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Incorporating CAD Software and Statistical Tolerancing to Improve DC Motor Brush Contact Design in Automotive Heating, Ventilating, and Air Conditioning (HVAC) Applications

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Abstract

In Blower DC Brush motors in Automotive HVAC application, the Brush to Commutator interface plays the key role in commutation and corresponding motor function. Conversely the motor to Brush interface also creates several key motor problems. One of the most common and critical problems in DC Brush motor is fluctuation of output characteristics when the Brush to Commutator interface is incorrect [1]. It is important to have a method to minimize this deviation in the contact between Brush and Commutator. The work done in the paper is to improve the deviation in the contact between brush and commutator by incorporating CAD software and statistical tolerancing.

Keywords: DC Brush Motor; Brush contact; Statistical Stack up tolerance; CATIA Sketch;

Introduction

In automotive fractional horsepower DC Brush Motors, the Brushes are contained in Brush holders with a spring arrangement. Spring tension force urge Brushes to make good, consistent contact with the Commutator segments. There is clearance between Brush and Brush holder to ensure that Brush slide freely in the Brush holder without sticking due to Brush worn dust and external debris. In addition, each component has their own manufacturing tolerance, so it is always difficult to control the contact between Brush and Commutator when DC Brush motor rotates

The motor component suppliers have spent a lot of time, effort and expense to reduce component tolerance as much as possible. The current approach is “Trial and Error” method, a fundamental method in problem solving. It requests to repeat the varied attempt of changing dimensions of brush, brush holder, commutator in the chain of worst case stack up tolerance until success or until stop trying. Because of that, it is so costly and under most circumstances, it is unpractical.

By using Computer Aided Design (in this case, we will use CATIA software) together with a statistical stack up tolerance calculation method, we can assess the contribution of each components tolerance to the contact problem between Brush and Commutator. And by balancing the tolerances of each component the deviations of the contact will get minimized without increasing the cost.

The rest of the paper is organized as follow: Describe the structure of DC Brush motor with permanent magnet, how to incorporate CAD software and Statistical tolerancing to improve brush contact design and Experimental result.

Structure of Dc Brush Motor with Permanent Magnet

Each Brush will tend to rotate within the Brush holder due to sliding friction force against the Commutator from the rotating Commutator and Brush to Brush holder clearance. Therefore, the center line C1 of the width of Brush does not coincide with center line of Brush holder and does not make correct contact with the Commutator anymore [1]. The corner of the Brush will make incorrect contact with Commutator surface as (Figure1). In this case, Brush noise (“tick-tick” sound) will be generated.

In order to solve this problem, the Brush holder will be tilted and offset (Figure 2) and back of the Brush (spring interface surface) will be designed with a back angle [3, 4] (Figure 3).

With Brush back angle design, offset distance “a” and Brush holder tilt angle “ α^o ”, the Brush and Brush holder have 2 contact points at 2 sides (Figure 3). The Brush is now stable in the Brush holder when DC motor is running. Brush vibration, which causes

