Energy efficiency of actuators with DC motors

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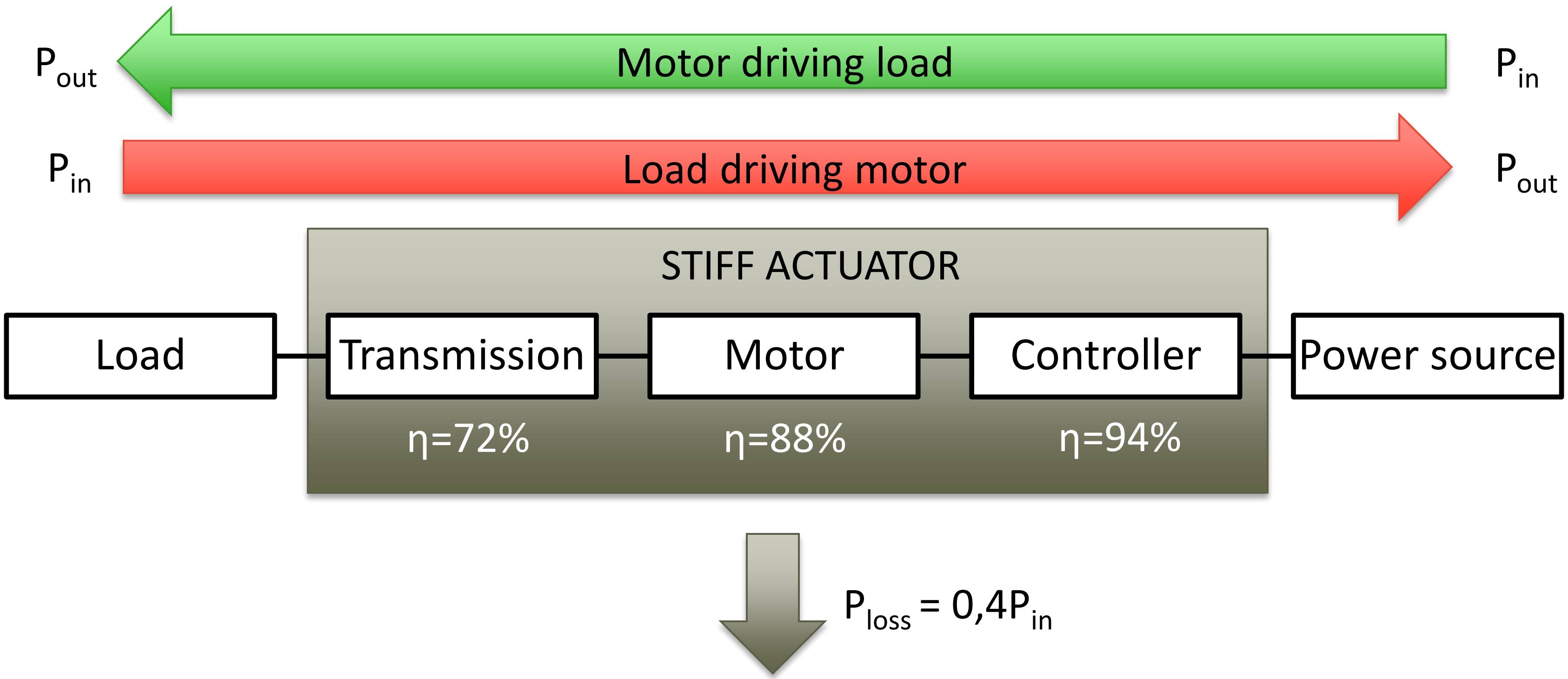
Stiff actuators

