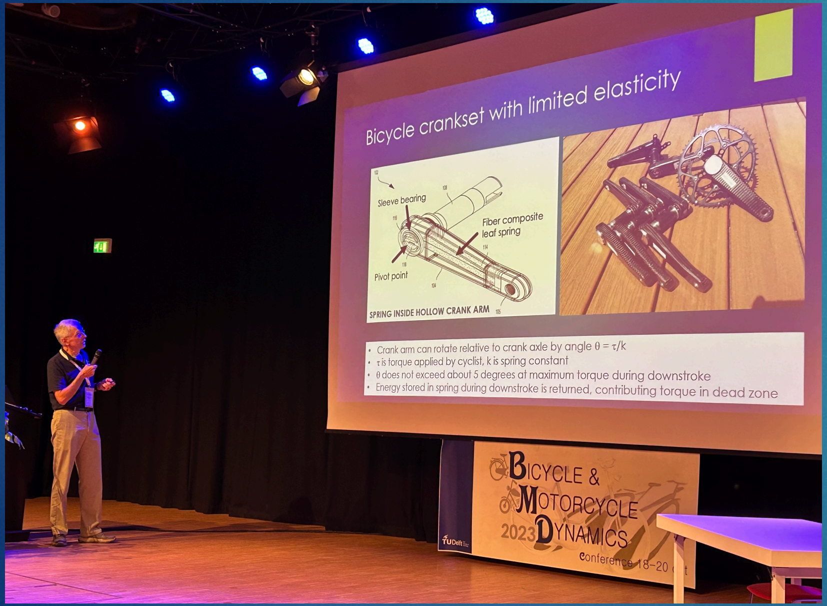
Huron Cycling presentation at 2023 BMD conference



Improvement of Cycling Efficiency for Drivetrains with Elasticity

WILLEM DEN BOER

HURON CYCLING LLC

OCTOBER 18, 2023

www.huroncycling.com

OUTLINE

- Intro
- Bicycle crankset with elasticity
- Test results
- Modeling of bicycle with inelastic and elastic drivetrains
- Losses in conventional drivetrains
- Modeling of losses in conventional drivetrains
- Summary

Intro

- Running shoes with carbon fiber plate enhance energy return > world records
- Carbon plates act as a spring-like mechanism, storing and releasing energy with each footstrike
- This increased energy return propels runners forward, enabling them to maintain higher speeds and cover greater distances with less effort

QUESTION:

- Is energy return possible on bicycles as well to mitigate dead zone of pedal revolution?

