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An Integrated Approach for Measurement and Control of Highly Critical Geometrical Parameters of Single Cylinder Reciprocating Air Compressor Crankcase through On–Machine Measurements

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Abstract: *Critical geometrical attributes of precision machined parts plays a significant role in overall quality of the end assembly product. The measurement of these critical geometric attributes involves high lead time and is often carried out offline in production industries. This paper proposes an overall integrated approach for measurement and control of two major critical geometric parameters viz,. Perpendicularity and concentricity in machined cast iron crankcase of single cylinder reciprocating air compressor during its machining process. Initially an experimental set-up was designed & developed in order to identify the critical geometric parameters of the crankcase that affects the performance of the air compressor. Consequently, an approach devising an on-machine-measurement (OMM) system has been built in the machining process in order to capture the deviations in the geometric parameters while machining the crankcase. Based on this OMM data, a series of iterative procedural systems & algorithms have been developed and integrated in the horizontal machining centers of the machining process thereby enhancing the cognitivity of the machining process. The developed model is validated by real time measurements of the machined crankcases in co-ordinate measuring machines (CMM) and the critical geometrical parameters showed significant improvement within the desired specifications thereby proving the accuracy of the OMM data and the developed model*

1. INTRODUCTION

The measurement & control of critical geometrical parameters of precision machined components gains extreme importance during its machining processes, as these parameters influence the quality of the end product to a very great extent. In precision machined components, unlike the dimensional parameters, the measurements of the various geometrical parameters like concentricity, perpendicularity, cylindricity, parallelism etc., are not carried out in line with the process accounting to various reasons. In majority of the cases, the reason is the inability of the measurement process to meet the pace of the production in downstream process owing to the high setup time and high cycle time elapsed for measurement. Indomitably, in most of the cases, the effect of the dimensional incompatibilities of these geometrical parameters could cause a heavy loss in terms of labour, cost, processing time and in quality of the end product. Hence these parameters are often inspected offline on sampling basis on corresponding co-ordinate measuring machines (CMM) at fixed time intervals as per the process quality control plan. This eventually leads to a limited control over the critical geometrical parameters during the machining process, as any chance or attribute cause will lead to deviation of the geometrical parameters of individual components from the nominal value. The deviations in the geometric parameters of the machined component is greatly influenced by the presence of kinematic error in the machining centers due to the dimensional, wear and form errors of the elements of its kinematic linkage system. Hence in order to have a robust quality control on the machining process of these geometrical parameters, the process capability of the machines has to be well within the control and the error prediction & calibration of machines has to be carried out in regular basis.

Handful of research work has been recorded on prediction and compensation of inherent geometric errors of machining centers that will greatly improve the accuracy of the machining process. *Sharif Uddin M et al (2008)* [1]identified the kinematic errors of a commercial five axis machining center with tilting rotary table by using DBB (Double Ball Bar) method and developed an error model for compensation of tool position & orientation using the measured geometric errors which can predict the error while machining. *Soichi Ibaraki et al (2010)* [2] came up with a methodology to formulate the kinematic errors of the five axis machining center from that of the geometric errors in the finished work piece. The formulated model is experimentally demonstrated on a commercial five axis machining center same as that of the one taken by *Sharif Uddin M et al (2008)* [1] and the estimates are compared to those estimated based on ball bar measurements. In 2010 [3], he again came up with a methodology to calibrate the location errors of rotary axes in an accurate, efficient and automated manner. The idea was to calibrate location errors of the rotary axes by On Machine Measurements (OMM) of a test piece by using a contact type touch–trigger probe installed on the machine's spindle. Investigations on the inherent geometric deviations of a five axis MCs with tilting rotary table was carried out by *Tsutsumi M. et al (2013)* [4] by using a measurement method (measured by two different settings of a ball bar in simultaneous three axis motion) based on cylindrical co-ordinate system. These geometric deviations are calibrated and to verify the effectiveness of this calibration method, the inherent geometric deviations were corrected through post processing of NC data for cutting of cone frustum. By application of OMM which involves a real time measurement data capturing from the machining processes, *Myeong-Woo Cho et al (2002)* [5] proposed an integrated error compensation method for profile milling operation by defining the surface errors with two parameters W_{err} and D_{err} and fitting these parameters using polynomial functions. The tool path is again corrected by an iterative algorithm by relating the cutting conditions and surface errors. In 2005 [6], he came up with a machining error compensation methodology for flat-end milling process based on polynomial neural network (PNN) trained using OMM inspection data. *Shaowei Zhu et al (2011)* [7] came up with a method that identifies & models the geometric errors of machine tools and compensates the errors by a software based method.

