Effects of Bicycle Tire Pressure on Transmitted Vibrations

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ABSTRACT

Bicycles have a maximum safe tire pressure which is known for being relatively high and transmits excessive road vibrations to the rider which can lead to injuries such as carpal tunnel and back pains over time. An optimal tire pressure would entail finding a tire pressure which causes the vibrations to dissipate the fastest, essentially minimizing the settling time. To find this optimal tire pressure, an accelerometer was attached to the rear of the bicycle frame and the vertical acceleration was recorded as the bicycle went over a step. The data was then fitted to obtain characteristics such as settling time, natural frequency and damping ratio. These results showed that the damping of the tire decreased linearly with pressure and the bicycle frame flexes and damps vibrations more as pressure was increased. This information gave rise to a quadratic relationship of the settling time with tire pressure which was then curve fitted to find the minimum response of 0.98s ± 0.40s at 88kPa.

INTRODUCTION

Cyclists can develop issues such as joint pains and carpal tunnel due to vibrations transmitted to the rider by imperfections such as pot holes on the road. [1] Adjusting seat height and improving body posture can minimize the damage caused by the vibrations but it won't reduce the vibrations. A method to directly change the transmitted vibrations is to change the tire pressure on the bicycle. Tire manufacturers have a safe pressure rating on tires which is rated on the higher end of a tires pressure range where most of the road vibrations get transmitted to the rider. [2] This is mainly because recommending a lower tire pressure could be a liability for manufacturers if the rider doesn't check their tires often and the pressure gets too low causing a pinch flat. [3]

An optimal tire pressure would be the pressure at which the time of vibration is minimized when the bike is subjected to an imperfection such as a bump or a pothole. Currently, there is no known value for the optimal pressure of a tire since the optimal pressure can vary depending on tire size, rider mass, ambient temperature and road conditions.

To find the optimal tire pressure, a bicycle is outfitted with an accelerometer on the rear of the frame near the tire and the bicycle is ridden over a curb to simulate a step input. The vertical accelerations are recorded to gather step response data and the process is then repeated with varying tire pressures. This accelerometer data is then analyzed to gather characteristic information of the bicycles response such as settling time and damping ratio and these variables are then developed into a relationship with tire pressure to understand details about the step response. The settling time information is then extracted from the accelerometer data to find a tire pressure at which the settling time is minimized.

PREVIOUS STUDIES

A study conducted by a team at the Texas A & M University has shown that transmitted vibrations in cars continues to decrease as pressure is reduced. However, decreasing it after a certain threshold will reduce the driver's control of the vehicle since the tire would give out and come off the vehicle under high lateral accelerations. [4]

Another study conducted by J. Vanwalleghem from the University of Malaysia, Pahang, shows that bicycle frames vibrate at a natural frequency and contain different modes of vibration when subjected to shock. [5] This knowledge would be essential when analyzing the accelerometer data since there would be a superposition of vibrations from the tire and the frame present in the data.

THEORY OF DYNAMIC SYSTEMS

Mechanically speaking, a bicycle can be modelled as a damped harmonic oscillator. The tire acts as the spring due to its ability to apply a variable load based on its compression. The tire also acts as a damper since it can dissipate energy as heat when compressed. [5] The frame of the bike can be modelled as a very stiff spring. Because of this, the bike frame cannot dissipate any of the vibrations on its own. The rider can be modelled as a damper since the rider can absorb the vibrational energy in the bike frame through the seat post and handle bars. [6]

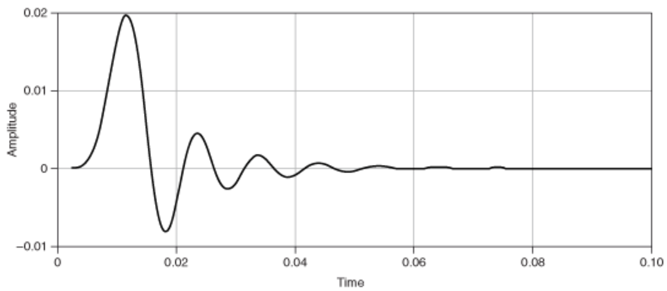

Figure 1: Plot shows a generic underdamped response of a system to an impulse input. The obtained accelerometer data is assumed to look like the figure.

