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COMPARISON OF GEOMETRICAL CHARACTERISTICS AGAINST ROTATING SHAFT VIBRATION

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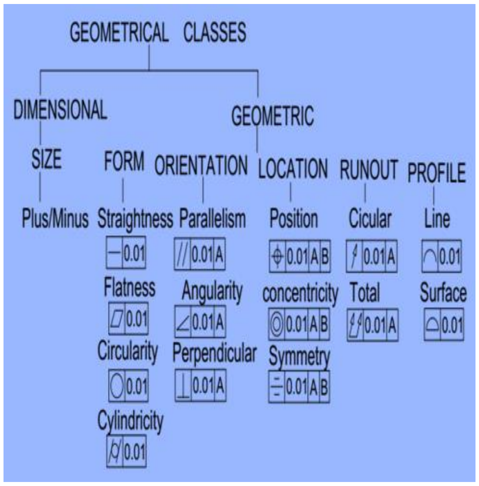
Graphical abstract



Abstract

Geometrical dimensioning and tolerance (GD&T) are an important element of the industry that uses high-speed rotation. Poor geometrical tolerance (GT) to components will cause the rotor to become unbalanced. Unbalanced rotor and shaft misalignment are the two major sources of vibration in the rotating system. This paper compares geometrical characteristics (GCs) to investigate the effects of vibrations generated by different GCs. Only four GC shafts were compared, straightness, parallelism, cylindricity, and concentricity, referring to the GD&T standard as ASME Y14.5-2009. These four GCs were selected owing to their direct involvement in the rotating system. Specimens are constructed with parameters of the same dimensions, length, and GT values only differ from GCs. Specimens were measured using a digital gage to find the GT value near 3000 micron at 3 mm. The magnitude of the shaft vibration during rotation was recorded using a VA-12 vibration analyzer with different rotational speeds: 510, 770, and 900 rpm. From the vibration data, the GCs' effect on the rotation shaft will be determined. GCs are found to have significant effects on the rotation of the shaft that should be considered in the design, installation, and maintenance of rotating shafts. The impact and degree of damage to critical parts of the system can serve as a benchmark for further studies for the optimization of tolerance values and for the maintenance of component performance.

Keywords: Geometrical Tolerance (GT), Rotational Speed, Rotating Shafts, Unbalanced Rotors, Shaft Misalignment, Vibration, Geometrical Characteristics (GC)

Abstrak

Dimensi & toleransi geometri (GD & T) merupakan elemen penting dalam industri yang menggunakan pusingan putaran berkelajuan tinggi. Toleransi geometri (GT) yang tidak baik terhadap komponen akan menyebabkan rotor tidak seimbang. Rotor yang tidak seimbang dan salah penjajaran aci adalah dua sumber getaran utama dalam sistem berputar. Kertas ini membuat perbandingan ciri-ciri geometri (GCs) bertujuan untuk menyiasat kesan terhadap getaran yang dihasilkan dari GCs yang berbeza. Hanya empat GCs aci dilakukan perbandingan seperti straightness, parallelism, cylindricity dan concentricity, merujuk kepada standard GD & T adalah ASME Y14.5-2009. Empat GCs ini dipilih kerana ciri-ciri ini terlibat secara langsung didalam sistem putaran. Spesimen dibentuk dengan parameter yang sama dimensi, panjang dan nilai geometrical tolerance (GT) cuma berbeza dari GC. Spesimen diukur dengan menggunakan tolok digital untuk mengetahui nilai GT menghampiri nilai 3000Micron@3mm. Magnitud getaran aci semasa putaran direkodkan menggunakan penganalisis getaran VA-12 menggunakan kelajuan pusingan yang berbeza iaitu 510 rpm, 770 rpm dan 900 rpm. Dari data getaran, kesan GCs pada aci putaran akan dikenalpasti. GCs didapati mempunyai kesan yang signifikan terhadap putaran aci akan diberi perhatian dan harus diambil kira dalam proses reka bentuk, pemasangan dan penyelenggaraan aci berputar. Impak dan tahap kerosakan bahagian kritikal dalam sistem boleh menjadi penanda aras bagi kajian lanjut untuk pengoptimuman nilai toleransi dan untuk mengekalkan prestasi komponen.