However, all the works cited above are in particular on enhancing the accuracy of the machining center through various approaches that includes the concept of OMM and validation of the developed model with conventional tests like cone frustum test, flat end milling process & as software models were carried out. However when it comes for a specific industrial & mass production application, for instance, on the machining process of the cast iron crank case of the **single cylinder reciprocating air compressors** used in commercial vehicles for generation of compressed air, the application of OMM on improving the geometric parameters is an area where no or only limited works has been recorded. In this precision machined cast iron crank case; there are very critical geometrical parameters of concentricity & perpendicularity with maximum unilateral tolerance level of 25µm. These geometrical parameters are very critical ones and any deviation of these from the nominal value affects the performance of the air compressor. Hence it is important to have an experimental model that validates & prioritizes the criticality of the geometric parameters of the machined parts in the compressor and an integrated approach to control it. This work proposes an experimental model to statistically arrive at the critical geometric parameters of the machined crankcase of a compressor and subsequently an integrated approach by using OMM in the machining processes of the crankcase has been discussed in order to enhance the cognitivity of the process and to have a better control over the critical geometrical parameters of the crankcase.

2. IMPORTANCE OF THE GEOMETRIC PARAMETERS IN CRANK CASE OF RECIPROCATING COMPRESSORS:

2.1 Air compressors

Compressed air gains paramount importance in domestic, civil, automotive & industrial applications in day to day life. It plays a vital role as an unparallel energy source and aids in transfer & mobility. There are various types of air compressors that are used to compress the atmospheric air to the desired pressure levels based on the specific requirement of the application. The broad categorizations are the positive displacement (intermittent flow) & continuous flow type compressors. The positive displacement type compressors are classified as the reciprocating and rotary types where the latter further classified as sliding–valve type, liquid piston type, straight lobe type & helical lobe type compressors. The continuous flow type compressors are the centrifugal type, axial type & mixed flow types. In portable and compact usage applications, for instance, in automotives, the single acting reciprocating air compressor is preferred than any other types due to its high portability & energy efficiency. The reciprocating or piston type air compressor was the first design of an air compressor and till today it remains as a viable type of compressor for the right application.

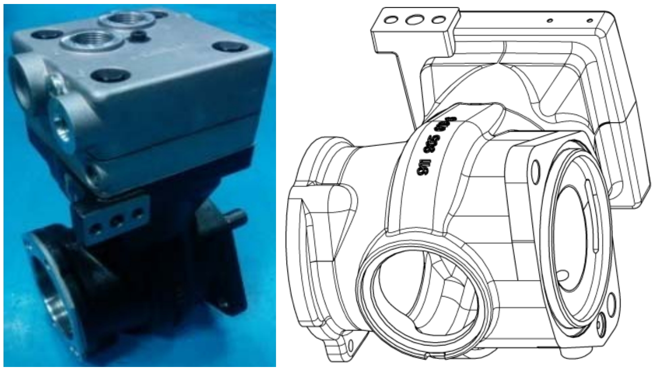


Fig. 1: 318 cm3 Compressor & its Crankcase

There are lot of categories by which the reciprocating air compressors are classified, the major category being the piston bore volume (cm^3) and the other categories are; Number of compression stages, cooling method (air, water, oil), drive method (motor, engine, steam, others), lubrication (oil, oil-free), packaged or customer built. The compressor taken for the work is a proprietary (of M/s WABCO INDIA LIMITED, pioneer & leading air brake systems manufacturer in India) 318 cm^3 single cylinder, air cooled, engine mounted and gear driven compressor used in the engines of heavy commercial vehicles for generation of compressed air (normally 8 bar) for braking & other applications in the vehicle. (Fig 1). This compressor comprises of a cast iron crankcase which houses the entire assembly and the crankshaft is rotated by a prime mover (belt drive / gear drive from the engine in cases of engine mounted compressors) and the crankshaft it is in turn connected to the piston by means of a connecting rod and a gudgeon pin. The reciprocating motion of the piston in the piston bore of the crankcase is used for compressing the air to the specified pressure.