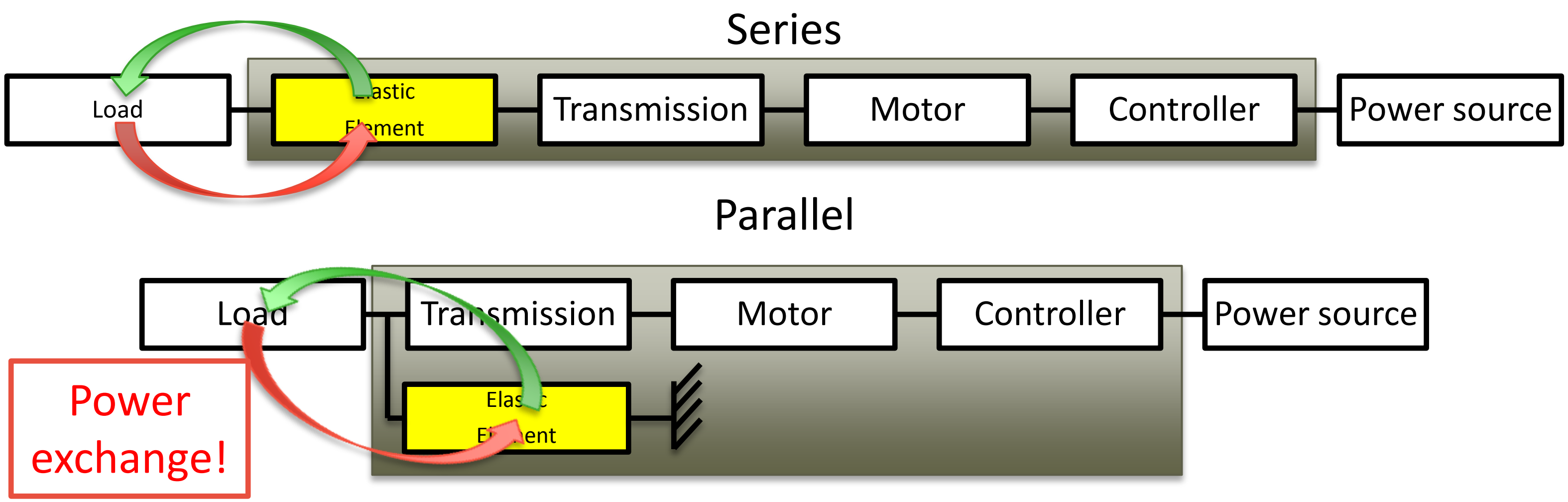
Typical topology



How to improve efficiency?

Bypass the lossy components

Introduce an energy storage buffer at the output!



