FORM ACCURACY ANALYSIS OF CYLINDRICAL PARTS PRODUCED BY RAPID PROTOTYPING

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Abstract

Solid Freeform fabrication processes are being considered for creating fit and assembly nature functional parts. It is extremely important that these parts are within allowable dimensional and geometric tolerance. The part accuracy produced by rapid prototyping process is greatly affected by the relative orientation of build and face normal directions. A systematic method is needed to find the reliability of the created product. This paper discusses the work done in this area and the effect of build orientation on the part form accuracy analysis of each specified tolerance like circularity and cylindricity. Feasible build direction that can be used to satisfy those tolerances is identified. It will help process engineer in selecting a build direction that can satisfy a mathematical model of form tolerance.

1. INTRODUCTION

The main advantages of Solid Freeform Fabrication (SFF) processes are that they don't require any part specific tooling and completely automated. In Fused Deposition Modeling (FDM) a three dimensional CAD model of the part is sliced into layers and the numerical data on the geometry of layers is then feed into the fabrication unit, which builds each layer sequentially until the entire part is fabricated.

SFF processes are conducive to the concept of distributed design and manufacturing where in process providers will list their constraint on website and designers will perform manufacturability analysis for their design. This helps to reduce redesign when manufacturing constraint are violated. In order to create defect free functional parts through rapid prototyping techniques, manufacturability of design tolerance with respect to process constraints is essential.

Until recently SFF processes were primarily used for creating prototype parts. Increasingly SFF processes are being considered for creating functional parts. In such applications, SFF can either be used for creating tooling i.e., patterns for casting, low volume molds, etc. or directly creating the functional part itself. In order to create defect free functional parts, it is extremely important to fabricate the parts within allowable dimensional and geometric tolerances. In order to determine whether a process can produce the part within required tolerances, we need to analyze manufacturability of design tolerances with respect to process constraints. Industries use 15.6% of parts produced by SFF by fit and assembly tests. Fit and assembly tests need evaluation of form errors for attaining correct fit during assembly. In this paper we primarily focus on circularity and cylindricity tolerances assigned to the cylindrical parts.

Fused deposition modeling (FDM) is a rapid prototyping (RP) process that fabricates parts layer by layer by deposition of molten thermoplastic material extruded from a nozzle. A proprietary software, Quickslice, processes the STL file to create the slices and roads and commands the FDM machine to generate layers of specified thickness and road width from the nozzle of a liquefier head. In general, the outer perimeter of the layer is laid down first, after which fill roads are created to fill the solid areas inside each layer. The types of fill patterns available are the raster, the contour or a combination of both. The layers are deposited continuously at any part build orientation to build the part bottom up. Geometric accuracy of components is one of the most important quality characteristics in layered manufacturing processes on which most rapid prototyping (RP) techniques are based. Layered manufacturing is an approximate fabricating process in which the final geometric error of the physical part is affected, not only by the approximation technique used, but also by the fabrication process.

2. ERRORS INDUCED IN LAYERED MANUFACTURING

Although the original RPTs were developed to provide style models, current RPTs are increasingly regarded as manufacturing technologies for tooling and production parts [3]. All manufacturing technologies for tooling and production parts must guarantee the accuracy of geometric dimensions and repeatability. The subject of geometric accuracy of parts is thus under intense debate as practitioners argue where and under what circumstances a rapid prototyping machine provides enough accuracy to be suitable for making tools [4]. Yan and Gu [5] categorised the most common sources of errors in rapid prototyping processes into mathematical error, process-related error and material-related error. Chalasani and Bagchi [6] identified tessellation, slicing orientation and slicing location as the three primary sources of error in the data preparation stage. Also, errors in the data preparation process were found in facet approximation, staircase effect and containment problem, and in laser beam path planning algorithms [7]. Process-related errors affect the shape of the layer in the x,y-plane and along the z-axis as well as the overall 3D shape [8]. The physical and chemical characteristics of the materials in the process of solidification involving liquid and powder materials have been studied by many workers [9] who showed that the principal process-related errors are shrinkage and distortion in using these materials. For solid sheet materials, little is reported for analysing component geometrical error relating to the fabrication process. From the viewpoint of component production process in layered manufacturing, it is very important to understand the error distribution and error transfer mechanisms in order to assess, predict and control the final geometric accuracy of the part. A geometrical model is used for assessing the effects of various errors and their accumulation and the final part geometry in RPT considering error interactions between the data preparation process and fabrication process.

