PROBABILISTIC DESIGN OF COMPOSITE WHEEL SPANNER

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Abstract: Probabilistic design offers tools for making reliable decisions with the consideration of uncertainty associated with design parameters and simulation models. This project discusses probabilistic design and its application into design of a composite wheel spanner for Toyota Camry cars with five (5) lug nuts. The project work is aimed at taking advantage of probabilistic design system approach over deterministic (traditional) approach to create an optimised design model of an existing composite wheel spanner. This new approach is to implement changes on a controlled, verifiable basis and deals majorly with the operating stress and material strength. The pre-existing design was rigid, robust and was only designed for a Volkswagen Beetle car with four (4) lug nuts while the new design is compatible with the Toyota Camry and all cars with 60.1mm Hub/Centre Bore, 14"-16" wheel size and 5 x 114.3mm bolt pattern. The design was drawn using SolidWorks design software and various design parameters were considered. The completed design was imported from SolidWorks to ANSYS software by converting the design into a Para solid which was then simulated by varying the speed of the shaft and the material in order to get the corresponding stress analysis. The rotational speed of the shaft was varied with different gear materials on ANSYS probabilistic design system software. The result shows that the lowest amount of stress was experienced when 7079 Aluminum Alloy ($\rho = 2700\text{kg/m}^3$) was tested at 100 rpm but Magnesium Alloy ($\rho = 1700\text{kg/m}^3$) at 100rpm gave a higher minimum operating stress value. In this project, a 5-nut composite wheel spanner was successfully designed using probabilistic design approach. The pre-existing composite spanner was improved upon using SolidWorks and ANSYS software to design and analyse respectively. The new design is very flexible, adjustable and easy to carry. It can be adopted by car manufacturing companies.

Key words: Operating Stress, Rotational Speed, Composite-spanner, Magnesium Alloy, 7079 Aluminum Alloy,

1. INTRODUCTION

1.1. Research Background

Engineering designs rely on complex computer codes for more accurate, faster and better performance analyses [1-2]. Deterministic design employs the idea of either: (a) running these codes with input variables at their worst case values, or (b) running this code with input variables at their nominal values and applying a safety factor to the final result of the output variable. In the generic sense of modeling a typical response like stress, the result of using either of these methods is unknown. Assuming the input distributions are correct, applying worst case scenarios is too conservative. Applying safety factors to a nominal solution can result in either too much or too little conservatism with no method to compute risk or probability of occurrence.

Probabilistic engineering design relies on statistical distributions applied to the input variables to assess reliability, or probability of failure, in the output variable by specifying a design point. Any response value passing beyond this design point (also referred to as the most probable point, or MPP) is considered in the failure region. This method also allows for reverse calculations such that a specific probability of failure can be specified for the response. The MPP is then determined by calculating the response value that yields the specified probability of failure. This concept of designing to

reliability instead of designing to nominal is clearly a superior method for engineering design. By choosing a desired reliability from a distribution on the response, a probabilistic risk assessment is built into the design process. [3] The foundation of probabilistic design involves basing design criteria on reliability targets instead of deterministic criteria. Design parameters such as applied loads, material strength, and operational parameters are researched and/or measured, then statistically defined. A probabilistic analysis model is developed for the entire system and solutions performed to yield failure probabilities [4].

1.2. Introduction to Probabilistic and Deterministic Design

Probability has been about interpreting the past and determining the future. Sometimes what we know in the past is no longer applicable in the future. We do not know for sure how good our sample is due to our uncertainty as humans, therefore we must try to generate sample data which indicates future behaviour in which we have very high confidence in. [5]. Probabilistic Design deals with the effects of random variability upon the performance of an engineering system during the design phase and these effects are related to quality and reliability. It offers tools for making reliable decisions with the consideration of uncertainty associated with design parameters and simulation models. One important task of a probabilistic

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design is uncertainty analysis; through which we understand how much the impact of the uncertainty associated with the system input is on the system output by identifying the probabilistic characteristics of system output. We then perform synthesis (optimization) under uncertainty to achieve the design objective by managing and mitigating the effects of uncertainty on system output (system performance). [6]

Probabilistic design methods, unlike deterministic methods, provide a means to quantify the risk of a design and to quantify the sensitivities of design variables. It allows engineers to quantify the reliability of the designed structure, as opposed to deterministic design which only determines whether the structure is safe or not. The clear difference between probabilistic design and deterministic design approach is that probabilistic design takes into account the uncertainties involved in the behaviour of the structures or machine under consideration [7]. The optimization stage of the engineering design process is a systematic process using design constraints and criteria to allow the designer to locate the optimal solution. Optimization achieves the "best" design relative to a set of prioritized criteria or constraints. These include maximizing factors such as productivity, strength, reliability, longevity, efficiency, and utilization. [8]. Engineers often identify appropriate design solutions and then decide which one best meets the need of the client. This decision-making process is known as optimization.

