ICMA 2021

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Piezoelectric ultrasonic micromotor

micromachines

MDPI

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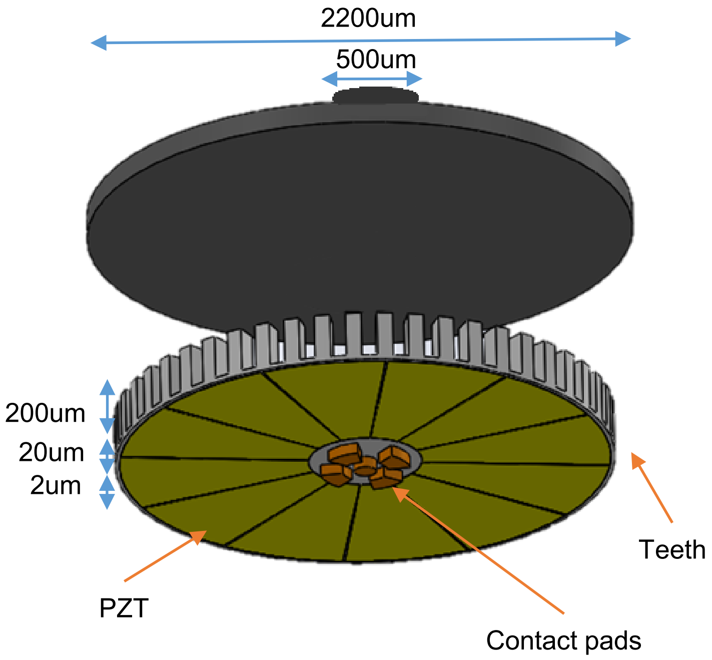
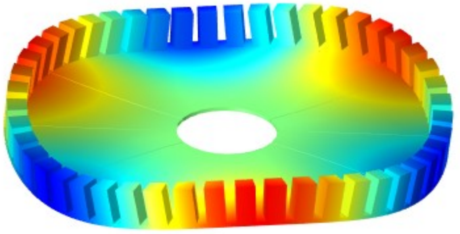
Piezoelectric ultrasonic micromotor

Motor design

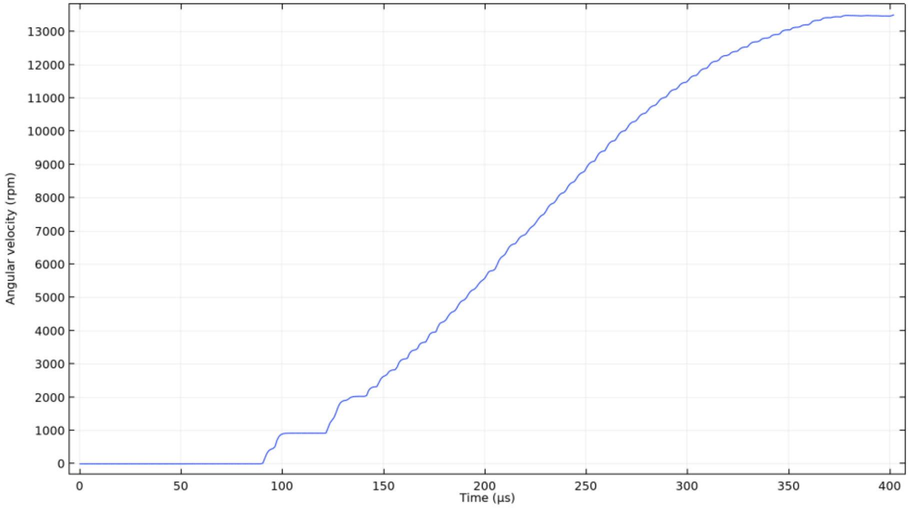


Chosen resonant frequency

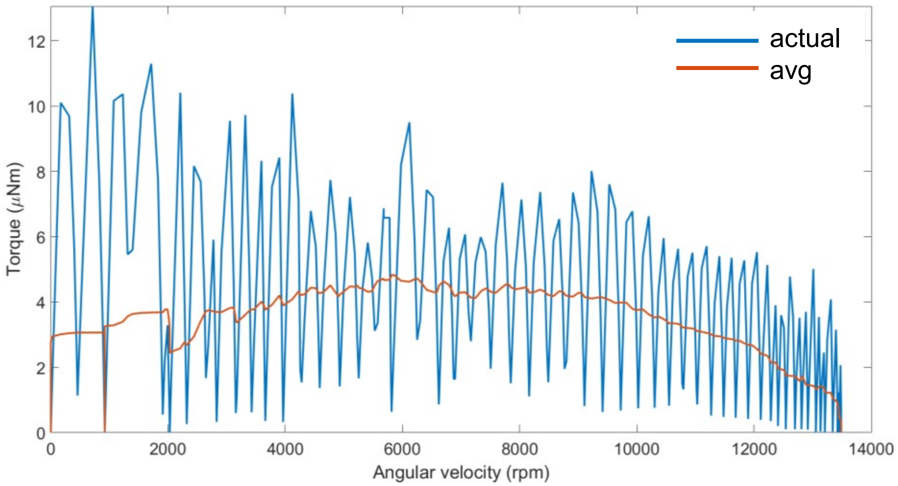


B03 = 49kHz

FE simulation results (speed vs time)