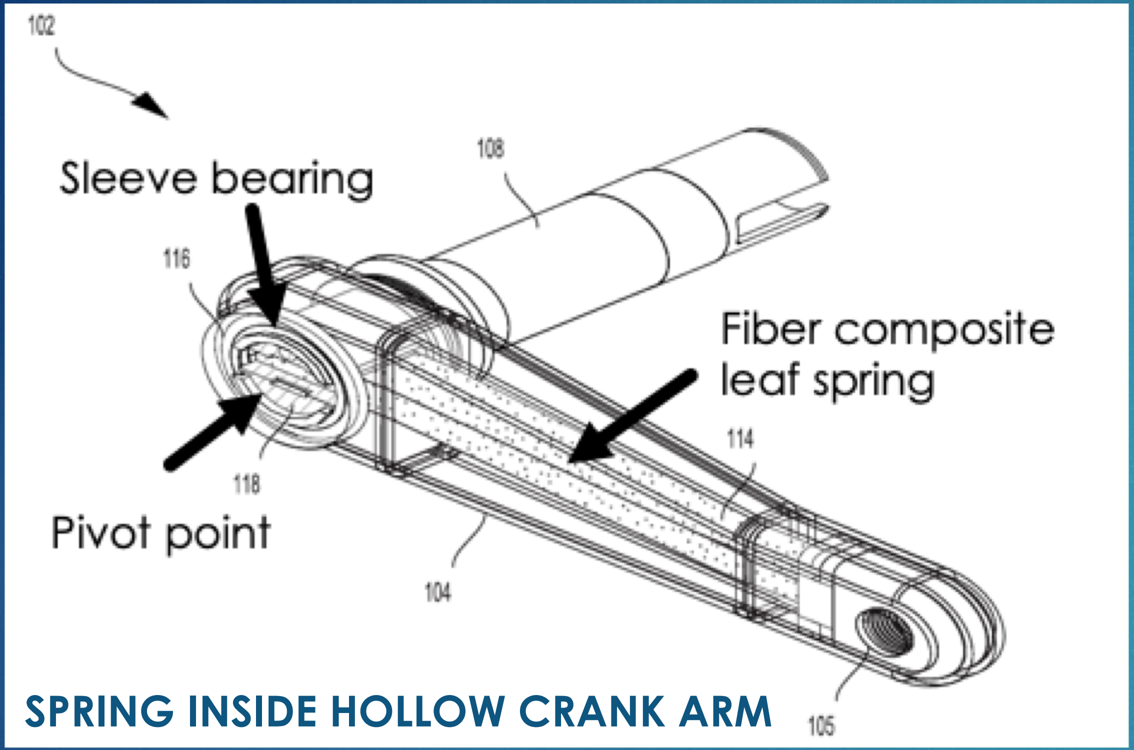
Source: Nike

Approaches to drivetrain elasticity

- Elasticity in spider – improved acceleration claimed from elimination of dead zone
- Elasticity in belt drive
- Elasticity/springs in crank arms – our approach

ELASTICITY IN SPIDER – Hamamoto, 2019

Bicycle crankset with limited elasticity



- Crank arm can rotate relative to crank axle by angle $\theta = \tau/k$
- τ is torque applied by cyclist, k is spring constant
- θ does not exceed about 5 degrees at maximum torque during downstroke
- Energy stored in spring during downstroke is returned, contributing torque in dead zone

Indoor Testing on Smart Trainer

- Novel crankset vs. conventional forged aluminum crankset
- More than 20 tests of 15 or 30 min under identical conditions comparing the two
- Input power measured with Powertap P1 power meter at left and right pedals
- Effective speed measured on Tacx Neo
- Speed to input power ratio as measure of cycling efficiency
- Tested by others as well (Eastern Michigan University, crankset manufacturer)

