] focused his attention on vibration and dynamic pressure methods, including the P-V diagram, for fault diagnosis and condition monitoring of RC. Elhaj [6] developed a new method for monitoring and diagnosis of valve faults in RC by using time domain and frequency domain. Ishll [7] studied the vibration of a RC compressor. These have been developed into a CM system for investigating the condition of valves in RC using conventional vibration analysis of the valve impact signature combined with the timing of events such as valve closure and opening times.

More recently, Liu [8] used neural networks and fuzzy logic to process IAS signals from diesel engines for the purpose of CM. Sweeney [9] has used IAS to analyse gearbox transmission errors. Ben-Sasi[10] used the variation in IAS for the monitoring of electric motors. Liang [11] demonstrated the capability of IAS from a transient motor to detect faults in the asymmetric power supply and the rotor bar.

The other aim of this study to investigate and compare the practical use of two different CM techniques; dynamic cylinder pressure and IAS, using both conventional transducers for machine monitoring and less well established types. The ultimate aim is to produce a 'Decision Table' which will allow; from the CM signals, the unique identification of any one of the given valve faults.

2.0 . Experimental Set-up:

A RC was adopted for the experimental study. In order to perform the experimental study, an optical encoder, pressure transducers, and other necessary instrumentation was attached to the compressor as shown in Fig1. The pressure transducers were installed on the heads of the first and second stage cylinders by drilling a small hole in the cylinder head, where the pressure sensor was installed. The optical encoder was mounted to the end of crankshaft on the flywheel at the compressor crankshaft side. A marker was used to give a trigger on every complete revolution of the flywheel. The data acquisition software is an updated Windows based interface, able to perform online data sampling and monitor compressor parameters such as IAS and dynamic pressure.

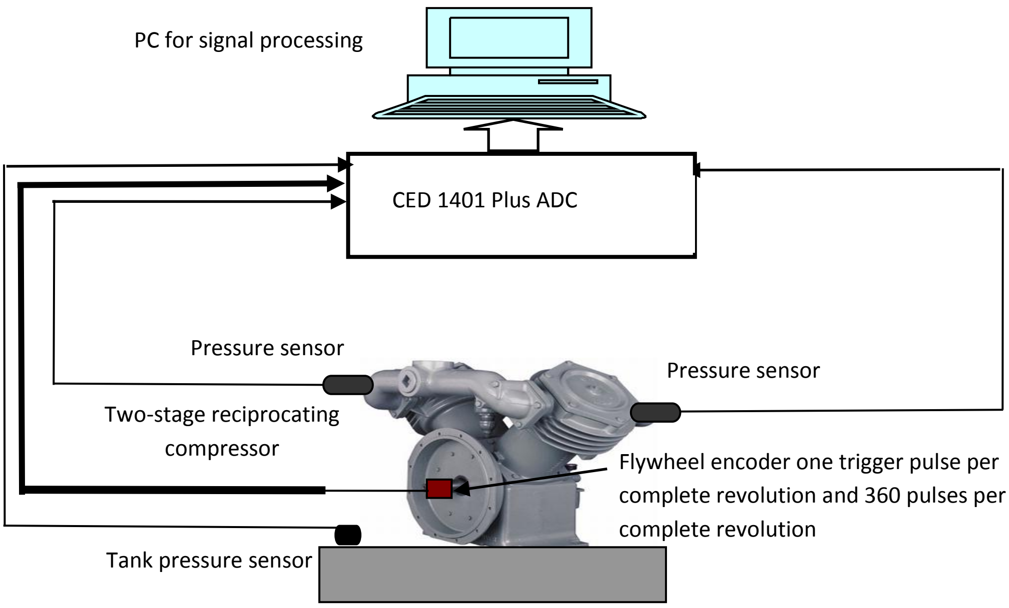

Figure 1- Schematic diagram of reciprocating compressor test system.

