SPECIFICATIONS FOR THE DEVIATION OF 3D REFERENCE AXES

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Abstract: In many precision machines and equipment, there are two or three reference axes intersecting at a point theoretically as per the drawing. One example is gyro spin axes construction. The other examples are N/C machine tool spindle axis and table axis as reference axes. Yet another example is the three bevel gear reference axes of space equipment like helicopter, intersecting at a common point. In all the above examples, theoretically the axes have to meet at a common point. But at manufacturing stage one has to specify the acceptable deviation. Presently each axis is measured separately for its straightness or perpendicularity with some surface. Though the axes are measured separately one cannot say to what extent they are meeting or how closely they are approaching to the theoretical intersection point. Further there is no standard to specify this error. The authors have earlier established and published different ways of fitting axis. Some six methods of specifying the deviation/error were also defined. In this paper a method of specifying the error namely Maximum Throat Deviation (MTD) is discussed and an algorithm to compute it is explained.

Keywords: GD & T, Evaluation of reference axes, Error evaluation.

1. INTRODUCTION

Measurement of straightness, flatness etc related to one dimension or two dimensions is well established. These are dependent on the availability of a suitable measuring instrument and an evaluation technique based on available 2D geometric tolerancing standard and evaluation technique. In any precision equipment or machine, there are two or three mutually perpendicular axes, corresponding to the slides and/or spindle. The present practice is to measure and evaluate each axis for its linearity/straightness, because of the limitations of a measuring instrument and because of the non-availability of a suitable evaluation standard. Presently the trend is complete elimination of 2D drawings and migration to 3D with dimensioning and tolerancing in 3D drawings. In this regard, a new ASME Y14.41-2003, STANDARD FOR CAD in to the digital domain is already available [1], (Digital product definition data practices and X dimensioning and tolerancing Y14.41 & Y14.5M). In this context, there is a need for suitable evaluation techniques for application in 2D and 3D tolerancing. A method for evaluation of two mutually perpendicular axes has been reported by the author [2], which evaluates an artefact with number of holes along two perpendicular rows for its hole positioning accuracy and alignment of the holes. A method for evaluation of three mutually perpendicular/non-perpendicular & intersecting axes has been reported by the author [3, 4], which evaluates the three likely intersecting axes of precision equipment.

After developing different methods for evaluation of the axes supposed to passing through a point six different ways of specifying the deviation are indicated. In this paper a specific method of specifying the error namely Maximum Throat Deviation is discussed and an algorithm is presented.

Matlab version 7.6.0 has been used for developing the algorithm and for simulation and verification of the proposed method.

2. PROBLEM DEFINITION

The problem definition and the work done so far are explained with the help of a figure. Fig.1 shows a Cartesian coordinate system with three likely intersecting axes (as per the design drawing of a helicopter gear box). The measurements corresponding to the three axes are represented with three different symbols (**o, +, ·**). The problem is: how to find-out the likely point of intersection of these axes and how closely they are approaching and how to evaluate and specify the deviations/error?

3. ANALYSIS

To analyse the problem different methods were proposed [4, 5]. In one of the methods best-fit axis for each reference axis is fitted and shortest distance is treated as the error. There are three shortest distances taking two lines at a time. If one considers the end points of these shortest distance lines, one gets six points (say P_1 to P_6). In another method three best fit planes are fitted taking two axes at a time and the intersection of the three planes gives a point of intersection. This can be considered as seventh point (P_7) to approximate the actual theoretical intersection point. The location of this from the theoretical one is the deviation. The above methods have been applied for different data and the results are satisfactory [6]. Theoretically all the 7 points mentioned above should converge to the theoretical point with zero deviation. However, the following deviations are defined for error specification.

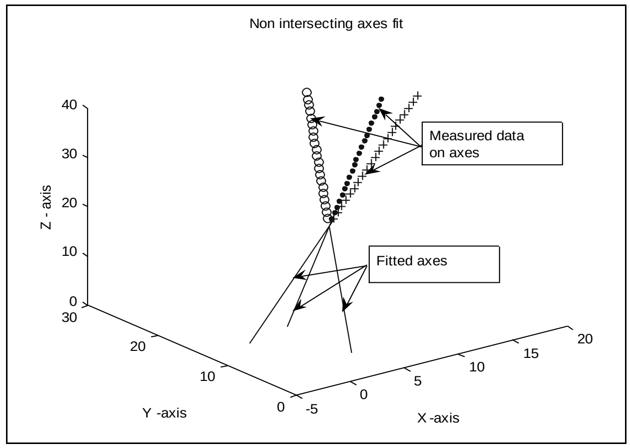

Fig. 1: Reference coordinate system along with the three axes to be evaluated.