2.1 Data Preparation Error (DPE)

In the RPT process, each 2½-D layer is generated as a "sweep" of a planar profile by depositing material on the interior of a 2D slice. Since the whole part is manufactured in this manner, the boundary of the part created is a stepped approximation of the boundary of the ideal part. As a result of this, compared with the parts created in the conventional manufacturing technologies such as milling and turning, parts produced in layered manufacturing exhibit a staircase effect. The error resulting from the staircase effect can be affected by the containment mode which describes the geometrical arrangement between the ideal part geometry and the sliced part contours[1]. There are three containment modes to approximate the ideal part in the RPT process. These are referred to as the positive situation (the sliced part profile slightly exceeding the ideal profile), negative situation (the sliced profiles situated within the ideal profile) and the hybrid situation [7]. The approximating accuracy in the slicing procedure also depends on the slicing orientation, location and slicing thickness as reported in [6]. These errors are not related to the actual fabricating process and on1y depend on the fabricating method selected and slicing parameters used. These errors are therefore lumped as data preparation error

(DPE) and they can be predicted theoretically by analyzing the extent of the staircase effect for a given containment situation and slicing parameters selected.

2.2 Fabrication Process Error

In the actual RPT part-building process there are additional errors which are affected by many process-related parameters, e.g. the machine path control accuracy, tool scan speed uniformity, tool shape stability, platform control accuracy, material properties, part thermal distortion, material feed uniformity, fixture stability, glue thickness (in LOM process) uniformity, and part thermal shrinkage and distortion. These errors interact with the DPE and when combined they determine the final geometrical accuracy of the part produced. There are three possible effects of these fabrication errors on the final geometry of the part:

1. Geometrical errors generated in the x- and y-directions only which are primarily associated with the scan path and tool shape control accuracy as shown in Fig. l(a).
2. Geometrical errors in the z-direction which are mainly related to the platform displacement accuracy and materials thickness uniformity (e.g. in LOM and SLS processes) as shown in Fig. l(b).
3. Geometrical errors in all directions (Fig. l(c)) as a result of scan speed variation (acceleration and deceleration), material flatness variation (e.g. in LOM process), thermal distortion of the part and other assembly errors. It can be seen that the errors resulting from the actual part building process can alter the extent of theoretical errors relating to the staircase and containment problem defined by the fabrication method. For the purpose of error analysis, all the errors generated during the part-building process are now defined as the disturbance error.

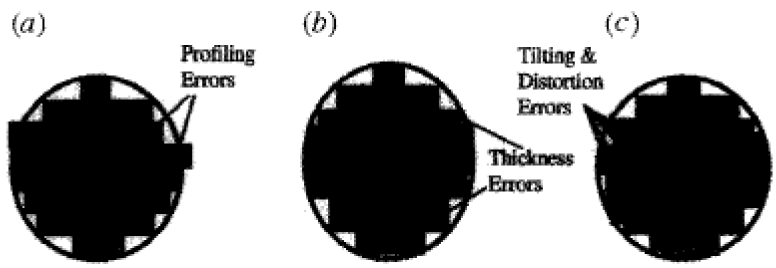


Fig.1. Disturbances in the RP part building process (a) Errors in the x,y-plane (e.g. contour geometry error). (b) Errors in the z-direction (e.g. layer thickness error). (c) Errors in x-, y-, and z-directions (e.g. layer flatness variation)

3. METHODOLOGY

Geometric dimensioning achieves the goal of identical dimensions through four simple obvious steps.

1. Convey the nominal distances and orientations from origin to other surfaces.
2. Establish boundaries / or tolerance zone for specific attributes of each surface along with specific rules for conformance
3. Allow dynamic interaction between tolerances (Simulating actual assembly possibilities) where appropriates to maximize tolerances.

A form tolerance is applied to a non-datum feature only where there is some risk that the surface will be manufactured which form deviations giving enough to cause problems in sub sequent manufacturing operations, inspection, assembly or function of the part. Circularity is a condition of surface. Circularity tolerance is a refinement of the size tolerance. In case of cylinder each circular element is independent of every other circular element that means that the part can look like stack of pennies that is misaligned but that can still satisfy a circularity inspection [10-11]. A circularity tolerance controls feature's circularity (roundness) at individual cross section. While sweeping the tolerance zone may continually adjust in overall size, but shall maintain the specified radial width. This effectively removes diametrical taper circularity control. Additionally this spine orientation and curvature may be adjusted within the constraints mentioned already. This effectively removes axial straightness from circularity control. The circularity tolerance zone need not be concentric with either size limit boundary.

In a layer manufacturing process such as FDM the part surface geometry is approximated along the building direction. The curved features are formed at the edges of a two adjacent slices. This results in an error resulting a staircase effect. The actual geometrical formed may be different, depending on the geometry of the part and orientation of part in the building process. It is assumed that the errors don't transfer between layer during the data preparation phase. The fabrication process will transfer the errors only in the part building direction.

Cylindricity is a condition where all points on the surface of a cylinder are equidistance from the axes. Unlike circularity the cylindricity tolerance applies to circular and longitudinal elements at the same time[11]. Cylindricity is a composite form tolerance that simultaneously controls circularity, straightness of a surface, and taper of cylindrical features. A roller bearing might be controlled with a cylindricity tolerance where as a conical surface (bearing) might be better controlled with profile tolerance. When the size tolerance doesn't control the form of a feature, a form tolerance may be specified as a refinement to cylindrical tolerance zones or material conditions which are appropriate for surface control.