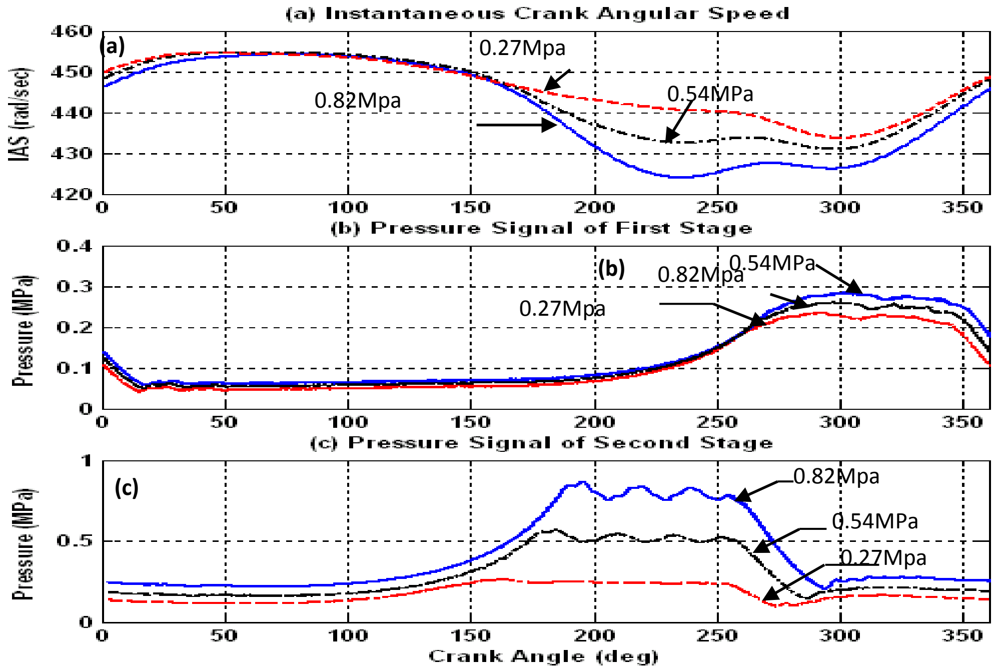

Figure 2 – Measured results; (a) IAS with different discharge pressures, (b) low pressure cylinder waveform, and (c) high pressure cylinder waveform.

Fig 2a, shows the measured of IAS over a compressor cycle for three values of the discharge pressure, 0.27MPa, 0.54MPa, and 0.82 MPa. The measured of the IAS was fluctuated over the cycle and varied with discharge pressure. Variation of IAS with variation of discharge pressure was encountered; variation was minor, 453 to 455 rpm. For 0.82 MPa the minimum IAS was 423 rpm, for 0.54 MPa - 428 rpm, and 0.27MPa - 434 rpm.

3.0 . Time Domain Analysis of Weakened Suction Valve Springs in Both 1st and 2nd Stages:

Spring wear is simulated in the compressor by artificially reducing spring stiffness. In the case of a weak suction valve spring, the valve will open at a cylinder pressure which is higher than for normal, healthy conditions and close later due to reduction of the spring stiffness. The reduction in the spring stiffness will lead to an increase in impact when the suction valve opens and closes, and to a change in valve opening and closing times. In a similar manner; in the case of a weak discharge valve spring, discharge occurs at a lower cylinder pressure than normal. Again this leads to increase in valve impacts and changes in valve opening and closing times.

3.1. Weakened 1st stage suction valves springs:

The measured effects of weakening 1st stage the suction valve spring are shown in Fig 3. The measured values of a weakened suction valve spring causes only minor deviations of the IAS from its baseline. Between crank angles of about 40^o to about 150^o there is a slight increase in IAS due to the weak suction valve spring allowing the valve to open earlier and allow the process gas to ingress earlier.

Also at about 250^o to about 350^o there is a decrease of the IAS as a result of higher pressure in the 1st stage, as seen in Fig 3b.