Simulated performance (torque vs speed)

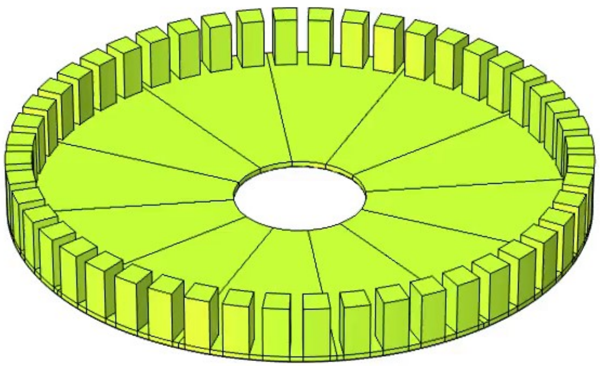


Abstract: Ultrasonic motors are characterized by low speed and high torque operation, without the need of gear trains. They can be compact and lightweight and they can also work in the absence of applied loads, due to the frictional coupling between the rotor and the stator induced by the traveling wave. In this work, we discuss a concept design based on thin piezoelectric films, sol-gel directly deposited onto a silicon substrate to provide high-torque motors compatible with wafer integration technologies. Due to the large dielectric constants and the enhanced breakdown strengths of thin piezoelectric films, such ultrasonic micromotors can lead to meaningful improvements over electrostatic ones in terms of energy density. As far as the fabrication of the micromotor at the mm-scale is concerned, an integrated approach is proposed with significant improvements regarding: the comb-tooth structure, to maximize/optimize the motor torque; a back and front etch lithographic process; the design of the electrodes, which provide the electric signal at the central anchor of the stator, taking advantage of low temperature soldering. The proposed design has been assessed through multiphysics simulations, carried out to evaluate the resonant behavior of the stator and the motor performance in terms of angular velocity, torque and output power, and it is shown to lead to promising results.

Keywords: travelling wave, ultrasound motor; MEMS; PZT; silicon.

Traveling wave ultrasonic motors

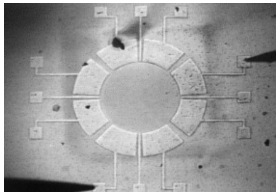
- Rotation is exploited because of the stator traveling wave vibration
- High frequency PZT actuation
- Traveling wave vibration
- Frictional contact



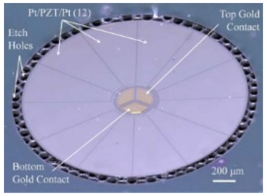
Map of the vertical displacement during time

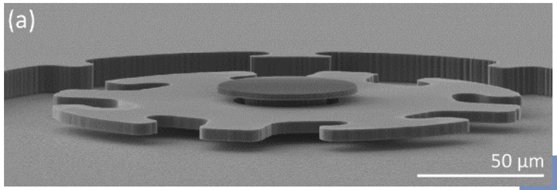
Is miniaturization possible?

