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Balance and control of a rear-wheel steered speed-record recumbent bicycle

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Abstract

The goal of the Human Power Team from the TU Delft and the Free University of Amsterdam is to break the world speed record in unpaced cycling (Sam Whittingham, 133.28 km/h). The design of such a faired recumbent bicycle is a challenge. The Delft design, called VeloX (Human Power Team (2013)), is a fully-faired monocoque front-driven recumbent bicycle, with minimized air drag and maximized space for a big and strong athlete. However, front driven bicycles have the disadvantage that the front driving induces unwanted steering and that the frontal area of the bicycle cannot be reduced any further. A solution would be rear-wheel steering. A common thought is that a rear-wheel steered bicycle cannot be laterally self-stable, and therefore hard to control. However, recent research (Knoll *et al.* (2012)) has shown that one can design a rear-wheel steered bicycle which shows a stable forward speed range.

Based on these results a rear-wheel steered recumbent bicycle has been designed, within the existing design constraints. Although not self-stable, this design shows a mildly lateral unstable behavior in the desired forward speed range of 0 to 40 m/s (0 to 144 km/h). Computer simulations demonstrate that the bicycle can be stabilized by adding a human controller model (Schwab *et al.* (2013)) to the bicycle model. For a set of expected lateral perturbations (side wind perturbations) it is shown that rider steer torque stays within human bounds, both in magnitude and in frequency. Future work is dedicated to building and testing a prototype of the design.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: bicycle; dynamics; control; design; rear wheel steering.

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1. Introduction

The 200 m flying start World Human Powered Vehicle speed record for single rider vehicles currently stands at 133.78 km/h and is was set by the Human Power Team Delft & Amsterdam (HPT) which consists of students of the Delft University of Technology and the Free University Amsterdam. The record was set with the third iteration design by the team in September of 2013 with their Velox 3 recumbent fully faired bicycle (see Figure 1). The new record was only a slight improvement over the previous record of 133.28km/h set by Sam Whittingham in de Varna Tempest 4 in 2009 at the same event, the World Human Powered Speed Challenge, in Battle Mountain, Nevada.

Figure 1.Velox3, recumbent fully faired bicycle, which holds the current World Human Powered Vehicle speed record for single rider vehicles at 133.78 km/h.

The HPT team develops their own recumbent fully faired bicycle each year. The first two bicycles that the HPT team developed, the Velox1 and Velox2 are similar to the Varna Tempest. Each being front wheel steered and front wheel driven recumbent bicycles, whilst the Velox3 is a front wheel steered, rear wheel driven recumbent bicycle (Human Power Team (2013)).

The development of a world record setting human powered vehicle is an interesting design problem with many trade-offs having to be made. However the most important aspect in designing such a high-speed bicycle is it's aerodynamic shape, usually described by the drag coefficient multiplied by the frontal area (C_dA). The power the rider produces to propel the bicycle forward at such high speeds mostly goes into overcoming the aerodynamic drag (Kyle and Weaver (2004)) Thus the more streamlined the shape of the fairing, or the smaller the frontal area, the higher the speed that can be attained.

With a Prone bike (prone position is a body position in which one lies flat with the chest down) a much smaller frontal area can be achieved than with a recumbent. However, the prone position is found to be more uncomfortable when breathing heavily, resulting in a lower power output by the rider, and thus the recumbent position is usually opted for. Whilst some designs have been made where the rider faces rearwards (Russo (2011)), most opt to keep the rider facing forward to reduce the mental load. In the recumbent position, with the rider facing forward, the rider's feet are located at the front end of the bicycle, thus requiring a long chain to drive the back wheel (as in the Velox3) with subsequent losses, or the front wheel is driven, causing unwanted steering due to the application of a moment on the steering assembly by the driven chain (as in the Velox1, Velox2 and Varna Tempest) resulting in an extra mental load for the rider who hast to counteract this steering torque by applying a counter torque to the handlebars.