Kata kunci: Toleransi Geometri (GT), Kelajuan Putaran, Aci Berputar, rotor tidak seimbang, aci tidak sejajar, Getaran, Ciri-ciri geometrical (GC)

1.0 INTRODUCTION

In the process of designing the rotating system, the important thing to be determined is the accuracy of the rotation. Unbalanced rotor and shaft misalignment are the two main causes of vibration in the rotating machine system [1, 2]. From the assessment, misalignment was found to be the cause of 70% of the turning hardware vibration issues [3]. High-magnitude vibrations can damage important parts of a rotating machine system, such as bearings, gears, and couplings. Many studies have been conducted regarding the effects of unbalanced rotor and shaft misalignment at critical speed and vibration amplitude in the rotating machine [4]. The accuracy of the rotation involves the issue of geometrical characteristics (GCs) to be considered for the rotating machine system. Rotational accuracy is influenced by various factors, such as the appropriate tolerance design, the parameters for the installation process, and the ability to make changes to the design of the parts. The accuracy of rotational parameters will give a direct impression on the performance of the rotating machine system. It is important to study the design with the accuracy of the rotation and investigate the optimum geometrical tolerance (GT) value to improve the performance of the rotating machine system. The design of high precision systems requires consideration of operating performance in determining the overall quality of the system [5].

Machines which involve shaft rotation are used in almost every industry, from automotive and aerospace to medical equipment. High rotational speed shafts and long hours of operations are common in rapid pump and turbo machinery industries. Attention should be given to the critical rotation of the shaft, and the damping system should be designed taking into consideration the effects of GCs. Such a condition will affect the very large lateral forces acting on the bearing during resonance. The turning speed of the rotating shaft is high; therefore, any weakness in the system design in geometry and material may damage the rotating shaft system [6].

High-performance modern machines typically operate at critical speeds that are considered the most important mods in the system, operating continuously at or near critical speeds. Maintaining a critical speed margin of 15% between the operating speed and nearest critical speed is the practice used in industrial applications [7]. The misaligned shaft on the drive shaft and the rotating machine occurs because these two elements are not in the same center point. The misalignment can generate an excessive force and increase the system's vibration which causes the diagnostic processes more difficult in the designing process. In addition, wrong alignment can also cause other effects such as thermal growth, uneven burden consumption and not fit to the system. Misalignment of the machinery shaft will also generates extra forces of reaction and moment in the coupling, affecting the machine system during rotation.

Most of the research on dimension and tolerance are focusing primarily on a model development in order to produce a tolerance-related studies. The methods for determining GCs are still a major issue in the modeling tolerance simulation because most tolerance determinations show abstraction of geometrical deviation [8]. Most tolerant collection models only consider operating weaknesses and parts rotation characteristics. GC is fundamental in the design and consists of tolerance analysis for GCs effect prediction on function and product quality. The GT has been introduced gradually with the aim of providing a more comprehensive way of determining the variation of geometrical products allowed for functional and technical requirements. Based on the GT value, it can describe various variations related to the shape, position, and orientation of the GCs [9]. The tolerance model adopted is the basis of the calculation of tolerance as it represents a mathematical model estimating the effect of a combination tolerance component on the assembly process [10]. Tolerance of parts has a significant impact on the formulation of the part manufacturing process plan. Within the allowed tolerance, the user can select the most cost-effective process plan [11].

Unbalanced force causes flexible flexural bending due to the speed of rotation and excessive vibration in the frequency of rotation. An imbalance can be seen as a component of vibration at rotational frequency []. The dynamic behavior of the rotating shaft is usually derived from unbalanced stiffness variations, shaft bending, and critical speeds related to resonance. The frequency changes when shift shaft rotates changes. Shaft misalignment in the rotating machine is one of the most common faults that cause damage and machine failure. It causes more than 70% of the vibration problems and the rotating machine system. Misaligned rotor will cause excessive force applied to the bearing, and extreme vibration will make the diagnostic process more difficult []. The accuracy of the manufacture will affect the dynamic geometry of the rotating cylinder. The size of the rotating cylinder changes depending on the centrifugal force and the stiffness variation of the cylinder shell. The centrifugal effect of dynamic geometry is the function of the rotating speed. The vibration analysis of the rotating system is important for detecting and locating major faults, such as mass unbalance, shaft alignment, and cracked shaft vibration [12].

This paper compares the GCs, with the aim of investigating the effects of vibrations generated from the four GC shafts, straightness, parallelism, cylindricity, and concentricity, referring to the GD&T standard as ASME Y14.5-2009. The impact of GCs on the rotating shaft that is significant to the shaft rotation will be noted and considered in the design, installation, and maintenance of the rotating shaft. The GC differences between the models give different effects on the rotating system. It is therefore important for us to identify GCs that have serious effects on the system. The impact and damage level of critical parts of the system can serve as a benchmark for further studies to improve system performance.