2.2 Geometrical parameters of crankcase & its effect on air compressors performance:

The accuracy of the dimensional & geometrical parameters of the crankcase greatly affects the performance of the compressor as this crankcase is the single most casted part in which the entire assembly is housed. Compared to the geometrical parameters of the crankcase, the dimensional parameters of the crankcase can be easily controlled in the machining processes and can be inspected even to an extent of 100% using pneumatic gauges & other inspection tools. Whereas the measurement of the geometrical parameters of the crankcase (like concentricity, perpendicularity, cylindricity etc with reference to various planes of the part) requires a lot of lead time & often they are carried out offline in co-ordinate measuring machines (CMM) on a sampling basis as per the control plan.

First, In order to support the design & logical factor tree analysis [8] on the geometric parameters of the crank case that affects performance parameters of the compressors, a series of experiments has been carried out with an experimental set up. 50 crankcases have been machined in the process & taken for the experimental study with no non-conformity on all the dimensional parameters. These are identified with serial no (1-50) and subjected to 100% measurement of all the geometrical parameters using a ZEISS ACCURA co-ordinate measuring machine by a setup shown in (Fig 2). On the other hand, it is evident that, all the performance parameters of these compressors will be in a very strong relation to the free rotation of the crankshaft of compressor and the torque required for the rotation of the crankshaft while running continuously at higher speeds also decides the fuel efficiency of the vehicle in cases of engine mounted air compressors in automotive applications. Hence, it was decided to consider the torque required to rotate the crankshaft can be considered as a critical performance measure of the compressor. An experimental set-up shown in (Fig 3) is developed with a servo motor drive in order to calculate the required torque for the rotation of the crankshaft of the compressor. The input signal to the servo motor gives a direct relation to the torque according to the following mathematical relationship, which in turn can be related to the geometric attributes of the crankcase keeping the dimensional attributes as constant values.

SERVO MOTOR POWER (watts),

$$P = R \times T \times 2\pi / 60 \qquad (1)$$

$$T = P \times 60 / (2\pi \times R) \qquad (2)$$

Where, T–Torque required to rotate the compressor & R–rpm

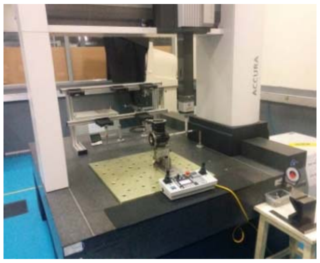


Fig. 2: Set – up in CMM for crankcase

All the identified 50 crankcases were assembled as compressors and the usual performance tests which include no load test, high speed test, performance test (that measures the build up pressure in a specific time) and oil carry over tests were carried out. Finally, the passed compressors are subjected to a test called free load test by means of which the torque required for free rotation of the crankshafts of compressors has been experimentally measured. In order to statistically evaluate the influence of the various geometric parameters of the crankcase to the compressors performance, it was decided that the performance parameter "FREE LOAD TORQUE" can be chosen as the input "y" range for a regression analysis that has been carried out with the various measured geometrical parameters of the crankcase as input "x" range. By this analysis, the influence of the various geometrical parameters on the torque is arrived. (Fig.4)