Representative test

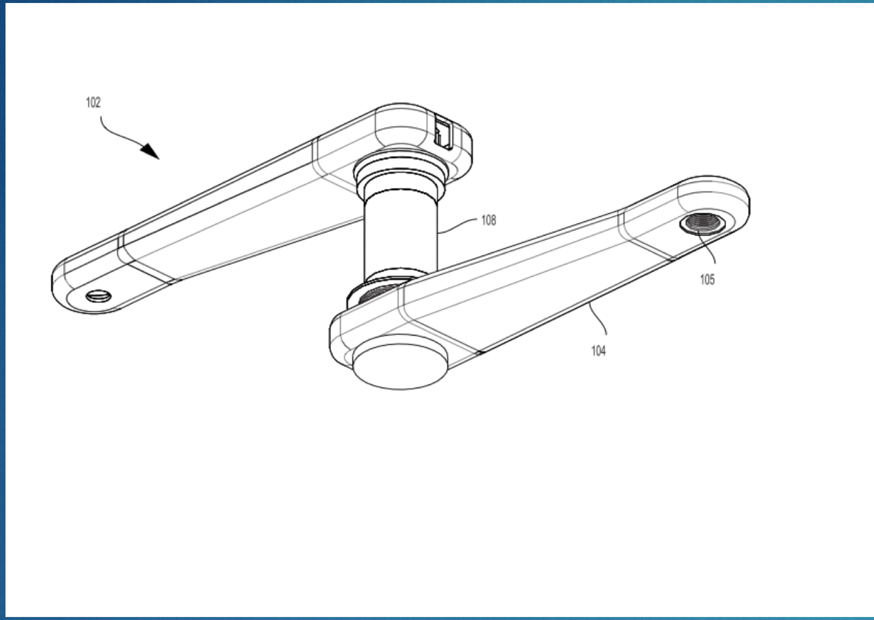
SETUP

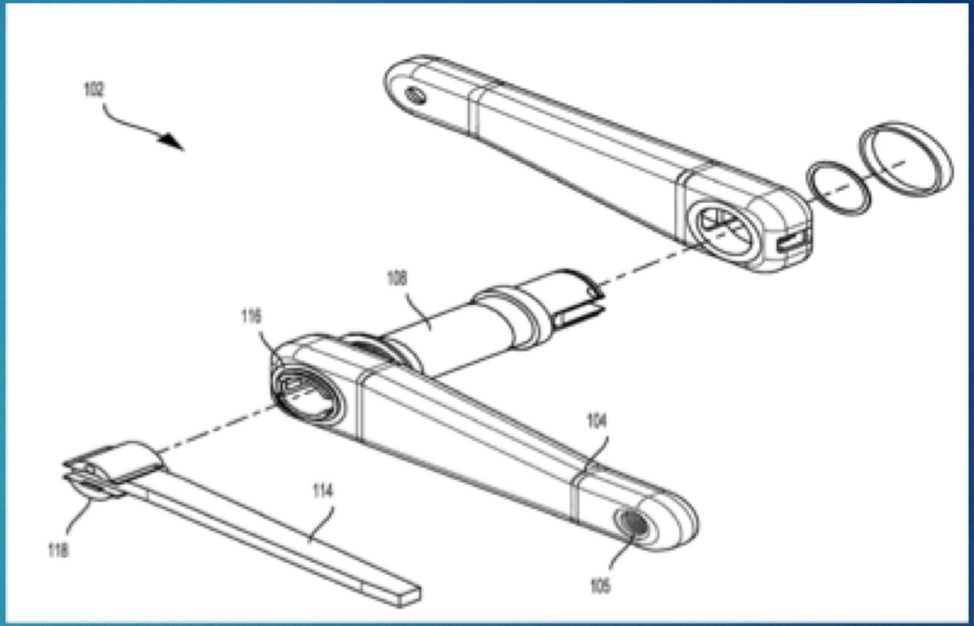
Test equipment	**Tacx Neo smart bike trainer**
Slope setting	3 %
Power target	200 W
Duration of test	15 minutes
Gear ratio	36/17
Power meters	Tacx Neo (better than 0.5 % accuracy) for speed Powertap P1 L/R pedal power meter for input power
Control conventional crank set	FSA Forged Aluminum - 175 mm crank length
Prototype novel crank set	Leaf springs with k=1000 Nm - 175 mm crank length

RESULTS

	Conventional crank set	**Novel crank set**
Average Speed Tacx (km/h)	19.4	19.4
Average Cadence Tacx (rpm)	71	71
Distance Tacx (km)	4.865	4.865
Average Power Powertap P1 (Watts)	200.5	196
Energy Powertap P1 (kJoule)	180.5	176.5
Speed to input power ratio	0.09675	0.099 (2.3 % higher)

