Effects of Spoke Patterns on the Stiffness of a Bicycle Wheel

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ABSTRACT

The purpose of this investigation is to evaluate the effects that the spoke patterns have on the stiffness of a bicycle wheel. The wire spokes are under tension to provide support and alignment to the wheel as well as transmit the torque from the hub to the rim. The spoke patterns considered for this investigation are radially crossed (0x) spokes with 9, 18, and 36 spokes that are modeled in a finite element analysis software. If time permits, other spoke patterns such as 1x, 2x and 3x may be imported into a finite element analysis software. These spoke pattern wheels will be subjected to radial, lateral and tangential loads and the results (stresses and strains) will be compared with one another to determine the relationship between the spoke patterns and stiffness of the wheel.
1. Introduction

The wheel is a load carrying device which has facilitated the movement of goods and transportation of people. The circular form of the wheel is used in many machinery applications today such as gears and pulleys. The bicycle wheel is an example of a wheel which has evolved over centuries to provide the same function as designed. The bicycle wheel consists of wire spokes crisscrossing each other, radiating outward from the hub at the center of the wheel to the rim, where the spokes are fastened to by threaded spoke nipples.

![Figures 1. Antiquated wheel [1] and modern bicycle wheel [2].](image)

1.1 Background

In ancient times, thick and heavy, rigid wooden spokes supported loads in compression. Nowadays, the wooden wheels are replaced by wire-spoked wheels due to their lightweight quality, durability and strength (see figures 1). However, wire spokes cannot be loaded in compression like their wooden counterparts. Instead, the spokes are prestressed in tension so that they can support compression loads, which results in reducing the tension in the spokes (see figure 2).

![Figure 2. Tension of a bicycle wheel spoke [3].](image)

The spoke patterns, spoke sizes (lengths and thicknesses), number of spokes, spoke and rim materials, and other factors contribute to the stiffness and overall strength of a
bicycle wheel. Bicycle wheel spokes come in different geometries and sizes, but for this project, only the spoke patterns will be considered. Spoke patterns are defined by the number of times a spoke crosses other spokes, e.g., zero-cross (0x) or radially spoked, one-cross (1x), two-cross (2x), three-cross (3x), and four-cross (4x) (see figure 3). The stiffness of a bicycle wheel has three components: radial, lateral and tangential (torsional) stiffnesses. The radial stiffness resists radial deflections of the rim, the lateral stiffness resists sideways deflections, and the torsional stiffness resists the torque that rotates the hub to propel the bicycle forward [4]. It is important to distinguish the difference between stiffness and strength. Stiffness does not necessarily equate strength; conversely, a wheel strong enough to withstand the applied loads is adequately stiff. For that reason, bicycle wheel designers do not consider stiffness as important as strength and durability [4]. Nonetheless, spoke pattern is an interesting subject worthwhile analyzing.

Figure 3. Left to right: 2x, 3x, 4x spoke patterns [5].

1.2 Problem Description

The purpose of this investigation is to evaluate the effects that the spoke patterns have on the stiffness of a bicycle wheel. The spoke patterns considered for this investigation are radially crossed (0x) spokes with 9, 18, and 36 spokes that will be subjected to radial, lateral and tangential loads. The stress and displacement results will be compared with one another to determine the relationship between spoke pattern and wheel stiffness. If time permits, other spoke patterns such as 1x, 2x and 3x with the same number of spokes (36) may be analyzed.
2. Methodology and Approach

The wire spokes, hub and rim will be the only structural parts considered for this investigation. The other parts of the wheel, such as the axle, bearings and tire, do not play a role in affecting the wheel’s stiffness. As for the spoke nipples, they will be omitted to simplify the finite element model and analysis. The spoke used for this analysis will be a 2 millimeter simple straight gage spoke. Additionally, the spoke and rim materials will remain unchanged for the four spoke patterns mentioned in the problem description section. The materials for this analysis will be 6061-T6 Aluminum Alloy for the rim and hub, and 304 Stainless Steel for the spokes. These are common materials used to manufacture bicycle wheels.

The finite element models will be created in Abaqus/CAE for simple geometries or imported as models from online resources for complex geometries that are difficult to create in Abaqus/CAE. The first finite element model will be a simple, two dimensional, radially-crossed spokes (0x), which will be created in Abaqus/CAE (see figure 4). The hub does not need to be modeled for a two-dimensional model. The two-dimensional model will be changed by varying the number of spokes and pattern (with no spokes crossing each other) to observe changes in loads, stresses and displacements. Due to time constraints and the difficulty in modeling complex geometries in Abaqus/CAE, the models will be imported from online resources (see figure 5) and modified in Abaqus/CAE for three dimensional models with 1x, 2x and 3x spoke patterns.
Figure 4. A two dimensional CAE model of radially-spoked bicycle wheel created in Abaqus/CAE.

Figure 5. A three dimensional CAD model of a bicycle wheel [6].

In the radially spoked finite element models, the center of the wheel was constrained in the three orthogonal directions (x, y and z). The elements used to model the rim and
spokes are linear 2-noded cubic beam elements (B33) and linear 2-noded three dimensional truss elements (T3D2), respectively. The truss elements only have axial loads. To model the pre-tensioning of the spoke wires, one method of doing this is to add a coefficient of thermal expansion. Another method is to add a bolt pretension load (231 pound force [7]), which was used for this analysis (see figure 6). The static analyses to be performed are radial, lateral and tangential loads analyses. The load in the radial direction will be the weight of an average human male (196 pounds [8]) applied as an upward force from the ground. The lateral load will include a force from hitting the curb. As for the tangential direction, a torque that simulates pedaling will be applied at the hub, and transmitted outward to the rim via the spokes. The results for each spoke pattern will be compared with one another to determine how the spoke pattern affects wheel stiffness.

2.1 Geometry:

Dimensions to be used:

1. Rim:
   - rim diameter = 26” common size for mountain bikes
   - rim effective diameter = 22” [3]
   - rim cross section = 3D models - to be determined; 2D models - dimensions from Reference (9)

2. Spokes:
   - spoke diameter = 0.07874" (2mm) straight gage spoke
   - spoke number = 9, 18, 36 for radially-spoked wheels and 36 for 1x, 2x and 3x wheels

3. Hub:
   - hub diameter = 2"
   - hub flange to center distance = 2"
   - hub spoke hole diameter = 0.098425" (2.5mm)

2.2 Assumptions:

- The number of spokes and distance from the hub will be the same for both sides (front and back) for 3-D models
- Buckling of the spokes will be ignored [10]
- The hub is rigid; no deformation of the hub [10]

Figure 6. Boundary conditions and loads of three radially spoked wheels. 
(Left to right) 36, 18, 9 spoked wheels are shown.
3. Results and Discussions

Results of the radially-crossed spokes with 9, 18 and 36 spokes subjected to a radial load are shown in figures 7 and 8. As expected, the stresses are generally the same (approximately 47440 psi) because the same radial and pretension loads were applied to all three models. On the other hand, the vertical displacements decrease with increasing number of spokes.

Figure 7. (Left to right) Stresses of 36, 18 and 9 radially-spoked wheels subjected to radial loads.
Similarly, for radially-spoked wheels with two different 18 spoke patterns, the stresses were the same (see figure 9) and the displacements decreased as the number of spokes were spread out (see figure 10).
Figure 9. Stresses of two 18-spoked wheels subjected to radial loads.

Figure 10. Displacements of two 18-spoked wheels subjected to radial loads.
4. Conclusion
5. References

1. Americanlisted.com
6. GrabCad.com
7. Parker Tool Spoke Tension Meter Instructions and Parts Diagram.