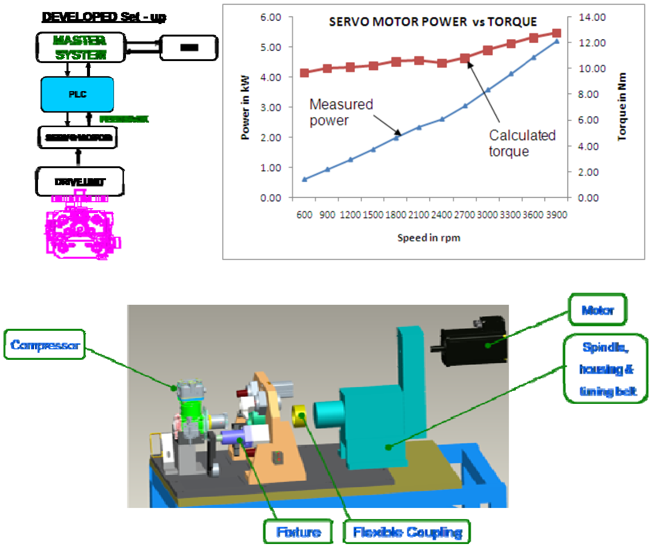
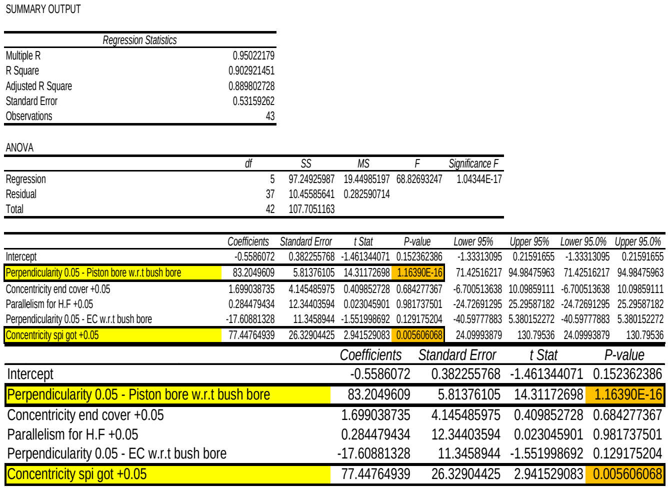


Fig. 3: Experimental set-up for calculating the rotational torque



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.95022179
R Square	0.902921451
Adjusted R Square	0.889802728
Standard Error	0.53159262
Observations	43

ANOVA

	df	SS	MS	F	Significance F
Regression	5	97.24925987	19.44985197	68.82693247	1.04344E-17
Residual	37	10.45585641	0.282590714		
Total	42	107.7051163			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.5586072	0.382255768	-1.461344071	0.152362386	-1.33313095	0.21591655	-1.33313095	0.21591655
Perpendicularity 0.05 - Piston bore w.r.t bush bore	83.2049609	5.81376105	14.31172698	1.16390E-16	71.42516217	94.98475963	71.42516217	94.98475963
Concentricity end cover +0.05	1.699038735	4.145485975	0.409852728	0.684277367	-6.700513638	10.09859111	-6.700513638	10.09859111
Parallelism for H.F +0.05	0.284479434	12.34403594	0.023045901	0.981737501	-24.72691295	25.29587182	-24.72691295	25.29587182
Perpendicularity 0.05 - EC w.r.t bush bore	-17.60881328	11.3458944	-1.551998692	0.129175204	-40.59777883	5.380152272	-40.59777883	5.380152272
Concentricity spi got +0.05	77.44764939	26.32904425	2.941529083	0.005606068	24.09993879	130.79536	24.09993879	130.79536

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Perpendicularity 0.05 - EC w.r.t bush bore	-17.60881328	11.3458944	-1.551998692	0.129175204
Concentricity spi got +0.05	77.44764939	26.32904425	2.941529083	0.005606068

Fig. 4: Regression analysis

From the regression analysis, it is evident that the geometrical parameters of the crankcase imparts a very strong influence on the free load torque as the R square value is 0.90 and in precise, the strong influence is driven by two geometrical parameters viz, Spigot concentricity with respect to bush bore ("A" in Fig 5–25 microns), perpendicularity of the piston bore with respect to the plane of the bush bore & the plane of the flange. ("B" in Fig.5–50 microns). These two parameters were hence concluded as very critical ones that strongly influence the compressor performance in terms of free load torque as both of these parameters yielded a P value less than 0.05. It has to be well noted that this regression analysis on the determination of the most critical geometric parameters of the crankcase yielded a very strong agreement with the logical factor tree analysis [8] based on the design failure mode effect analysis of the compressors.