Summary test results novel crank set

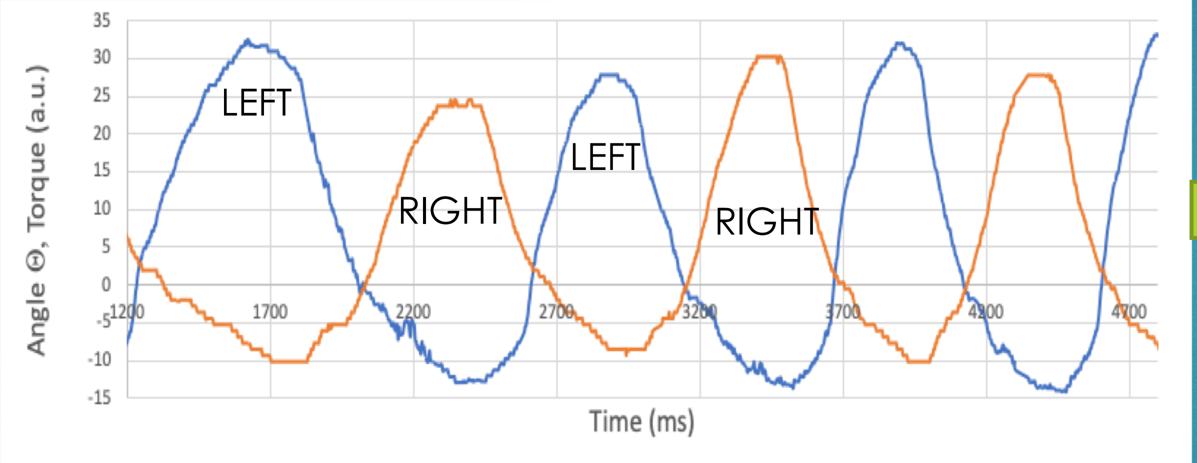




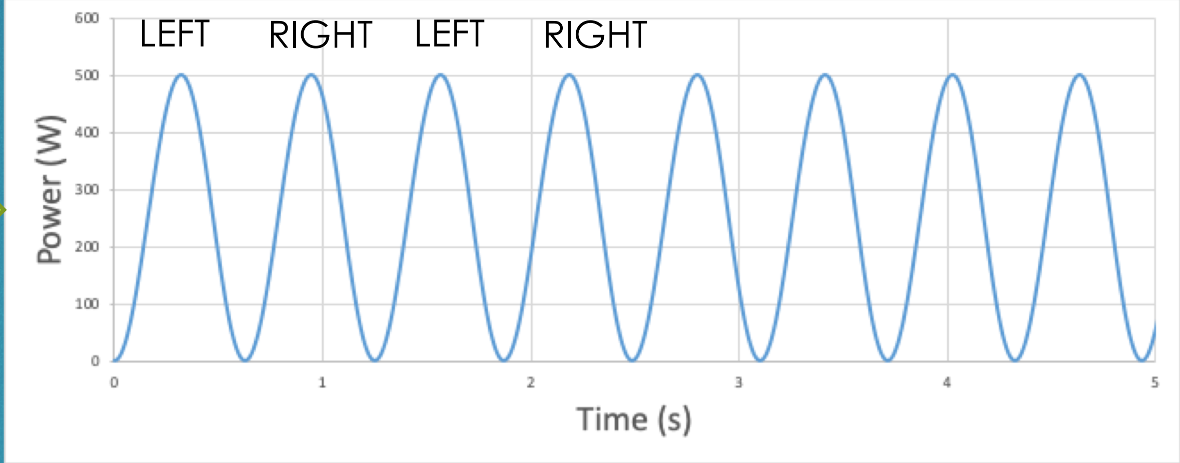
- Speed power ratio 1 to 4 % higher for novel crankset
- Typical test: 2.3 %
- Translates into one minute gain in 45 minute time trial
- Large gain vs. incremental improvements from aerodynamic optimization