It specifies a tolerance zone bounded by two concentric cylinders whose Radii differ by an amount equal to the tolerance value. The tolerance zone cylinder may adjust to any diameter, provided their radial separation remains equal to the tolerance value. This effectively removes feature size from the cylindricity control.

Co-axiality is the relationship between multiple cylindrical or revolute features sharing a common axis. Coaxiality can be specified using run out, concentricity, or positional tolerance. A runout tolerance controls surface deviations directly, without regard for the features axes. A concentricity tolerance controls the mid points of the diametrically opposite points. Coplanarity can be specified using either a symmetry or positional tolerance. A symmetry tolerance controls the mid points of opposed surface points.

Runout is the variation in the surface elements of round feature relative to an axis. In precision assembly, run out causes misalignment and or balance problems [11]. Examples are run out of the ring groove diameters relative to the pistons diameters might cause the ring to squeeze unevenly around the piston or force the piston off centre in its goal. A motor shaft that run out relative to its bearings will cause the motors to run out of balance, shortening its working life. It is called wobble and lop sidedness. Total run out adds further refinements to the requirements of circular run outs. FIM (full indicator movement) is the difference in mm between an indicator most positive and most negative movements during run out. It can be measured using CMM. Circular run out tolerance applies at every possible circle on the feature's surface but each circle may be evaluated separately from the others. One should add run out tolerance for each journal to refine the feature's tolerances.

If the FIM reading difference for each circle is below the run out tolerance, it can be said that the part satisfies the run out tolerances. In case total run out, its tolerance sweeps over the entire control surface rather than each circular element being evaluated separately. The total run out FIM encompasses the highest and lowest of all readings obtained at all circles. Any taper in the controlled feature will increase the FIM.

Circular run out tolerance is often ideal for 'O' ring groove diameters. Run out tolerances are especially suited where alignments and dynamic balances are critical.

Circular run out = circularity + concentricity

Total run out = cylindricity + concentricity

Runout tolerance applies directly to surface elements where as positional tolerance RFS controls only the coaxiality of feature's actual mating envelop. It doesn't provide form control for the surface. Position tolerance is considered instead of run out when interaction is desirable and size limits will adequately control form. A feature's run out tolerance need not be less than size tolerance. Hence each run out tolerance has to be considered independently and carefully. A few well thought out run out tolerances are evolved to control combinations of relationships. Run out tolerance yields a worst case inner boundary equal in size to the feature's small limits size–the value of its run out tolerance and a worst case outer boundary equal in size to the feature's large limit size + the value of its run out tolerance. The inner or outer boundary can be exploited to protect a secondary requirement for clearance without using a separate positional tolerance.

4. MATHEMATICAL MODEL

The entire feature surface shall every where be contained within the tolerance zone. The interpretation of semantics of tolerance is burning topic in form tolerance. The variance area of each tolerance zone can be derived. The tolerance zone means the region or area which limits the real feature's movement. The real feature is feature with error, and is composed of points in the nominal feature after some ways of movement. Tolerance of a cylindrical feature is concerned with the constraint on the cylinder surface or on the cylindrical axes. For the same feature, the matrix equation of different tolerances can be the same. But the movement ranges of degree variables in the equations are generally different. Hence, establishment of the constraint model of each degree variable according to tolerance definition is the urge of the day. In this work each tolerance zone' mathematical model is established with inequality based on the degree of the feature. Each of the symbols is as follows:

C_d is the direction vector of tolerance zone; C_p is the position vector of tolerance zone; P is a point in the tolerance zone; r is the normal radius of the cylinder; e_s, e_i are the upper and lower specification limits of the cylinder' diameter; T_{cir} is the form tolerance; d_x, d_y, d_z are the