2.0 METHODOLOGY

ASME is in the process of expanding and enhancing the use of GD&T language with standard ASME Y14.5-2009 release. The ISO Geometrical Product Specification Standards have also evolved with significant progress in the ISO GD&T standards. In the GD&T applications, there are 14 GC symbols in five categories. The GC symbols are used on planar surfaces, and GT is used to control the value of shape deformation as presented in Table 1.

In the GC application, only four characteristics, straightness, parallelism, concentricity, and cylindricity, are involved in the study. Table 2 presents the experiment parameters. These four GCs were selected owing to their direct involvement in the rotating system. Specimens are constructed with fixed parameters for the dimensions, length, and GT value of 3000 micron at 3 mm. Specimens are formed by using the GC type and spindle speed as the variable parameters to obtain characteristics that cause the highest cause of vibration that affects the system [13]. Shaft specimens are formed using turning machine four jaw, three jaw, and press machine for bending the shaft.

Table 1 Geometrical characteristic control

GEOMETRICAL CHARACTERISTIC CONTROL 14 characteristics that may be controlled		
TYPE OF FEATURE	**TYPE OF TOLERANCE**	**CHARACTERISTIC**
INDIVIDUAL (No Datum Reference)	FORM	FLATNESS
		STRAIGHTNESS
		CIRCULARITY
		CYLINDRICITY
INDIVIDUAL OR RELATED FEATURES	PROFILE	LINE PROFILE
		SURFACE PROFILE
RELATED FEATURES (Datum Reference Required)	ORIENTATION	PERPENDICULARITY
		ANGULARITY
		PARALLELISM
	RUNOUT	CIRCULAR RUNOUT
		TOTAL RUNOUT
	LOCATION	CONCENTRICITY
		POSITION
		SYMMETRY

Table 2 Experiment parameter

Experiment					
Variable Parameter	**Fixed Parameter**				
	Rotating Speed, rpm (rev/min)			**Shaft Dimention (mm)**	**GT Value (micron)**
Straightness	510	770	900	Dia 1=50; Dia 2=34; Long=350	3000
Parallelism	510	770	900	Dia 1=50; Dia 2=34; Long=350	3000
Cylindricity	510	770	900	Dia 1=50; Dia 2=34; Long=350	3000
Concentricity	510	770	900	Dia 1=50; Dia 2=34; Long=350	1000, 3000 and 5000

2.1 Straightness

Figure 1 shows a straightness tolerance charateristic in which describes the state of an axis or element to be placed. The straightness tolerance is used in the view where the controlled elements are represented by a straight line and the condition in which the surface or axial element is a straight line.

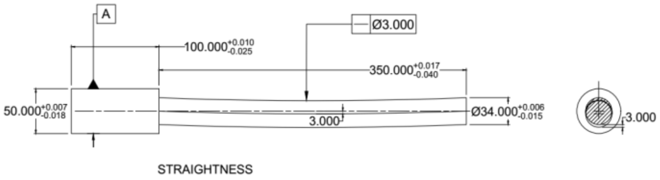


Figure 1 Straightness characteristic control

2.2 Cylindricity

Figure 2 shows the cylinder tolerance characteristic which is to determine a tolerance zone that is bounded by two concentric cylinders. The center line point of the cylinder has to be placed in which the surface state of the revolution of all surface points is equal to the general axis. Cylindricity is similar to circularity in which both have a radius tolerance zone.

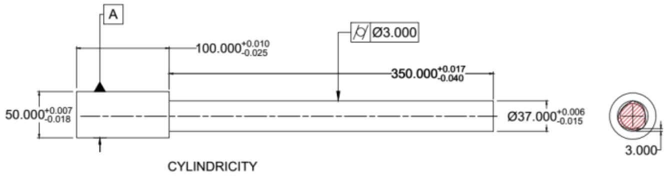


Figure 2 Cylindricity characteristic control

2.3 Parallelism

Figure 3 presents the tolerance of parallelism characteristic which is to determine the tolerance zone represented by two parallel planes or lines. The linesare aligned with the datum or axial plane, where the surface or axis of each character can be placed.

