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VALVE DYNAMIC MEASUREMENTS
IN A VIP COMPRESSOR

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ABSTRACT

The need to know details of the valve motion in a reciprocating compressor has long been recognized. An accurate measurement or calculation of the dynamics is needed to predict the efficiency and reliability of the compressor. For this reason, many researchers over the last five decades have compared measured and calculated results usually with excellent agreement.

During development of the new Valve-In-Piston™ (VIP) compressor, valve dynamics were calculated using conventional methods, and it was intended to confirm the accuracy of these by laboratory testing. It turned out that due to complexity of the design, these measurements were difficult to make and less accurate than we expected. The reasons for this are discussed and the measurements made are compared with results of calculations. Based on this, the empirical constants required for a valve dynamics calculation for the two valve types used in this compressor are examined and some observed differences in their behavior discussed.

INTRODUCTION

The valve in a positive displacement compressor is as essential and as important as its counterpart in nature, namely - the human heart valve. The performance of a compressor is largely determined by the efficiency with which a valve can admit and deliver the fluid to its destination. Hence the understanding of the dynamics of a valve and its impact on performance and reliability assumes great importance, particularly in a new type of compressor like a VIP, where the complexity of the dynamics is further accentuated by the motion of the complete discharge valve which also serves as the piston.

The valves are self acting and the motion of their elements is determined by various forces acting on them, mainly, gas dynamic in the form pressure and drag, mechanical in the form of inertia, damping and stiction. Since knowledge of valve dynamics is crucial for analyzing the performance of a compressor, the quest towards understanding valve dynamics started in the 1950's. Costagliola (1950) formulated a mathematical model to describe the motion of a valve in the form of two non-linear differential equations; one based on fluid flow equilibrium and the other on equilibrium of mechanical forces acting on the valve. This was followed by subsequent detailed investigations by numerous investigators including Wambsganss and Cohen (1967), and MacLaren and Kerr (1970) who not only made use of digital computers for solving the basic equations, but also identified the need to include additional effects to account for damping, pulsation and stiction. In addition, all these investigators measured valve motion using the sensors available at that time for validating their theoretical modeling. Woollatt (1974) developed a simpler method for predicting valve motion based on parameters identified to be responsible for controlling the valve dynamics and hence the performance. His method showed good agreement with prediction made using the more complex and time consuming, earlier methods. In the recent past, Machu (1994) has proposed a two dimensional mathematical model for considering the tumbling motion of a valve plate.

This investigation was carried out mainly to provide experimental data for validating the modifications done to a valve dynamics prediction program used for a compressor with fixed valves to make it applicable for a VIP compressor with moving valves (see Schoonmaker, 1994). Inductive and capacitive sensors cannot be used with PEEK moving elements or with large displacements, so optical sensors were selected for this study. Optical sensors were used by Woollatt and Wertheimer (1990) for valve motion measurements in a valve with concentric ring type elements. The availability of slightly larger range optical sensors encouraged the authors to try to make measurements in the moving discharge valve also. In addition to making some sample measurements in the discharge valve, this investigation was able to identify specific problem areas requiring further advancement in

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optical sensing technology for enabling accurate measurement of valve motion, particularly in moving valves. The experiments also helped in identifying some distinctive features of the dynamics of a single element, mass-damped plate valve as well as the multi element Magnum™ valve.