Flynn, 1995



Smith, 2015



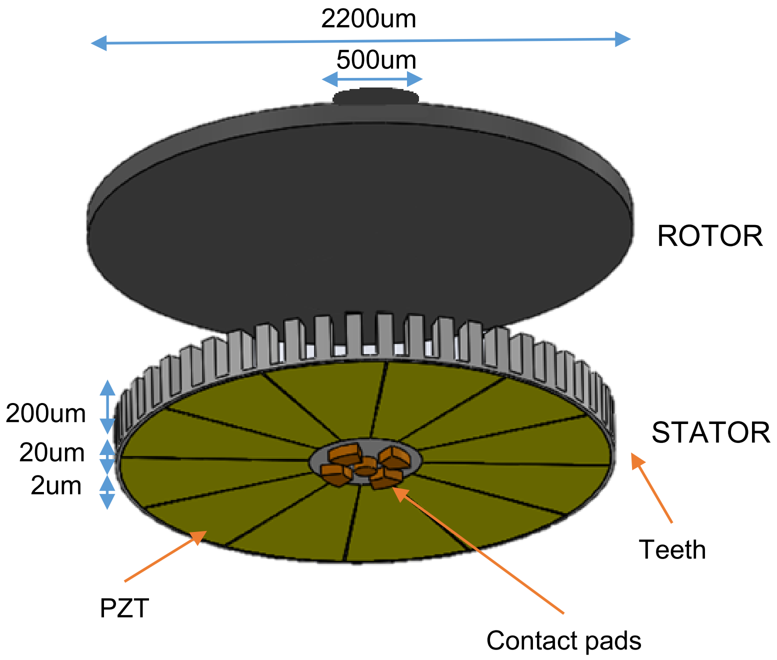


Eisenhaure, 2015

(*) Images from Internet

Stator design

- Fabrication of a comb-tooth structure to enhance rotor motion
- Contact pads that work as an anchor for the stator
- PZT thin film deposition on the bottom with a specific electrode pattern



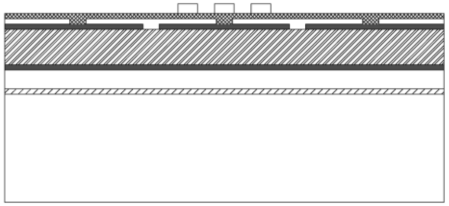
PZT layer:

- $t = 2\ \mu\mathrm{m}$
- $V_{max} = -30\ \mathrm{V}$

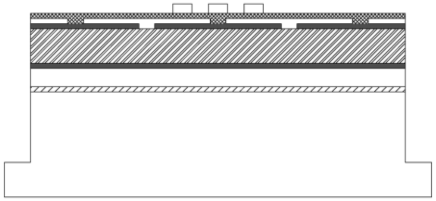
	Radius [µm]	Thickness [µm]
Stator	1100	20
Rotor	1150	200
PZT layer	250 < r <1100	2
Tooth	1000 < r < 1100	200