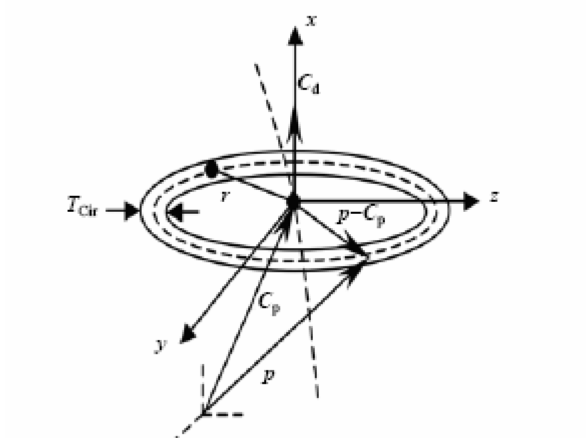


Fig 2 Definition of Circularity tolerance zone

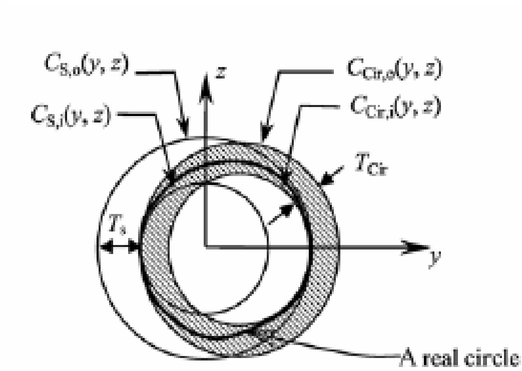


Fig 3. Maximum shift of circularity tolerance

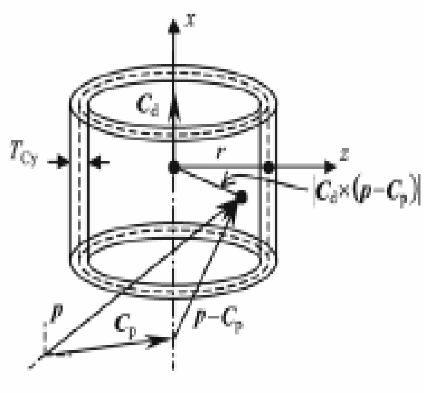


Fig.4 Cylindricity tolerance zone definition

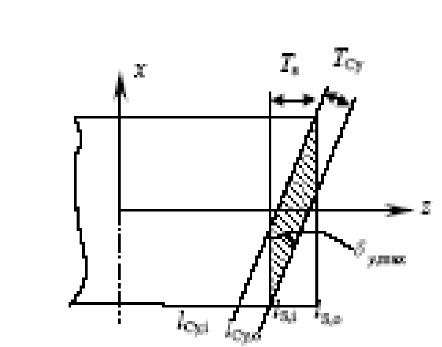


Fig 5 Maximum orientation angle of cylindricity tolerance zone

translation range of the coordinate origin along the axes x, y and z respectively. δ_x, δ_y, δ_z represents translational along the axial and rotation range around the axial is δ_θ,δ_ϕ and δ_ψ respectively. Generally a complete tolerance specification is constructed with the default tolerance specification and the specified tolerance. Here the correctness cannot be guaranteed for such tolerance specification and following three aspects should be considered:

1. Is the given tolerance and size reasonable?
2. Is the given tolerance complete?
3. Is the given tolerance specification valid?

The tolerance validity is evaluated by generating variational geometries. The tolerance semantics has four basic attributes say position, direction, form and size. The size is specified by the designers. Hence, the key to exactly represent tolerance semantics is to determine the position and direction of the tolerance zone. The traditional tolerance types like circularity and cylindricity do not convey the real meaning. Hence, tolerance zone floated is new way of classification of tolerance. The variational geometry can be generated by generating all the variational elements like surface and axis and then regenerate the whole variation part through the surface to surface or curve to curve or surface to curve intersection. For a cylinder surface it is sliced equally into many equal segments along the direction perpendicular to the direction. The variational cylinder surface of the each slice is generated which satisfies the tolerance requirement. Then skinning operation of the generated surface completes the process.

The study helps integration of CAD/CAM and interpreting the semantics of form tolerances exactly and completely. It helps the designer to fix the correct cylindrical tolerances to real production experience that facilitates assemblies in groups that meet the functional requirements based on variance area of each tolerance zone [12].

The mathematical model of the hole tolerance is as follows:

The inequality equation of each degree variables' movement range of cylindricity tolerance is as follows.

$$-T_{cy}/2 \leq \sqrt{(y+\delta_y+x.\delta_\psi)^2+(z+\delta_z+x.\delta_\phi)^2}-r \leq T_{cy}/2 \quad \text{……….1}$$

Where

$$-T_{cy}/2 \leq \delta_y \leq T_{cy}/2,\ -T_{cy}/2 \leq \delta_z \leq T_{cy}/2 \quad \text{……….2}$$

The inequality in equation 1 shows points in the cylindricity tolerance zone and determines the size and form of the cylindricity tolerance zone.

$$\left\{\begin{array}{c} -(T-2T_{cy})/2l \leq d_\phi \leq (T-2T_{cy})/2l \\ \hline -(T-2T_{cy})/2l \leq d_\psi \leq (T-2T_{cy})/2l \\ \hline e_i - T_{cy} \leq d_y \leq e_s \\ \hline e_i - T_{cy} \leq d_z \leq e_s \end{array}\right\} \quad \text{……….3}$$

From equation 3, each degree variables' movement range of the cylindricity tolerance zone's coordinate system can be evaluated. This determines the position and direction of the cylindricity tolerance zone. Based on the mathematical model described in form of equations above, we can derive the simulation cylinder of the hole. The above equation determines the position and direction of the cylindricity tolerance zone.

$$-T_{cir}/2 \leq \sqrt{(y+\delta_y)^2+(z+\delta_z)^2}-r \leq T_{cir}/2 \quad \text{……….4}$$