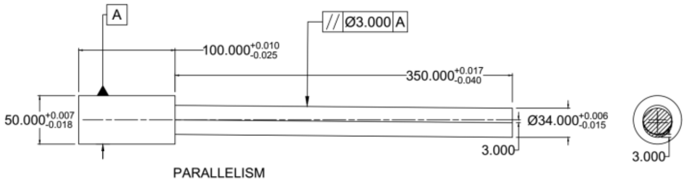


Figure 3 Parallelism characteristic control

2.4 Concentricity

Concentricity is defined as the relationship of the axes of cylindrical shapes as shown in Figure 4. It is a condition where the axes of all elements cross-section the surface of the general feature of the revolution to the datum axis. Concentricity tolerance characteristic will determine the cylinder tolerance zone where the axes coincide with the datum axis and where all the cross-section axis of the controlled feature must be placed. A perfect concentricity exists is when the axes of two or more cylindrical features are in perfect alignment.

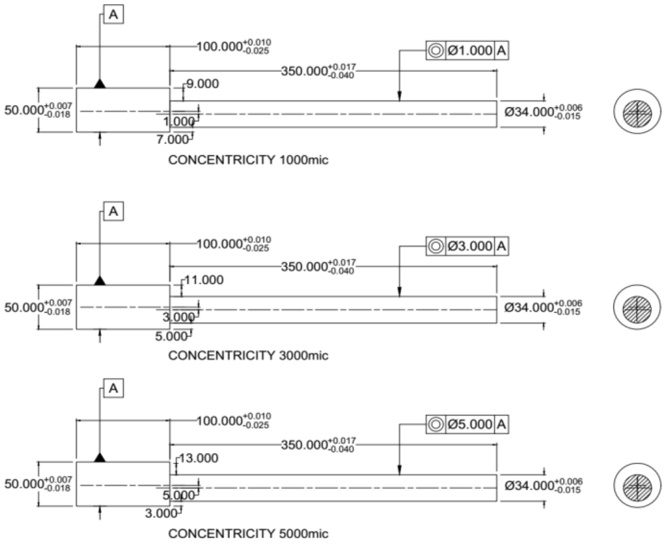


Figure 4 Concentricity characteristic control

2.5 Measure the Geometrical Tolerance Value

The shaft is usually an object shaped like a circle or a cylinder. In the manufacturing process, it is quite difficult to produce a shape with the correct GT value. GT and GC values will have different vibration effects on the shaft rotation. This study aimed to determine the relationship between the manufacturing accuracy and GT value and the GCs that have been determined. Specimens were measured using a digital dial gage to find GT values near fixed parameter values of 3000 micron at 3 mm. Large GT values are used to facilitate the comparative analysis of GCs performed with clearer data. In this case, due to the large GT value, the digital dial gage is best used compared with other tolerance measurement tools which are only suitable for values less than 1000 microns or 1 mm. Figure 5 presents the data extraction method using the digital gage to obtain the actual GT value.

Figure 5 Measurement of the geometrical tolerance value

2.6 Measure the Vibration Value

In the design process of the shaft, it is necessary to investigate the frequency of the rotating shaft. Different GCs will produce different vibration effects on the rotating system. The rotation depends on the centrifugal force and the variation of the cylinder stiffness. The centrifugal effect of dynamic geometry is a function of rotational speed [14]. Improper geometry of the shaft will generate vibrations in the rotating component and produce irregular sound and noise. In round cases, such as shafts, GCs refer to ideal GCs as circles [15]. It deals with vibration energy, vibration measurement in the medium frequency range (10 Hz to 1 kHz), unbalanced detection, misalignments, and vibration assessment refer to ISO (10816, JIS B 0906). Shaft vibrations during rotation were recorded using VA-12 vibration analyzer with rotation speeds of 510, 770, and 900 rpm. Spindle measures the velocity to quantity for indicate the amount of time per unit change. There are seven specimens with different characteristics to be performed without shaft, straightness, parallelism, cylindricity, concentricity 1000 micron at 1 mm, concentricity 3000 micron at 3 mm, and concentricity 5000 micron at 5 mm. The procedure was repeated on each shaft specimen to obtain vibration effects on different GCs. Figure 6 presents the method of capturing vibration data by using the VA-12 vibration analyzer during spindle rotation at a specified speed. The vibration data obtained will be analyzed to determine which GCs have the most impact on vibration.