A general underdamped harmonic oscillator has a displacement equation of

$$x = Ae^{-Bt}(\sin(Ct + D)) \tag{1}$$

where A is maximum amplitude of the response which depends on the magnitude on the input. B determines how quickly the exponentials decays and

$$B = \zeta\omega_n \tag{2}$$

where ζ is the damping ratio which determines the damping strength and ω_n is the natural frequency of vibration of the bicycle in radians/second. C is the damped frequency in radians/second, ω_d which represents how frequently the bicycle oscillates when subjected to damping where

$$\omega_d = \omega_n\sqrt{1 - \zeta^2} \tag{3}$$

and D is the phase lag which tells us how much delay is present in the output response.

Since the data being collected is acceleration data, the equation used for curve fitting would be the second derivative of equation 1 which is

$$\ddot{x} = Ae^{-Bt}[(B^2 - C^2)\sin(Ct + D) - 2BC\,cos(Ct + D)] \tag{4}$$

To extract ω_n from the obtained equation we use

$$\sqrt{C^2 + B^2} = \sqrt{\omega_n^2(1 - \zeta^2) + \omega_n^2\zeta^2} = \omega_n \tag{5}$$

Using that ζ can be obtained from equation 2 which will be used for as variables to analyze our datasets. The 10% settling time $t_{10\%}$ of the bicycle can also be obtained which tells us the time where the response amplitude reduces to 10% of the initial value. This is done by finding the height of the first peak y and the A and B values from equation 4 and plugging it into

$$t_{10\%} = \frac{\ln\left(\frac{10A}{y}\right)}{B} \tag{6}$$

Using the 10% settling time and the point where the response initially began, the total response time of the system can be found.

EXPERIMENTAL DESIGN

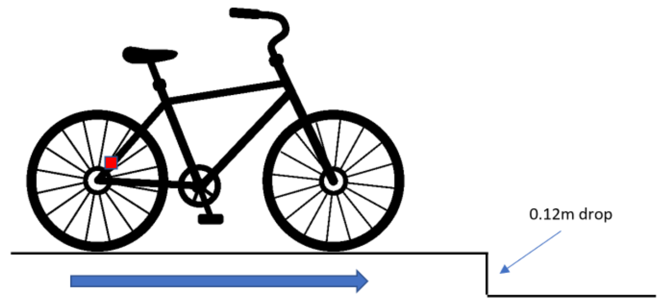

Figure 2: Diagram illustrating experimental setup where accelerometer (red) is attached to the rear of the bicycle frame next to the tire. The bicycle is ridden over the step which has a drop of 0.12m

The bicycle used for these experiments is the Mongoose Malus which has 26x4 inch tires. The bicycle has no shock absorber, so all vibrational data collected will be from the tire and frame. The rider used in the experiment has a mass of 65kg. A Vernier 25g Accelerometer was attached vertically (Arrow on sensor facing perpendicular to ground) with double sided tape to the rear of the bicycle frame as close as possible to the tire. Most of the systems mass rests on the rear tire, so the rear tire is the one that transmits and absorbs most of the vibrations which is why the accelerometer was placed near the rear tire. A Vernier LabQuest 2 was used for data collection with a sampling rate of 5000Hz and was attached using zip ties near the handle bars.