One of the main aerodynamic disturbance features that currently all bicycles have is a relatively large gap in the bodywork around the front wheel. This gap is required to ensure that the wheel can be steered. The size of the gap depends on the required turning radius, where a larger radius allows for a smaller gap. The shell of the Velox is designed using CFD with aim of having a laminar airflow as far as possible along the body (Epema et al. (2012)). The gap induces turbulent airflow which is detrimental to the aerodynamic design.

Furthermore by steering the front wheel the fairing of a recumbent bicycle also has to encapsulate a larger frontal area as the legs also have to move laterally when steering in order to not touch the tyre. The larger encapsulated area at the front means that the fairing further back also encapsulates a larger area and therefore increases the surface area and thus the friction drag. This is because to keep a laminar flow, detachment of the airflow must be prevented, which can be achieved by keeping adverse pressure gradient small, meaning that the radius of curvature of the fairing must be large, preventing the fairing from fitting snugly around the rider and instead greatly increasing the inside volume.

All these design restrictions suggest that a large gain can be made by changing to a front wheel driven, rear wheel steered recumbent bicycle. By steering the rear wheel (where the airflow is already turbulent) the detrimental (for the laminar airflow) gap around the front wheel can be minimized and as such the introduction of the turbulent airflow can be minimized too. The encapsulated frontal area as a result can also be kept smaller around the front wheel, and thus also the surface area of the whole fairing can be reduced in turn reducing the friction drag. A short chain that is directly connected to the front wheel reduces energy losses and by not powering the same wheel as the wheel that is steered the rider has less mental load.

The common conception is that a rear wheel steered bicycle is laterally highly unstable and therefore dangerous to ride, certainly at high speed. Whilst true in most cases, recent research has shown that it is possible to develop self-stable rear wheel steered bicycles (Kooijman et al. (2011)) and that these laterally self-stable bicycles can be ridden (Knol et al. (2012)) at least at low and medium speeds**.** Whilst searching for more self-stable rear wheel steered configurations a racing recumbent configuration was recently found as shown in Figure 2.

This paper compares the handling qualities of the Velox1 (shown in Figure 2) and a possible Rear Wheel Steered Velox (RWSVelox) configuration. The handling qualities are evaluated by comparing the steering effort required to follow a straight line when perturbed laterally (side wind) for the two configurations.

After this introduction, the paper continues with the description of the two bicycles, and the used rider models. In section 3 the results of the simulations with the two configurations are presented and discussed. The paper ends with some conclusions and direction for future work.

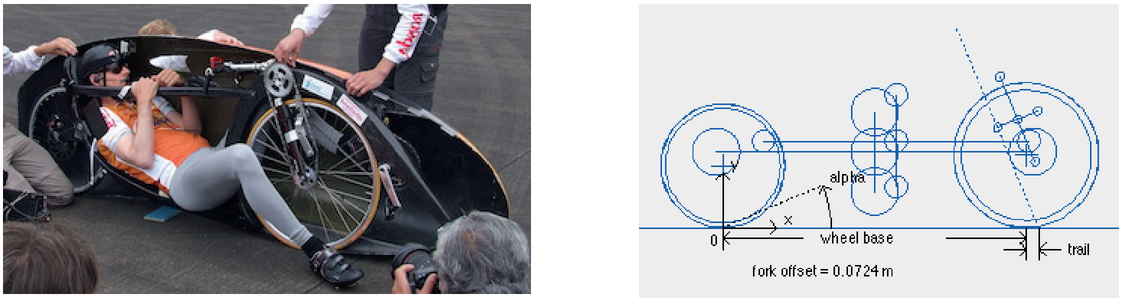

Figure 2 *Left*: Velxo1: front driven and front wheel steered recumbent bicycle. *Right*: Layout of the Velox1 as generated by the JBike6 software (JBike6 2003). The bicycle is moving from left to right. The blue dotted line is the steering axis. Mass and mass moment of inertia of the individual rigid bodies are depicted by 6-mass balls lined up in pairs in the three principal directions. The mass of every ball is 1/6 of the total mass (the circle at the centre represents both a right mass and a left mass hidden behind it). The relative volumes indicate the relative masses of those two assemblies. The largest body is the rider (90 kg), next comes the rear frame (20 kg) and then comes the front steered frame (3 kg).