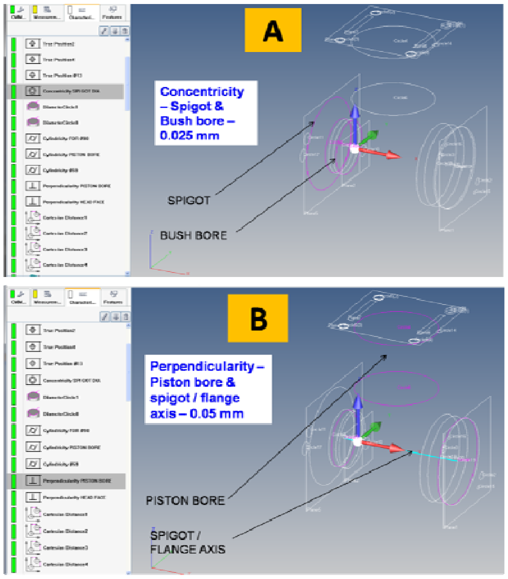

Fig. 5. Critical geometrical parameters of crank case

Hence, it is experimentally evident that these two geometric parameters in the crankcase are the highly critical ones which influence the performance of the compressor to a very great extent thereby justifying the vital need to measure & control these during the crankcase machining process.

3. ON–MACHINE MEASUREMENT & CONTROL OF GEOMETRIC PARAMETERS IN CRANKCASE MACHINING PROCESS

3.1 Machining process of crankcase:

The raw cast iron crankcase is subjected to machining processes in three stages, exclusive of the other non-machining processes like marking, oiling, leak checking and deburring. The three stage machining process of the crankcase includes a first set-up & second set up operation in a 4 axis BFW (Bharat Fritz Werner)–Maxpro H650 horizontal machining center (HMC) followed by a final third stage machining that is carried out in a 4 axis AMS MCV–400 vertical machining center (VMC). The first set up operation (Fig 6a) of the crankcase carries out the machining process of four crankcases simultaneously which includes the bore operation, head face milling & drilling in the piston bore side (Ref: 6a), sump bore operations on the opposite side (sump bore side). The second set up again is a four-component configuration that covers the spigot side & flange side operations (Fig 6b) in a vertically mounted pattern which are in turn the highly critical operations that controls the geometric parameters. In order to ensure the minimal or null effect of the location errors due to clamping & location of the crankcases, in the first & second set up, the air pressure part sensing fixtures were used. By routing compressed air of normally 0.3 to 1.3 bar (5-20 psi) to the datum locators, the presence of any location error is found out using the concept that the properly located part will seal of the small air ports thereby creating the back pressure which can be measured by a pressure switch. The air pressure sensing mechanism is interfaced to the machine & if the increase in pressure (due to the back pressure) is not acknowledged, the machine cycle is disabled until the crankcase is located properly. This process in-built control mechanism assures the correct location of the part during the loading in first & second set up.

As the fixture design of the machining process inherently controls the errors due to component loading & clamping, it can be considered that the machining operation in the HMC is free of location & clamping errors and the second set up operation that includes the spigot & flange side machining process is the only critical machining process where the parameters A & B are finished & controlled. The detailed machining process steps carried out in the second set up is listed in fig 7.

As discussed in the section 2.2, the two critical geometrical parameters during the machining process are A–The concentricity of the spigot face (“2”, “3” in Fig.7) with respect to bush bore (“5” in Fig.7) & B–The perpendicularity of the piston bore with the line connecting plane F & D. The following section will explain the approach adopted for controlling these two geometric parameters during the machining process using on machine measurement (OMM) methodology.