EXPERIMENTAL RIG, INSTRUMENTATION AND EXPERIMENTS

The measurements were done in natural gas, in a single stage, double acting, VIP compressor, installed in a closed loop compressor test rig. All measurements were confined to the head end of the cylinder. To measure suction valve motion, a Philtec model D170-W fiber optic displacement sensor was installed as shown in Fig. (1) in a suction valve seat hole by passing it through the cylinder head. The sensor had a 0.188-in. diameter stainless steel tip with a 0.17-in. diameter fiber optic bundle. The size of the sensor was a compromise between its sensitivity and range, determined by the number and hence the size of the bundle and its light output, and the extent of its influence on valve motion caused by local flow distortion due to the presence of the sensor. The tests were conducted with both D-R Magnum™ and D-R PF plate valves. For measuring the motion of the moving element of the discharge valve, which itself was moving, a specially designed sensor (Philtec Model D171-ETW) with a longer tip length and a much larger measurement range (approximately 2 inches) was chosen. It was installed as shown in Fig. (1) by passing it through the cylinder head as well as the suction valve. The selection of the location was such that the probe passed between adjacent valve elements in the suction valve and was aligned with one of the moving elements of the discharge valve. Since the layout of the valve hole geometry is not truly axisymmetric, the measurement location was chosen in one of the holes in the middle row in order to make the data as representative as possible of the complete valve geometry. Due to the experimental difficulties related to the size of the target described in a later section, discharge valve motion measurements were possible only for Magnum™ valves.

A 4 channel Nicolet oscilloscope was used to simultaneously record the suction and discharge valve motion traces as well as the suction and discharge line pressure traces. The oscilloscope sweep was triggered by a signal from an optical encoder, which was synchronized to occur at the top dead center (TDC). Suction valve motion was measured in both Magnum™ and PF plate valves at 4 conditions; pressure ratios of 1.5 and 3.0, and speeds of 900 and 1200 rpm. A P-V card was obtained for all the above cases using a PFM 2000 cycle analyzer.

The suction and discharge valve sensors were calibrated *in situ* before and after the experiment. For this purpose, a dial gauge was used to measure the distance of the sensor from the target and the sensor was moved over its measurement range and the voltage output by the sensor was recorded. The suction and discharge valve sensors were finally located at 0.25 ins. and 0.4 ins. respectively from the valve elements in order to keep them sufficiently away from the valve elements for minimizing flow interference and also to restrict measurement to the maximum linear range of the calibration curve.

MEASUREMENT DIFFICULTIES

Measurement difficulties can be attributed to a variety of sources. The compressor being of a Valve-In-Piston™ type, the moving element can not be accessed for measurement by passing the probe through the guard even in the case of the discharge valve. This makes noninvasive measurement impossible. Also, in the case of the Magnum™ valve, the valve elements and hence the passages in the seat feeding them were small which would make flow interference unavoidable even for the smallest possible optical sensor which can be employed. This was further accentuated by the need for a sensor with a large measurement range (which conflicts with the need for a smaller diameter sensor), particularly in the case of the discharge valve, since it was moving.

Since the valve elements were made out of PEEK, inductive sensors could not be used. The optical sensors were found to be sensitive to changes in pressure, gas composition, contamination of the light path by droplets of oil or its vapor, the target surface characteristics like – color and texture, and even background light. In fact, attempts were made to increase the probe sensitivity by coating the target valve surface with sputtered gold/palladium to increase the reflectivity. However, this was found to decrease the signal to noise ratio and the natural surface of the PEEK material was found to be better.

Natural gas was used in the experiments. Although calibration was done *in situ*, it was done in air. It is known that the refractive index and the transmittivity of the medium affect light transmission. Since the calibration was done in air and not in natural gas, and because the authors expected the optical properties of the medium to depend on the gas composition and pressure, experiments were done to estimate the effect of gas composition and pressure on the sensitivity of the probe. A simple device was set up to study the effect of composition on the sensitivity of

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the probe. The experiments done at the same pressure (atmospheric) in air, nitrogen and natural gas showed only minimal differences. However, experiments conducted in natural gas, to study the effect of pressure on the output of the probe revealed significant effect as shown in Fig. (2). This was found to be one of the important limitations of this investigation which relied on calibration in air at atmospheric pressure. The authors have so far not come across any literature documenting these effects in detail and hence think that it would be an important area for more investigation, particularly since optical sensors are used in various fields.