Fabrication process

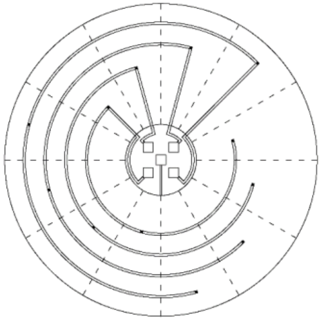
Front → Back → Assembly



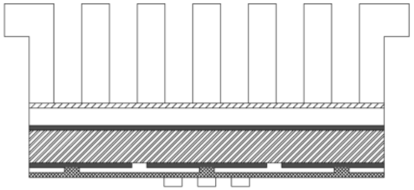
PZT stack



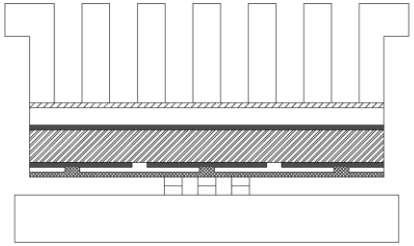
DRIE/deep etching



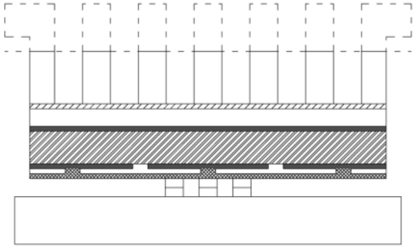
Top view



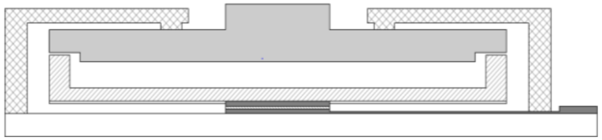
Deep etching



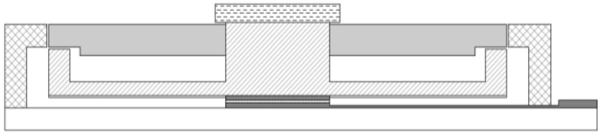
Die soldering



Lapping/etching



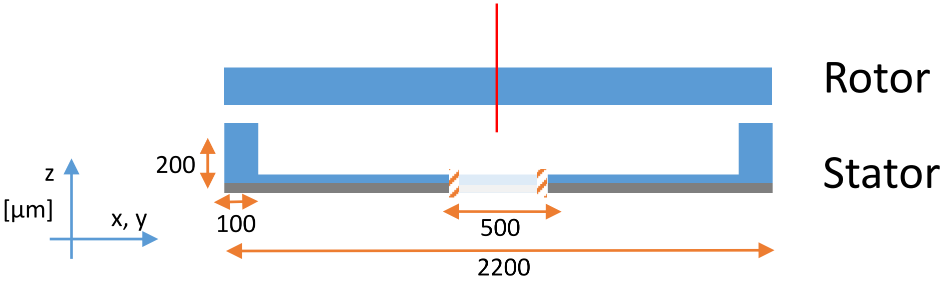
or



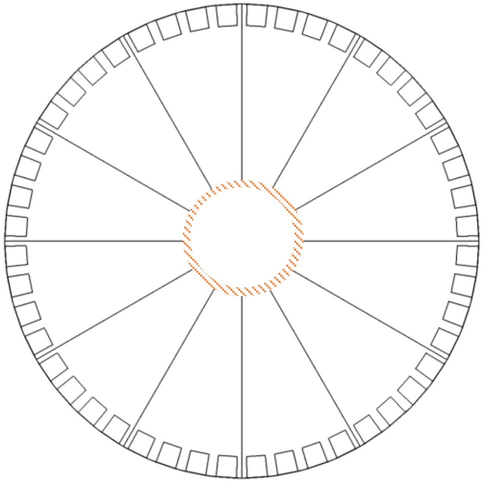
Stator resonance behavior – FE model

COMSOL Multiphysics is used for the simulations:

- Rotor is free to rotate at 5um vertical displacement from the stator
- Stator is fixed at the center



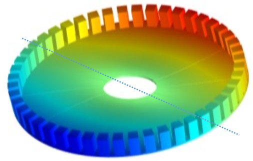
Rotor and fixed area

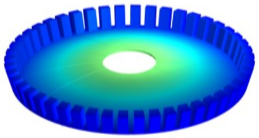


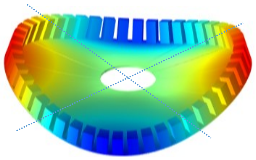
Stator resonance behavior

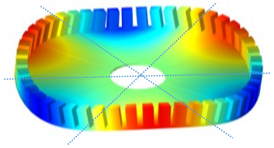
Modal analysis with zero applied voltage, to define:

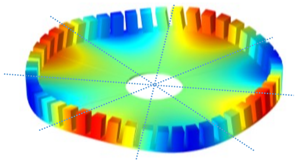
- Working frequency = 49kHz
- Mode shape = B03 (3 nodal diameters)

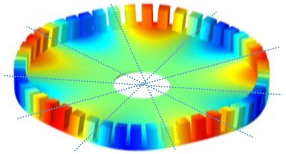

B01 = 19kHZ


B00 = 20kHz


B02 = 26kHz

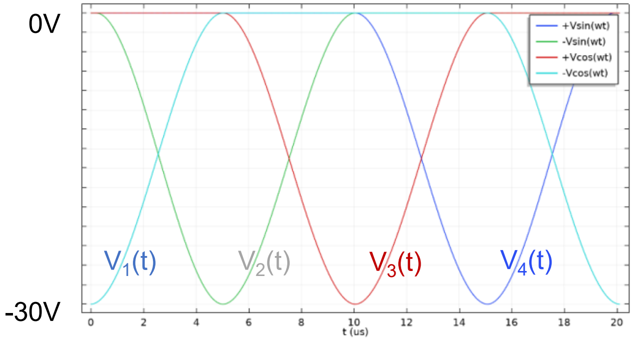

B03 = 49kHz


B04 = 83kHz


B05 = 122kHz

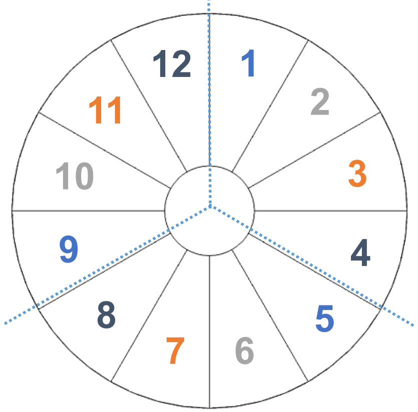
BXY with X=n° of nodal circles and Y=n° of nodal diameters

