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Conceptual Design of Out-of-Roundness Test Equipment for Aircraft Wheels

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ABSTRACT

Abnormal flight events such as hard and overweight landings will have an impact on the aircraft wheels. In this case, the aircraft wheels can be out-of-roundness and cause further issues including vibrations and increased tire wear, which can affect the safety of the passengers. There are several methods that have been applied to measure the out-of-roundness of the aircraft wheels and one of them is the dial indicator. For this study, two conceptual designs of the out-of-roundness test equipment for aircraft wheels are developed. The designs are modelled in Autodesk software, which is also used to conduct the FEA simulation analysis on the design models. Three different materials are considered in this study to build the equipment and they are steel, Delrin and Nylon 6/6. Based on the simulation results, Design 1 has been shown to have a significantly better performance than Design 2. For Design 1, with regards to the material, all of them can appropriately satisfy the design requirements and correspond to comparable performance. Nonetheless, Delrin or Nyon 6/6 is proposed for use due to their added advantages.

Keywords: Dial indicator method, Nylon, Out-of-roundness, Aircraft wheel, Test equipment

I. INTRODUCTION

In the aviation industry, safety is always viewed as an utmost important issue. For commercial airlines, it is vital to ensure their passengers' safety throughout their offered flight services. One of the main aspects to lower aviation safety risks is the effective maintenance of the aircraft fleet, which is crucial to prevent avoidable accidents or incidents due to mechanical failures of the aircraft system [1]. It can be noted that aircraft maintenance procedures are typically classified into four different types: corrective, preventive, scheduled and also predictive [2]. In short, the corrective maintenance is often called as repair or trouble clear mend, which involves the repair activities to make any identified malfunctioned or broken equipment back to their technical state for operation [3]. On the other hand, preventive type of maintenance work is done before failures occur and this is done to avoid or mitigate the consequences of the faulty system during operation [4]. In this case, the maintenance activities are scheduled at certain regular intervals in order to possibly detect the issues before failures actually occur. It should be noted that preventive maintenance can also be seen as a form of scheduled maintenance as well. However, the key difference is that preventive maintenance can also be performed without a proper scheduling when there is an urgent need while scheduled maintenance is always done at fixed intervals. Lastly, predictive maintenance is usually known as condition-based maintenance, where a detection of any abnormal conditions from the aircraft system during operation creates the need for a maintenance task and the interval to perform this task is predicted based on several factors [5]. The abnormal system condition and predictive factors are obtained from the installed monitoring system such as the engine health monitoring system. On the whole, a good maintenance planning and strategy is important to ensure flight safety, increase in-service reliability and also reduce the operational and maintenance costs [6].

In today's aircraft, the wheels are one of the parts that are subjected to high level of stress. Among others, impact loads, cyclic loads, corrosion and burn outs can contribute

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towards the failure of the landing gear wheels [7]. One of the abnormal incidents that will cause a great stress to the aircraft wheels is the heavy or hard landing, which occurs when its vertical acceleration exceeds the limited value of airplane type during flight landing phase [8]. The effect of a hard landing on the aircraft wheel can vary depending on the severity of the landing, and the design and condition of the wheel. Some potential impacts of a hard landing on an aircraft wheel include the damage to the wheel rim or other structural components of the wheel, the deformation of the wheel that can disturb its roundness, cracking or breaking of the wheel, and the damage to tires including punctures or sidewall bulges. Since hard landings are impossible to be fully avoided or prevented, it is therefore necessary for the aircraft wheels to be inspected and maintained aptly to avoid them from becoming safety threat to the passengers and crew. Figure 1 shows an example of damage to aircraft wheels during landing.