The discharge valve posed additional challenges which made accurate measurement extremely difficult. Even aligning and locating the probe inside the cylinder [see Fig. (1)] posed a serious mechanical challenge. Particularly, in the case of the plate valve, it had to pass through the moving suction valve plate. It was further complicated by the fact that the diameter of the light beam at the valve plate location when it was about 2 ins. from the sensor was too big to be intercepted and reflected only by the valve plate and not by the valve seat, without which it would be impossible to isolate the motion of the valve element from that of the moving valve. This did not allow meaningful data to be collected on the plate valve and may have decreased the accuracy of the Magnum™ valve readings. The sensor was measuring the total valve element motion which was the sum of the valve motion and the element motion with respect to its seat. Hence to isolate the element motion, the valve motion was subtracted by using the kinematic relations for the mechanism driving the piston. This meant finding the difference of two big numbers to arrive at a small number, which would result in large errors. In addition to mechanical errors arising from machining and assembling tolerances, any error in setting the optical switch to trigger at TDC would also contribute to the total error described above. A possible way to overcome this difficulty would be to simultaneously measure the motion of the valve as well as the piston using two identical sensors and subtracting the two displacements. This would also require the light-transmitting medium to be identical for both sensors. This method of isolating valve plate motion is planned to be used in future investigations.

COMPARISON OF EXPERIMENTAL DATA WITH PREDICTION

Calculation Method

The method used to calculate the valve dynamics was conventional. The motion was assumed to be one dimensional, characterized by the lift, and pulsation was neglected. All parameters such as the equivalent area of the valve as a function of lift, and the drag coefficient, were obtained from steady flow tests using air at low pressure. The base values of rebound coefficient and damping factor were obtained from experience with other valve types.

Magnum™ Valve

The Magnum™ valve had 96 separate moving elements. The lift – time trace for one of these was recorded. The Valve-In-Piston™ design, feeds the valve with a quite uniform flow, so all elements were assumed to see the same pressure drop.

Typical results for the suction valve are shown in figs. (3) – (8) and (10) – (11). Note that in these figures, the heavy lines are the calculated curves; the lighter ones are those measured from consecutive compressor cycles. All curves have been scaled so that the minimum and maximum values are 0% and 100%. This was done to remove the uncertainty in the experimental calibration caused by the effects of gas composition and pressure, and oil collection on the probe or element. As the valves reach full lift in all cases, this is reasonable. Allowance should be made for the effect of any noise on the measured cards when viewing the results.

An unexpected feature observed in all the experimental diagrams was the change in lift when the valve is closed. There was no drift of the probes during calibration, and this effect, which is amazingly repeatable from cycle to cycle, might have been caused by a change in the light transmission due to a gradual depletion of the oil from the surface of the element, or by a gradual change in the angle of the element as it settled into its seat. The effect degrades the results to some extent, and we have no way to cancel the effect. Further work on this would be interesting.

The lift curves do not repeat well from cycle to cycle which, in the authors' experience, is very unusual. The results at each of the four conditions all showed this lack of repeatability, and in all cases, it was most severe in the first bounce off the guard (the stop at full lift). We suspect that it is caused either by the unsteady nature of the highly complex 3D flow or by the differences in motion between the 96 elements. The pressure drop across the valve, and hence the force on any one element, will depend on the average position of all elements. Thus there is an interaction between the motion of different elements. This may amplify the effects of small differences in

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motion from cycle to cycle. It is also possible that the geometry of the elements is such that their interaction with the guard is less repeatable from cycle to cycle than that of the plate, ring and linear element valves tested previously.

Fig. (4) shows the effect on the calculated result of increasing the rebound coefficient from 0.2 to 0.5. This gives results closer to the average measured in this case, but not in all cases. Fig. (5) is an example where a rebound coefficient of 0.2 gives good results whereas 0.5 used in Fig. (6) does not. Experience with other valve types suggests that 0.2 is a more normal value.

A possible reason for the larger than expected bounce off the guard was the effect on the flow of the probe. The valve seat was modified so the flow area around the probe was the same as the area in the original seat. However the probe could still cause additional restriction and thus reduce the pressure force on the one element measured. All other elements would see the full force. To account for this effect, steady flow tests on a single element valve, with and without a probe installed, were run. These were used to derive the blocking effect of the probe. The above calculations were run with this effect applied to the one element, whose motion was measured. A calculation with the blocking removed is shown on Fig. (7), which can be compared to Fig. (3). The change is small.