1.3. Robust Design

Robustness is the property of being strong and healthy in constitution. When it is transposed into a system, it refers to the ability of tolerating perturbations that might affect the system's functional body. In the same line Robustness can be defined as "the ability of a system to resist change without adapting its initial stable configuration" [9]. It has been discussed that robustness has two dimensions: resistance and avoidance. [10]. Robust design has been shown to be very effective in improving product or process design in manufacturing. In practice, most robust design applications have been limited to small systems with traditional statistical experimental design and analysis methods [11]. Robust Design is a methodology that addresses product quality issues early in the design cycle. The goal of Robust Design is to deliver customer expectations at affordable cost regardless of customer usage, degradation over product life and variation in manufacturing, suppliers, distribution, delivery and installation. [12].

The aim of this research work is to come up with an optimized and robust design of a composite wheel spanner which can tighten and loosen a 5-nut wheeled car using probabilistic approach method. The specific objectives of this project are: (i) To modify the existing design of a composite wheel spanner (ii) To vary design parameters and observe the effects by using SolidWorks for 3D software and ANSYS Probabilistic Design System (PDS) for modeling and simulating respectively. The project work will focus on the design modification and performance analysis of an existing composite spanner.

2. PROBABILISTIC DESIGN CONCEPT

The major advantage of designing with a probabilistic approach is the possibility to quantify the reliability of the structure. Instead of using characteristic values which correspond to upper or lower boundary values, a probabilistic approach allows engineers to quantify the reliability of the design. In most cases, the probabilistic approach of designing a structure gives results that are closer to reality and thus less conservative than a deterministic approach. This is of interest in design since it would allow us to design structures differently and save on materials and on money, as well as assessing the reliability of an existing structure and determining how far it is from failure. Moreover, it is a useful tool for assessing the reliability of existing structures since parameters can be adapted with respect to target reliability or importance of the building. Some basic concepts related to probability and statistics are: (i) probability density, with the mean value and standard deviation (ii) distribution function, with median value (iii) normal distribution, widely used for engineering and science applications in the context of structural design in engineering, it is of interest to quantify the safety and reliability of a structure, especially for existing structures.

2.1. Quantifying the Reliability of a Structure

Estimating the probability of failure is a good approach of quantifying the reliability of a structure. Probability of failure is a reliable indicator of structural safety and a useful tool from an engineering point of view. The basic principles of statistics and probability can be applied to a probabilistic analysis of structural safety and allow to mathematically express this concept of reliability. Two values need to be considered: (i) limit function G : $G = R - S$ (where, R is resistance and S is solicitation). (ii) Reliability index b , from which the failure probability (P_f) can be directly determined

The failure probability of a structure is defined analytically as follows:

$$P_f = \int_{-\infty}^{\infty} f_s(x) \cdot Fr(x) dx \quad (1)$$

Cumulative distribution function, Fr ,

$$Fr(x) = P(R < x) = \int_{-\infty}^{\infty} fr(x) dx \quad (2)$$

Probability density function, f_s

$$P[a < S < b] = \int_a^b f_s(x) dx \quad (3)$$

In the SIA Standards for new constructions, β is fixed at 4.7, corresponding to a failure probability of 10^{-6} . The design value defined through a probabilistic approach is defined as:

Solicitation

$$S^* = S_m \cdot (1 + \beta \cdot \alpha_s \cdot v_s) \quad (4)$$

S_m = mean value, $\alpha = \frac{\sigma_s}{\sigma_G}$ = influence value and

$v_s = \frac{\sigma_s}{S_m}$ is variation coefficient.

The gear shaft is a cylindrical shaft found in the gear box that carries the three (3) pinion gears which rotates when the handle of the composite spanner is being turned thereby allows the transmission of the torque from the pinion to the spur gears.

Fig.3. Gear Shaft

The adjustable stand is a long hollow cylindrical pipe that has holes where the stopper/pin passes through after the gear box has been set at a desirable height. It holds the gear box in place.