Figure 1 Possible aircraft wheel damage during landing phase [9]

In general, modern aircraft wheels are typically made from durable materials such as aluminum or steel, and are designed to withstand the stresses of take-off and landing [10]. Similar to other aircraft components, aircraft wheels are also subject to routine inspections based on the lifetime and priority scale according to the governing international flight regulations [11]. An aspect of the wheel maintenance for an aircraft is ensuring that the wheel is round and has a consistent diameter. If the wheel is out of roundness, it can cause problems including vibrations and increased tire wear [12]. There are few methods that are currently used to measure out-of-roundness of aircraft wheels including dial gauge method and laser scanning method.

Use of dial indicator to check for out-of-roundness in aircraft wheels offers several advantages such as simplicity, accuracy, repeatability, low cost, versatility and also ease to maintain. The dial indicator is a simple and easy-to-use measuring instrument that does not require any specialized training or expertise to operate [13]. The dial indicator is a highly precise measuring instrument that could accurately measure the deviation from ideal round shape of the wheel to within a few thousandths of an inch. Furthermore, this method can be used multiple times to measure the out-of-roundness of the wheel and the results are consistent each time, which provides high level of repeatability. Moreover, the dial indicators are relatively inexpensive compared to other measuring instruments, and it is often small and also lightweight, making it easy to transport and use in different locations. In addition, a dial indicator could also be used to measure different types of deviation such as radial, axial or both and it can also measure other geometric parameters like runout as well. All in all, this method is durable. It has a long service life and is easy to maintain. This technique is frequently used to examine the roundness of automobile wheels in the commercial automotive sector.

On the other hand, laser scanning method is a precise and accurate method for measuring the out-of-roundness of aircraft wheels by using laser scanner to scan the surface of the wheel and creating a 3D model of the wheel. In spite of its high accuracy, this method has some disadvantages. One drawback of this method is its complexity as it needs a high level of technical skill and expertise to operate the laser scanner and analyze the data. Moreover, it requires a specialized software for creating and analyzing 3D models of the wheel. The laser scanners can also be expensive and require regular maintenance, which can be costly. Plus, the cost of the specialized software can also be high. The laser scanner might not be able to reach all areas of the wheel, making it hard to get accurate measurements. The surface of the wheel must be clean and free of debris and/or other obstacles, otherwise the laser scanner will not be able to produce accurate measurements. Besides, the temperature of the wheel and the environment can affect the accuracy of the laser scanner, thus it is important to ensure that the wheel is at the correct temperature before scanning.

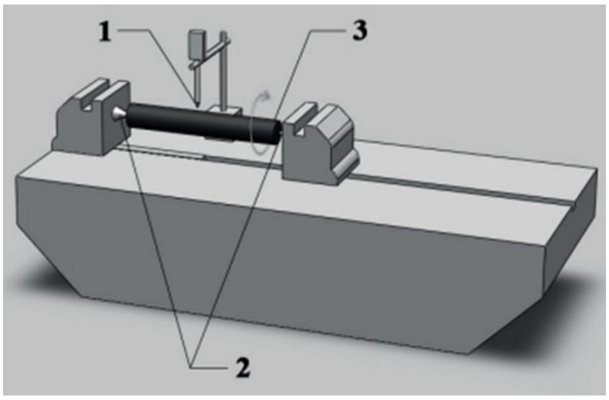


Figure 2 Radial change measurement equipment for roundness check: (1) dial indicator, (2) centers, (3) work piece [14]

In general, the measurement of roundness is critical in numerous industries especial manufacturing. In view of this, the measuring test requires a specialized equipment that is capable of delivering accurate and repeatable results. Over the years, a variety of roundness test equipment have been developed to meet the diverse requirements of the different industries. It should be noted that effectiveness of the equipment also depends on the industry requirements. Example of such equipment is depicted in Figure 2, which detects the out-of-roundness condition based on the radial change [14]. This approach has been used to evaluate form deviations of cylindrical surfaces. As can be observed, the roundness deviation is measured by using the bench center and the dial indicator to detect any radial changes. In this case, the cylinder work piece is placed between the centers and the dial indicator is located perpendicular to the work piece. In general, this method of measurement is quick and simple.