The bicycle tire pressure was measured with a JACO BikePro tire pressure gauge that has a range of 0 – 60PSI. To start the testing, the tires were filled to 96.5kPa (14PSI), the bicycle was held straight (perpendicular to the ground) and the accelerometer was zeroed. The bicycle was then pedaled to a speed of 5kmph and as the step approached, pedaling was stopped to remove any unnecessary vibrations. After the bicycle goes over the edge, the bicycle moved forward for 5 seconds without additional pedaling to allow the vibrations to dissipate.

This procedure was repeated 5 times to reduce uncertainty and after that the pressure was reduced by 6.9kPa (1PSI) using the air bleed function on the pressure gauge which allowed for accurate reduction of tire pressure. This process was repeated with 6.9kPa decrements until 68.9kPa (10PSI) to give a total of 25 accelerometer readings. A wider range wasn't used because pressures higher than 96.5kPa would've exceeded the maximum safe recommended pressure of the bicycle and pressures lower than 68.9kPa deflates the tire too much and the tire doesn't hold its round shape.

RESULTS AND DISCUSSION

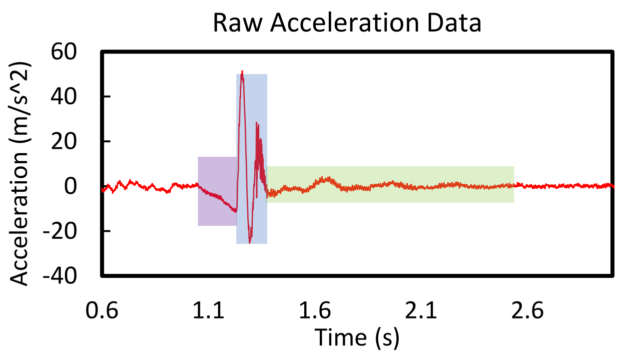

Figure 3: Graph shows a sample run of data collected at 10PSI. The purple shaded area represents the bike going over the step and dropping towards the ground. The blue represents the short-term response from the bike hitting the ground and the green shows the long-term oscillatory response of the bike settling.

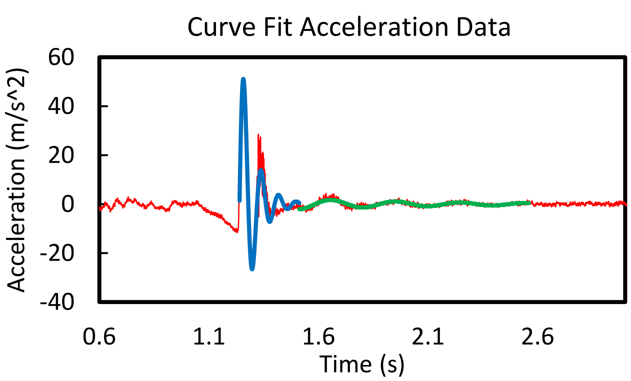

Figure 4: Graph shows the data in figure 3 that is curve fitted to equation 4 in the blue and the green shaded regions separately. The black star represents the point where the response begins in the system and the yellow star represents the peak to be used to find the settling time.

In figure 3, the long-term and short-term response regions were defined so that curve fitting can be done. As seen in figure 4, the long-term response region and the short-term response region was curve fitted separately with equation 4 to extract characteristic information of the bicycles' response. The key values to be extracted from all the datasets are ω_n, ζ and $t_{10\%}$.

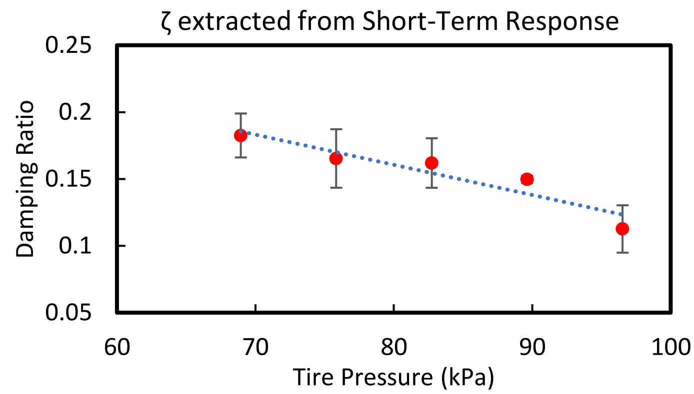

Figure 5: Graph shows ζ value from the short-term response. The average values at each tire pressure is show in red along with its uncertainty. This data was curve fitted with a linear relationship of y=Ax+B where A = -0.00226 ±0.00064 and B = 0.341 ±0.054.