Fig.4. Adjustable Stand

The adjustable stand Pin helps hold the adjustable stand in place at a desirable height. It passes through the holes of the stand and rests on top of the base stand. The base stand is a rectangular box designed for stability. It carries the total weight of the composite spanner and holds the adjustable cylindrical pipe in place with the help of pin

Fig.5. Adjustable Stand Pin

Fig.6. Base Stand

Fig.7. Newly Designed Composite Spanner

Fig.8. Composite Spanner Tool Box

Fig.9. Closed Composite Spanner Tool Box

3.2. Advantages of the New Design

- 1) The composite spanner improved on the number of nuts to be removed or tightened on the wheel hub.
- 2) Better gear ratio which makes the user exert less energy while using the new composite spanner compared to the old design
- 3) The new design can be raised or lowered to any convenient height with the help of the adjustable stand.
- 4) This new model can be used with all vehicles with 60.1mm Bore Centre or Hub
- 5) It can be easily assembled and disassembled which makes it more compactible

3.3. Design Parameters and Considerations

The following considerations were taken into account when designing the gears: (i) The centre distance between the centre of the hub and the wheel nut (as shown in figure 10) (ii) Speed of the driving (iii) speed of the driven gear or velocity ratio (iv) power transmitted from the driving to the driven gear. Also the following requirements must be met in the design of a gear drive; (i) the teeth of the gear should be strong enough to resist failure during operation under both static and dynamic loading (ii) the drive gear should have the required material properties to perform its function (iii) the best material must be chosen for economic reasons (iv) the alignment of the gears and deflections of the shafts must be considered because they have effect on the performance of the gears (v) the lubrication of the gears must be satisfactory.

Fig.10. Taking Measurements of the Distance between the Centre Hub and Lug Nuts

3.4. Design of the Pinion (Driver) and Driven Gears

The composite spanner was to be designed for 120.2 PCD, so the center between the gears had to be 60.1mm. The average torque removal for one nut is 130Nm. Spur gears were selected due to the function and the type of motion to be transferred. The velocity ratio in the gears is constant. The above factors were considered in selection and design calculations of the gear.

$$\text{Centre Distance} = m \cdot (N_1 + N_2)/2 \quad (6)$$

Number of teeth for Pinion is N_1 ; Number of teeth for Spur is N_2 . To find Module from Centre Distance eq. (6)

is used given the center distance. The Pitch Diameter is given by eq. (7). Whereas, the circular pitch is given by eq. (8). The diametrical pitch, gear ratio, outside diameters for pinion and gear, root diameters for pinion and gear, base circle diameters for both gears, base pitch and contact ratio for both gears are given by eq. (9), (10), (11), (12), (13), (14) and (15) respectively.

$$D = mN, \quad (7)$$

$$P_c = m\pi \quad (8)$$

$$P_d = N/D \quad (9)$$

$$G = N_2/N_1 \quad (10)$$

$$D_o = m(N+2) \quad (11)$$

$$D_R = D - 2.5m \quad (12)$$

$$D_B = D \cos\alpha \quad (13)$$

$$P_B = m\pi \cos\alpha \quad (14)$$

$$C_R = (\sqrt{R_{O1}^2 - R_{b1}^2} + \sqrt{R_{O2}^2 - R_{b2}^2} - C \sin\alpha) / m\pi \cos\alpha; \quad (1 < C_R < 2) \quad (15)$$

The torque spanner provides the required torque for the bolts without over tightening or under tightening of the lug nuts. The manufacturers catalogue (Toyota Camry) for tightening M12 nut is given as 350Nm. Therefore, to determine the required force that should be applied to the handle of the composite wheel spanner; we use the relation between force and torque in eq. (16).

$$\text{Force} = \frac{\text{Torque}}{\text{Radius}} \quad (16)$$

Therefore, a force of **158N** is to be applied to a lever length of 0.55m to produce the desired effect, which is to tighten the bolt to the required torque without failure of the bolts. The table below shows the torque that should be applied to different sizes of bolts and the length of the lever that should be used to produce the given torque.

3.5. Shaft Design

The shafts that will be used in transmitting power and rotational motion in the composite wheel spanner is a solid shaft {that is, not hollow}. To determine the diameter of the shaft, the eq. (17) is used;

$$D = \text{Diameter of shaft} = \sqrt[3]{\frac{16T}{\pi S_s}} \quad (17)$$

Where, T = Torque; S_s = Allowable shear stress is 55MN/m^2 for shafts without keyway and 40MN/m^2 for shafts with keyway. To calculate for angle of twist, eq. (18) is applied

$$\theta = \frac{TL}{GJ} \quad (18)$$

Where G = Modulus of rigidity = 79.3GPa for Structural Steel. J , the polar moment on inertia of shaft cross section is given by eq. (19).