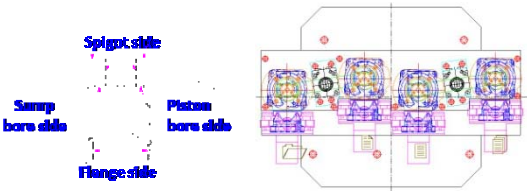

Fig. 6a: First set-up configuration

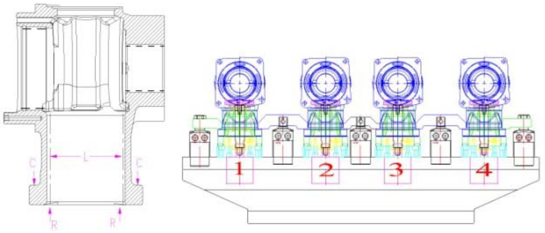

Fig. 6b: Second set up configuration

3.3 OMM approach to control the geometric parameters in the machining processes:

The OMM approach enables us to perform the inspection process in the same machining center by exchanging the cutting tool for a measuring probe. This exchange might result in the inspection error at the probe tip [6] & an appropriate methodology suggested in [5] has been adopted to improve the accuracy of the inspection process in the machining center. The second type of error that affects the inspection accuracy of the OMM system is the geometric error in the machining center due to the dimensional and form errors of the elements of its kinematic linkage system and the angular & the positional misalignments between them. Hence it is necessary to carry out a calibration of the four axis horizontal machining center using the appropriate methodology [1] before the OMM methodology is integrated in the machining center. From the profile in fig.7, it can be understood that the operations 11, 12 & 13 are the final finishing operations that finishes the two critical parameters A & B. The operation indicated as 11 & 12 in fig.7 covers a semi-finish & finish boring of the two sides of the crank case using a special boring combination tool using CBN inserts of CCGW 060202CBN110 grade from SECO. The operations indicated as 13 in fig.7 are the OD finish of the bush & grooving of the spigot side of the crankcase using a face milling arbor & cutter with grade SNEN0903ENE-M06 CBN200 inserts. To begin with, it is very important to identify & employ the possible type of probe that can be used for the OMM in the horizontal machining center. A touch trigger probe type (RENISHAW–OMP 60–optical machine probe) of 6mm diameter & 50mm stylus length is chosen for this application of probing the machining processes of second set up operation. This optical probe is installed in the machine with an OMI-2 receiver & machine interface that conveys and processes the signals between the inspection probe & the CNC machine control. (Fig.8). The geometric parameter “A” which is on the spigot side of the crankcase is having a close unilateral tolerance of 25 micrometers (0.025mm) & the finish machining process (13 in fig 7) is carried out by the CBN tool as explained before. In this work, it is proposed to implement the probing process just before the finish operation after a thorough cleaning of all the components in the setup using flush coolant. Using the probe, the coordinates of the bush bore is defined on a single plane using a probing program virtually and a macro program is integrated in the CNC program in order to arrive at the exact center point coordinates of the bush bore (fig.8). The machining command of the next tool (finishing tool of the spigot outer diameter) is now fed automatically by the CNC program based on the X&Y coordinates of the center obtained from the probing cycle of the bush bore thereby maintaining the concentricity parameter “A”.

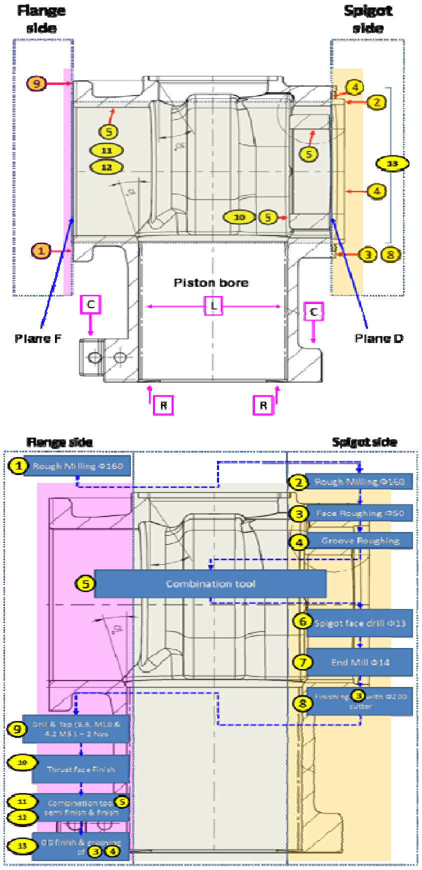

Fig. 7: Machining details of the second setup operation.

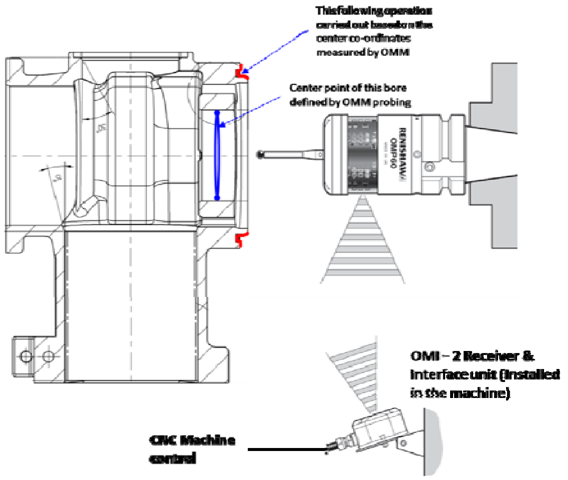

Fig. 8. Controlling the concentricity parameter “A” using OMM.