From figure 5, there is a linearly decreasing relationship between ζ and tire pressure. Since the only component of the bicycle that gets effected by tire pressure is the tire itself, we can say that the short-term response is due to the tire oscillation. This can be practically thought of the tire becoming harder and changing shape less to dissipate energy as the pressure increases. This also means that as pressure increases, more of the vibrations would get transmitted to the frame of the bicycle which would are absorbed by the rider. To verify that a linear is true, a quadratic fit was checked and was found to be statistically insignificant.

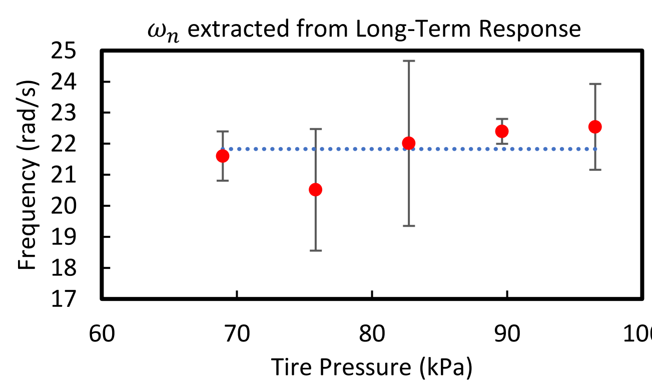

Figure 6: Graph shows the natural frequency obtained from the long-term response. The average

values at each tire pressure is shown along with their uncertainties. This data was curve fitted with a horizontal line at $\omega_n = 21.83\, rad\, s^{-1} \pm 0.59\, rad\, s^{-1}$

Figure 6 shows that the natural frequency doesn't change for the long-term response as pressure varied. Quadratic and linear data fits were found to be statistically insignificant, so the data was fitted to a constant value. This constant value can be tied back to the study conducted by the University of Malaysia, Pahang, which says that the bicycle oscillates at its natural frequency. With this data, we can confirm that the long-term response is indeed due to the oscillation of the bicycle frame and the short-term response is due to the oscillation of the tire.

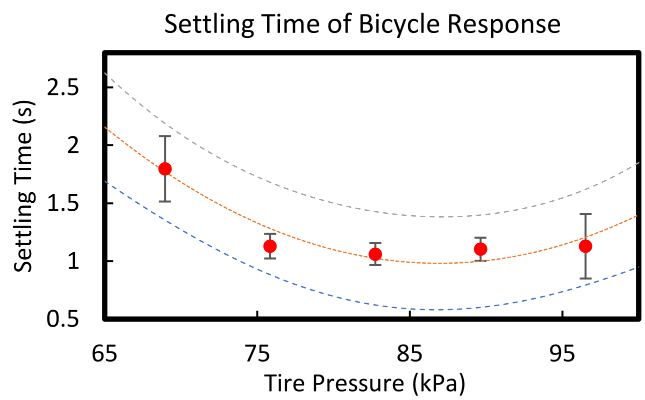

Figure 7: Graph shows the analytical settling time of the bicycle obtained using equation 6. The red dots represent the average settling times at each recorded tire pressure along with its uncertainties. This data was fitted with a quadratic relationship $Ax^2 + Bx + C$ where $A = 0.00245 \pm 0.00092$, $B = -0.43 \pm 0.15$ and $C = 19.5 \pm 6.3$. The red dotted line shows the curve fit and the black and blue dashed lines show the margins of where the curve fit is true.