4 out-of-phase monopolar voltage signals to avoid repoling of the PZT thin film



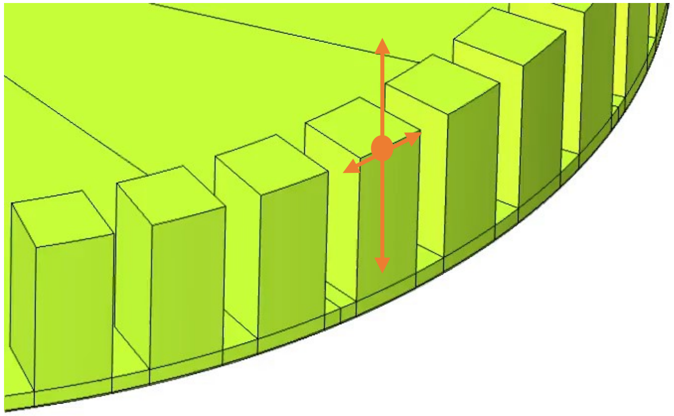
$$\begin{cases} V(t) = -30\sin\left(2\pi f t + n\frac{\pi}{2}\right) & if\ V(t) < 0 \\ V(t) = 0 & if\ V(t) \geq 0 \end{cases}$$

Electrode design, 12 PZT elements

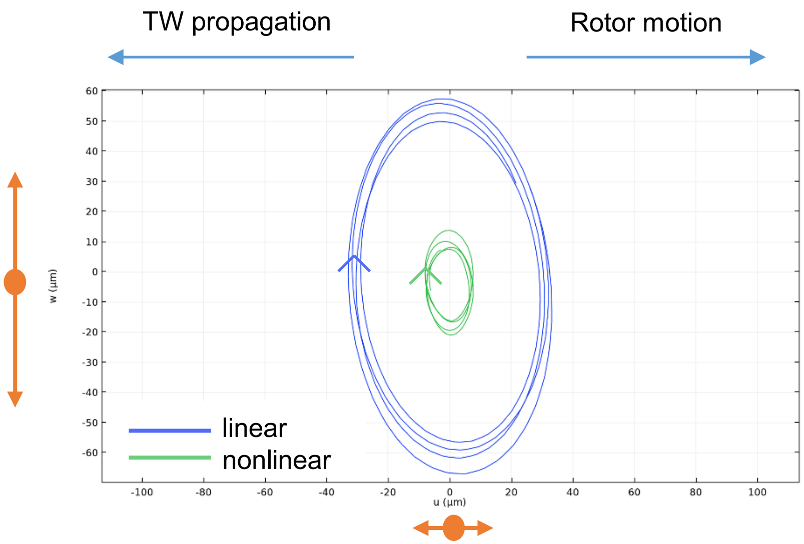


Stator resonance behavior – elliptical motion

- Stator teeth describe an elliptical trajectory caused by the traveling wave
- **Out-of-plane** displacement ensures a solid contact by generating a normal contact force
- **In-plane** displacement is what generates motion by sweeping the rotor and providing tangential forces