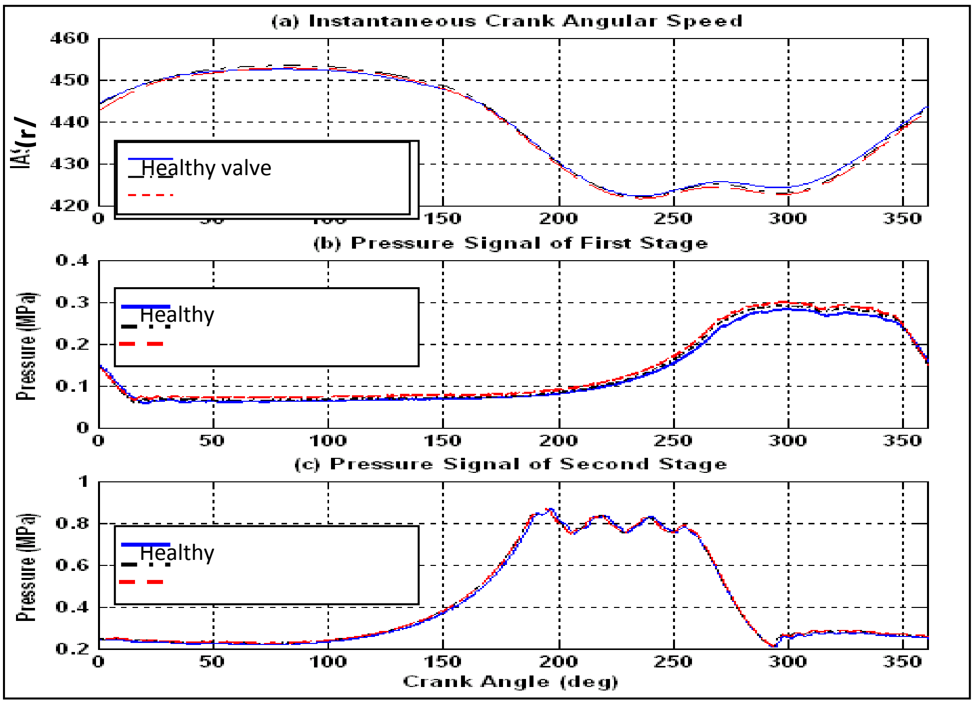

Figure 3 – Measured crankshaft IAS as a function of weakened 1st stage suction valve spring; a) IAS waveform, b) cylinder pressure of 1st stage, and c) cylinder pressure signal of 2nd stage.

3.2. Weakened 2nd stage suction valves springs:

The measured effects of weakening the 2nd stage the suction valve spring are shown in Fig 3.1. The measured values show that a weakened suction valve spring causes deviations of the IAS from its baseline. The shift in the peak value of IAS (453rpm) occurs at around 50°. The weakened 2nd stage suction valve spring causes the 2nd stage suction valve to open early as seen in Fig 3.1c, allowing more air into the cylinder and causing a higher than normal pressure which results in a reduction of the IAS during the 2nd stage compression, from about 160° to about 330°. The high pressure in the 1st stage causes a shift upward in the IAS in the second peak at 428 rpm at 20° to about 120° as seen in Fig 3.1a.

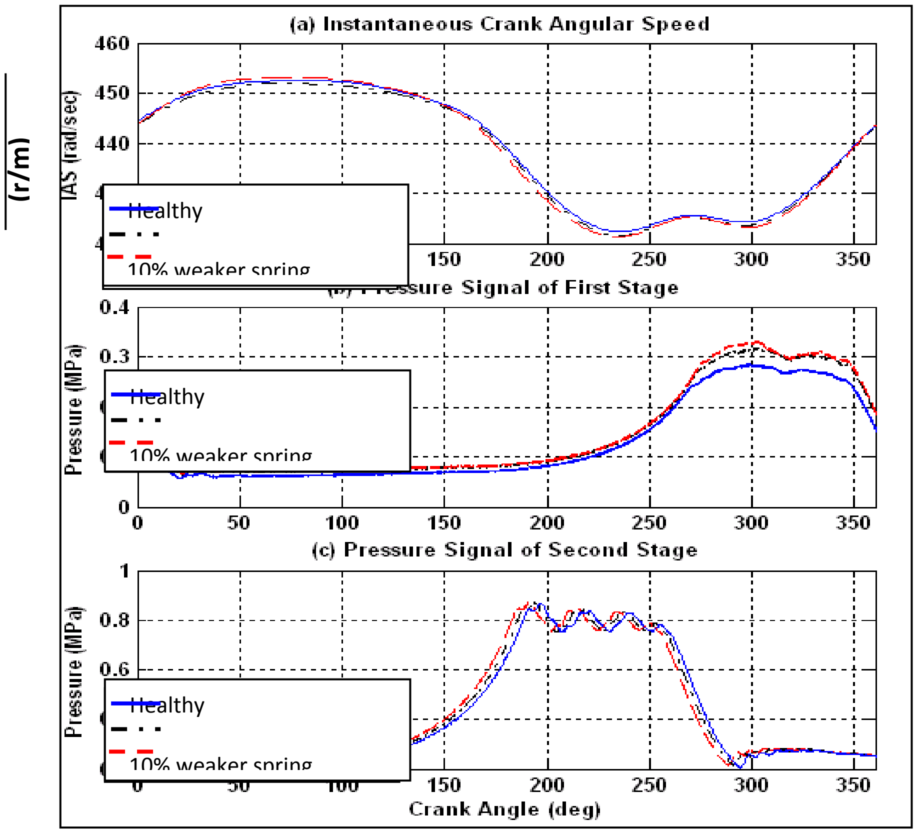

Figure 3.1 – Measured crankshaft IAS as a function of weakened 2nd stage suction valve spring; a) IAS waveform, b) cylinder pressure of 1st stage, and c) cylinder pressure signal of 2nd stage.