Modeling of torque and power

MEASURED



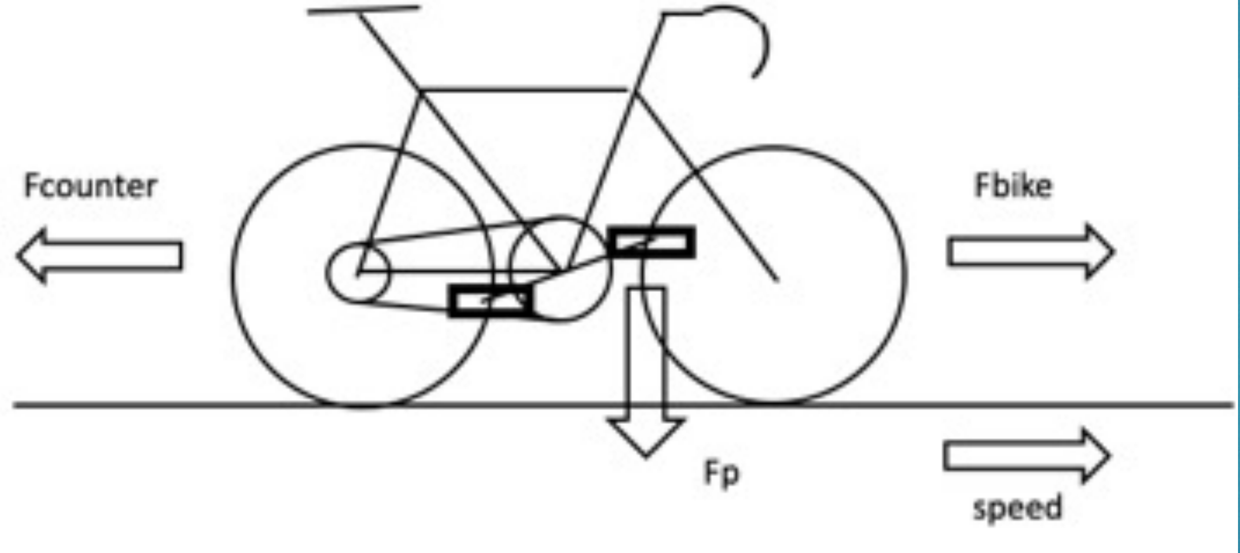
MODEL



- θ measured with magnetic rotary sensors @ 1500 Hz sampling rate (< 0.1 degree accuracy)
- Torque: $\tau = k * \theta$

- Sum of left and right torque approached by: $\tau \sim \sin^2 \omega * t$ (ω = crank angular velocity)
- Power: $P = \omega * \tau = P_0 * \sin^2 \omega * t$