Where

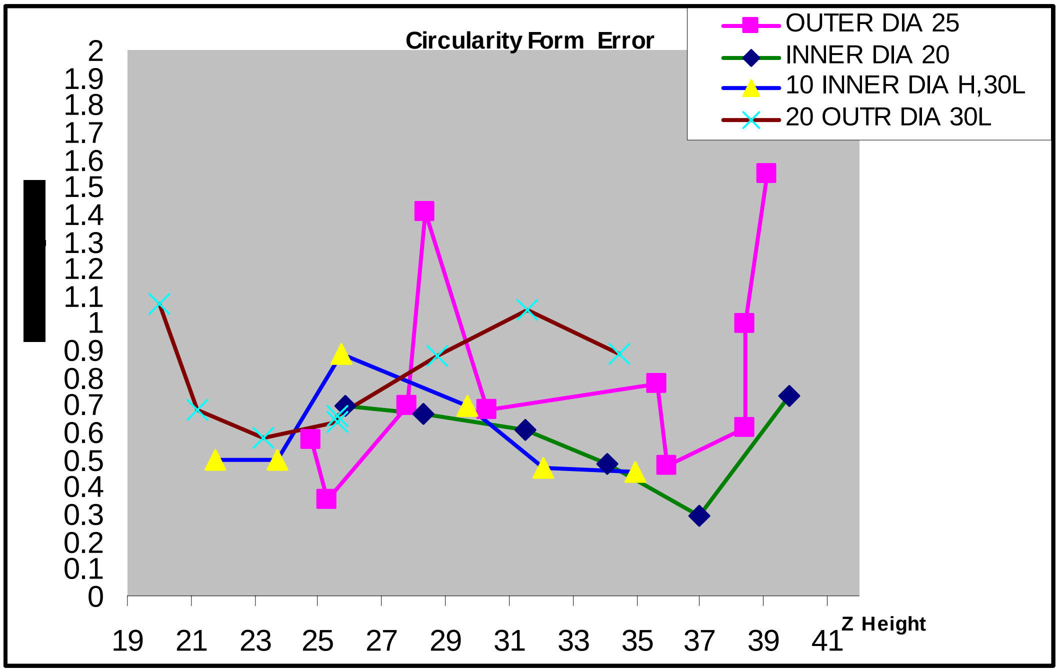
$-T_{cir}/2$ is $\leq \delta_y \leq T_{cir}/2$, $-T_{cir}/2$ is $\leq \delta_z \leq T_{cir}/2$

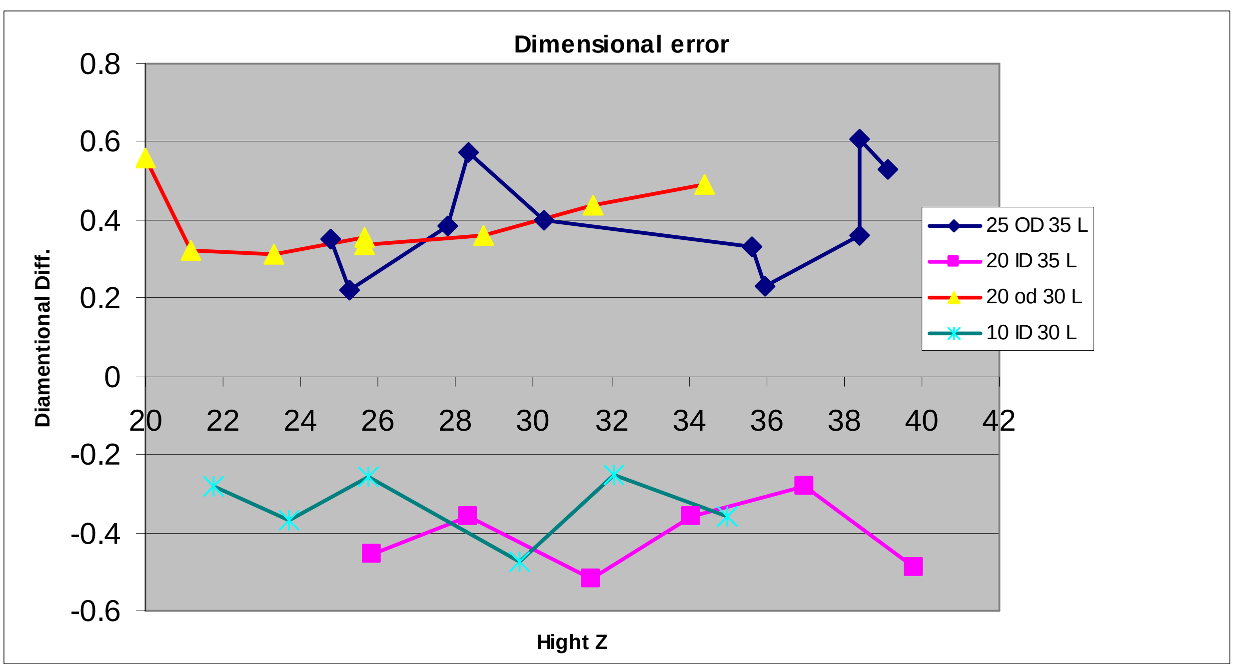
Usually the radius of the circularity tolerance zone is not equal to the radius of size tolerance zone. The degree variable's variation zone of circularity tolerance zone's axes is as follows.