4.0. Time Domain Analysis of Weakened Discharge Valve Springs in Both 1st and 2nd Stages:

4.1. Weakened 1st Stage Discharge Valve Springs :

Fig 4a, shows that weakened 1st stage discharge valve springs cause little deviation of the IAS signal from its baseline.

During the suction time there is a shift upward between 30° - 130°, and a slight change between 300° to about 350°,which is the result of low clearance pressure in the cylinder; which causes the suction valve to open earlier as seen in Fig 4b.

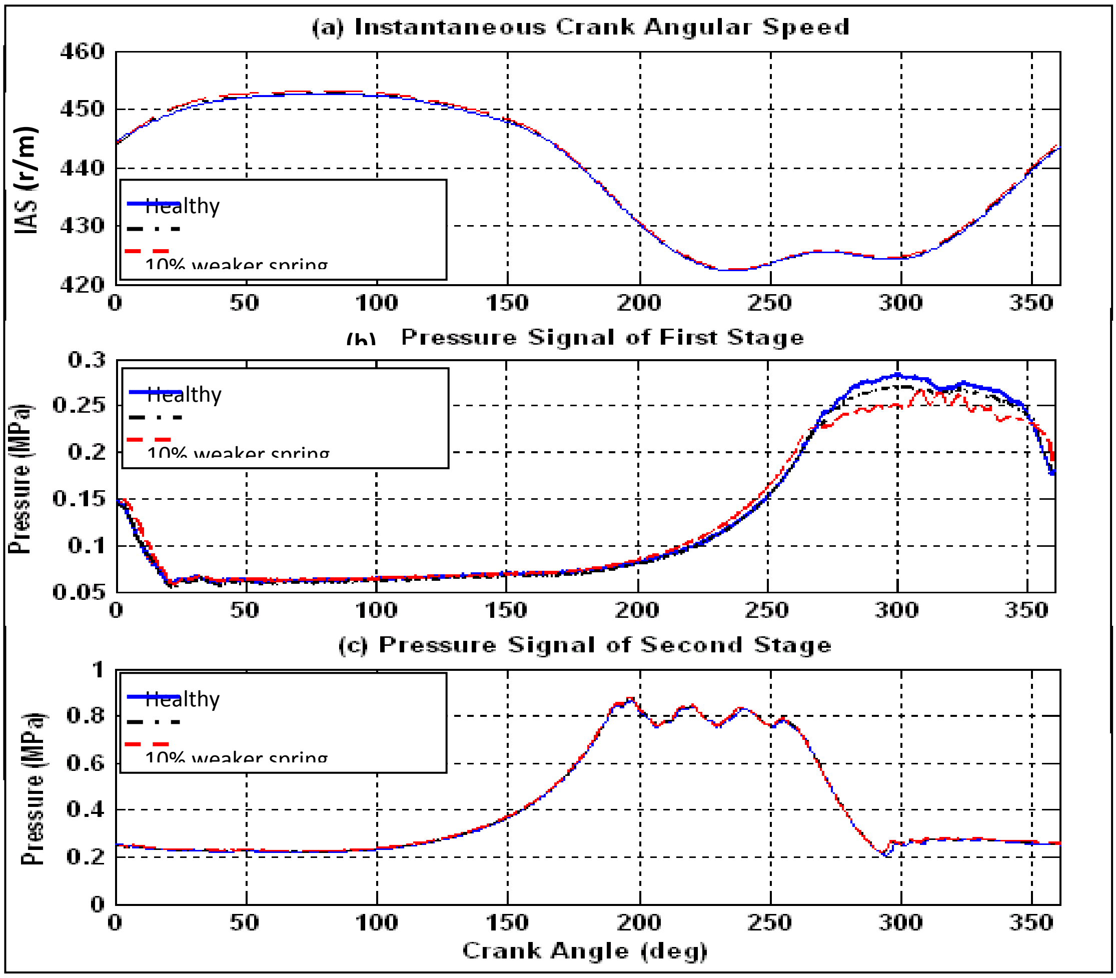

Figure 4 – Measured crankshaft IAS as a function of weakened 1st stage discharge valve spring; a) IAS waveform, b) cylinder pressure of 1st stage, and c) cylinder pressure signal of 2nd stage.