The final result for the Magnum™ Valve, Fig. (8) shows the effect on the calculated diagram of a large increase in the damping. Fig. (8) should be compared with Fig. (3). These suggest that the valve motion is not sensitive to damping and that the same low damping used in Ring and Feather valves would suffice for the Magnum™ valve even though the sliding contact area is much higher in the Magnum™.

Fig. (9) shows a sample discharge valve motion measurement at the 1200 RPM, 3.5 pressure ratio condition compared with its prediction. The high pressure ratio condition was chosen, since that would confine measurement over a smaller range near TDC where a larger signal to noise ratio could be achieved. Even at this condition, the valve opening occurs when it is approximately 2 ins. from the sensor where the sensor was still not sensitive enough to resolve the valve element motion as indicated by the poor agreement between prediction and experimental data. However, the agreement appears to improve as the valve moves closer and the crank angle at which the valve closes, which is very important for analyzing the dynamics of a discharge valve, is predicted reasonably satisfactorily. It is also interesting to note that as in the case of the suction valve at the same operating condition, the discharge valve does not appear to stay fully open during the valve event but instead exhibits an oscillatory behavior.

Plate Valve

Results from one of the four test conditions run with plate valves installed are given as Figs. (10) and (11). The lift curves for plate valves repeated very closely from cycle to cycle and only two cycles are shown. This confirms that the lack of repeatability seen with Magnum™ valves is due to the valve design rather than the test compressor. The Plate valve has only one element, while in the case of the Magnum™ valve, the motion of each of the 96 elements is independent, but influenced by the motion of the other 95 elements. Hence, the motion of each element during a cycle as well as the motion of a single element during successive cycles could be different.

The PF style plate valves used here uses mass damping which comes into effect at 75% lift. The springing force is doubled as well as the moving mass increased during the final 25% of the lift. The effect of mass-damping is clearly seen in Fig. (11). The valve opens only briefly to its full lift and then settles down at 75% lift until it starts to close.

During its time at 75% lift, the plate is not constrained to remain parallel to the stop; it is supported on 12 springs. This is probably the cause of the large oscillations that build up in the lift curve. The lift was measured near the outside of the plate and the oscillation is thought to represent wobbling of the plate. Earlier tests with three probes have shown this.

The final curve, Fig. (11), shows the calculated diagram with increased damping. The only significant change is in the final opening just before the valve closes, since maximum oscillation of the element was occurring during that phase only. The measured oscillations of the plate can only be predicted by a model with more than one degree of freedom.

The results at the other conditions tested were similar to those shown above. The results show that under all the test conditions the mass-damping reduces the effective lift of the valve. Unless it is essential for reliability, it should not be used.

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CONCLUSION

This paper describes a technique and provides insight in to the difficulties in making accurate valve motion measurements in a compressor, particularly with moving valves. The detailed experimental data obtained for the suction valve showed that the overall dynamics of the valve was predicted well for both Plate and Magnum™ valves. Even the sample measurements presented for the Magnum™ discharge valve showed reasonable agreement during the second half of the valve event.

The results for the two valves demonstrated the subtle differences, which exist between a single element Plate valve and a multi element Poppet type valve, both of them exhibiting oscillatory behavior, although for different reasons. This demonstrates a need for using models with multiple degrees of freedom if an accurate prediction is to be made. Presumably, random perturbations of the pressure field, stiction or another variable would be needed to simulate the observed motion.