For this study, the objective is to develop a conceptual design of a wheel out-of-roundness test equipment for the aircraft wheels. The specific focus is for the aircraft wheels of Boeing 737 aircraft types. Several alternative concepts for the equipment are analyzed to derive the best design. In addition, selection of the appropriate materials used to build the roundness test equipment is important, especially when it involves heavy parts such as the aircraft wheels. The method proposed in this study in order to check for out of roundness in aircraft wheels is by using a dial indicator method. This technique is frequently used to examine the roundness of automobile wheels in the commercial automotive sector, but according to the authors' knowledge, very few studies were done to consider this technique for aircraft wheels.

Roundness measurement using a dial indicator technique is only utilized in other industries than aircraft. Most of the materials do not offer anti-scratch characteristics. For the technique to be applied to aircraft wheels, it is very crucial to have anti-scratch material to prevent damage to the inner part of the wheel, particularly the bearing area. The designed equipment must also be capable of supporting the load without exhibiting any physical changes. Thus, this study is principal in order to determine suitable material that can be used with this technique, and at the same time is cost effective and lightweight for remote testing. Furthermore, the existing method by using steel as the material has a drawback; high stress value which makes it unable to sustain a certain applied load. Thus, this new approach by using Delrin and Nylon 6/6 has some benefits, including ease of maintenance, durability, and simplicity. It demonstrates the potential for this technology to be applied in the aviation sector.

II. SETUP AND METHODOLOGY

For the initial stage, conceptual design for the out-of-roundness test equipment for aircraft wheels is developed. In this study, two conceptual designs have been considered, which are designated as Design 1 and Design 2. It should be noted that the conceptual designs of the equipment are inspired from the automotive tire changer equipment that can be commonly found in the tire workshops. Specifically, the Dannmar T-50 swing arm tire changer that is depicted in Figure 3 has been chosen as the main reference. In short, for design concepts of the out-of-roundness test equipment, the wheel will be placed on top of the equipment while the dial indicator will protrude and touch the edge of the wheel. Any deviation of readings represents the out-of-roundness of the wheel. The limit of out-of-roundness for the aircraft wheels is set in reference to the manufacturer's manual on the landing gear system.

Figure 3 Dannmar DT-50 Swing Arm Tire Changer (https://www.dannmar.com)

Once the design concepts have been developed, their corresponding computer-aided design (CAD) models are constructed using Autodesk software. These CAD models are then applied in the finite element analysis (FEA), also using the Autodesk software, in the selection of the proper materials to be used in the out-of-roundness test equipment for aircraft wheels. It should be noted that FEA simulation analysis has been widely-used in many engineering studies for various purposes such as structural analysis of flapping wing mechanism [15], aircraft passenger seat [16] and also aircraft wing box [17]. For this study, the FEA simulation analysis is tailored for use of aircraft wheels for the Boeing 737 aircraft types. Based on the simulation analysis results, appropriate materials for the equipment are selected.

Three different types of materials have been selected for consideration: Steel, Delrin (polyacetal homopolymer-POM) and also Nylon 6/6. When it comes to engineering plastics, Delrin and Nylon are popular materials known for their excellent mechanical properties and their widespread applications in various industries. Both materials possess a high resistance to scratching and scuffing, which makes them suitable for the inner part of the wheel, especially at the bearing area. In the meantime, recently steel is widely used for roundness test equipment in automotive field and therefore, it is chosen here as the reference material. Table 1 lists the properties for these three considered materials.

It should be noted that both CAD models for Design 1 and Design 2 are tested in the conducted FEA simulation analysis for each of these three considered materials. Since the focus is for this out-of-roundness test equipment to be applied on aircraft wheels of Boeing 737 aircraft types, the weight of the aircraft wheel is taken to be 800 N. Hence, the designed equipment must be capable of supporting this amount of load without exhibiting any physical changes. Maximum stress and displacement of the equipment under the loading of the aircraft wheel are measured in the FEA simulation analysis for comparison.