4.2. Weakened 2nd stage discharge valve springs:

The effects of weakening the 2nd stage discharge valve spring shown in Fig 4.1, shows that a weakened discharge valve spring causes significant deviations of the measured IAS from its baseline.

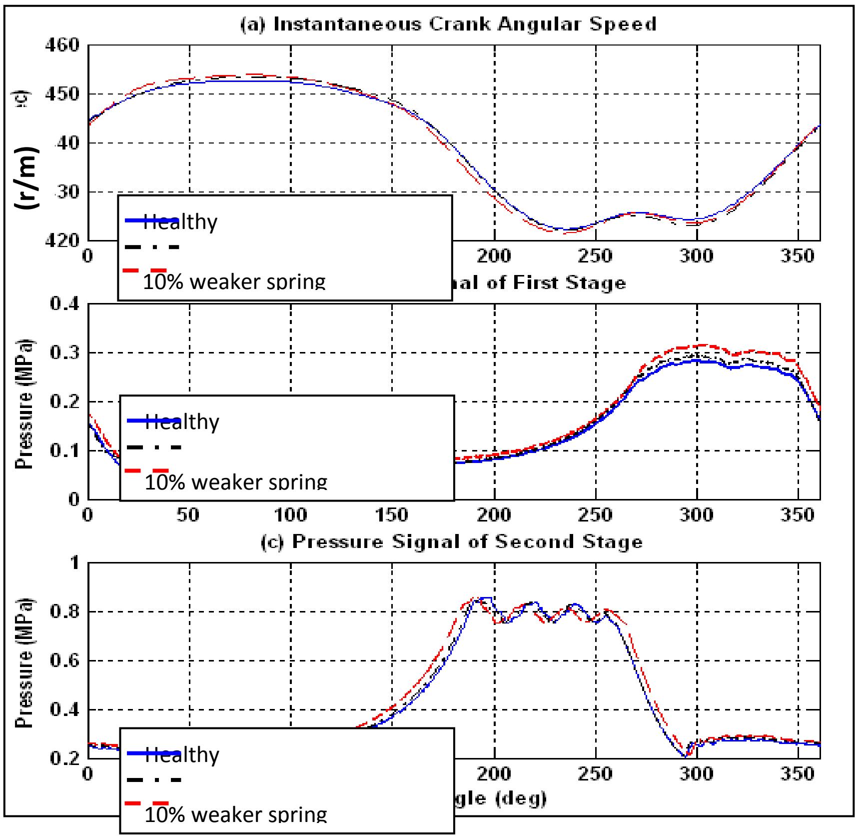

Figure **4.1 –** Measured crankshaft IAS as a function of weakened 2nd stage discharge valve spring; a) IAS waveform, b) cylinder pressure of 1st stage ,and c) cylinder pressure signal of 2nd stage.

Between crank angles of about 20° to about 150° there is an increase in IAS due to higher pressure in the 2nd stage cylinder during its compression stroke. Between crank angles of about 170° to about 340°

there is a decrease in IAS due to higher pressure in the 1st stage cylinder during its compression stroke this is due to late opening of the 2nd stage suction valve and subsequent rise in the pressure at the 1st stage discharge valve, causing it to open later; raising the cylinder pressure of 1st stage as shows in Fig 4.1b.

5.0. Dynamic Pressure Analysis:

Table 1. and 1.1, shows the Truth Table for the dynamic cylinder pressure signal for the four common valve faults. Here a time domain analysis only was performed, and information about the valve fault is contained in the amplitude of the pressure signal and its time of occurrence

Signatures / Faults	1st stage Suction valve				1st stage Discharge valve				1st stage CP		2nd stage Suction valve				2nd stage Discharge valve				2nd stage CP	
	Valve open		*Valve close*		*Valve open*		*Valve lose*				*Valve open*		*Valve close*		*Valve open*		*Valve lose*			
	-	+	-	+	-	+	-	+	L	H	-	+	-	+	-	+	-	+	L	H
1st stage weak spring SV	♦				♦					♦					♦					
2nd stage weak spring SV		♦				♦		♦		♦	♦				♦		♦			
1st stage weak spring DV		♦			♦				♦											
2nd stage weak spring DV		♦				♦		♦		♦		♦			♦			♦	♦	

within the cycle.