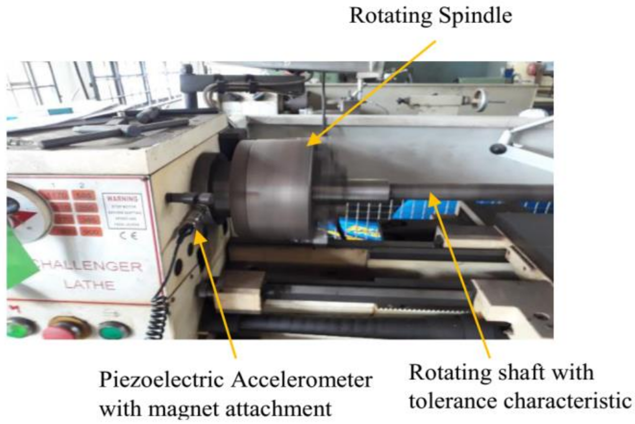


Figure 6 Measurement of the vibration value

3.0 RESULTS AND DISCUSSION

Model design enables consideration various types of deviations geometrical properties in tolerance analysis [16]. In this study, large GT values were used to simplify the machining process and to elucidate the effects of vibration during shaft rotation. Digital dial gauges are used because they are best suited for the measurement of large tolerance values. GT Data for shaft specimens taken with digital dial gage to be compared with GT fixed value of 3000 micron at 3 mm. This experiment using the same parameters for each shaft is just different is GCs. In this case, it is also difficult to obtain such tolerances in fixed parameters, but this result does not affect the purpose of determining GCs that influence shaft rotation.

To measure the straightness characteristic, 36-point is marked where each point is 10mm along the shaft distance and then the marks are measured using a digital dial gage. Table 3 shows the results of the measurement of the true GT value of the straightness characteristic, and Figure 7 is the data profile obtained, from which it is found that the GT value is 2671 microns at 2.671 mm and is almost to the GT value at fixed parameters.

Table 3 Data GT measurement for straightness characteristic specimen

GDT MEASURING TOOL	CATEGORY AND GEOMETRICAL CHARACTERISTICS																	
	FORM																	
Dial Gage	Straightness (3000 mic)																	
Point (Distance) (mm)	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
Geometrical Tolerance (mm)	0	-0.164	-0.340	-0.472	-0.646	-0.804	-0.981	-1.138	-1.281	-1.436	-1.607	-1.765	-1.927	-2.086	-2.245	-2.362	-2.441	-2.450
Point (Distance) (mm)	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	Tolerance
Geometrical Tolerance (mm)	-2.405	-2.284	-2.118	-1.921	-1.750	-1.570	-1.335	-1.185	-0.998	-0.791	-0.638	-0.424	-0.235	-0.065	0.145	0.325	0.429	2.671

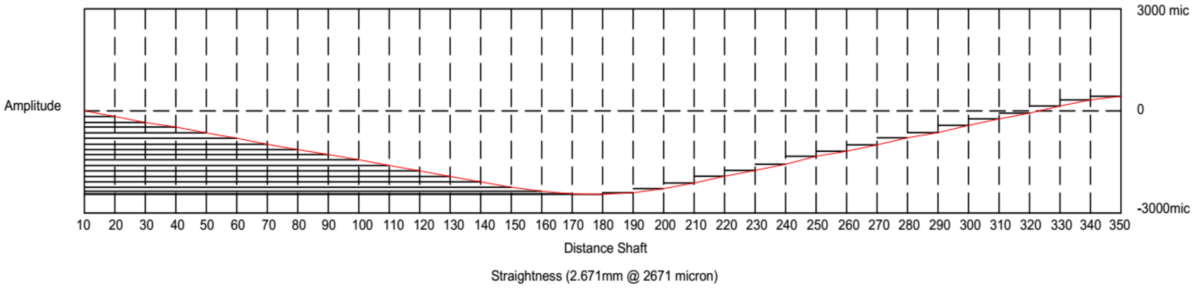


Figure 7 Profile GT measurement for straightness (2.671 mm at 2671 micron)

To measure the cylindricity characteristic, 24 angles is marked on the shaft surface and then the marks are measured using a digital dial gage. Table 4 presents the results of the measurement of the true GT value of the cylindricity characteristic, and Figure 8 is the data profile obtained, from which it is found that the GT value is 2671 microns at 2.201 mm and is close to the GT value at fixed parameters.

