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Practical Realization of a Theoretical Optimal-Handling Bicycle

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Abstract

Although conventional bicycles have evolved into the familiar design, there likely exist bicycles that handle better when performing lateral maneuvers. Moore, et al. have calculated theoretically optimal designs that have unconventional geometric features, such as large negative trail [1]. The present research aims to practically realize and fabricate one of these theoretically optimal bicycle designs and evaluate whether it does in fact have better lateral handling qualities than a traditional bicycle.

Our measure of handling difficulty is the theoretical handling quality metric (HQM) presented in [2]. This HQM is a function of frequency and quantifies the human control effort needed to stabilize and direct bicycles of a given design. Smaller values of HQM correspond to better lateral handling. HQM can be predicted for any given set of bicycle design parameters. Figure 1a shows the HQM for the three bicycle designs discussed herein.

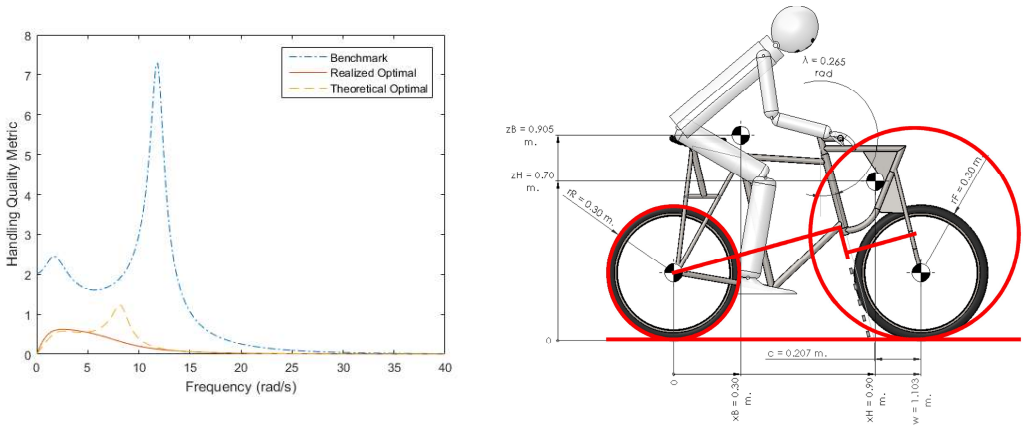

Figure 1. (a) Plot of HQM vs. frequency for the benchmark, realized optimal, and theoretical optimal bicycles at 4 m/s; (b) Schematic of theoretical optimal bicycle (red, large front wheel) overlaid on the practically realized optimal design.

In the present research, the calculated parameters of the optimal bicycle for a 4 m/s travel speed [1] (see Fig 1b) were set as the target for practical realization. This bicycle is identical to the "benchmark bicycle" presented in [3] except for differing values of the trail, wheelbase, steer axis tilt, and front wheel radius. Note that this optimal bicycle has the same wheel rotational inertia as the benchmark; only its geometry differs. Thus, the wheel radius is a proxy for angular momentum by effectively increasing/decreasing wheel angular rate at the specified speed.

The practically realized design, also Fig 1b, utilized a preexisting standard bicycle frame, which was measured and modeled using CAD software. Modifications were made to this frame to

bring the steer axis tilt and wheelbase to the optimal bicycle parameters. An inertially realistic human rider model must be accounted for to ensure center of mass equivalency. Thus, to achieve the benchmark bicycle inertia, the rider was required to be above the rear wheel, well behind the conventional seatpost location. This required expanding the frame by adding an additional seat tube and support structure. The fork was custom designed to ensure both the trail and center of mass location match the target parameters from the optimal bicycle and so it had sufficient structural integrity. However, we found it impossible to realize the fork inertia tensor, see (Table 1), likely due to the lack of realism of the benchmark bicycle.

Table 1. Parameter values that differed significantly between the realized and theoretical target.

Parameters [3]	I_{Bxx}, I_{Bxz}, I_{Byy},, I_{Bzz} (kg-m^2)	I_{Hxx}, I_{Hxz}, I_{Hyy},, I_{Hzz} (kg-m^2)	I_{Fxx}, I_{Fyy} (kg-m^2)
Theoretical	9.2, 2.4, 11, 2.8	0.05892, -0.00756, 0.06, 0.00708	0.1405, 0.28
Realized	9.8, -0.48, 11, 3.2	0.04000, 0.0184, 0.06, 0.0298	0.09622, 0.19

Finally, the theoretical optimal design calls for a large front wheel radius that has the inertia of the benchmark bicycle wheel, but we wanted to avoid constructing this unique custom large wheel. Equivalent rotational angular momentum of a smaller standard wheel can be achieved if the rotational inertia of the realized wheel is proportional to the theoretical inertia by the constant $\frac{r_{realized}}{r_{theoretical}}$. We achieved this alternative target inertia by adding mass to the rim of the smaller wheel.

The practically-realized design parameters were used to compute the HQM of the realized bicycle design. Despite the aforementioned deviations from the theoretically optimal parameters, Table 1, the realized bicycle design exhibited an HQM less than two tenths of the HQM of the benchmark bicycle, in addition to having a slightly lower HQM than the theoretical design. A comparison between the HQM plots of the benchmark, realized, and theoretically optimal bicycles can be found in Figure 1a.

Our initial goal was to realize a bicycle with the same dynamics as the theoretically optimal bicycle but we found it impossible to do so. The theoretically optimal bicycle's stable capsize and unstable caster eigenvalues were nearly matched, but the realized bicycle has an unstable weave mode (1.80+/-6.51i instead of -0.35+/-9.10i). This is fortunately of little concern, however, because it is easy stabilized by the human controller and results in a lower HQM.

The next step is to actually fabricate and test the bicycle in typical lateral maneuvers. We expect to report on this in the proposed conference paper if accepted.

References

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[3] J. P. Meijaard, J. M. Papadopoulos, A. Ruina, and A. L. Schwab, "Linearized dynamics equations for the balance and steer of a bicycle: A benchmark and review," Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 463, no. 2084, pp. 1955–1982, Aug. 2007.