Table 1- Dynamic pressure truth table for valve faults in reciprocating compressor.

From the Truth Table 1, a number of identification markers for the different valve faults can be seen. For example, lower than normal 1st stage pressure combined with a 1st stage discharge valve that opens early is a strong indication of a weak 1st stage discharge spring. The same fault may also exhibit a lower than normal 1st stage cylinder pressure with a 2nd stage discharge valve that opened late.

1st stage CP	Cylinder Pressure of 1st stage
2nd stage CP	Cylinder Pressure of 2nd stage
L	Low pressure
H	High pressure
–	Valve open earlier
+	Valve open later

6.0. IAS Measurement and Analysis:

Table 2, shows the Truth Table for the IAS signal for the four common valve faults. Here a time domain analysis only was performed, and information about the valve fault is contained in the amplitude of the angular speed and its time of occurrence within the cycle. This leads to increases the load acting on the crank shaft.

From the Truth Table 2, a number of identification markers for the different valve faults can be seen. For example, lower than normal IAS over the range of crank angles between 250^o – 350^o,and increase between 40^o-150^o, indicates a weak spring 1st stage suction valve. A slight decrease in IAS from about 160^o to about 330^o and slight increase between 20^o –

120^{o} should be taken as a strong indication of a weak spring of suction valve of 2nd stage.

Table 2 - IAS Truth Table for valve faults in reciprocating compressor.

Faults \ Signature	Changes in IAS
1st stage weak spring SV	Decrease between 250^{o} – 350^{o},and increase between 40^{o}-150^{o}.
2nd stage weak spring SV	Decrease between 160^{o} – 330^{o} , and slight increase between 20^{o}-120^{o}.
1st stage weak spring DV	Increase between 30^{o}-130^{o}, and Slight increase between 300^{o}-350^{o}.
2nd stage weak spring DV	Increase between 20^{o} – 150^{o},and decrease between 170^{o} – 340^{o}.

7.0. Synthesis of Results - Decision Table:

Examination of the two Truth Tables shows that each of the four faults introduced into the compressor causes a number of changes to the normal signals. By judicious examination of each individual fault in each of the two Truth Tables, a Decision Table can be compiled which lists the defining and unique characteristics for each fault.

The Decision Table 2.1; shown below, lists the major signatures corresponding to each of the four faults. Strictly, only three signatures are required to identify which of four faults is occurring providing there is a unique correspondence and, as can be seen from the Decision Table, it is possible to identify each of the four faults.

It is considered that the use of the Decision Table could be a significant development in CM techniques. There are two reasons for this. In an industrial situation the Plant Manager or Controller will be provided with more information concerning any particular machine and its possible faults, and this will allow better decision making. The different monitoring processes will provide different and separate information about the same fault which can be cross-checked automatically; and where a fault is not confirmed, eliminate false alarms. Of course, where the fault is confirmed then the alarm will be given. Such an approach has been adopted in industrial fire fighting systems to great benefit in the Abu-Kammash - petrochemical plants where; in the author's, experience the introduction of such a system.

Table 2.1 - Decision Table for unique identification of valve faults.

Faults \ signatures	1st stage				2nd stage				Valve Imp.		Cylinders pressure				Change in IAS
	SV		*DV*		*SV*		*DV*				*1st stage*		2nd stage		
	-	+	-	+	-	+	-	+	*L*	*H*	L	H	L	H	
1st stage weak spring SV	O		O				O			♦		♦			Decrease between 250° – 350°,and increase between 40°-150°.
2nd stage weak spring SV		**O**		**O C**	O		O C			♦		♦			Decrease between 160° – 330° , and slight increase between 20°-120°.
1st stage weak spring DV		**O**	O							♦	♦				Increase between 30°-130°, and Slight increase between 300°-350°.
2nd stage weak spring DV		**O**		O C		**O**	O	**C**		♦		♦	♦		Increase between 20° – 150°,and decrease between 170° – 340°.