The perpendicularity parameter “B” on the other hand needs to be controlled during the semi finish & finish machining process (11 & 12 in fig. 7) which is carried using the custom designed combination tool using CBN inserts. The bore that is machined by this combination tool needs to satisfy its perpendicularity with respect to the piston bore (fig.9). Hence in order to control this parameter, the axis of the piston bore has to be defined first using a suitable probe type. The existing probe configuration and styli of the OMP60 probe will not be suitable here due to its straight stylus configuration as the axis to be probed is not in parallel with the HMC’s spindle axis.

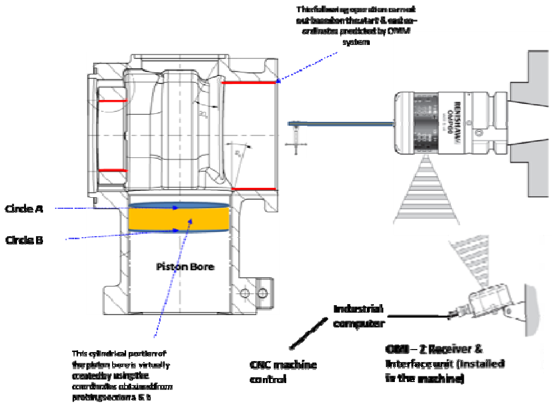

Fig. 9: Controlling the perpendicularity parameter “B” using OMM.

A custom designed probe head with Renishaw M5 star styli (A-5555-0215) having probe balls diameter of 5mm and a stylus length of 55mm in the axis parallel to the piston bore is selected for this application. It is proposed to make use of this star styli type custom designed probe for identifying the circular coordinates of the piston bore in two areas (circle A & circle B in fig 9) using the appropriate probing program and to virtually plot this cylindrical portion of the bore in calypso software in an industrial computer integrated to the machining center. Based on the obtained cylindrical portion, the center axis is defined & the exact coordinates perpendicular to this axis are arrived using the lab view access language.

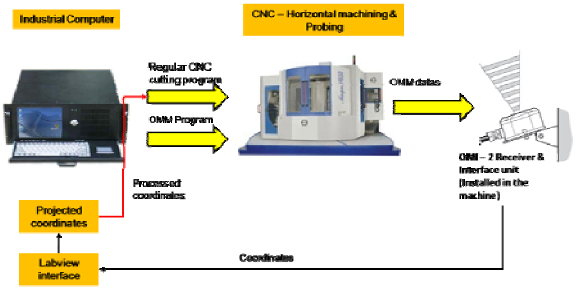

Fig. 10: Proposed OMM system configuration

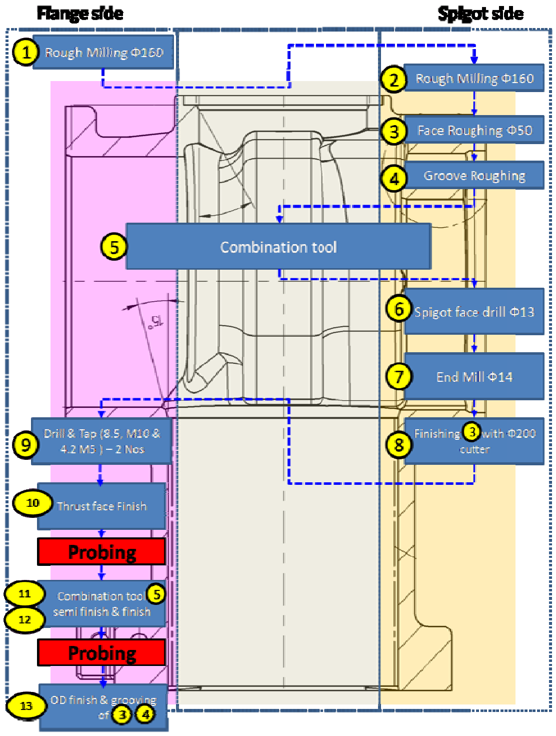

Fig. 11: Machining process sequence after including OMM

The subsequent finishing operation by the combination tool is carried out on the axis predicted by this lab view access language & the program is fed through DNC (Direct numeric control) mode to the machining center thereby maintaining the perpendicularity parameter “B”. The interface diagram (fig.10) will explain the OMM system structure that has been proposed in order to predict and control the possible errors in the machining processes of critical geometric parameters of the crankcase