Table 4 Data GT measurement for cylindricity characteristic specimen

GDT MEASURING TOOL	CATEGORY AND GEOMETRICAL CHARACTERISTICS											
	FORM											
Dial Gage	Cylindricity (3000 mic)											
Point Angle	0/360°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	
Geometrical Tolerance (mm)	0	-0.023	-0.069	-0.647	-1.212	-0.675	-0.030	0.037	0.083	-0.040	0.025	0.293	
Point Angle	180°	195°	210°	225°	240°	255°	270°	285°	300°	315°	330°	345°	Tolerance
Geometrical Tolerance (mm)	0.014	0.942	0.420	-0.533	-0.703	-0.028	0.408	0.167	-0.286	-1.031	-1.259	-0.299	2.201

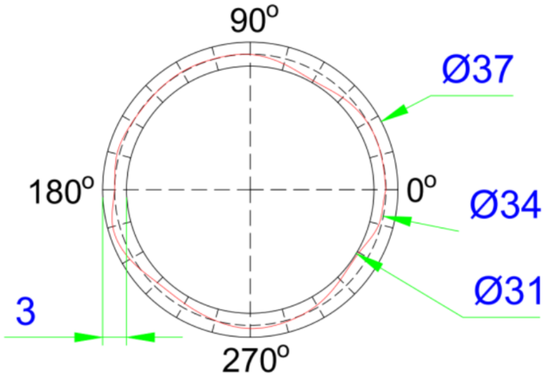


Figure 8 Profile GT measurement for cylindricity (2.201 mm at 2201 micron)

To measure the parallelism characteristic, 35 angles is marked on the shaft surface, and then the marks are measured using a digital dial gage. Table 5 presents the results of the measurement of the true GT value of the parallelism characteristic, and Figure 9 is the data profile obtained, from which it is found that the GT value is 2372 microns at 2.372 mm and is close to the GT value at fixed parameters.

Table 5 Data GT measurement for parallelism characteristic specimen

GDT MEASURING TOOL	CATEGORY AND GEOMETRICAL CHARACTERISTICS																	
	ORIENTATION																	
Dial Gage	Parallelism (3000 mic)																	
Point Distance (mm)	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
Geometrical Tolerance mm	0	-0.003	-0.031	-0.077	-0.140	-0.211	-0.286	-0.371	-0.435	-0.507	-0.599	-0.669	-0.748	-0.822	-0.901	-0.983	-1.064	-1.146
Point Distance (mm)	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	Tolerance
Geometrical Tolerance mm	-1.217	-1.288	-1.364	-1.435	-1.506	-1.575	-1.640	-1.714	-1.791	-1.863	-1.945	-2.014	-2.093	-2.158	-2.234	-2.304	-2.372	2.372

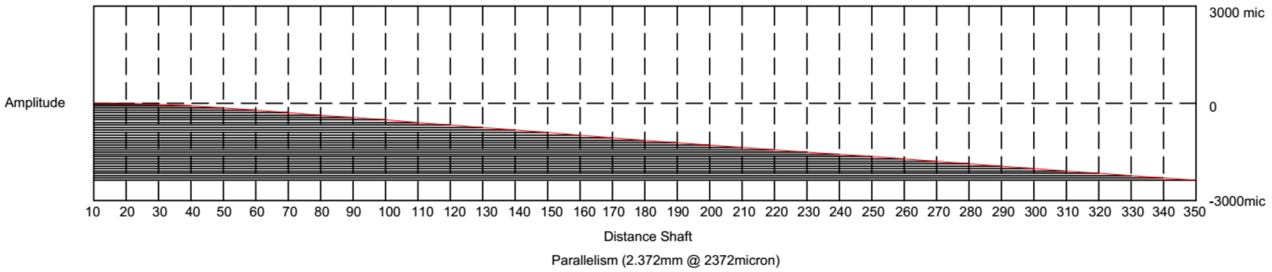


Figure 9 Profile GT measurement for parallelism (2.372 mm at 2372 micron)

There are three GT values to measure concentricity characteristics, i.e., 1000, 3000, and 5000 microns, which shows that different GT values on the same GC will produce different vibration values. To measure the concentricity characteristics, 4 angles are marked on the shaft surface, and then the marks are measured using a digital dial gage. Table 6 shows the results of the measurement of the true GT value of the concentricity characteristic, and Figure 10 is the data profile obtained, from which it is found that the GT value is 1313 micron at 1.313 mm, 3358 micron at 3.358 mm, and 4801 micron at 4.801 mm and is almost to the GT value at fixed parameters.