The data shown in figure 7 is key. It shows that the quadratic relationship between settling time and tire pressure. This is because at low pressures, the tire is highly underdamped and bouncy which causes it to damp the vibrations over a longer period. At higher pressures, the tire doesn't damp that much of the oscillations which was seen in figure 5. Higher pressure causes the tires to transmit more of the vibrations to the bicycle frame which dissipates those vibrations through the rider. The optimal tire pressure is such that the tire and the frame share vibrational loads with just the right ratio to maximize the overall damping to minimize the settling time.

This optimal tire pressure is found at the minimum of the quadratic fit which is at 88kPa with a settling time of 0.98s ±0.40s. The uncertainty in the minimum settling time was found plotting the settling time data in MATLAB and viewing its upper and lower bounds. This has a high uncertainty due to variables in the conditions of the experiment such as how much of the riders' mass was on the seat or pedals when the bicycle was settling.

These results are valid for only this specific bicycle and rider since other bicycles will have different tire sizes, frame geometry and rider mass. There is no generalized formula to find the optimal tire pressure for all types of bicycles due to the variables mentioned before. To determine the optimal tire pressure for other bicycles, further experiments would need to be conducted in a similar manner.

CONCLUSION

An accelerometer was used to obtain the bicycles' response to going over a step with various tire pressures. From these experiments, it was determined that the bicycle shows a complex response which is a mixture of the tire oscillating at various frequencies with different amounts of damping, and the frame oscillating at its natural frequency while the rider absorbs the vibrations since the frame has no damping of its own. It was found that the short and high amplitude oscillation is due to the tire and the longer oscillation is due to the frame. This was confirmed by the short-term response damping ratio linearly decreasing with tire pressure and had the equation of $y = Ax + B$ where $A = -0.00226 \pm 0.00064$ and $B = 0.341 \pm 0.054$. The long-term response had a constant natural frequency of $\omega_n = 21.83\, rad\, s^{-1} \pm 0.59\, rad\, s^{-1}$. In the end, the settling time had a quadratic relationship of $Ax^2 + Bx + C$ where $A = 0.00245 \pm 0.00092$, $B = -0.43 \pm 0.15$ and $C = 19.5 \pm 6.3$ which is because of the tire being too bouncy at lower pressures and a lot of the vibrations being transmitted to the frame at higher pressures. An optimal tire pressure was found where there was a mix of tire and frame oscillation at 88kPa with a minimum settling time of $0.98s \pm 0.40s$

For further experimentation, an accelerometer which is less noisy could be used for more accurate data collection. The bicycle would also need to be in a more controlled environment such as placing the bicycle vertically on a treadmill with a mass attached to the seat and disturbances on parts of the treadmill to simulate an impulse. If this approach were to be used, the accelerometer could even be replaced with video analysis of the rear wheel to the obtain displacement data. Furthermore, Finite Element Analysis could be conducted on the bicycle frame to understand different modal oscillations.

Even though these results are valid for the bike used in this experiment, similar trends could be seen with other bikes where the step response would be similar, the damping ratio of the tire would reduce as tire pressure increases and the settling time would follow a quadratic response. Varying the tire pressure would allow the rider to have a noticeable increase in comfort and reduce their chances of getting issues related to fatigue from long-term vibrations.

ACKNOWLEDGMENTS

The author would like to acknowledge Dr. Peter So. for his insight and ideas on conducting this experiment and Dr. Barbara Hughey for her immeasurable guidance throughout the whole process. The author would also like to thank Prof. John Leonard for teaching various useful skills during lectures which contributed greatly to the success of the experiment. The author also acknowledges the teaching assistants of 2.671 for improving experimental setup and their guidance throughout the experiment. Finally, the author would like to thank his father for sparking his passion towards bicycling and motorcycles and for inspiring and supporting him throughout the experiment.

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