$$J = \frac{\pi D^4}{32} \quad (19)$$

Table 1. Torque values to be applied to a bolt

Square drive size	Torque tool (Nm)	Hand tool breaker / T-handle (Nm to ISO3315)	Biggest bolt/nut	Socket size (mm)	Bolt/nut torque (Nm)	Length of lever to center of hand(s) for lower torque limit
1/4"	25	62 /55	M8	13	25	0.12m (one hand)
3/8"	110	202 /180	M10	17	76	0.32m (one hand)
1/2"	350	512 / 455	M12	19	87	0.55m (one hand)
3/4"	1500	1412 / 1255	M18	27	294	0.88m (two hands)
1"	4500	2515 / 2236	M30	46	1440	3.13m (two hands)

Fig.11. Exploded view of gear and shaft arrangement

Fig.12. Gear arrangement

Fig.13. Exploded view of the composite spanner

Fig.14. Stress analysis of the gears using carbon steel ($\rho = 7858 \text{ kg/m}^3$)

Fig.15. Stress analysis of the gears using plain steel carbon ($\rho = 7800 \text{ kg/m}^3$)

4. RESULTS AND DISCUSSIONS

Shown in figures 11 - 13 are the components that were analysed using the ANSYS probabilistic design software. The composite spanner was designed with SolidWorks software and analysed using ANSYS Probabilistic Design Software to check the stress pattern. When the carbon steel material was used, the maximum stress recorded at 300rpm was $4.894 \times 10^8 \text{ Pa}$ and the minimum stress recorded at 100 rpm was 187.83Pa. From figures 14 – 18, that Maximus Stress is experienced when materials are put under high speed while the lowest amount of stress was experienced when 7079 Alloy was tested at 100 rpm. There is an obvious pattern which shows that the stress on the pinion gear and spur gears is a function of the rotational speed applied.

Fig.16. Stress analysis of the gears using cast alloy steel ($\rho = 7300 \text{ kg/m}^3$)

Fig.18. Stress analysis on the gears using 7079 alloy ($\rho = 2700 \text{ kg/m}^3$)

Fig.17. Stress analysis of the gears using magnesium alloy ($\rho = 1700 \text{ kg/m}^3$)

Table 2. Stress analysis varying gear materials and speed

Material	RPM	Min [Pa]	Max [Pa]
Carbon Steel Sheet ($\rho = 7858 \text{ kg/m}^3$)	100	187.83	5.438×10^7
	200	751.25	2.175×10^8
	300	1690.50	4.894×10^8
Plain Carbon Steel ($\rho = 7800 \text{ kg/m}^3$)	100	187.93	3.438×10^7
	200	751.8	2.175×10^8
	300	1691.5	4.895×10^8
Cast Alloy Steel ($\rho = 7300 \text{ kg/m}^3$)	100	187.95	5.438×10^7
	200	751.77	2.175×10^8
	300	1691.5	4.895×10^8
Magnesium Alloy ($\rho = 1700 \text{ kg/m}^3$)	100	187.96	5.438×10^7
	200	751.76	2.175×10^8
	300	1691.40	4.894×10^8
7079 Alloy ($\rho = 2700 \text{ kg/m}^3$)	100	5.87	1.489×10^7
	200	23.50	5.959×10^7
	300	52.84	1.341×10^8

5. CONCLUSION

In engineering, the aim is usually to reduce time spent on doing work and to make work done as easy as possible. With the design of the composite wheel spanner, this was achieved. The new composite wheel spanner which has been designed with SolidWorks and analysed with ANSYS Probabilistic Design System software to loosen and tighten five (5) lug nuts at the same time in order to reduce the time spent in carrying out this operation has been achieved. With this design, each vehicle has its own compact composite wheel spanner which can be easily assembled and disassembled back into its box.

The new design can work for various models of salon cars which has 60.1mm hub/center bore especially the Toyota brands such as Avalon, Camry, Solara, Celica, Corolla XRS, Cressida, Highlander, Previa, Sienna amongst others which is commonly used in this part of the world. The aim of the project is to reduce the time spent on loosening/tightening the five (5) lug nuts of a wheel and to reduce the amount of force exerted to loosen/tighten the bolts/nuts by changing the gear ratio. The composite wheel spanner is reliable and easy to use. During the design phase of the 5-nut composite wheel spanner, the problem encountered was how to arrange the gears, with a small pinion gear to drive five (5) spur gears in order to increase output torque all on one shaft in the gear box. This was resolved by thinking outside the box and offsetting the spur gears by introducing two extra pinion gears. With this design, the challenge was solved and the design of the composite wheel spanner was completed.

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