ACKNOWLEDGMENTS

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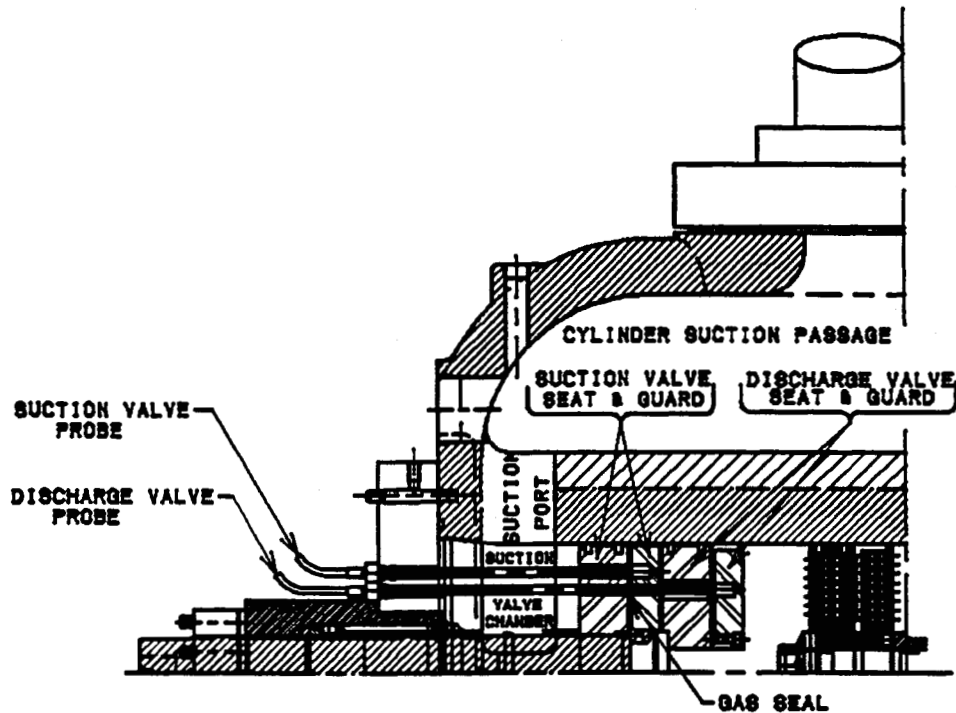Purdue University, West Lafayette, IN, USA – July 25-28, 2000

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Fig. (1): A Sketch Showing the Design for Instrumenting
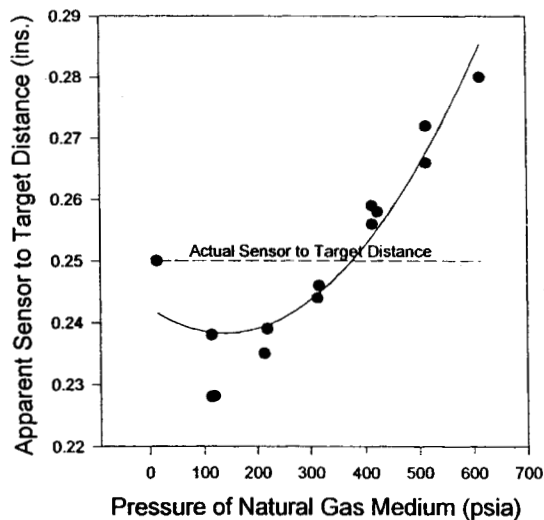Optical Sensors in the Suction & Discharge Valves

Fig. (2): Effect of Pressure of Light transmission
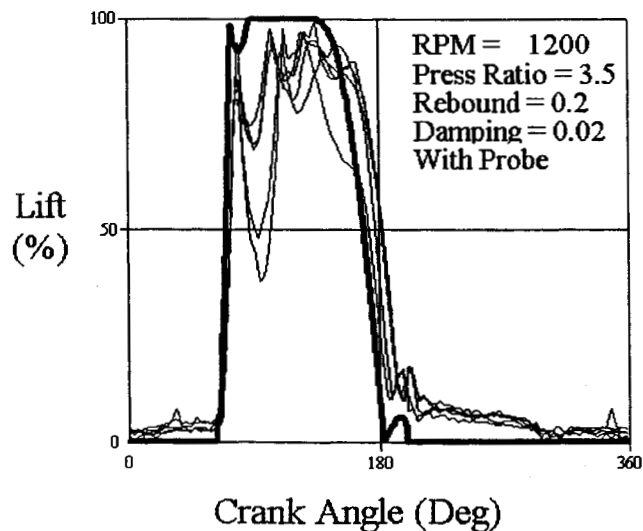medium on measurement sensitivity of
the Optical Sensor