Table 2.2 - Key to Symbols

Valve Imp.	Valve impact
Cylinder Pressure (L)	Low pressure
Cylinder Pressure (H)	High pressure
_	Valve open and close earlier
+	Valve open and close later
O	Open
C	Close
SV	Suction Valve
DV	Discharge Valve

8.0. Conclusions:

Dynamic cylinder pressure and IAS of reciprocating compressor are directly related and both proved useful information for fault detection and diagnosis. Dynamic pressure is an extremely powerful CM tool, the deviation of the pressure signal from the normal can be seen clearly. The valves' opening and closing for both 1st and 2nd stages can be clearly observed and show the difference between healthy and faulty valves . Also the increase of cylinder pressures due to weak valve spring can be clearly observed.

The experimental work demonstrated that IAS analysis is capable of characterising compressor operation at different discharge pressures, and successful detection of valve faults (e.g. weak valve spring) can be made from deviation of the IAS waveform from its baseline.

IAS measurement of a reciprocating compressor flywheel is a very convenient, economic, reliable and non-invasive technique. Because the

IAS is closely related to the air pressure in the cylinder and the power torque acting on the crankshaft, and provide useful information. Variation in IAS is more obvious with faults in the 2nd stage valves than in the 1st stage, and with weak valve spring.

Truth Tables which combine and synthesise the information on fault signatures shows the capabilities of the technique used and presents this in such a way that allows easy comparison of the fault signatures of each individual fault. Comparison of the Tables shows the relative merits of the different techniques in determining any given fault – that is the relative capabilities of the various techniques.

Truth Table 1, shows how variation in cylinder pressure may be combined with changes in the angles at which the valves open and close to diagnose specific valve faults. Comparison of these Tables confirms the data regarding valve opening and closing times, and additional information is gained on either impact levels or cylinder pressure.

The information shown in Truth Table 2, is totally different from that shown in the other Truth Tables, and shows how variation in IAS can be used for specific fault identification. The Decision Table 2.1, lists the major signatures detected by each method, corresponding to each of the four valve faults.

9.0. Acknowledgment:

Author thanks the NASR, Tripoli –Libya for their sponsor and financial support of the research.

10.0. References:

[1] Mohamed Regeai, M. Elhaj. (2015). Mechanical Fault Detection for Motor-Gear Driving System Using Motor Current Signal Spectrum Analysis. 16th IEEE conference, Tunisia.

[2] Steven M., Charles A. and Robert P. (2007). Reciprocating compressor Condition Monitoring, proceeding of the thirty-sixth Turbomachinery symposium. Pp, 107-114.

[3] Gu, F., and Ball, A. (1996). Valve Fault Diagnosis in Reciprocating Compressors. Journal of Maintenance, Vol. 11, No. 3, pp 19 - 22s.

[4] Imaichi K., Ishii, N., and Imasu, K. (1984). A Vibration Source in Refrigerant Compressors. Journal of Vibration, Acoustic, Stress, and Reliability in Design. Vol. 106, pp 122-128.

[5] Daniel J. (1994). Vibration-Based Diagnostics of Reciprocating Machinery. PhD Thesis, Massachusetts Institute of Technology.

[6] Mohamed Elhaj, M. Al-Qattan, F. Gu, A. Ball, A. Albarbar (2004). Numerical Simulation Study of a Two Stage Reciprocating Compressor for Condition Monitoring. COMADEM conference, Cambridge, UK.

[7] Ishll, N., and Imaichi, K. (1975). Vibration of a Small Reciprocating Compressor. ASME Journal Paper, Vol. 75, No. 44, pp 4 - 14.

[8] Liu, S. , Gu, F. and Ball, A D. (2002). The On-line Detection of Engine Misfire Using Multiple Feature Fusion with Fuzzy Pattern Recognition, Proc. IMechE Part D, Journal of Automobile Engineering, Vol. 216, pp 391-402.

[9] Sweeney, P. and Randall, R. (1995). Sources of Gear Signal Modulation, Journal of IMech E, C492/027, pp183 - 198.

[10] Bensasi, A., Gu, F., and Ball, A D. (2004). Instantaneous Angular Speed Monitoring of Electric Motors, Journal of Quality in Maintenance Engineering (JQME), Vol. 10 No. 2, pp 1355-2511.

[11] Liang, B., (2000). Condition Monitoring and Fault Diagnosis of Three-phase Electrical Motors, PhD Thesis, University of Manchester.