2. Method

The lateral dynamics and stability of the bicycle design can be determined from the linearized equations of motion for the bicycle (Meijaard et al. (2007)). A human rider-like controller from literature (Schwab et al. (2013)) is added to the model to simulate rider control and determine rider effort required to balance the bicycle after perturbations. Lateral perturbations are generated based on a gust of side wind. The power spectral density of the steer torque quantifies rider effort. The steer effort for the original front wheel steered Velox1 design is compared with the ones for the new rear wheel steered design RWSVelox.

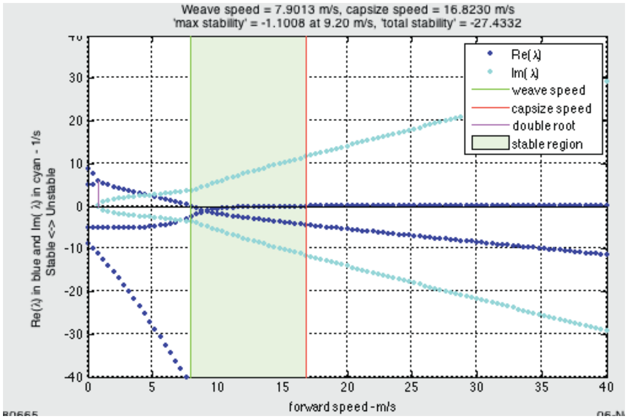

Figure 3. Eigenvalues λ from the linearized stability analysis for the Velox1 bicycle from figure 2, where the dotted blue lines correspond to the real part of the eigenvalues (Re(λ)) and the dotted light blue line corresponds to the imaginary part (Im(λ)) of the eigenvalues, in the forward speed range of $0<v<40$ m/s. The speed range for the asymptotic stability of the Velox1, that is where all real parts of the eigenvalues are less than zero (Re(λ)<0), is $v_w<v<v_c$. The zero crossings of the real part of the eigenvalues are for the weave motion at the weave speed $v_w=7.9$ m/s and for the capsize motion at capsize speed $v_c=16.8$ m/s, and oscillations emerge at the real double root at $v_d=0.7$ m/s.

The original design, Velox1, is shown in Figure 2. This is a front wheel driven and front wheel steered recumbent bicycle. The stability of the lateral dynamics, as determined from the linearized bicycle model (Meijaard et al. (2007)), is depicted in Figure 3. Clearly the bicycle is initially unstable at low speed but starts to be self-stable at 7.9 m/s. At 16.8 m/s the bicycle becomes mildly unstable in capsize, however this instability is so mild (0<Re(λ)<0.1), that from a practical point of view the bicycle is self-stable from 7.9 m/s to very high speed. Because this model is self-stable we expect that the steer effort for balancing after lateral perturbation will be low.

The design of the rear-wheel steered recumbent bicycle (RWSVelox) is done by trial and error. To keep the design within the limited space of the fairing, and to have an identical rider posture as in the Velox1, only a few free design parameters remained: the headangle (angle of the steer axis), the trail (caster of the rear wheel) and the position of the centre of mass of the steer assembly. Figure 4(left) shows the RWVelox layout, the rear steered wheel has a trail of 0.2 m and the steering axis makes and angle of 30 degrees with the horizontal. The stability of the lateral motions is shown in Figure 4(right). Clearly the RWSVelox is not self-stable, it turned out to be impossible to find a self-stable design within the strict design limits. However, the instability at high speed is comparable to the instability at rest, and we suspect that at these high speeds it should be fairly easy to balance by steering.