Fig. (3): Comparison of Suction Valve
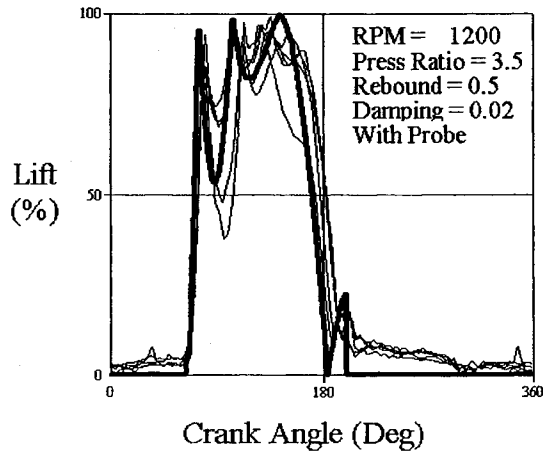Motion Prediction With
Experiment for Magnum™ Valve

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Lift
(%)

RPM = 1200
Press Ratio = 3.5
Rebound = 0.5
Damping = 0.02
With Probe

Crank Angle (Deg)

Fig. (4): Comparison of Suction Valve
Motion Prediction With
Experiment for Magnum™ Valve

Lift
(%)

RPM = 900
Press Ratio = 1.5
Rebound = 0.2
Damping = 0.02
With Probe

Crank Angle (Deg)

Fig. (5): Comparison of Suction Valve
Motion Prediction With
Experiment for Magnum™ Valve

Lift
(%)

RPM = 900
Press Ratio = 1.5
Rebound = 0.5
Damping = 0.02
With Probe

Crank Angle (Deg)

Fig. (6): Comparison of Suction Valve
Motion Prediction With
Experiment for Magnum™ Valve

Lift
(%)

RPM = 1200
Press Ratio = 3.5
Rebound = 0.2
Damping = 0.02
Without Probe

Crank Angle (Deg)

Fig. (7): Comparison of Suction Valve
Motion Prediction With
Experiment for Magnum™ Valve

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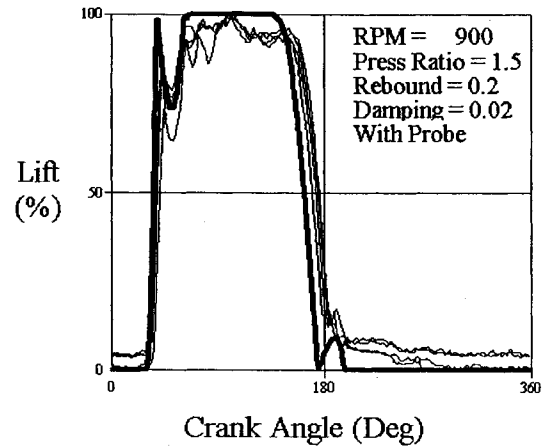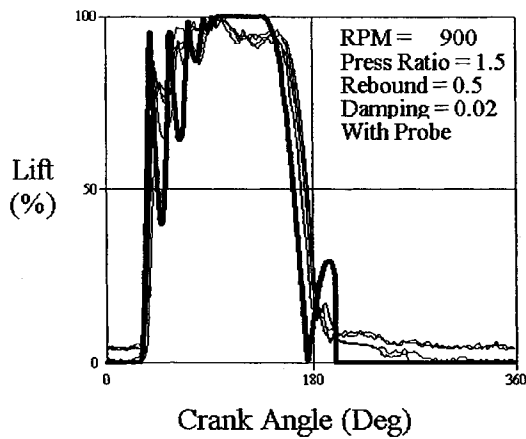
Fig. (8): Comparison of Suction Valve
Motion Prediction with
Experiment for Magnum™ Valve