Series or Parallel?
A performance perspective

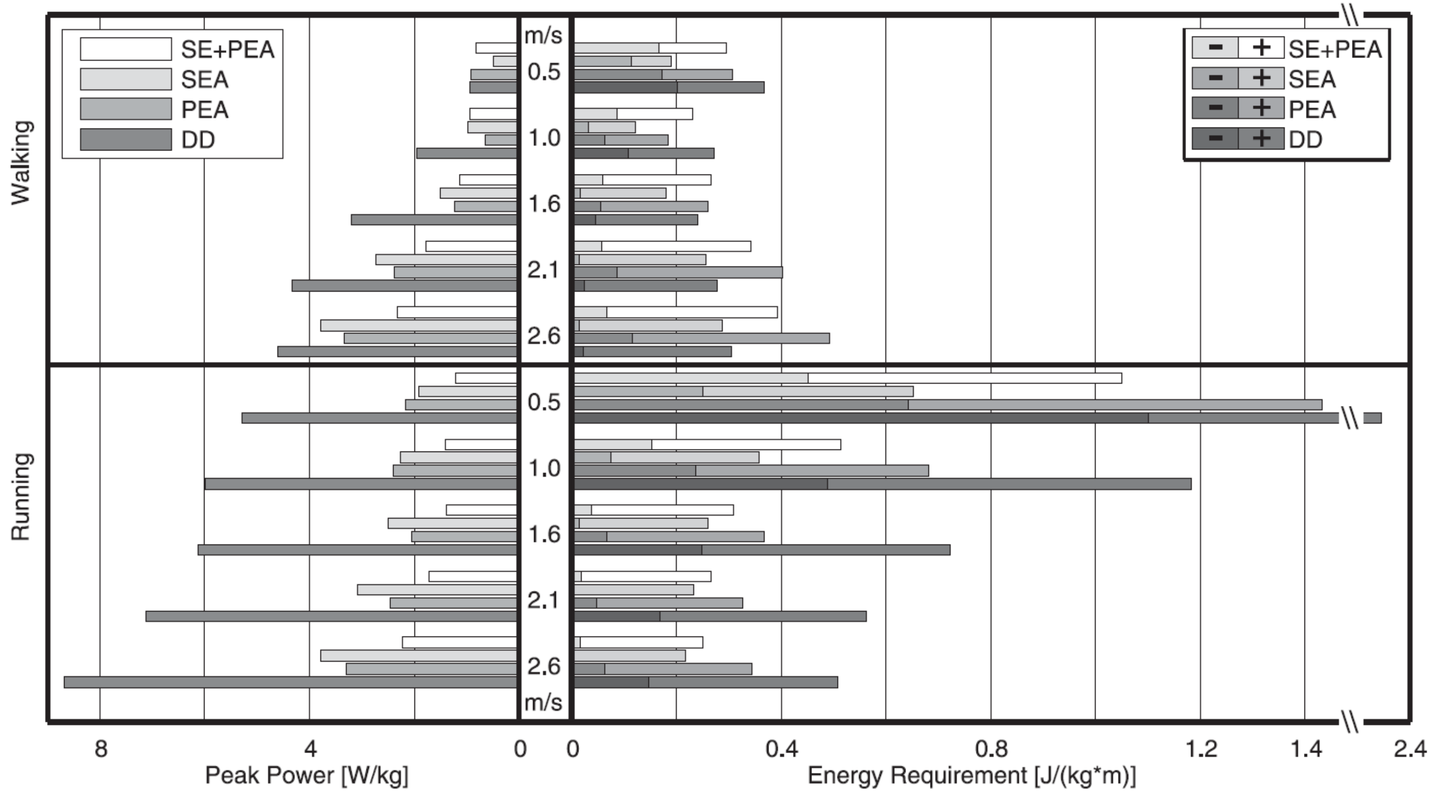
Series

- Decoupling of motor and load (additional DOF)
  = increased safety
- Force control
- Extra antiresonance frequency
- Reduction of motor speed

Parallel

- No decoupling of motor and load
  = no increase in safety
- Position control
- Shift of resonance frequency
- Reduction of motor torque

Series or Parallel?
An efficiency perspective



Grimmer et al., A Comparison of Parallel- and Series Elastic Elements in an actuator for Mimicking Human Ankle Joint in Walking and Running (2012)

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Series or Parallel?

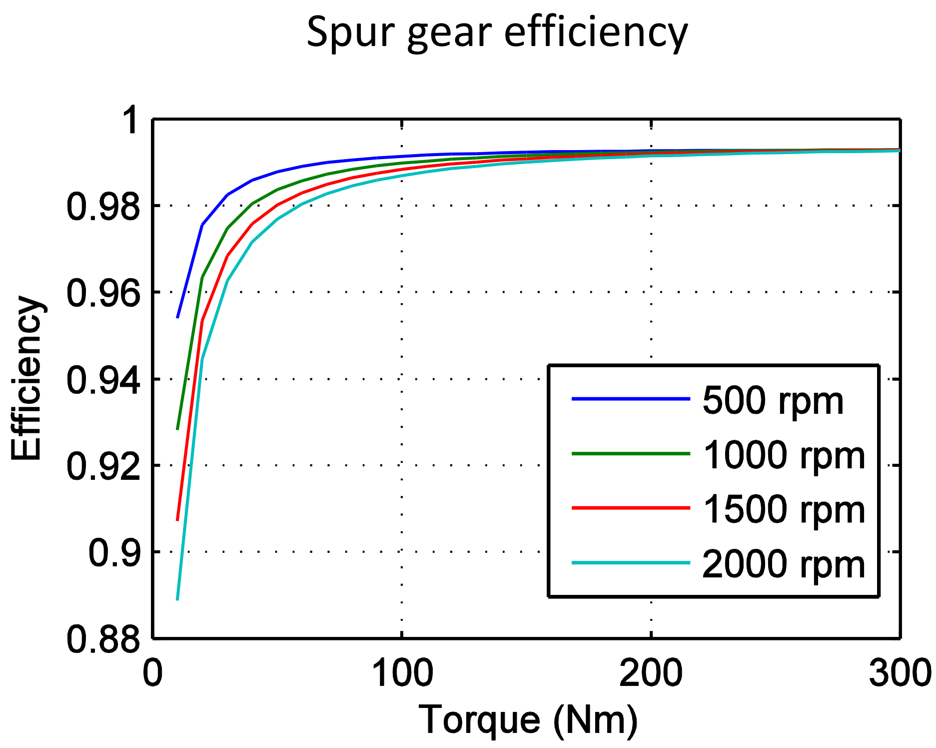
But… energy calculated as:

$$\text{Energy} = \int |P_{load}|dt$$

- Absolute value
- Only mechanical energy, no (speed- and load-dependent) gearbox, motor and controller losses!