Table 6 Data GT measurement for concentricity characteristic specimen

GDT MEASURING TOOL	CATEGORY AND GEOMETRICAL CHARACTERISTICS				
	LOCATION				
Dial Gage	Concentricity (1000 mic)				Tolerance
Point Angle	0/360°	90°	180°	270°	1.313
Geometrical Tolerance (mm)	6.695	8.058	9.321	8.059	
Dial Gage	Concentricity (3000 mic)				Tolerance
Point Angle	0/360°	90°	180°	270°	3.358
Geometrical Tolerance (mm)	4.698	8.391	11.413	8.392	
Dial Gage	Concentricity (5000 mic)				Tolerance
Point Angle	0/360°	90°	180°	270°	4.801
Geometrical Tolerance (mm)	2.871	8.35	12.473	8.351	

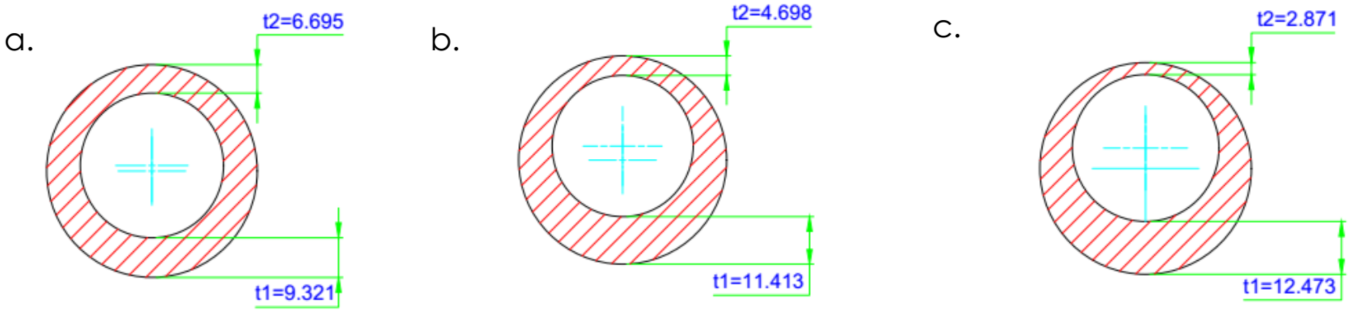


Figure 10 Profile GT measurement for (a) concentricity (1.313 mm at 1313 micron) (b) concentricity (3.358 mm at 3358 micron) (c) concentricity (4.801 mm at 4801 micron)

These characteristics will be determined by the rotating system response to compensate for the excitation moving from an easy single-mass system to a multi-mass system. With mass and stiffness will cause some changes due to damping natural frequency is still related. The rotating machine system is considered to have gone through a critical speed when the speed of the rotor exceeds the speed in which the rotor with an appropriate unbalanced distribution exerts a suitable natural frequency, and the properly positioned outputs display different peaks in response against speed [12].

Result measure the vibration value shown in Figure 11: Vibration amplitude and GC for RPM 510 It is found that concentricity characteristics produce the highest amplitude, Figure 12: Vibration amplitude and GC for RPM 770 It is found that concentricity characteristics produce the highest amplitude and Figure 13: Vibration amplitude and GC for RPM 900 It is found that GC concentricity very high amplitude. From the data obtained, concentricity was found to have a significant impact on the shaft rotation.