Fig. (9): Comparison of Discharge Valve
Motion Prediction with Experiment
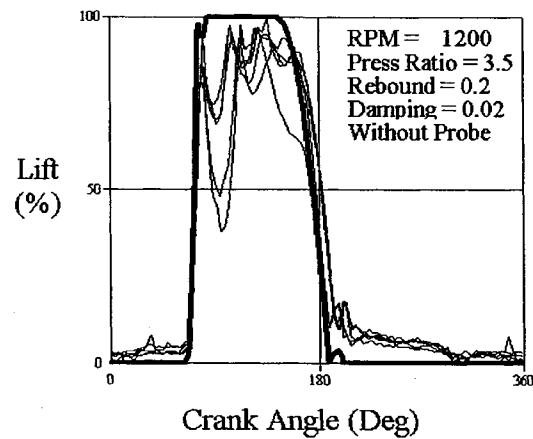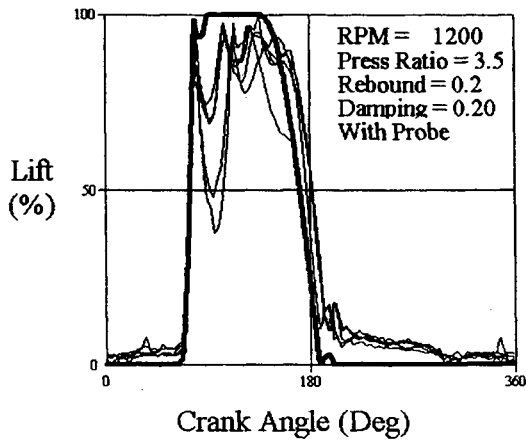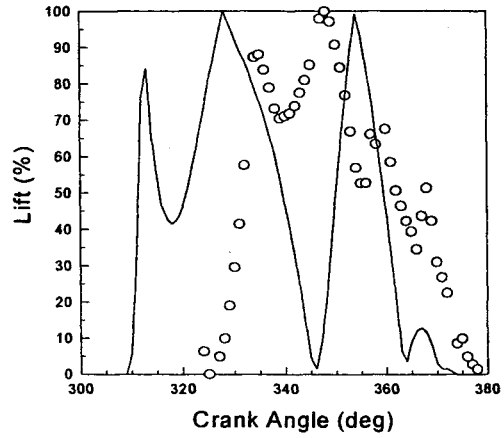for Magnum™ Valve; Pr. Ratio = 3.5,
RPM = 1200, Rebound = .5, Damping = .02,
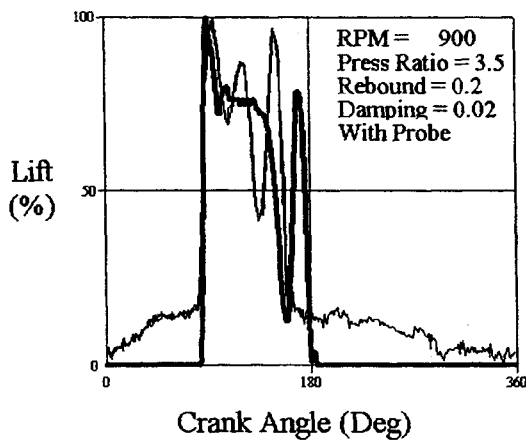Seat Stiction = 5

Fig. (10): Comparison of Suction Valve
Motion Prediction With
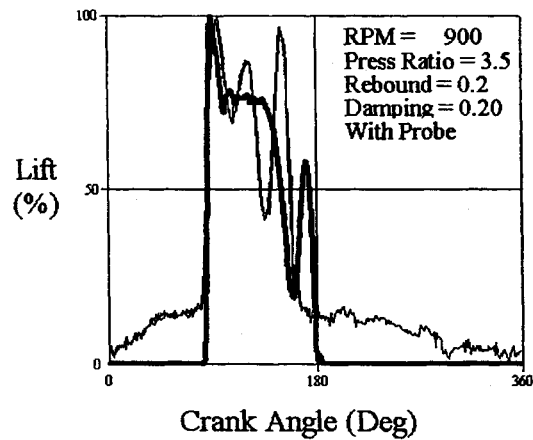Experiment for Plate Valve

Fig. (11): Comparison of Suction Valve
Motion Prediction With
Experiment for Plate Valve

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