Gearbox efficiency

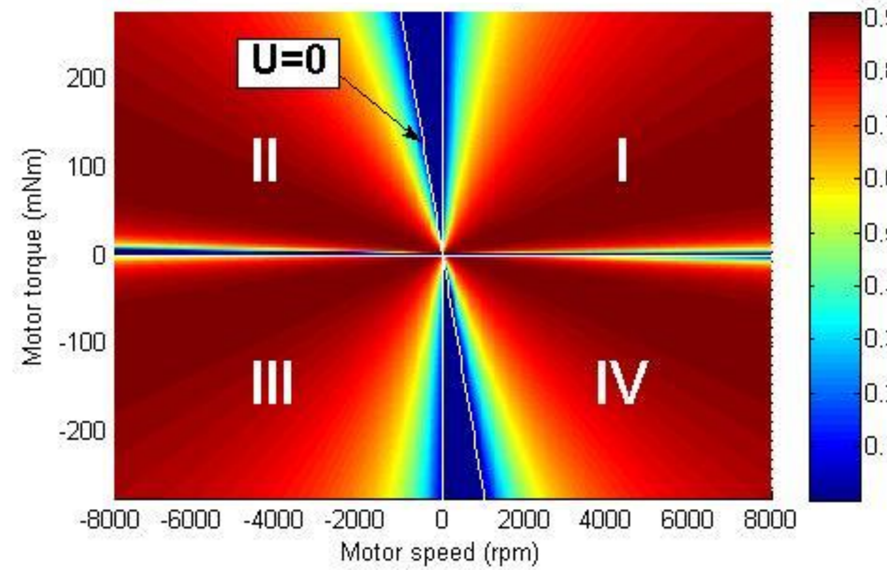
- Strong decrease at low torques
- Small dependence on input speed



Motor efficiency

- Max. efficiency only in small region
- Difference between negative-power and positive-power quadrants
- Two zero-efficiency regions
- Resistive losses more crucial

DC Motor efficiency map

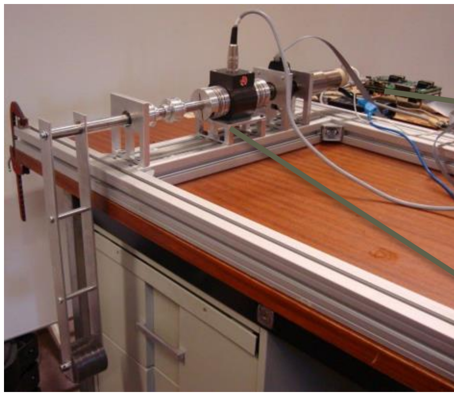


$$P_{elec} = \frac{T + \upsilon\dot{\theta}}{k_t} \cdot \left(R\,\frac{T + \upsilon\dot{\theta}}{k_t} + k_b\dot{\theta} \right)$$

Damping losses

Resistive losses

Case study: driven pendulum



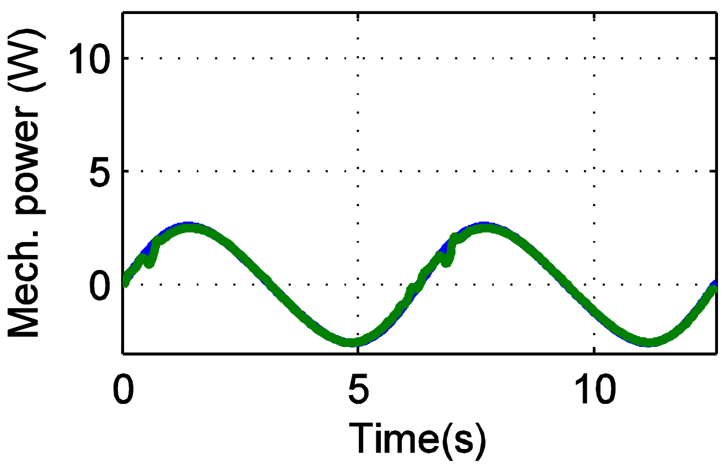
Elec. power measurement (controller input)