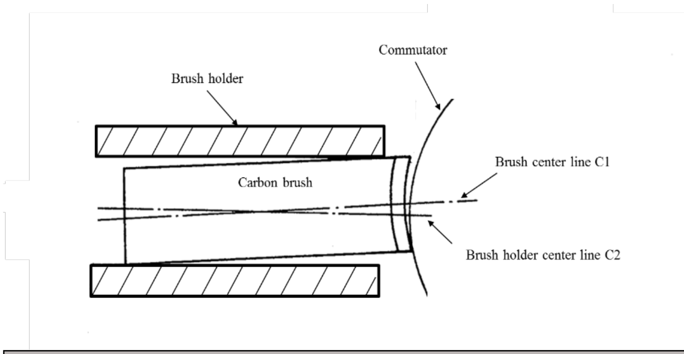


Figure 1: Cross section view of basic Brush and Brush holder configuration

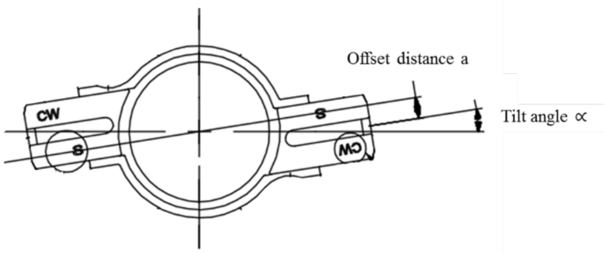


Figure 2: Brush holder design with offset and tilt angle

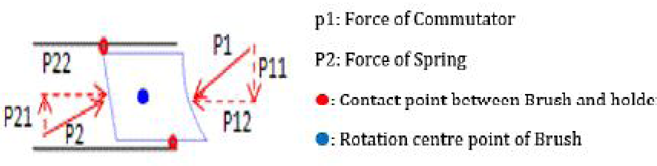


Figure 3: Cross section view of improved Brush design with back angle

resonant vibration in Brush holder and supporting part will be reduced. Therefore, Brush tick noise can be reduced as well [4].

However, after the motor has been running for a while, contact position of surface of the Brush against the Commutator surface changes in response to the wear of the Brush. The center line of the Brush C1 does not coincide with a central line of the sliding contact surface C11; it generates the functional distance F between contact point of Brush with Commutator and center line of Brush (Figure 4). The contact area of Brush at the central portion with Commutator is increased gradually, due to the wear of the Brush. Therefore, contact position between the surface of the Brush and Commutator is difficult to maintain in the fixed position. Therefore, it causes fluctuating electrical vibration [1].

According to (Figure 5), the surface of Brush is formed along an arch A1, which has the center point O1 and radius R. The Commutator is the circle A2 with the center point O2 and radius r (r<R to prevent Brush edge contact Commutator slot at the beginning and generate Brush noise problem). Because A1 and A2 contact with each other

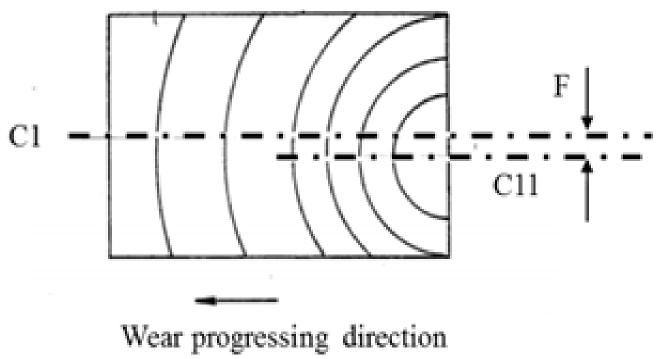


Figure 4: Brush Wear progressing

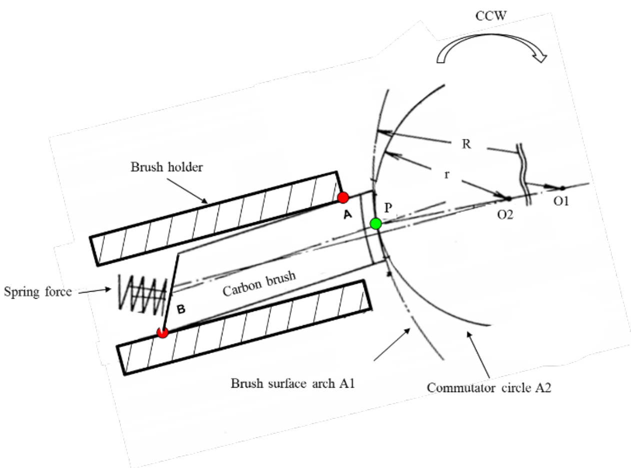


Figure 5: Cross section view of improved Brush and Brush holder configuration

at contact point P internally, so O1, O2 and P are lying on 1 line with O1O2 = R – r [1].

So ideally, in order to ensure that contact point P maintain at fixed position even though when Brush wear, this contact point P has to lie on the center line C1. It means that the functional distance F between contact point P to Brush center line C1 is equal 0 [1].

But in practical, this ideally condition never happen because of component's tolerance.

The entire component has tolerance, so when they are integrated into each other, end stack up tolerance will be big. So, the first approach to overcome this is to try to reduce as much as possible the component's tolerance by mean of using worst case stack up tolerance method [6].

However, the problem with this method is that the factor that impact to functional distance F is a lot as table 1. So, if we want to have small end tolerance, we have to create very tight, impractical and costly component tolerance [6]. And besides that, because those dimensions are not lying on the straight chain, so we cannot see whether the defined tolerance of each component will minimize the deviation in the Brush contact or not.