Table 1 Properties for considered materials [18]

Properties	Delrin	Nylon 6/6	Steel
Tensile strength	80 MPa	85 MPa	355 MPa
Young Modulus	2.8 GPa	2.5 GPa	210 GPa
Mass density	1.41 g/cm^3	1.13 g/cm^3	7.85 g/cm^3
Wear resistance	Good	Best	Poor
Chemical resistance	Good	Poor	Poor
Cost	Expensive	Less Expensive	Less Expensive

The calculation of stress, which is defined as the ratio of applied force to the cross-sectional area and is given in unit of force per unit area, can be done by using Equation (1). In this equation, σ is the normal stress, F_n is the normal force acting perpendicular to the area and A is the area.

$$\sigma = \frac{F}{A} \tag{1}$$

Meanwhile, displacement refers to the deformation or movement that is experienced by the material or structure under load or stress. When a load is applied to a structure, the material experiences displacement, causing it to stretch, compress or bend [19]. In this test, the displacement value is measured from original position line before the loading to the new position line after the loading. Moreover, design safety factor, also known as the factor of safety, is a critical concept used in engineering design process to ensure that the structure, component or system can handle the planned loads and stresses without any failures [20]. As presented by Equation (2), this safety factor is calculated as a ratio that compares the maximum load or stress that a structure can withstand to the actual applied load or stress. It provides a margin of safety, taking into account for uncertainties and unexpected conditions that might occur during the lifespan of the structure. In Equation (2), the ultimate stress is taken as maximum load or stress that the structure can withstand without failure while the working stress is the stress that the structure experiences during normal operation or under the expected loads.

$$\text{Factor of Safety} = \frac{\text{Ultimate Stress}}{\text{Design or Working Stress}} \tag{2}$$

III. RESULTS AND DISCUSSION

Two conceptual designs for the out-of-roundness test equipment for aircraft wheels are developed in this study. Recall that the focus in this study is for the test equipment to be applied on the aircraft wheels of Boeing 737 aircraft types. As such, the diameter of the half wheel has been set to 24.22 inches while the width is set to 13.085 inches. In essence, according to Safran Landing System Component Maintenance Manual (CMM) of B737 Main Landing Gear Wheel Assembly, aircraft wheels must be discarded if the out-of-roundness is more than 0.51 mm or 0.020 inches. Design of the test equipment is based on the dimension of the half wheel. As per Figure 4, the diameter of the half wheel (B) is 24.22 inches and the width (D) of is 13.08 inches.

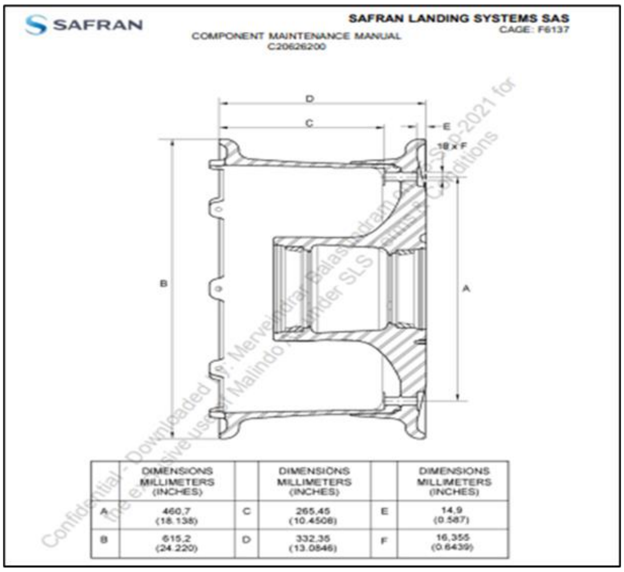


Figure 4 Dimension of half wheel [21]

The first design, designated as Design 1, is illustrated in Figure 5. For this design, the aircraft wheel will be set on the test equipment before the out-of-roundness test. A dial test indicator has been positioned such that it touches the aircraft wheel's surface. The aircraft wheel will then be marked in four different locations in order to identify any defects.