1. Enclosed Spherical Deviation (ESD): It is defined as the diameter of the minimum sphere enclosing all the 6 coordinates of the end points of the three shortest distance lines.
2. Maximum Distance Deviation (MDD): It is defined as the maximum distance among the 15 distances (${}^6C_2$ = 15, distance between six different points P_1 to P_6 taken two at time).
3. Maximum Shortest-distance Deviation (MSD): It is defined as the maximum of the three shortest distances.
4. Tangential Spherical Deviation (TSD): It is defined as the diameter

of the smallest sphere tangential to all the three lines

5. Maximum Throat Deviation (MTD): It is defined as the maximum throat of the hyperboloids constructed with each of the lines about a theoretical mean axis.
6. Simple Spherical Deviation (SSD): It is defined as twice the maximum distance computed from the theoretical axis intersection point to the end points of shortest distance lines.

The approach for computations of ESD is given by the author [6]. The computation of MDD and MSD is simple and explained in [4, 5, 6]. The TSD has some importance. The method of computing TSD is interesting and is explained in [8] and given below in brief, as it is partly required in the derivation of MTD.

3.1 Method to Compute TSD

In this method the following logic is used. Let one assume a theoretical mean axis or the specified mean axis for measurement and evaluation purpose to be specified in GD & T. When all the three axes are projected on to a plane perpendicular to the mean axis or specified axis, one gets three lines in the 3D plane. The three lines give three points of intersection forming a triangle as shown in Fig.2. The triangle so formed in 3D space is shown in Fig.3, where the space lines are the lines joining the pair of points {(a_1, b_1, c_1), (a_2, b_2, c_2)}, {(a_3, b_3, c_3), (a_4, b_4, c_4)}, and {(a_5, b_5, c_5), (a_6, b_6, c_6)}. The corresponding pair of projected points on to a plane are {(x_1, y_1, z_1), (x_2, y_2, z_2)}, {(x_3, y_3, z_3), (x_4, y_4, z_4)}, and {(x_5, y_5, z_5), (x_6, y_6, z_6)}. Fig 3 also shows a small triangle formed by extending the projected lines (See near x_2, y_2, z_2).

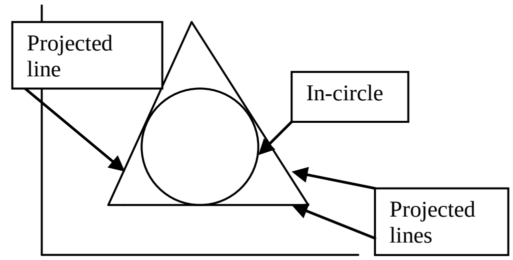

Fig. 2: Axes projected in the plane perpendicular to the specified mean axes.

The in-circle tangent to all the three sides of the triangle represents the sphere tangent to all the three axes in space. Its diameter is the TSD.

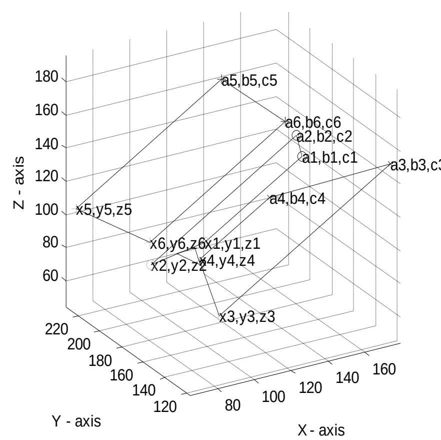

Fig. 3: Three space lines {line 1 joining points (a_1, b_1, c_1), and (a_2, b_2, c_2) etc.} and their projections {projected line 1 joining (x_1, y_1, z_1) and (x_2. y_2, z_2) etc.} in the plane **$lx + my + nz = p$**

3.2 Method to Compute MTD

Maximum Throat Deviation (MTD): It is defined as the maximum throat of the hyperboloids constructed with each of the lines about a theoretical mean axis.

To compute the size of the throat that may be formed by the three space lines the following steps/concepts are used.

Fig.4 shows coaxial hyperboloids formed by rotating a space line about an axis. If the 3 space lines meet at a point (intersect the axis) the throat will be zero. And the hyperboloids will be simplified to cones. To determine the throat of the hyperboloid to be formed by the three space lines the following method is attempted.

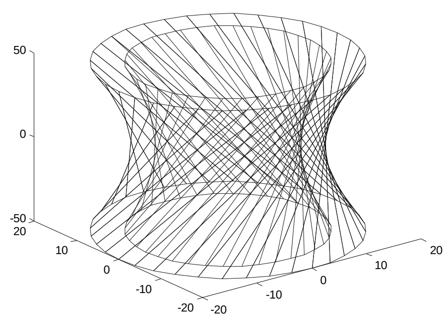

Fig.4: Coaxial hyperboloids

A plane normal to the axis (mean viewing axis direction) is considered. The intersection of the normal plane with all the three space lines gives three points. The three points form a triangle in that plane as shown in Fig.5. A circle can pass through the points. The diameter of the circle is the likely cross section in that plane. Different planes normal to the axis are considered and different circles are fitted. The smallest diameter of the circles so formed is taken as the MTD. This can be visualized from Fig.5 and Fig.6. The Fig.6 is the enlarged portion near the throat.