The modified sequence of the machining process is shown in fig. 11, where the probing operations were added just before the finishing operation using the combination tool and just before the final finish operation of the spigot outer diameter and grooving.

4. RESULTS AND DISCUSSION

The discussed OMM methodology is mainly to enhance the capability of the crankcase machining process by integrating the measurement of the key dimensions during the machining processes. The effectiveness of the proposed approach which is implemented on a real time machining process is validated by taking 50 crankcases for a long-term process capability study (based on a defined sampling plan) & all the crankcases were subjected to 100% measurement of all the geometric & dimensional parameters in CMM. Fig.12 will elucidate the correctness of the adopted methodology, where both the critical geometric parameters “A” & “B” have shown a very good improvement after the implementation of the OMM system thereby enhancing the accuracy of the machining process of these geometric parameters & therefore the process capability of the process.

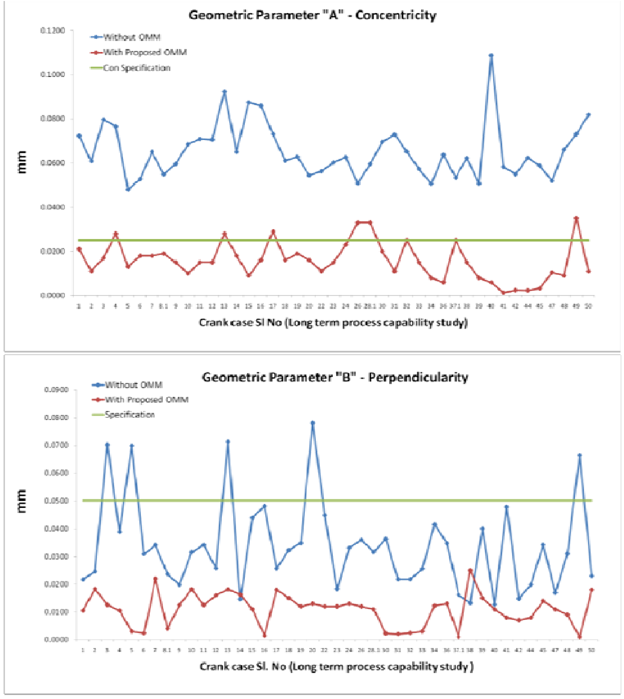

Fig. 12: Results after the OMM system implementation

5. CONCLUSION

The main purpose of this work is to experimentally determine the critical geometric parameters of the machined cast iron crankcase of 318cc single cylinder single acting reciprocating compressor. For this, an experimental setup was developed and the “FREE LOAD” torque required to rotate the crankshaft of the compressor was experimentally calculated for 50 compressors and it has been related to the geometric parameters of the crankcase and the most critical geometric parameters were arrived using regression analysis. An appropriate methodology involving OMM has been proposed in the horizontal machining center and the critical geometric parameters, spigot–bush bore concentricity (parameter “A”) & the piston bore–spigot axis perpendicularity (parameter “B”) has been controlled and the effectiveness of the system was validated using real time CMM measurement.

With the increased customer focus on the quality of the product, the process control solutions are gaining a dominant importance in the machining process of the critical geometries of the product. This requirement triggers the need for the day to move from the post process monitoring systems to active in process control system solutions during the machining process. The proposed approach using the OMM methodology can be a viable & effective - active in-process control system for the crankcase machining process of the single cylinder reciprocating air compressors which will yield the improved field Quality of the compressors. The future research will be carried out by considering even more number of trivial geometrical parameters for controlling in the machining process and adding even more crankcase types with totally different geometrical configurations.

6. ACKNOWLEDGEMENTS

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