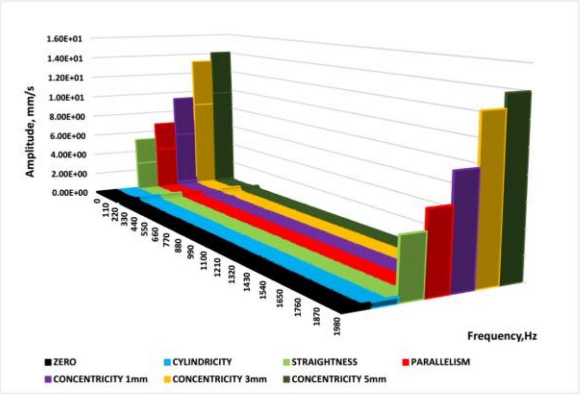


Figure 11 Vibration amplitude and GC for RPM 510

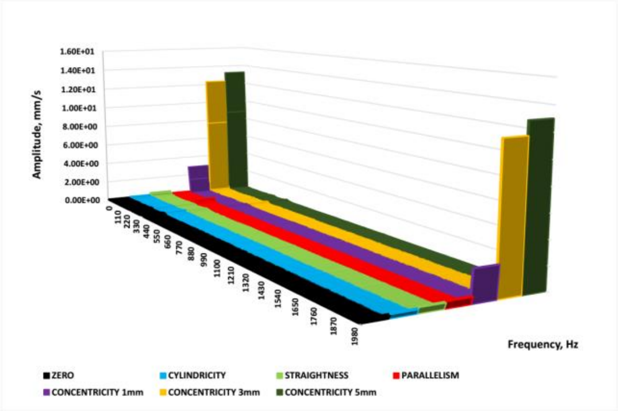


Figure 12 Vibration amplitude and GC for RPM 770

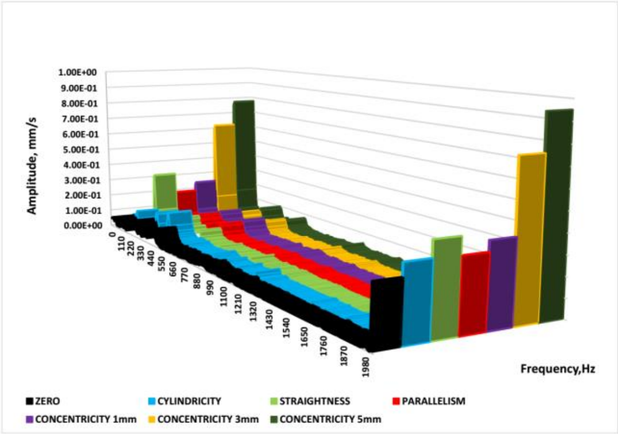


Figure 13 Vibration amplitude and GC for RPM 900

It is found that the higher the rpm, the lower the vibration value due to resonance frequency. From observation the rotor rotates by vibrating occurs when the frequency of the function forces harmonic periodically coincides with the natural frequency of the rotating system. Very large amplification may occur when the frequency of excitation is getting closer.

Resonant can defined when the frequency of excitation corresponds to a humid natural frequency. Excavation near the resonance can result in massive impression that the amplitude is controlled by damping. This change will cause many natural frequencies in every natural frequency to have a unique mode of shape that corresponds to the different parts of the structure vibrating at different amplitudes and different phases compared with another excellent number of texts will be difficult to quickly pull the necessary practical attention [12]. When the frequency of excitation is close to the frequency causes a very large amplification to occur. The amplitude is controlled by the damping magnitude when the high damping does not have a real peak and is said to be over damped. Table 7 and Figure 14 present continuous amplitude to decrease for all higher frequencies.

Table 7 Data for GC compare with RPM

GEOMETRICAL CHARACTERISTICS (GC)	GT VALUE (mm/s)	RPM 510	RPM 770	RPM 900
ZERO	0	4.42E-01	3.65E-01	3.03E-01
CYLINDRICITY	2.201	5.35E-01	5.35E-01	3.66E-01
STRAIGHTNESS	2.671	4.87E+00	5.63E-01	4.45E-01
PARALLELISM	2.372	6.47E+00	6.50E-01	3.61E-01
CONCENTRICITY 1 mm	1.313	8.87E+00	2.70E+00	4.13E-01
CONCENTRICITY 3 mm	3.358	1.29E+01	1.19E+01	7.69E-01
CONCENTRICITY 5 mm	4.801	1.40E+01	1.30E+01	9.51E-01

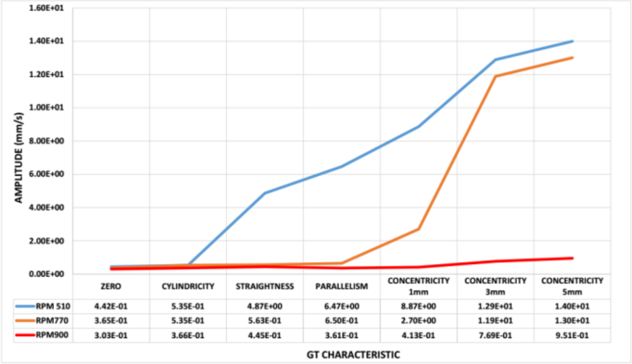


Figure 14 Vibration amplitude for GC and RPM

4.0 CONCLUSION

This paper analyses the effects of geometrical characteristic on vibrating rotational shafts concentricity was found to have a significant impact on the shaft rotation. Therefore, designers, makers, and assemblers should pay attention to concentricity as this feature can have a profound effect on the performance and lifetime of the system. The accuracy of the manufacture will affect the dynamic geometry of the rotating cylinder. During the manufacture, it impossible to produce components with exact size and dimensions, even with the most accurate production methods, and it can be very difficult and expensive to produce highly accurate components in terms of their dimensions and geometry. Therefore, these parts need to be produced with basic sizes and proper tolerance value to simplify the manufacturing process and not to impact the performance of the system. The design created should know the geometry features that will have the most impact and should know the maximum GT value in a system used. In-depth research on dynamic strength and vibration is useful for understanding and diagnosing errors. The adjustment or scheduling of shaft angles does not exist in a three-dimensional space.

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