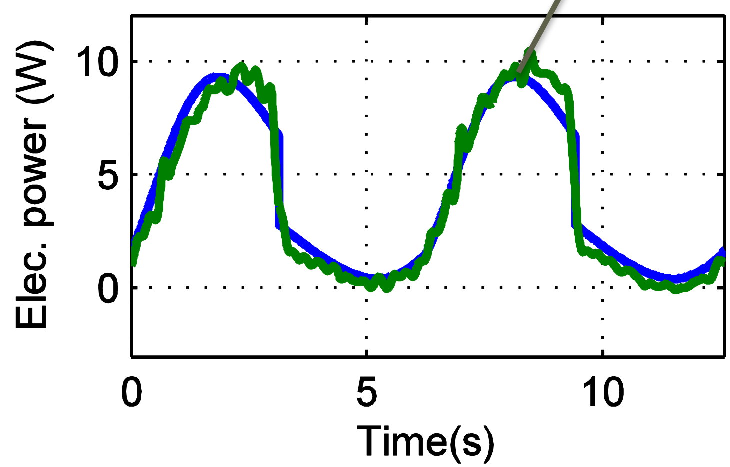
Mech. power measurement

$$\boxed{\theta = \theta_0 \sin(\omega t)}$$

Losses are load- and speed- dependent and distort power profile!

Power profiles





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Example calculation

TABLE III

MEASURED AND MODELED ENERGY CONSUMPTION FOR ONE PENDULUM PERIOD, AT FREQUENCIES OF 0.5, 1 AND 2 RAD/S.

		0.5 rad/s	1 rad/s	2 rad/s
measured		51.08 J	29.90 J	18.30 J
1QCE	E_{elec}	46.32 J	22.53 J	9.87 J
	$E_{elec,abs}$	49.37 J	36.15 J	28.76 J
4QCE	E_{elec}	45.51 J	27.30 J	16.57 J
	$E_{elec,abs}$	45.51 J	30.14 J	21.96 J
4QCEI	E_{elec}	45.31 J	26.88 J	15.68 J
	$E_{elec,abs}$	45.31 J	29.46 J	19.65 J
FMM	E_{elec}	52.10 J	29.09 J	16.02 J
	$E_{elec,abs}$	52.10 J	31.34 J	19.87 J

→ Measured values

→ No load- and speed-dependency

→ Load- and speed-dependent DC motor model

Verstraten et al., Energy Consumption of Geared DC Motors: Comparing Modeling Approaches (2015)

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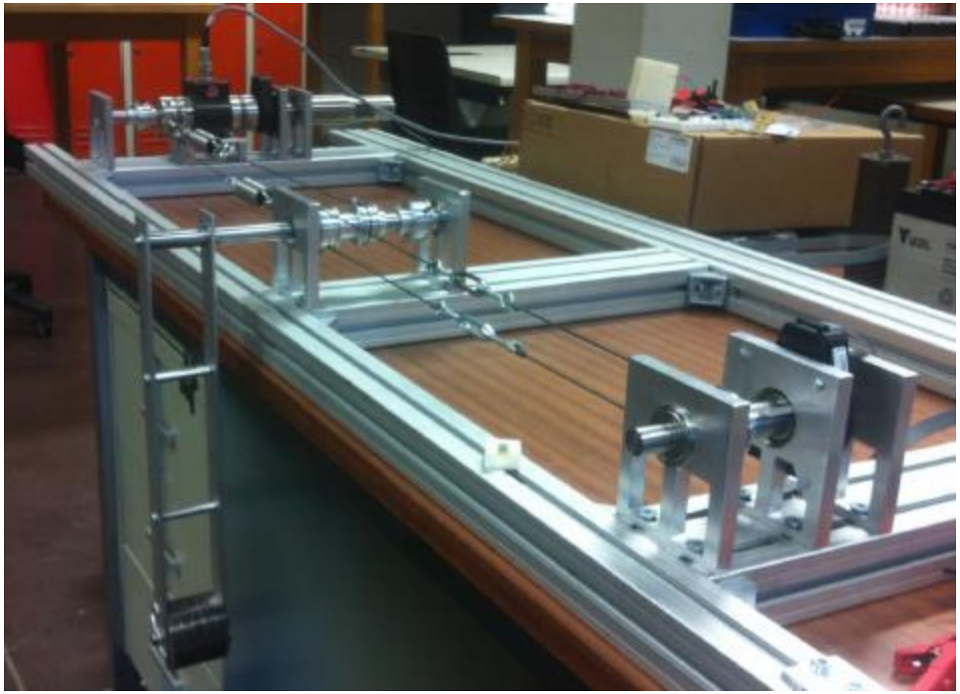
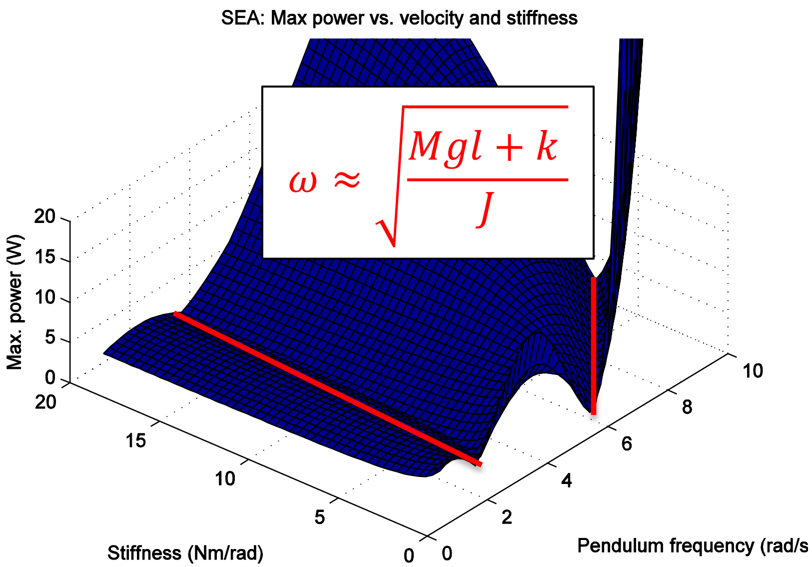
So what about VSAs?