Modeling of speed and crank angular velocity



$$P = P_0\,(\sin \omega t)^2 = P_0(1 - \cos(2\omega t))/2$$

$$\tau = \frac{P}{\omega}$$

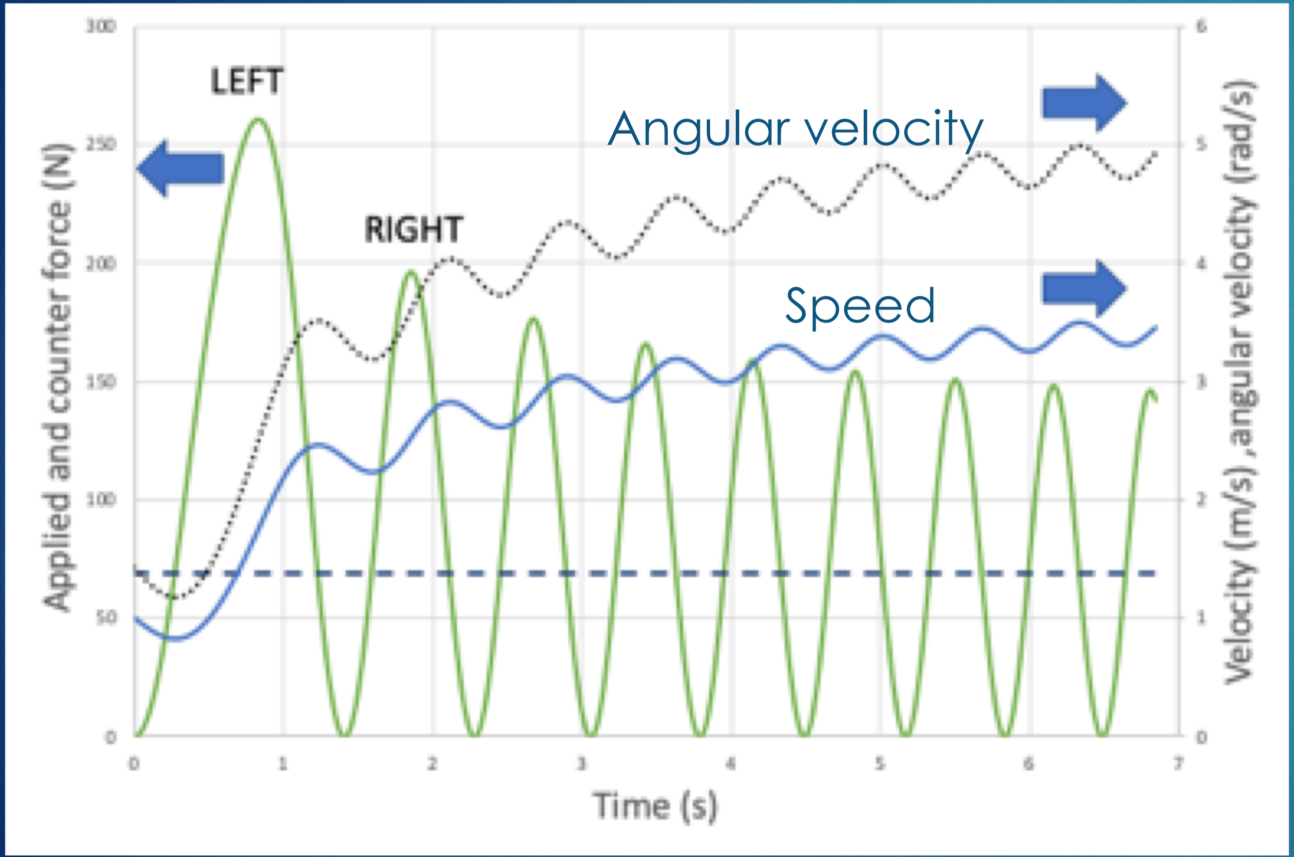
$$F_{bike} = \frac{P}{v}$$

$$F_{counter} = mgsin\,\alpha \quad (\alpha \text{ is slope})$$

$$F_{net} = F_{bike} - F_{counter}$$

$$\mathrm{d}v = \frac{F_{net} * \mathrm{dt}}{m}$$ (Newton's law)

Modeling results inelastic drivetrain



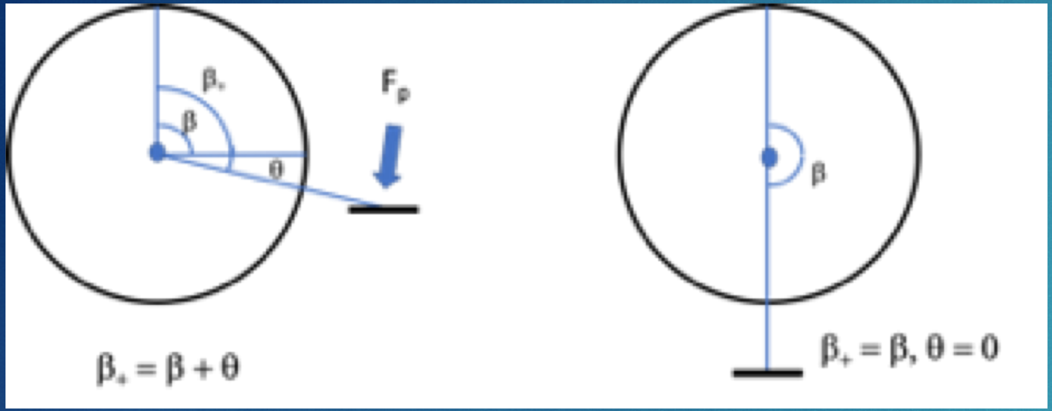
Input conditions:

- m = 70 [kg] (bike + rider)
- v_0 = 1 [m/s] (initial speed)
- P_0 = 500 [W] (for an average power of 250 W)
- R = 0.35 [m] (rear wheel radius)
- GR = 2 (gear ratio)
- Uphill slope α = 0.1 rad (6.37 %)

Results:

- Same % oscillations in v and ω: $v = \omega * R * GR$
- Speed oscillations proportional to: P_0/cadence
- Speed peaks 45 degrees after applied force peaks

Modeling novel, elastic drivetrain



Crank axle angle: β
Crank arm angle: $\beta_+ = \beta + \theta$
θ peaks during down stroke
θ goes to zero in dead zone