So, we have to come up with another approach to minimize the functional distance F as following.

Incorporating Cad Software and Statistical Tolerancing to Improve Brush Contact Design

A. Create model of statistical stack up tolerance in Excel software

Different with worst case stack up tolerance, the statistical tolerancing assumes that components are chosen atrandom. The component variation within tolerance is described by a distribution.

The histogram, is often assumed to be normal with center µD at the middle of the tolerance range and with standard deviation such that [2]

± 3 standard deviations = ± tolerance (1)

Or

$$\sigma_D = \frac{1}{3} \times TOL_D \quad \text{(TOL: tolerance)} \qquad (2)$$

$$[\mu_D - 3\mu_D, \mu_D + 3\mu_D] \quad = \text{tolerance interval} \qquad (3)$$

Statistical stack up tolerance equation [2]:

$$\sigma_Y^2 = \sigma_{a_0}^2 + a_1 \times X_1 + \ldots + a_n \times X_n$$
$$= \sigma_{a_0}^2 + \sigma_{a_1 \times X_1}^2 + \ldots + \sigma_{a_n \times X_n}^2 = (a_1 \sigma_{X_1})^2 + \ldots + (a_n \sigma_{X_n})^2 \qquad (4)$$

Notes:

Y: Output dimension (end dimension, in this paper, Y is the functional distance F)

Y: Standard deviation of functional distance F.

σX$_n$: Input dimension (detail part dimension, in this paper, X are the dimensions in table 1)

a_i

X: Standard deviation of detail part; σ_X = TOL/3

: Sensitivity coefficient for the term in the linear tolerance stack

The sensitivity coefficient a_i can then be determined by calculus or numerically by experimenting, making changes in X while holding the other X 's fixed at their nominal value and assessing the rate of change in Y in each case, i.e., for each i =

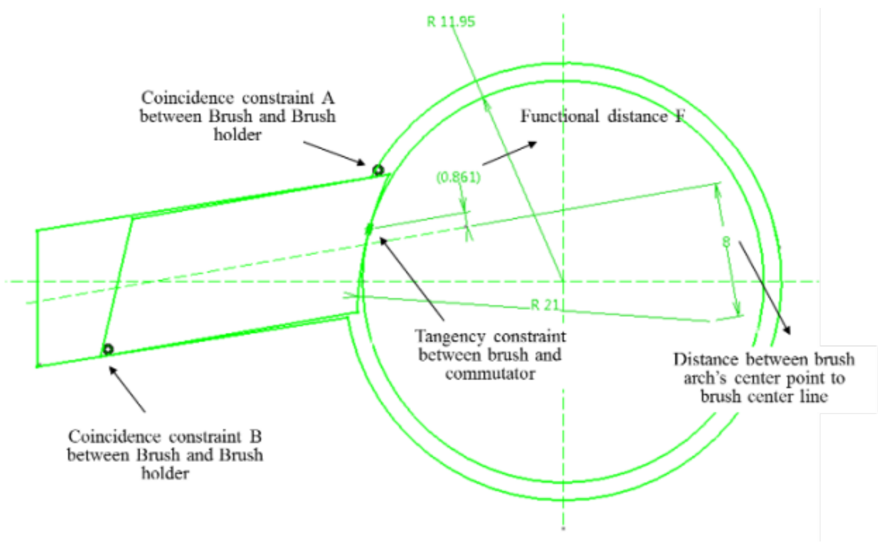


Figure 6: CATIA sketch to calculate functional distance F

Table 1: Statistical stack up tolerance calculation model

A	B	C		D	E	F	G	H	I			K	L	M	N	O
Items	Component	Dimension (mm)		Nominal	Upper tol	Lower tol	USL	LSL	Distribution			σ	F Start	F End	Sensitivity	Sigma^2*Sens^2
1	Carbon brush	w	Brush width	7.80	-0.02	-0.10	7.78	7.70	+/-	3.00	σ	0.01	0.26	0.45	2.38	0.001
3		R	Brush surface arch	22.00	1.00	-1.00	23.00	21.00	+/-	3.00	σ	0.33	0.86	-0.05	-0.46	0.023
4		dl	Distance between brush arch center point to brush center line	8.00	0.30	-0.30	8.30	7.70	+/-	3.00	σ	0.10	0.00	0.72	1.19	0.014
5	Commutator	r	Commutator diameter	11.95	0.02	-0.02	11.97	11.93	+/-	3.00	σ	0.01	0.35	0.37	0.43	0.000
6	Brush holder	W	Brush holder width	8.00	0.05	-0.10	8.05	7.90	+/-	3.00	σ	0.03	0.59	0.24	-2.36	0.003
7		a	Brush holder offset dimension	3.90	0.10	-0.10	4.00	3.80	+/-	3.00	σ	0.03	0.57	0.14	-2.16	0.005
															Tolerance of functional distance F	
														Y	Sigma	0.22
														T	Tolerance 6σ	1.30