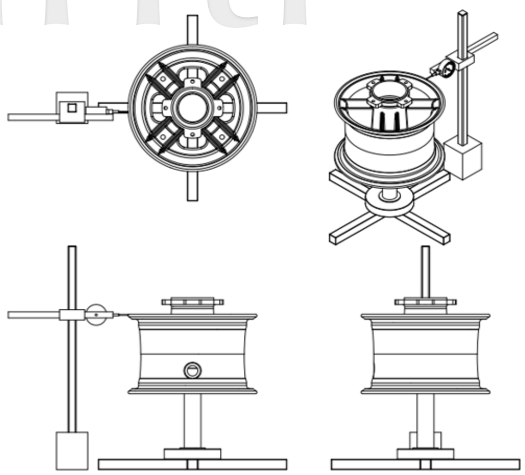


Figure 5 Constructed CAD Model for Design 1

The testing equipment is freely rotatable in both directions (i.e. clockwise or anti-clockwise). Dial indicator readings that are negative or positive indicate a wheel that is not round. Meanwhile, the second conceptual design of out-of-roundness equipment for aircraft wheels is depicted in Figure 6.

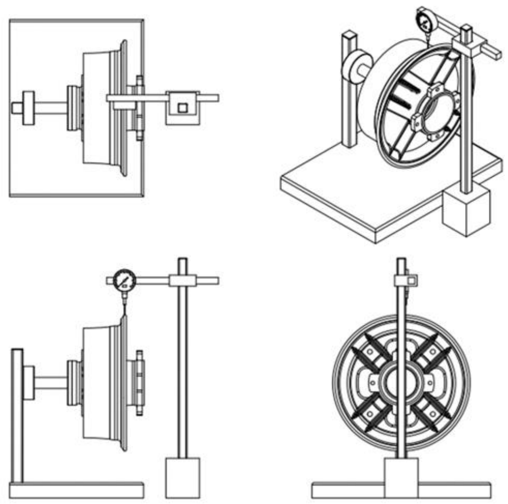


Figure 6 Constructed CAD Model for Design 2

In short, this design that is also designated as Design 2 works by having the wheel turning sideways. A dial test indicator has been positioned such that it touches the aircraft wheel's surface. Similar to previous Design 1, the aircraft wheel will be marked in four different locations in order to identify any defects. The testing equipment is freely rotatable in both directions (i.e. clockwise or anti-clockwise). It should be noted that a dial indicator reading that is either negative or positive indicates the wheel is not round.

FEA simulation analysis results for these two designs with the three different considered materials are tabulated in Table 2. The plots of the results for maximum stress are presented in Figure 7 and Figure 8 for Design 1 and Design 2, respectively. It should be noted that, in both cases, the weight of the aircraft wheel is simulated as a negative 800 N force that is acting downwards in y-direction.