Theoretical study on pendulum setup



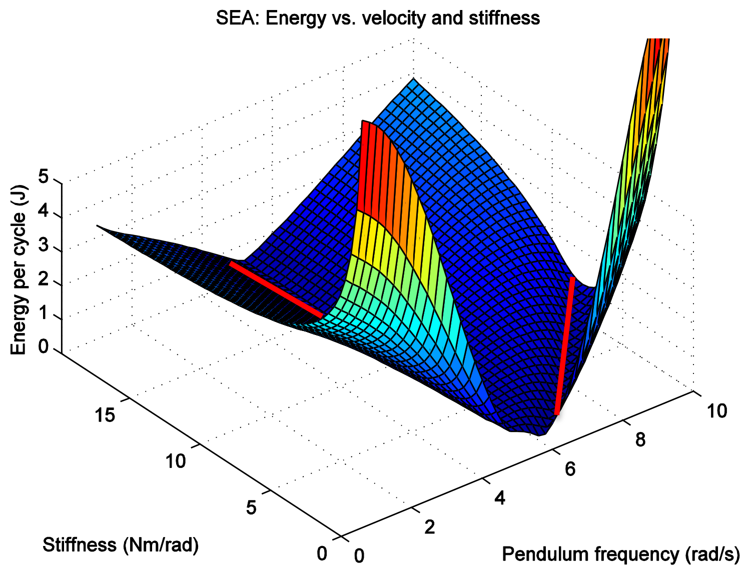
Series Elastic Actuator
Peak power



Properties

- 2 resonance frequencies (2nd only at small angles)
- 1 antiresonance frequency (strongly dependent on spring stiffness)

Series Elastic Actuator
Energy consumption



Properties

- Lowest energy consumption at resonance and antiresonance
- High energy consumption at low stiffness
- Resistive losses at antiresonance

$$P_{elec} = \frac{T + \cancel{\nu\dot{\theta}}}{k_t} \cdot \left(R \frac{T + \cancel{\nu\theta}}{k_t} + \cancel{k_b}\dot{\theta} \right) \Rightarrow P_{elec} = R \frac{T^2}{{k_t}^2}$$