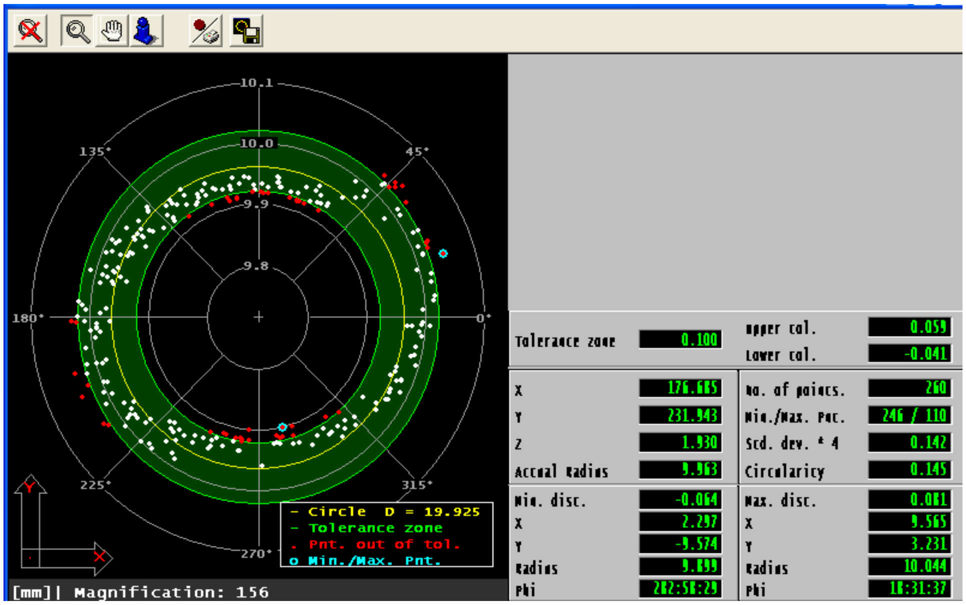
$$\left\{\begin{array}{c} \dfrac{(e_s^{\,2}-e_i^{\,2})/4+(e_s-e_i+2T_{cir})*r}{4r+e_s+e_i} \leq d_y \leq \dfrac{(e_s^{\,2}-e_i^{\,2})/4+(e_s-e_i+2T_{cir})*r}{4r+e_s+e_i} \\ \\ \dfrac{(e_s^{\,2}-e_i^{\,2})/4+(e_s-e_i+2T_{cir})*r}{4r+e_s+e_i} \leq d_z \leq \dfrac{(e_s^{\,2}-e_i^{\,2})/4+(e_s-e_i+2T_{cir})*r}{4r+e_s+e_i} \end{array}\right\} \quad \text{……….5}$$

5. RESULTS AND DISCUSSION

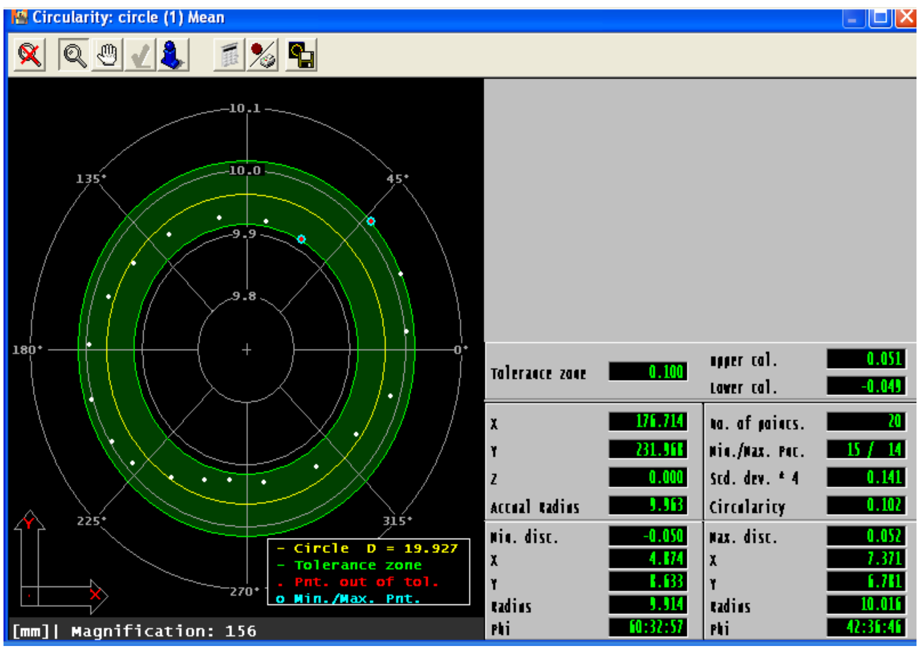
Cylinders of various diameter are fabricated using fused deposition rapid prototype machine (FDM) with varying orientation angles 0 to 90 degrees, and measured with Mitutoyo Coordinate measuring machine (CMM). The circularity error and dimensional error of various sections at various height are shown below.