3.3 Mathematical Analysis

The intersection points of the line with the plane are obtained by solving the equation of the line and the plane. The equation of line 1 and the plane are given by

$$\mathbf{(x-a_1)/l_1 = (y-b_1)/m_1 = (z-c_1)/n_1 = K_1}$$

and

$$\mathbf{lx + my + nz = p}$$

Solving one gets

$$\mathbf{x = a_1 + K_1 l_1}$$

$$\mathbf{y = b_1 + K_1 m_1}$$

$$\mathbf{z = c_1 + K_1 n_1}$$

where K_1 is given by

$$\mathbf{K_1 = (p-l_1a_1-m_1b_1-n_1c_1)/(ll_1+mm_1+nn_1)}$$

Similarly the intersection points with other lines are obtained and joined as in Fig.5 to form a triangle.

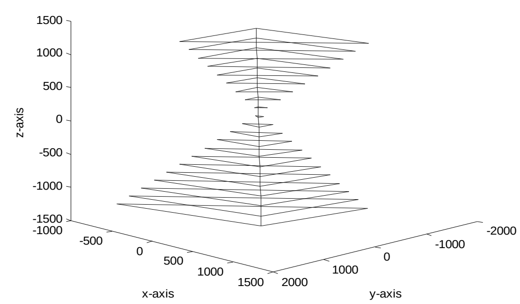

Fig.5. Intersection points of the three space lines (joined to form a triangle) with different parallel planes

4. RESULTS

Table 1 shows the results of the analysis for a specific simulated data. The first three rows show the direction cosines of the three lines and the fourth row shows the viewing direction data.

Table. 1 Results of proposed method for MTD

	Direction cosines of lines		
line	l	M	n
line 1	-0.43	-0.65	0.62
line 2	-0.27	0.80	-0.53
line 3	0.70	-0.18	-0.69
view direction	-0.0016	-0.0411	-0.9992
	Points on lines		
point i	a (i)	b (i)	c (i)
point 1 on line 1	169.36	190.73	125.59
point 2 on line 1	142.57	150.51	163.85
point 3 on line 2	173.95	117.13	153.88
point 4 on line 2	150.44	188.23	107.04
point 5 on line 3	117.38	176.75	192.57
point 6 on line 3	147.81	169.05	162.50
	Projected points		
point i	x(i)	y(i)	z(i)
projected point 1	169.34	190.16	112.01
projected point 2	142.49	148.45	113.77
projected point 3	173.89	115.53	115.07
projected point 4	150.45	188.43	112.11
projected point 5	117.25	173.47	112.78
projected point 6	147.72	167.02	113.00
	Vertices of the triangle at the throat (p=-136)		
vertex 1 of triangle	167.60	188.08	128.11
vertex 2 of triangle	161.73	154.10	129.51
vertex 3 of triangle	181.46	160.53	129.22
Results			
Radius of Circum circle (R1) at different sections (p =-142 to -128) near throat			
	Sr No	P	R1
	1	-142	20.86
	2	-140	18.74
	3	-138	17.62
	3	**-136**	**17.45**
	5	-134	17.96
	6	-132	18.94
	7	-130	20.06
Location of throat	At p = -136		
Radius at throat	17.45 units		
MTD	34.90 Units		
TSD[8]	7.62 Units		

Next data shows two points on each line (a_1, b_1, c_1), (a_2, b_2, c_2), etc. and then the projected coordinates (x_1, y_1, z_1), (x_2, y_2, z_2), the vertices of the triangle formed at the throat and finally maximum throat deviation (MTD). The value of tangential spherical deviation (TSD) [8] is also given. A portable CMM is used [9] for measurements.

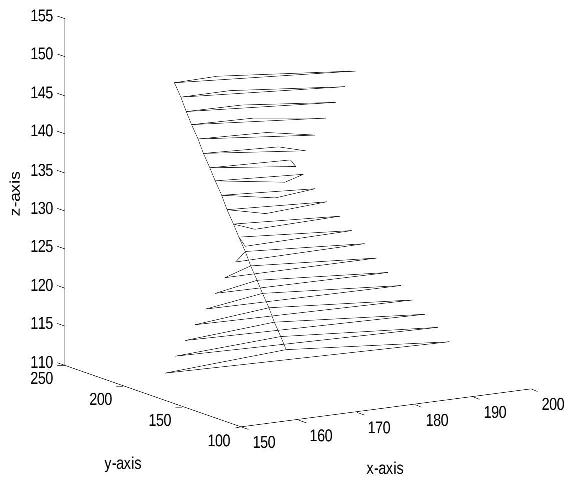

Fig.6 Enlarged view near the throat

5. CONCLUSIONS

Different methods developed to find best fit space axes satisfying the constraints to some extent for the randomly oriented three axes of a precision machine or equipment like helicopter gear box are briefly explained. Also six different ways of specifying the error are defined. Finally methods of computation of TSD and MSD are explained. Further minimum zone values can be found by the methods suggested in [10]. The approach discussed along with its algorithm is found convenient. The results of the algorithm are also given in the form of a table. The future work involves in developing algorithm for SSD etc.

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