EFFECTIVENESS OF FRONT SUSPENSION VIBRATION DAMPING IN OFF-ROAD CYCLING

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Introduction

The rapid development of mountain biking has stimulated considerable innovation in bicycle design. While suspension systems are not typically incorporated on road bicycles, the rough terrain encountered in off-road cycling has made such systems a common component of both high performance competition bikes as well as low-end consumer equipment. However, the appropriate choice of a suspension fork is often left to the consumer and based on subjective statements, with little mechanical testing results available. A variety of suspension forks are now available to the consumer and include relatively simple elastomer "bumpers", air-oil telescopic shock absorbers, linkage designs with a flexible connection of fork to frame, and various full frame suspensions.

Riding over terrain can be thought of as an input signal with a certain frequency content; a suspension system can act as a smoothing filter for that signal. The effectiveness of the suspension system would be described by its ability to attenuate a wide range of input frequencies. The purpose of this investigation was to describe the damping effectiveness patterns associated with various suspension forks over different surface conditions. Using a setup similar to that of Orendurff et al. (1996), accelerations were collected along the fork axis at the axle and the frame and a spectral analysis performed to determine the range of frequencies associated with riding on gravel or trail conditions.

Methods

Suspension Conditions. Five suspension conditions were tested to reflect the most common options that were available on the market. A standard rigid fork/rigid frame system (R-R) was compared against three suspensions systems: air-oil (A-R), elastomer (E-R), and linkage (L-R) design forks. The air-oil and linkage design forks were further tested with a rear-suspended frame (designated A-S and L-S, respectively). In the suspended frame, a rear suspension system was integrated with the frame which provided some impact dampening to the back wheel. Fork stiffness settings were set according to the manufacturer's recommendations based on rider characteristics.

Bike Instrumentation. The instrumentation of the bike was similar to that of Orendurff et al. (1996). Two uniaxial accelerometers (PCB UB353B31) were screwed onto aluminum plates which were secured at the axle and the frame (Figure 1). An aluminum plate was used to fit the accelerometer axes parallel to that of the forks. Coaxial cables were used to transmit the accelerometer outputs to a microcomputer via an analog-to-digital (A/D) conversion board (Keithley-Metrabyte DAS-16). Accelerometer data were sampled at a frequency of 1000 Hz. To avoid attenuation of the acceleration signals, no filtering procedures were used during the acceleration data processing.

Testing Procedures. Each suspension condition was tested on two types of terrain conditions. The "trail" condition consisted of a leveled stretch of hard-packed dirt. This condition was similar to that encountered in single-track riding. The "gravel" condition was made up of coarse gravel similar to that found along railroad tracks. The rider was instructed to ride passively over the trail or gravel slightly elevated out of the saddle. The sequence of suspension conditions was randomized for each surface condition. Data collection was triggered manually and acceleration data were collected for 4 seconds at 1000 Hz. The end of the ride was marked with a 10-cm bump which allowed for post-synchronization. For each fork, four trials with speed between 6.5 and 7 m/s were used for analysis.

Axle Accelerometer Frame Accelerometer

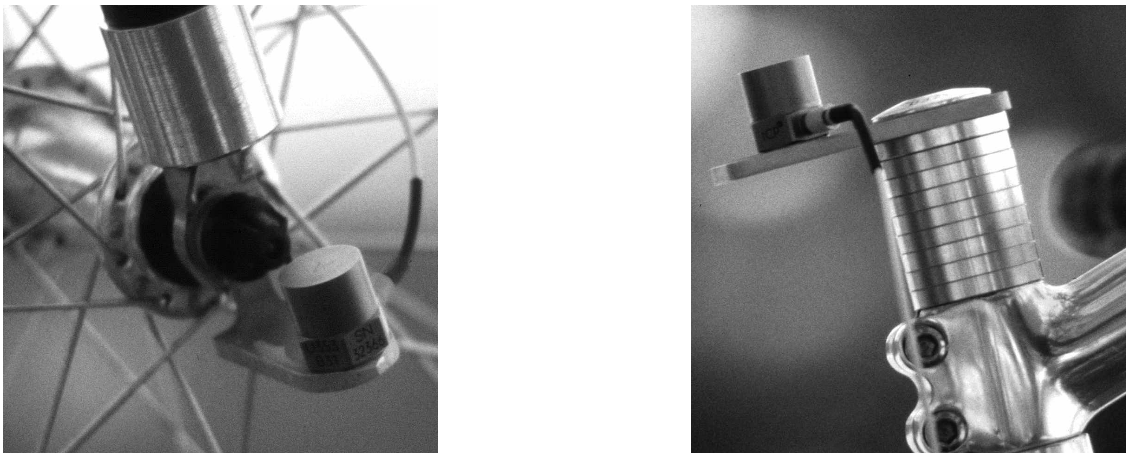

Figure 1: Accelerometer Setup

Data Analysis. From the 4-second data collection, a one-second sequence was taken using the post-synchronizing peak point as a starting point and taking 1000 data points prior to that point (which allowed the calculation of harmonic amplitudes from 0 to 500 Hz at intervals of 1 Hz). The subsequent spectral analysis of the accelerometer signals from the axle and frame was performed for each suspension condition and for every trial. The Fourier coefficients were calculated for each trial and the mean amplitude calculated for each harmonic. The difference in signal amplitude between the axle and the frame represented the damping effectiveness at each harmonic level.