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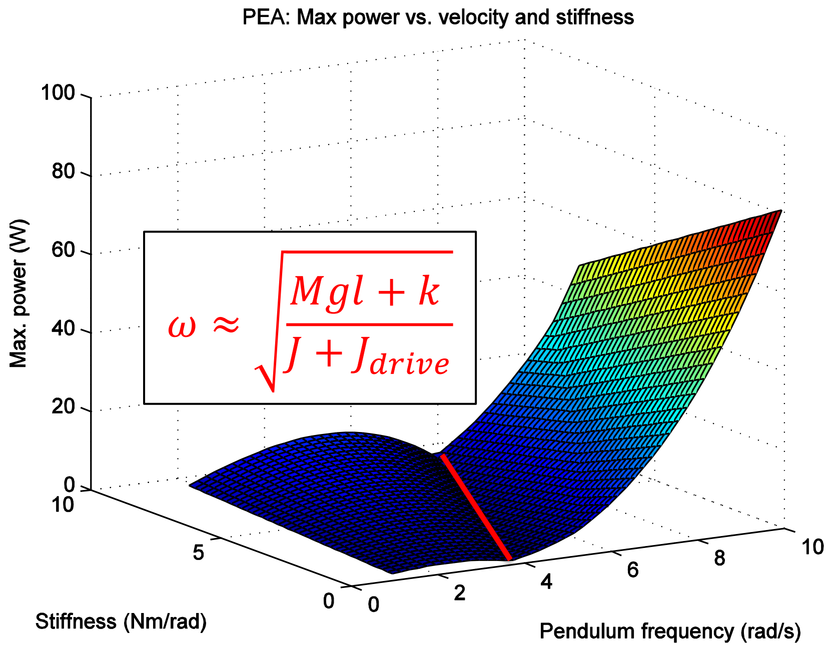
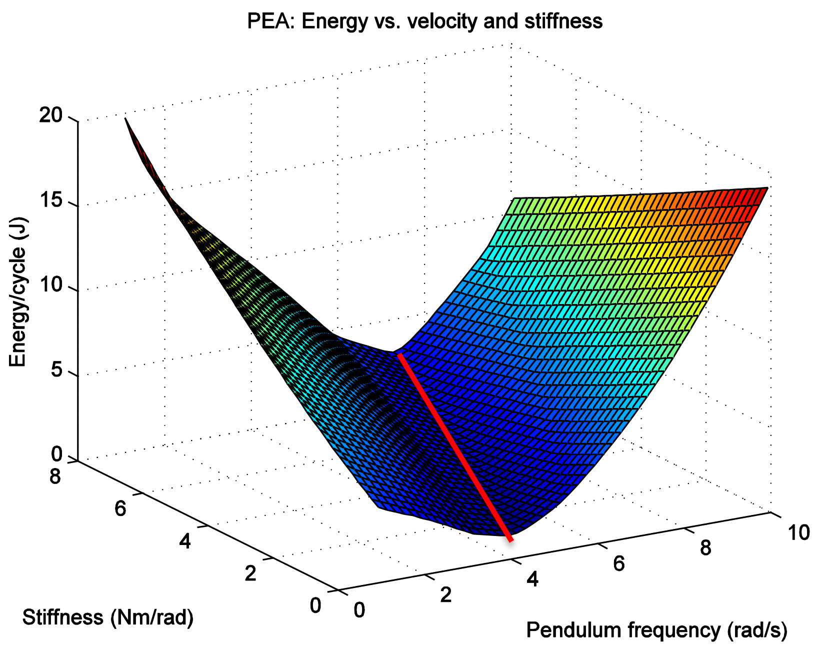
Parallel Elastic Actuator
Peak power



Properties

- 1 resonance frequency, strongly dependent on spring stiffness

Parallel Elastic Actuator
Energy consumption



Properties

- Minimum consumption at resonance frequency (controllable)
- Damping (viscous friction) at resonance

$$P_{elec} = \frac{\cancel{T} + \upsilon\dot{\theta}}{k_t} \cdot \left(R\frac{\cancel{T} + \upsilon\dot{\theta}}{k_t} + k_b\dot{\theta} \right) \quad \Rightarrow \quad P_{elec} \approx \frac{\upsilon k_b \dot{\theta}^2}{k_t} = \upsilon\dot{\theta}^2$$

Conclusions

- Load-and speed-dependency of motor and gearbox losses cannot be neglected
- Parallel vs. Series topology have very different properties:

Series

- Exploiting stiffness-dependency of antiresonance
- Reduction of motor speed
- Resistive (Joule) losses dominate
- **Electrically less efficient at antiresonance**

Parallel

- Exploiting stiffness-dependency of resonance
- Reduction in motor torque
- Damping (friction) losses dominate
- **Electrically more efficient at resonance**