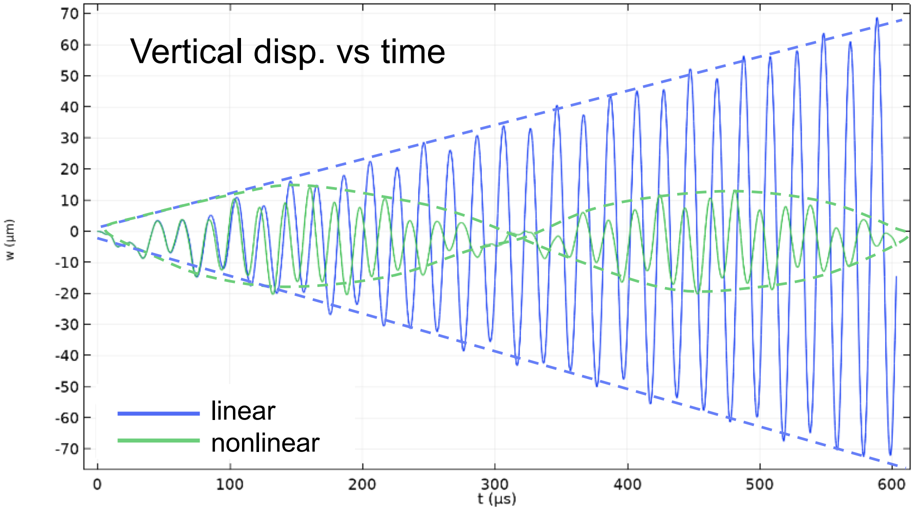
Traveling wave motion



elliptical trajectory of a tooth

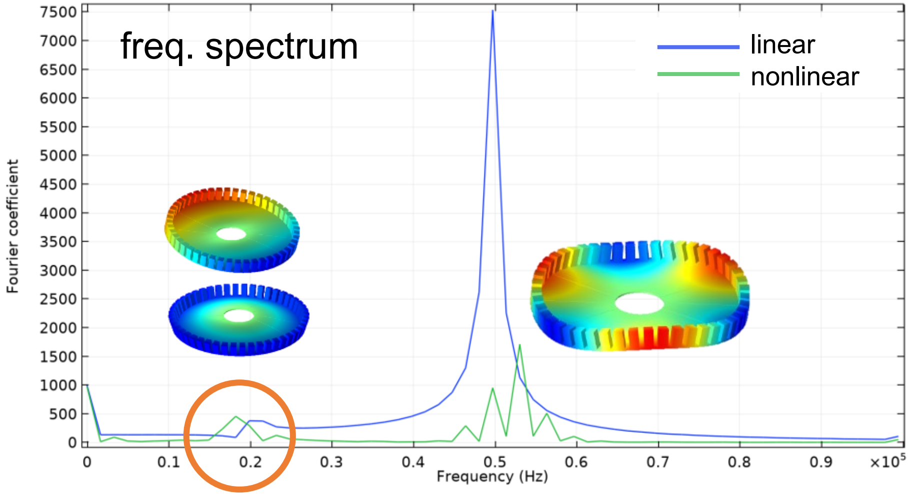
Stator resonance behavior – vertical displacement

- Interference with other resonant modes when geometric nonlinearities are considered due to:
- Actuation voltage
- Similar mode shape



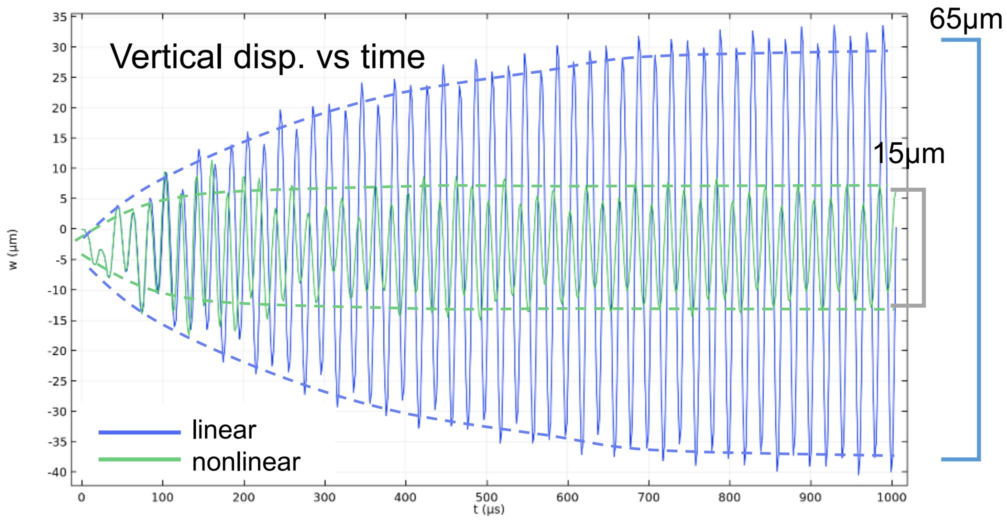
- Monopolar actuation leads to greater deflection towards $-z$
- Time average w-displacement is

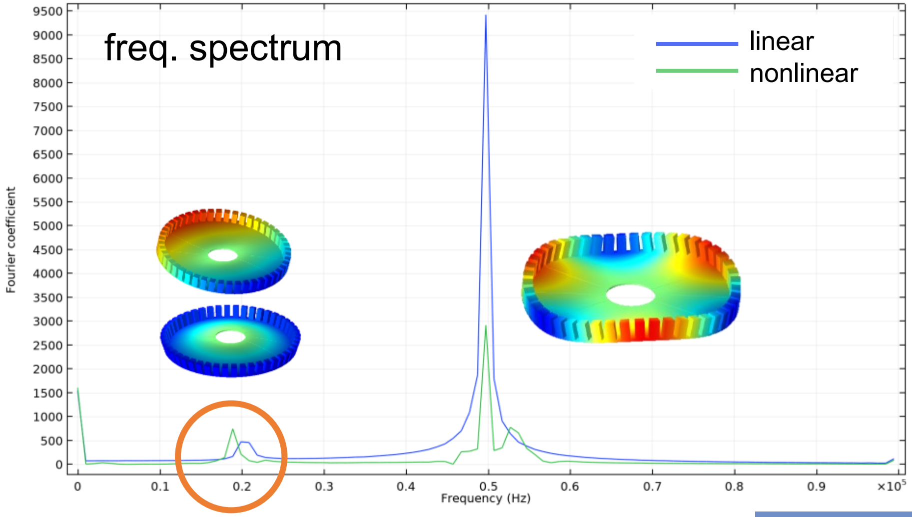
		Displacement
Stationary	Linear	−3.68 µm
	Nonlinear	−3.69 µm
Time dependent	Linear	−3.35 µm
	Nonlinear	−3.27 µm