1, . . . , n [2]. So, with this complicated structure like Brush and Brush holder in DC Brush motor, the only way to calculate a_i is to use CATIA sketch in the (Figure 6).

From (1), (2), (3), (4) we develop an excel file to calculate statistical stack up tolerance from CATIA sketch as table 1:

Whereas:

A, B, C column are the dimensions which will impact the functional distance F.

D column: Nominal value

E column: Upper tolerance

F column: Lower tolerance

G column: Upper specification limit

H column: Lower specification limit

I column: Distribution 3σ

K column: Standard deviation $\sigma = \dfrac{(USL - LSL)}{(distribution \times 2)}$ (5)

L column: The value of functional distance F when change one of dimensions with USL while keeps the rest at nominal value

M column: The value of functional distance F when change one of dimensions with LSL while keeps the rest with nominal value

(L, M can be derived from CATIA sketch model in Figure 6)

N column: Sensitivity = $\dfrac{End - Start}{USL - LSL}$ (6)

O column = $\sigma^2 \times sensitivity^2$ (7)

$$Y\ column: \sigma\ of\ functional\ distance\ F,\ according\ to\ (4),\ it\ is\ equal\ \sqrt[2]{SUM(0column)}$$

$$T\ column:\ end\ tolerance\ of\ functional\ distance\ F,\ according\ to\ (2),\ (3)$$

Build Catia Sketch Model to Calculate the Sensitivity of Each Dimension

Using Catia sketch calculate the sensitivity of each dimension in statistical model.

According to real condition of Brush, Brush holder, spring force and Commutator when DC Brush motor rotates in CW (clockwise direction), we will make the coincidence constraint for Brush and Brush holder at A and B, and tangency constraint for Brush with Commutator at contact point P follow Figure 5.

So, the sketch on CATIA software follow this constraint will be as (Figure 6).

After finishing this sketch, we will start change each dimension with USL and LSL to have the Start and End value of functional distance F.

For instance, when we change dimension “w” (Brush width) by USL and LSL value (7.78 and 7.7 respectively) while keeping all other dimensions with nominal value (D column). The Start and End value will be 0.26 and 0.45 respectively, after that table 1 will calculate the Sensitive value of Brush width “w” automatically according to (6). Keep doing the same for the rest of all dimensions, table 1 will calculate the tolerance of functional distance F automatically (T column).

In addition, from Figure 6 and table 1, we can see visually how big the functional distance F will be when we change USL and LSL of each dimension, so that we will know which component's tolerance should be reduced firstly to reduce the functional distance F.

In this case, the tolerance of Brush surface arch radius contributes the most to the functional distance F, its tolerance makes the distance F bigger than another dimensions. So, if we find out any problems for this DC Brush motor in terms of the fluctuation of output characteristic, we should work with Brush's supplier to improve the tolerance of Brush arch surface radius first.

Experimental Result

To prove the effective of present approach compared to the current approach, the prototype samples were built with the new Brushes with new arc surface radius R = 23.9 after using this method to calculate and working with brush's supplier to define the feasible brush tolerance as (Figure 7). Except brush arc surface radius R, current and improvement samples will be built with the same configuration as following: 0.9*12T(S)*25T*14Slots,