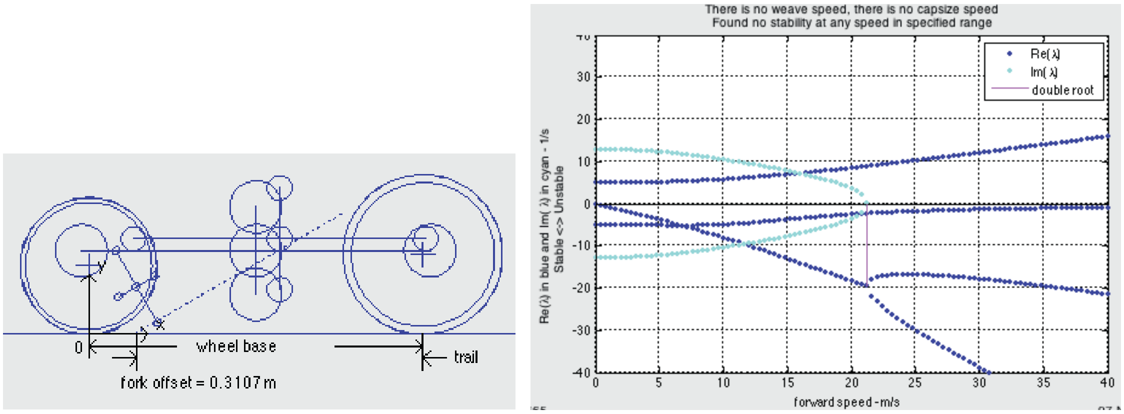

Figure 4. *Left:* Layout of the rear-wheel steered recumbent bicycle (RWSVelox) as generated by the JBike6 software (JBike6 2003). The bicycle is moving from left to right. The blue dotted line is the steering axis, which makes a 30 deg angle with the horizontal and is positioned such that the trail of the rear wheel is 0.2 m. *Right:* Eigenvalues λ from the linearized stability analysis for the RWSVelox bicycle from Figure 4(left), where the dotted blue lines correspond to the real part of the eigenvalues (Re(λ)) and the dotted light-blue line corresponds to the imaginary part (Im(λ)) of the eigenvalues, in the forward speed range of $0<v<40$ m/s. This rear-wheel steered bicycle is unstable throughout the complete forward speed range. The nature of the instability is non-oscilatory, the bicycle is falling over like an inverted pendulum.

3. Results

The performance of the RWSVelox is based on a comparison of steer effort with the original front wheel steered Velox1. The power spectral density of the rider applied steer torque determines the steer effort during a simulated run. The rider is modelled according to a Least Square Regulator (LQR) design from literature (Schwab et al. (2013)). This is a linear controller, with gain scheduling for the various forward speeds, which uses the full state vector as input and generates an applied steer torque as output, which stabilizes the bicycle. In the simulated runs, the system is perturbed by gusts of side wind, which are modelled by an applied lean torque with the characteristics of 1 Nm maximum amplitude and white noise spectrum. The runs are performed in the forward speed range of 35 to 40 m/s, each for 100 seconds.

Figure 5 shows the steer torque and the power spectral density of the steer torque for the Velox1 at 40 m/s. The steer torque amplitude is low, 0.02 Nm, and most steering is done at low frequency, around 1 Hz. This low effort is expected because the system is self-stable. Figure 6 shows the same results but now for the RWSVelox. The steer torque amplitude is 0.1 Nm, which is five times higher than with the Velox1, but still well within physiological

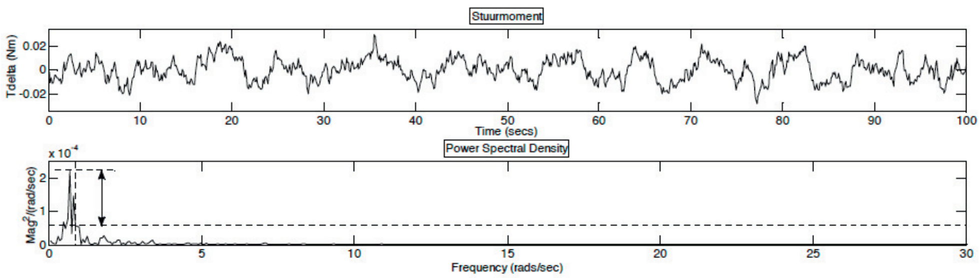

Figure 5. Steer torque as a function of time, and power spectral density of the steer torque from the 100 second simulation of the Velox2 bicycle with LQR rider model under lateral perturbations, riding at 40 m/s.

limits. More alarming however is the frequency contents. The steer torque is broad spectrum with a first peek is at 7 Hz, which is high and demands attentive steering. The high frequency contents is probably not realistic since in reality this would be damped out by (non-modelled) damping and friction in the system.