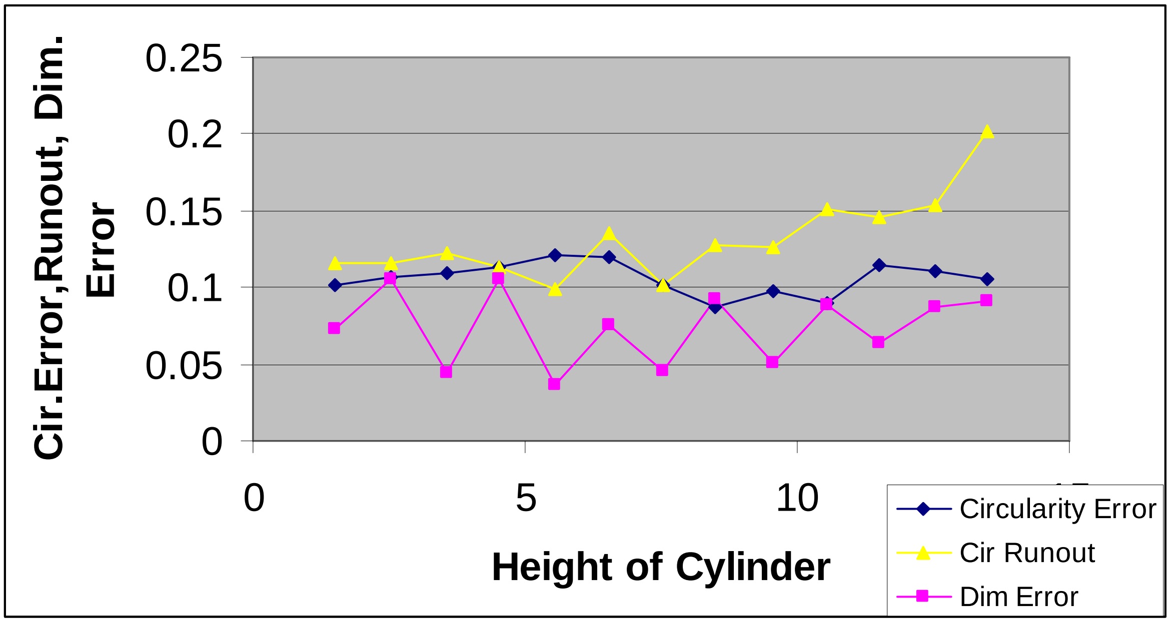




Cylindricity data of 20 mm dia Cylinder. CMM graphic output. (90^0 orientation)



Cicularity of 20mm dia Cylinder at height of 1.5mm, CMM graphic output. (90^0 orientation)
The circularity error, Runout and dimensional error for cylinder of 20mm Outer diameter at zero degree orientation is shown below of various circular cross-sections at various heights.



The various error of 20mm cylinder at zero degree orientation at different heights is shown below. The cylindricity error is O.145, and average diameter of cylinder is 19.925mm

For 0 Deg Orientation 20mm Outer Dia

S.No	Z height	Circularity Error	Nominal Radius	Circular Runout	Measured Displacment Dx	Dy	Max. allowable deviation
1	1.514	0.1020	9.9635	0.116	0.020	0.016	0.075499
2	2.528	0.107	9.9475	0.116	0.007	0.018	
3	3.577	0.110	9.978	0.123	0.004	0.014	
4	4.530	0.113	9.9475	0.113	0.006	0.021	0.078232
5	5.559	0.121	9.982	0.099	0.019	0.015	
6	6.534	0.120	9.962	0.136	0.043	0.032	
7	7.542	0.101	9.9775	0.102	0.034	0.033	0.075246
8	8.502	0.087	9.954	0.128	0.053	0.036	0.071745
9	9.549	0.098	9.9745	0.126	0.041	0.048	0.074493
10	10.569	0.090	9.9555	0.151	0.054	0.053	
11	11.512	0.115	9.968	0.146	0.049	0.054	
12	12.527	0.111	9.9565	0.153	0.060	0.047	
13	13.507	0.106	9.9545	0.202	0.067	0.076	0.075499

All dimensions are in mm .

Average	0.1062	19.926	0.132	0.038	0.037	0.074
Std Dev	0.0101	0.0228	0.0262	0.0200	0.0186	0.0228

For 0 Deg orientation Inner 20mm Dia (cylindricity 0.133)

S.No	Z height	Cir Error	Nominal Radius	Circular Runout	Measured Displacment Dx	Dy	Max. allowable deviation
1	1.466	0.08	9.993	0.094	0.011	0.018	0.069999
2	2.41	0.07	9.9625	0.072	0.012	0.015	0.067502
3	3.479	0.075	9.973	0.083	0.012	0.006	0.068746
4	4.471	0.094	9.981	0.09	0.019	0.024	0.073501
5	5.5	0.069	9.9825	0.09	0.02	0.04	0.067247
6	6.494	0.065	9.9815	0.072	0.021	0.029	0.066247
7	7.508	0.061	9.997	0.104	0.028	0.043	0.065246
8	8.407	0.084	9.947	0.106	0.025	0.047	0.070992
9	9.446	0.066	9.9865	0.135	0.038	0.056	0.066493
10	10.442	0.074	9.952	0.143	0.04	0.059	0.068496
11	11.499	0.055	9.9815	0.173	0.048	0.072	0.063748
	Average	0.072917	9.976042	0.11208	0.0267	0.0406	
	Std Dev	0.01042	0.014655	0.03615	0.0129	0.0219	