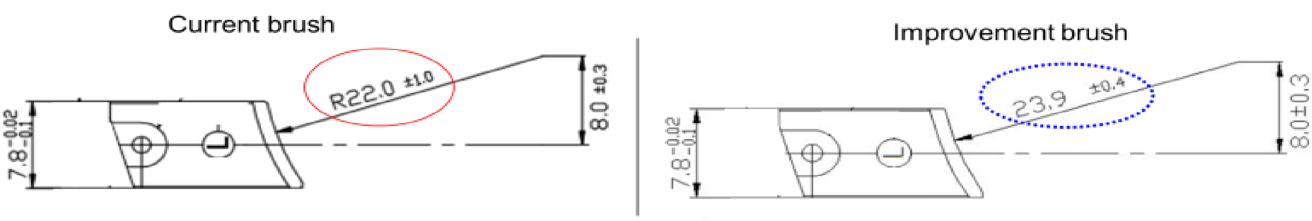


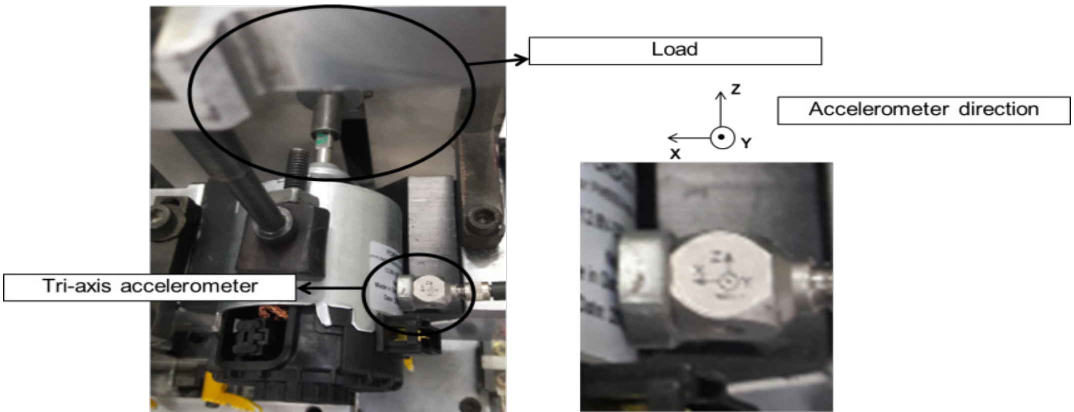
Figure 7: Brush arc surface radius improvement

Whereas:

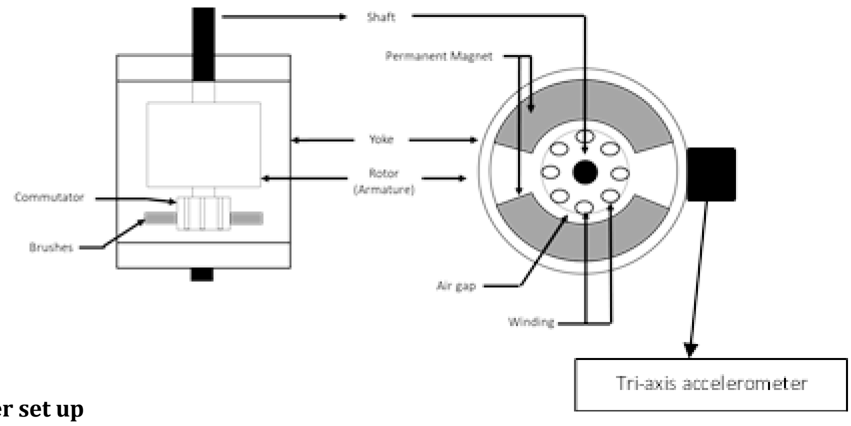
- 0.9 is the copper wire diameter
- 12T is number of turns
- S is the single winding
- 25T is the thickness of Rotor Core
- 14 is the number of Rotor Core slots

The deviation in contact between brush and commutator will cause the electrical vibration [1]. So, the vibration test in frequency domain with bare motor will be done to validate new motor prototype sample. Bare motor will be loaded in the DC motor performance tester machine with a dummy load 0.6Nm and run at 1400 RPM (according to performance specification from customer) and the accelerometer will be attached on the motor yoke between 2 magnets to pick up the vibration response as (Figure 8).