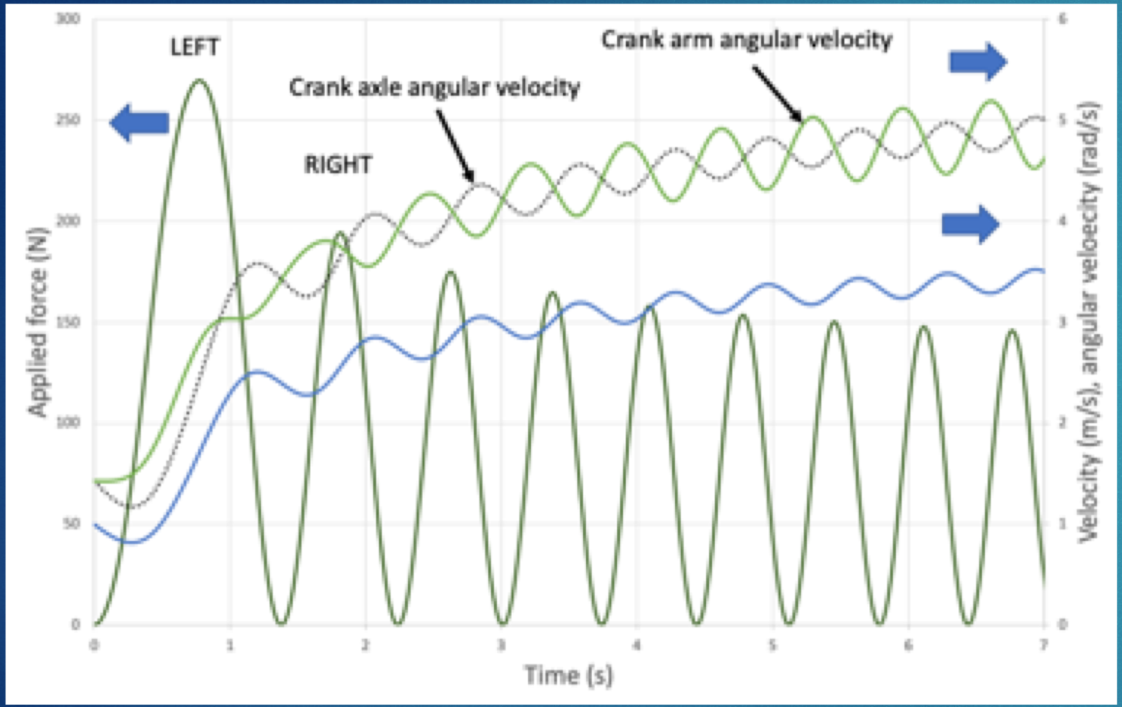
Angle θ between crank arm and crank axle:

- $\tau = F_p * r = k\theta$
- $\omega_+ = \frac{d\beta_+}{dt} = \omega + \frac{d\theta}{dt}$ (angular velocity of crank arm)
- $F_p = \frac{P}{\omega_+ r}$

Energy stored in spring:

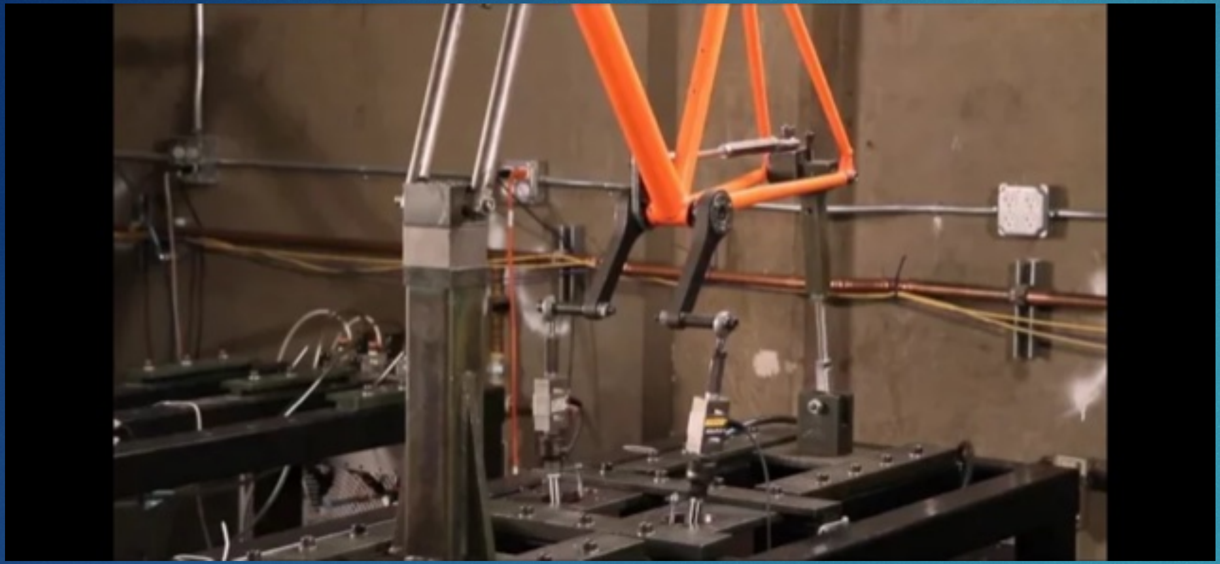
- $E_{spring} = \frac{1}{2}k\theta^2$
- $P_{spring} = -\frac{dE_{spring}}{dt} = -k\theta\frac{d\theta}{dt}$
- $F_{spring} = -F_p * \frac{P_0 \sin(2\omega t)}{\omega_+ k}$
- $F_{ax} = F_p + F_{spring} = F_p(1 - \frac{P_0 \sin(2\omega t)}{\omega_+ k})$
- $F_{bike} = \frac{F_{ax} * r}{R * GR}$

Modeling results elastic drivetrain



- *k* = 1000 Nm (spring constant)
- Crank arm angular velocity is now different from crank angular velocity (out of phase in this example)
- Force and speed profile do not change enough to explain test results
- Speed power ratio close for elastic and inelastic drivetrains
- Does not explain 2% improvement
- How to explain test results?
- Losses in conventional drivetrain have not been considered yet

Losses in conventional cranksets



Frame fatigue test with pedaling forces:
Lateral flexing of frame – no energy return
https://www.youtube.com/watch?v=8blo6O_KIAs

Crank fatigue test with pedaling forces:
Twisting of crank arms – no energy return
https://www.youtube.com/watch?v=7rZ1L6brkNE
Up to 1.6 % loss at 100 rpm, more at lower rpm

Modeling of losses

In conventional crankset strain energy from deformation D_1 of frame and crank arms : $E_{def1} = \frac{1}{2}qD_1^2$

This energy is lost and not returned to propel the bike.

In novel crankset this strain energy is partially absorbed by springs in crank arms: $D_2 < D_1$

- Total strain energy: $E_{spring} + E_{def2} = \frac{1}{2}k\theta^2 + \frac{1}{2}qD_2^2$ with $\frac{1}{2}qD_2^2 < \frac{1}{2}qD_1^2$
- Irreversible strain losses are converted into reversible strain losses

Example:

When $E_{def1} = \frac{1}{2}qD_1^2$ is about equal to $E_{spring} = \frac{1}{2}k\theta^2$, the model shows a reduction in speed of 2.8 % from energy losses in flexing of frame and twisting of crank arms if all deformation strain energy is absorbed by springs.

Summary

- Test results indicate that fiber composite plates in crank arms can improve cycling efficiency by 1 to 4%
- From modeling the most likely explanation is the reduction of energy losses occurring in conventional crank sets
- More detailed modeling needed including FEA and material parameters
- Hollow crank arms for the novel crankset can be built from separate parts or in one piece by 3D printing of carbon or metal

THANK YOU FOR YOUR ATTENTION !!

QUESTIONS ?

www.huroncycling.com