Stator resonance behavior – vertical displacement

- When damping is considered, interference with other resonant modes is reduced and narrower peaks are obtained in the frequency spectrum



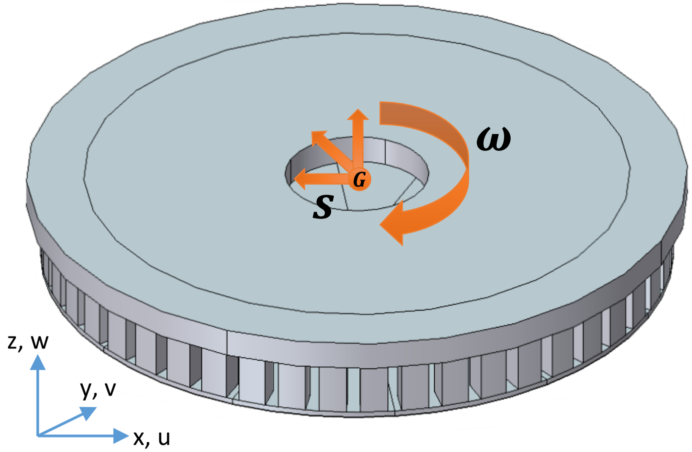


Performance – FE model

- The rotor is considered as a rigid body made of silicon. Angular velocities and displacement b.c.:
    - $\omega_x^G = \omega_y^G = 0$
    - $u^G = v^G = 0;\ w^G \sim 0$
- Coulomb's friction model (Si-Si)
    - Static friction: $\mu = \mu_{stat}$
    - Dynamic/sliding friction:

$$\mu = \mu_{dyn} + (\mu_{dyn} - \mu_{static})\exp(-|v_{slip}|)$$

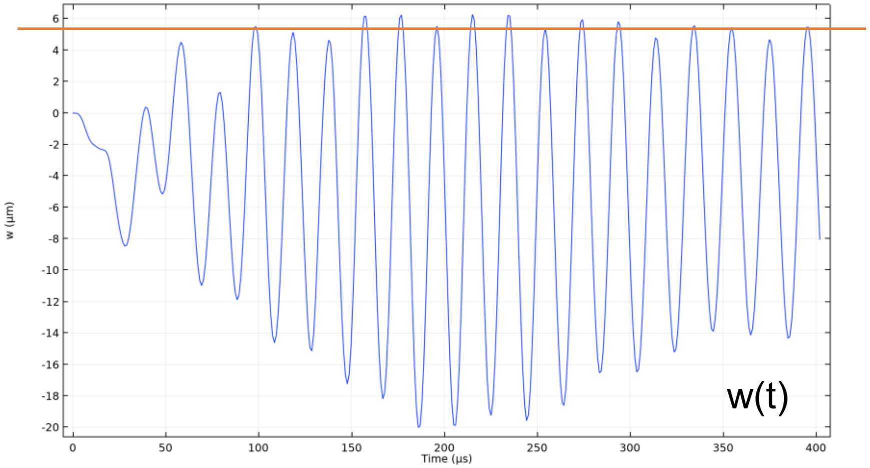
- Geometric nonlinearities are considered
- Rotor-stator initial gap: 5 µm