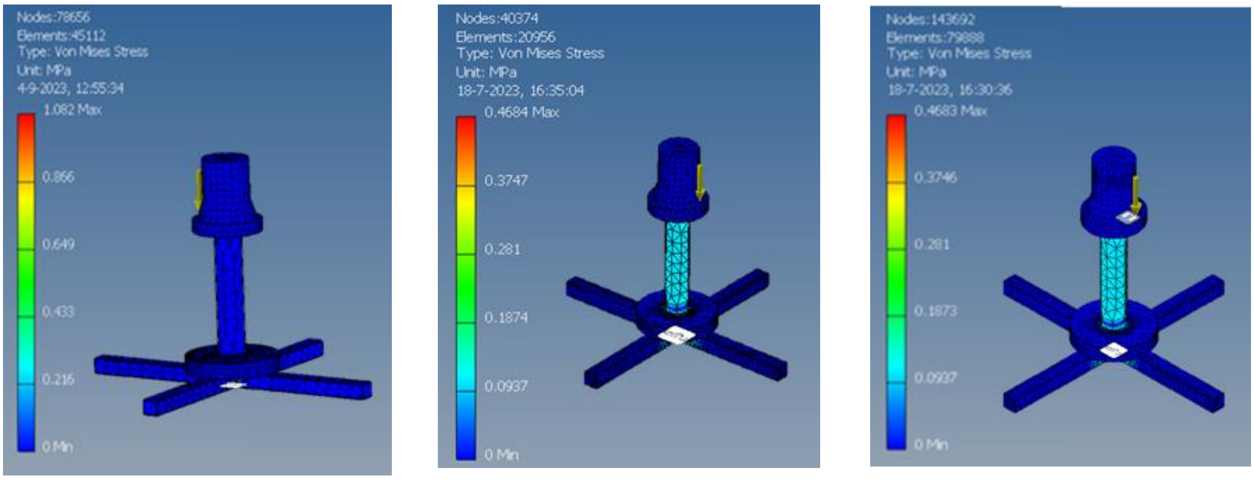
Table 2 Summary of FEA simulation analysis results

Design	Material	Maximum Stress (MPa)	Maximum Displacement (mm)
1	Steel	1.0821	0.0005
	Delrin	0.4684	0.0280
	Nylon 6/6	0.4683	0.0330
2	Steel	31.0170	0.9950
	Delrin	33.5140	63.4140
	Nylon 6/6	12.9220	8.461

In the preliminary simulation tests, the number of elements of 79,888 proved to be sufficient to obtain reliable calculation results. Increasing the density of the grid beyond this dimension does not significantly affect the calculation, and only causes an increase in their duration. The out of roundness test equipment model was constructed in such a way that the equipment's body is capable of supporting the mechanical load which is the weight of the aircraft wheel at 800 N, that will be applied as the boundary condition. The conceptual designs were performed and validated based on the current roundness test equipment used in the automotive sector using steel as the material. Thus, the design with steel is the reference case (baseline). Additionally, few assumptions need to be made in order to perform the simulation:

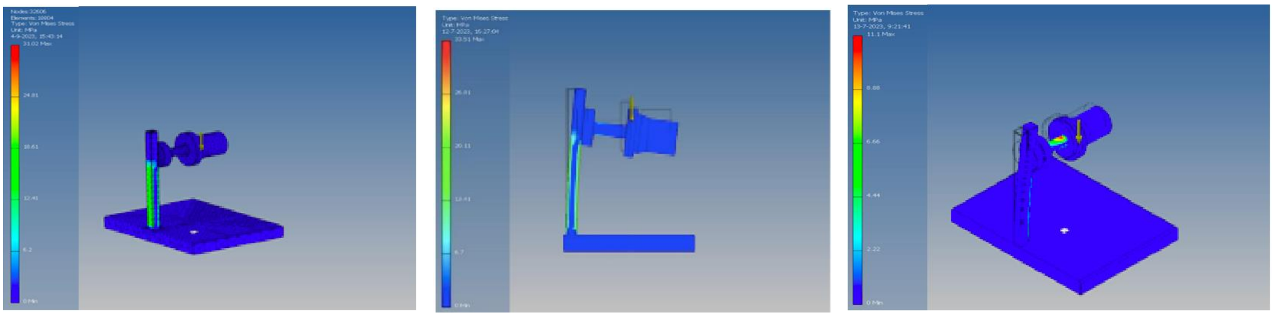
- The materials suggested in this study (Delrin and Nylon 6/6) have anti-scratch characteristics to prevent damage to the inner part of the wheel, particularly the bearing area.
- Both Delrin and Nylon 6/6 have low friction properties, low water absorption and good chemical resistance.
- The designed equipment is capable of supporting the load without exhibiting any physical changes.
- The dial indicator is a highly precise measuring instrument that can accurately measure the deviation of the wheel up to within a few thousandths of inch.
- The measurement results from the dial indicator method are consistent, providing a high level of repeatability.