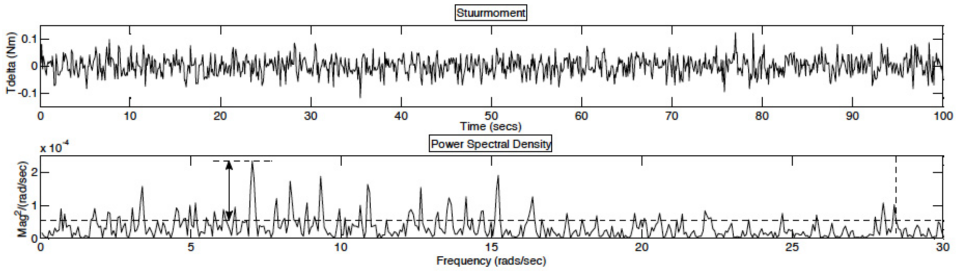

Figure 6. Steer torque as a function of time, and power spectral density of the steer torque from the 100 second simulation of the rear wheel steered recumbent bicycle (RWSVelox) with LQR rider model under lateral perturbations, riding at 40 m/s. Note the first peak in the PSD at 7 Hz. The higher frequency contents is probably not realistic since in reality this would be damped out by (non-modelled) damping and friction in the system

4. Conclusion and Discussion

The result from the simulation show that the presented rear-wheel steered recumbent bicycle (RWSVelox) is probably not a good design. The physical steer effort required for balancing is not too large, but the mental effort and reaction speed required to ride the bicycle at high speed are very high. The steer effort requires too much high frequency contents at high forward speeds. Future work will be directed to enhancing the design space, which could result in a less-unstable and easier controllable rear-wheel steered bicycle.

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References

Schwab, A. L., de Lange, P.D.L., Happee, R., Moore, Jason K., 2013. Rider control identification in bicycling using lateral force perturbation tests. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics August 2013, 227(4):9.

Epema, H.K., van den Brand, S., Gregoor, W., Kooijman, J.D.G., Pereboom, H.P., Wielemaker, D.C., Zweep, C.-J. van der, 2012. Bicycle Design: A different approach to improving on the world human powered speed records. In: Procedia Engineering, Volume 34, p.p 313-318.

JBike6 software, 2003. http://ruina.tam.cornell.edu/research/topics/bicycle_mechanics/JBike6_web_folder/.

Kooijman, J. D. G., Meijaard, J. P., Papadopoulos, J. M., Ruina, A., Schwab, A.L., 2011. A bicycle can be self-stable without gyroscopic or caster effects. Science 15 April 2011, 332(6027):339-342.

Meijaard, J. P., Papadopoulos, J. M., Ruina, A., Schwab, A.L., 2007. Linearized dynamics equations for the balance and steer of a bicycle: a benchmark and review. Proceedings of the Royal Society A 463:1955-1982.

Human Power Team Delft & Amsterdam (2013): http://www.hptdelft.nl/en/.

Knol, M., van Dijk, T., Huiskens, T., de Vette, M., 2012. Rijden op een achterwiel gestuurde fiets. BSc report (in Dutch), TU Delft, 11 June 2012.

Kyle, C. R., Weaver, M. D., 2004. Aerodynamics of human-powered vehicles. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 218.3: 141-154.

Russo, F., 2011. Eiviestretto - The World-Record-Speedbike. http://www.russo-speedbike.com/eiviestretto.html.