The various error of 20mm cylinder at 45 degree orientation at different heights is shown below. The cylindricity error is O.188, and average diameter of cylinder is 19.895mm

For 45 Deg. Orientation 20mm Outer Diameter

S.No	Z height	Cir Error	Nominal Radius	Circular Runout	Measured Displacment Dx	Dy	Max. allowable deviation
1	1.20	0.134	9.9435	0.137	-0.005	0.003	0.100505
2	2.48	0.114	9.9315	0.118	-0.004	0.000	0.085486
3	3.44	0.127	9.9325	0.126	-0.016	0.007	0.094728
4	4.504	0.135	9.9375	0.138	-0.018	0.023	0.100742
5	5.586	0.113	9.9435	0.104	-0.019	0.025	0.084729
6	6.47	0.109	9.9515	0.109	-0.016	0.027	0.081749
7	7.447	0.099	9.9475	0.104	-0.023	0.031	0.074237
8	8.566	0.108	9.9495	0.118	-0.030	0.034	0.081486
9	9.480	0.128	9.9485	0.128	-0.025	0.043	0.095984
10	10.522	0.108	9.9445	0.113	-0.035	0.045	0.080997
11	11.477	0.116	9.9535	0.125	-0.026	0.057	0.086999
12	12.487	0.115	9.953	0.118	-0.024	0.044	0.086239
13	13.482	0.161	9.968	0.159	-0.028	0.044	0.120747
14	13.485	0.142	9.9655	0.153	-0.024	0.046	0.106981
15	14.295	0.140	9.968	0.137	-0.041	0.036	0.105504
	Average	0.123	9.949	0.126	-0.022	0.031	
	Std Dev.	0.0162	0.022	0.016	0.010	0.016	

All dimensions are in mm.

For 25 Deg orientation 20mm Outer Diameter. (cylindricity 0.1327)

S.No	Z height	Cir Error	Nominal Radius	Circular Runout	Measured Displacment Dx	Dy	Max. allowable deviation
1	1.455	0.106	9.921	0.098	0.009	0.001	0.079011
2	2.509	0.096	9.926	0.098	-0.013	0.011	0.072514
3	3.498	0.087	9.921	0.088	-0.01	0.009	0.06526
4	4.524	0.095	9.9165	0.092	-0.012	0.019	0.071253
5	5.499	0.082	9.922	0.077	-0.018	0.013	0.061501
6	6.552	0.072	9.923	0.084	-0.03	0.014	0.053996
7	7.526	0.086	9.9295	0.1	-0.036	0.025	0.064498
8	8.527	0.093	9.93	0.109	-0.032	0.033	0.070251
9	9.489	0.087	9.933	0.093	-0.028	0.023	0.065257
10	10.51	0.08	9.9305	0.1	-0.038	0.032	0.059999
11	11.45	0.077	9.93	0.088	-0.034	0.028	0.057754
12	12.49	0.113	9.931	0.125	-0.04	0.041	0.084738
13	13.36	0.085	9.93	0.105	-0.028	0.042	0.063748
14	14.29	0.105	9.938	0.128	-0.042	0.038	0.078769
15	1.455	0.106	9.921	0.098	0.009	0.001	0.079011
	Average	0.09028	9.925	0.099	-0.025	0.023	
	Std Dev	0.01132	0.0112	0.0139	0.014	0.012	

The consistency of the data point mentioned above is tested using Chauvenet's criterion and it is found that there is no inconsistency in the test data points.
From these reading it is observed that the circularity, diametrical and runout errors are minimum for zero degree orientation for the cylinder. The cylindricity error is also minimum at zero degree orientation. However the maximum translation error is more at zero degree orientation. This clearly shows that decisions cannot be based purely on conventional form error like circularity error, cylindrcity and dimensional error.
The translational error and rotational error are much more important in assembly operations and dynamic service condition. Hence a tolerance zone mathematical model established by inequality based on the degree of feature is more important to take care of translational errors.

6. CONCLUSION

1. Real feature can be called feature with error due to translation and rotation and is composed of points in the nominal feature after some ways of movement. Hence a generic mathematical model is developed which can use real feature tolerance for calculating the form error to give more accurate results. This approach will reduce the difficulties in assembly operation.
2. A tolerance zone mathematical model is established and variance area of each tolerance zone is obtained. The equations developed can be used for determining the maximum transfer along the axis.
3. This approach helps to create simulation cylinder of the hole during assembly or dynamic operation. This simulation model will help in identification of the possibilities of seizure of piston during its operation in cylinder or seizure of bearings for shaft.

4. This tolerance model is essential for integration of CAD and CAM. This integration can mitigate the problems while bridging the gap between CAD and CAM

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