In Table 2, for Design 1, maximum stress for steel can be observed to be higher than that for other two materials, which is recorded as 1.082 MPa. On contrary, Nylon 6/6 and Delrin seem to have comparable low maximum stress. However, steel still has the lowest value of displacement as compared to Delrin and Nylon 6/6, which is just 0.0005 mm. Furthermore, Design 2 seems to perform worse than Design 1 with regard to maximum stress and displacement for all considered materials. This situation has been rather expected due to the need to hold the heavy aircraft wheel sideways during testing operation, which essentially adds more loading to the equipment. For instance, for Design 2 with steel material, it corresponds to more than 27 times and 1989 times of the maximum stress and displacement, respectively, against the analysis results for Design 1 with steel material. Summary of comparison between Design 1 and Design is tabulated in Table 3.



(a) Steel (b) Delrin (c) Nylon 6/6

Figure 7 Simulation analysis for maximum stress of Design 1



(a) Steel (b) Delrin (c) Nylon 6/6

Figure 8 Simulation analysis for maximum stress of Design 2

Table 3 Comparison of Design 1 and Design 2

Material	Parameter	% Difference of Design 2 to Design 1
Steel	Maximum Stress	+ 2,766.37%
	Maximum Displacement	+ 198,900.00%
Delrin	Maximum Stress	+ 7,054.99%
	Maximum Displacement	+ 226,378.57%
Nylon 6/6	Maximum Stress	+ 2,659.34%
	Maximum Displacement	+ 25,539.39%

As can be observed in Table 3, the staggering increase in maximum stress and maximum displacement for Design 2 in comparison to Design 1 clearly indicate that Design 1 is the better conceptual design. The big difference between these two designs is due to the force acting in the vertical direction which is the actual weight of the wheel. This force applied is linked with the torque acting on both designs. Torque (moment of force) is the force that can cause an object to rotate about an axis. In Design 1, this torque value is 0 because the force (weight of the aircraft wheel) is acting in the same direction as the out-of-roundness equipment's axis. Thus, this causes the wheel in Design 1 to not rotate or to be displaced even when the load is applied to the equipment. Meanwhile in Design 2, the direction of the out-of-roundness equipment is perpendicular to the load (wheel) applied. This results in torque force acting on it and causes the object to rotate/to be displaced.

In terms of materials, steel obviously performed better with consistently lowest value of displacement, which is very crucial for equipment such as the out-of-roundness test equipment. Nevertheless, for Design 1, both Delrin and Nylon 6/6 have been also shown to correspond to a reasonably good performance. Although their maximum displacement is more than steel, it is below 1 mm, which could be taken to be very small. Considering some of additional advantages that Delrin and Nylon 6/6 materials can offer against steel, the findings in this study seem to suggest that Design 1 with either Delrin or Nylon 6/6 as its material is potentially the best alternative for the out-of-roundness test equipment for aircraft wheels.

IV. CONCLUSIONS

Scheduled maintenance is essential to ensure that the aircraft system is able to operate as intended and the safety of the passengers is secured. One of the important parts of aircraft maintenance is to evaluate the out-of-roundness of the wheels. This is vital since an aircraft wheel that is not appropriately round can cause numerous issues that, in the worst case scenario, might affect the safety of passengers. In this study, two conceptual designs of out-of-roundness test equipment for the aircraft wheels have been developed. The designs are then assessed through the FEA simulation analysis in Autodesk software to select the best option and also to choose the best material for building the equipment. Based on the results, it is proposed that Design 1 is the best design concept for the out-of-roundness test equipment as it has performed better than Design 2 in terms of maximum stress and maximum deflection. In terms of the material, it is suggested that either Delrin or Nylon 6/6 is used instead of steel due to some of their added advantages.

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