The electrical vibration result is as (Figure 9).



a) Bare motor set up on performance tester machine



b) Tri-axis accelerometer set up

Figure 8: Electrical vibration test set up

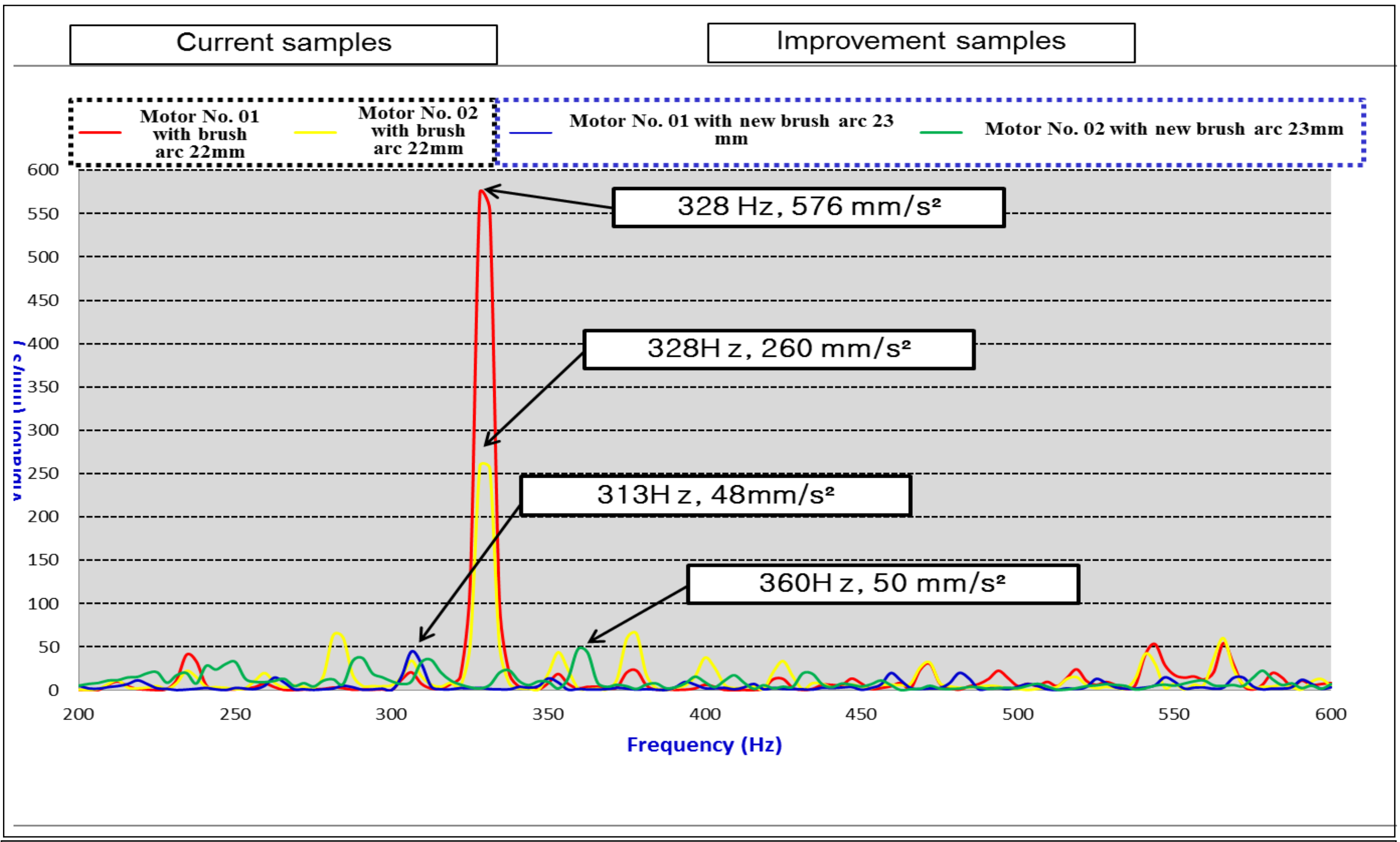


Figure 9: Electrical vibration test result

Roughly frequency 328Hz will be taken in to account for the electrical vibration test, because motor has 14 slots (14 orders) and according to the equation [5].

Frequency = (Rotational speed * Order No)/60 (8)

As the data on the graph, we can see that the electrical vibration of the sample with the improvement brush arc surface was almost disappeared at the concerned frequency compared to the current samples with current brush arc surface radius.

Conclusion

With this new method, we can easily see and control the tolerance of each component which impact to the Brush contact problem without creating very tight and unrealistic tolerances. Beyond Brush and Commutator contact issues, we can use this method to calculate the tolerances for all other component in a DC motor which cannot use the normal worst case stack up tolerances, like magnet angle with Brush angle and Commutator angle.

Acknowledgment

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