Results & Discussion

This investigation looked at the two surface conditions as a signal, and used the suspension systems as filters. While the quantitative results are limited to the acceleration data in Table 1, and the spectral analysis graphs, clear relationships were observed. The acceleration magnitude ranges at the axle were higher on gravel than on the trail. However, the opposite relationship was observed at the frame. The acceleration ranges at the frame were lower on gravel for most conditions. Only the air-oil and rigid fork had frame signal ranges greater on gravel than on trail. Moreover, the linkage design fork with suspended frame (L-S) allowed greater vibration at the wheel than all other forks on both gravel and trail surfaces. Still, the dampening observed at the frame for the L-S condition was similar to that of all the other suspension forks.

	GRAVEL		**TRAIL**	
	Axle	Frame	Axle	Frame
Air-Oil Fork **Rigid** Frame	-21.1 to 23.5	-7.5 to 5.5	-16.1 to 19.1	-5.7 to 6.5
Elastomer Fork **Rigid** Frame	-19.0 to 23.4	-7.4 to 5.3	-14.6 to 19.7	-9.9 to 13.0
Linkage Fork **Rigid** Frame	-23.9 to 27.8	-7.6 to 4.8	-22.6 to 27.0	-12.1 to 11.4
Air-Oil Fork **Susp** Frame	-19.1 to 23.0	-7.1 to 5.1	-21.4 to 29.1	-12.1 to 10.1
Linkage Fork **Susp** Frame	-33.0 to 39.8	-6.9 to 7.5	-23.4 to 27.2	-13.2 to 13.0
Rigid Fork **Rigid** Frame	-23.3 to 29.2	-9.1 to 17.0	-14.9 to 19.2	-8.8 to 12.4

Table 1: Acceleration ranges at axle and frame (in g)

The spectral graphs (sample in Figure 2) showed that the amplitude of the signal at the frame is decreased in all suspension conditions in the 0 to 100 Hz range. Only the rigid condition did not follow this pattern. Therefore, all suspension conditions seem to effectively dampen the vibrations at the frame. However, it was difficult to differentiate the effectiveness of the forks performances.

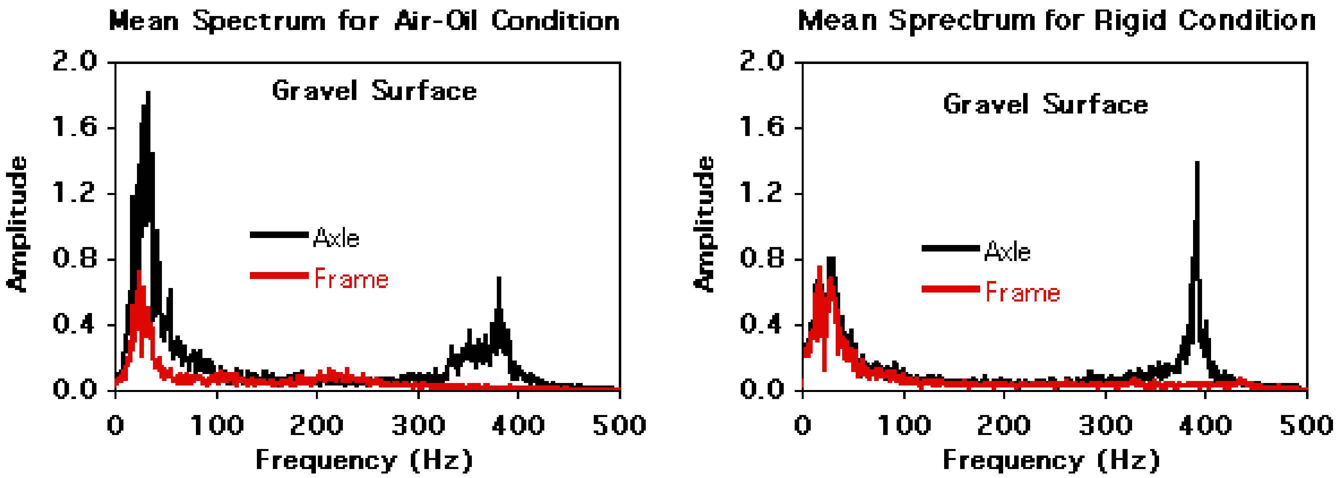

Figure 2: Sample Spectral Analysis for Air-Oil and for Rigid Forks

The second area with peak amplitudes at the axle was located between 300 and 400 Hz. All fork conditions revealed the same peak patterns. However, the amplitude of the frame spectrum was minimal and it can be concluded that the forks dampen the limited signal of the axle within that range. This pattern was observed for all suspension conditions including the rigid fork. This observation would suggest that another form of dampening must be involved in the high frequency range.

It should be noted that the rider most likely contribute to a signal input at the frame and axle. Wang and Hull (1997) have previously modeled an off-road cyclist using the arms and legs as damping elements. They also included the rider's visceral mass natural frequency as an input signal. The results found here suggest that the rider input needs consideration to assess and explain the effectiveness of suspension forks.

The low frequency range dampening suggests that the effectiveness of a suspension fork can be quantified. However, the spectral graphs involve rather noisy harmonic amplitudes which may be due to the limited number of trials used in the analysis. Indeed, it is quite unlikely that a fork would have such dramatic amplitude changes from one harmonic to the next. With more trials, the average amplitudes would likely follow a smoother curve which would improve the description of fork effectiveness.

References

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