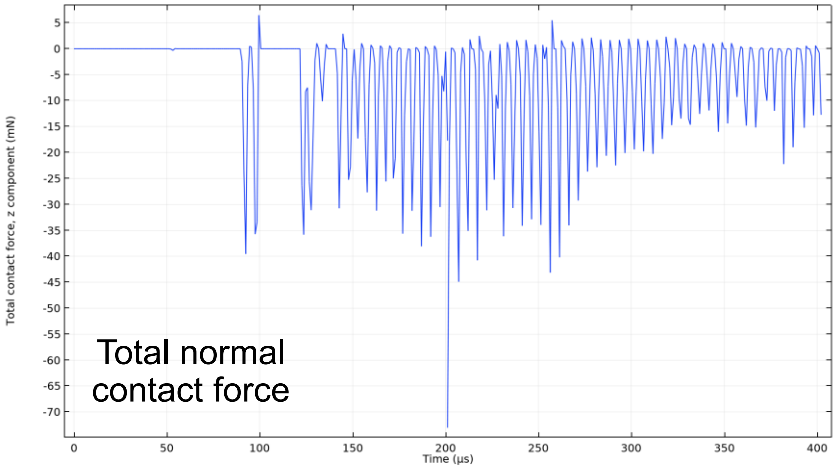


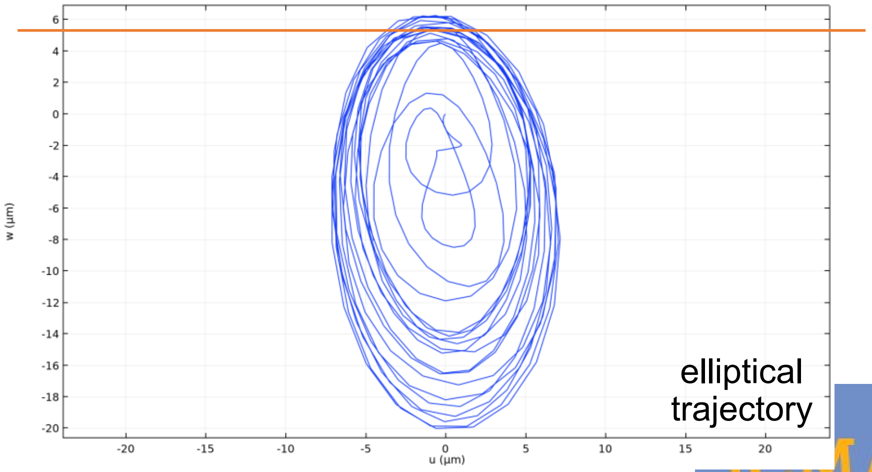
Performance – stator behavior

- The contact is limiting the displacement in the $+z$ direction
- Tens of mN of total normal force are detected, still discontinuous.
- $\text{torque} = \tau = R\mu F_z \sim \mu\text{Nm}$

Stator hitting the rotor at 5µm

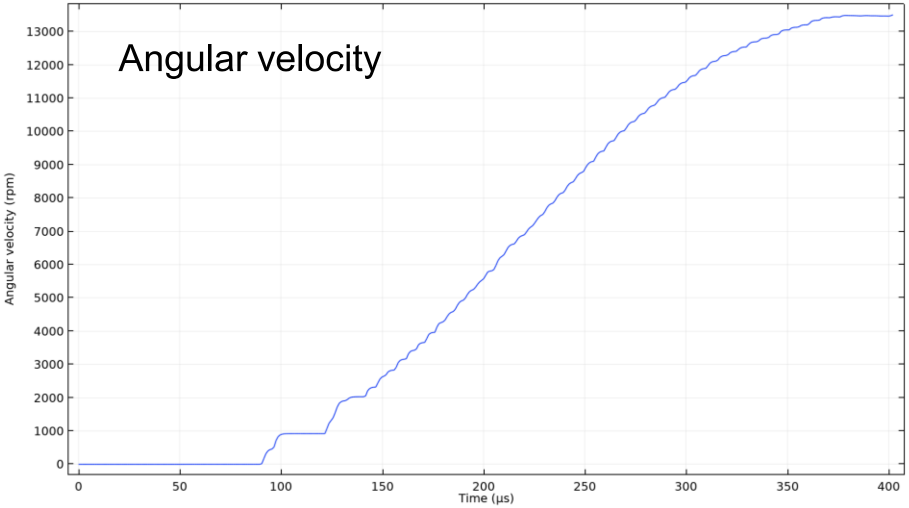


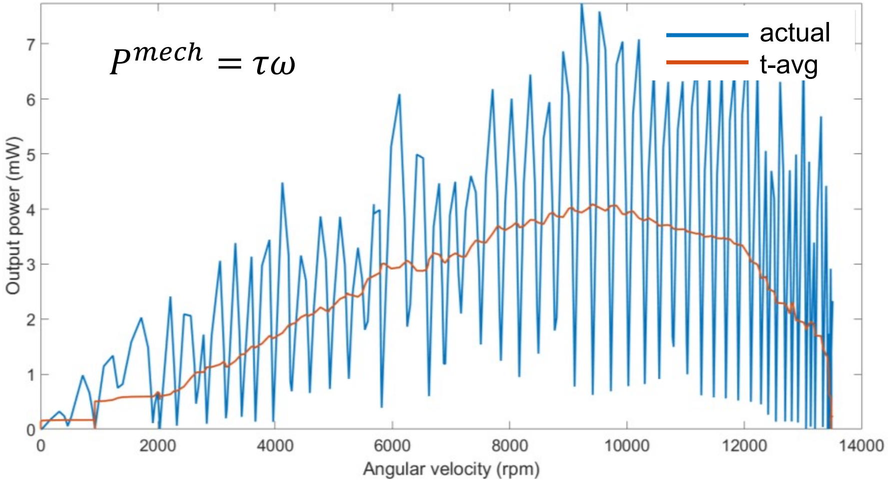


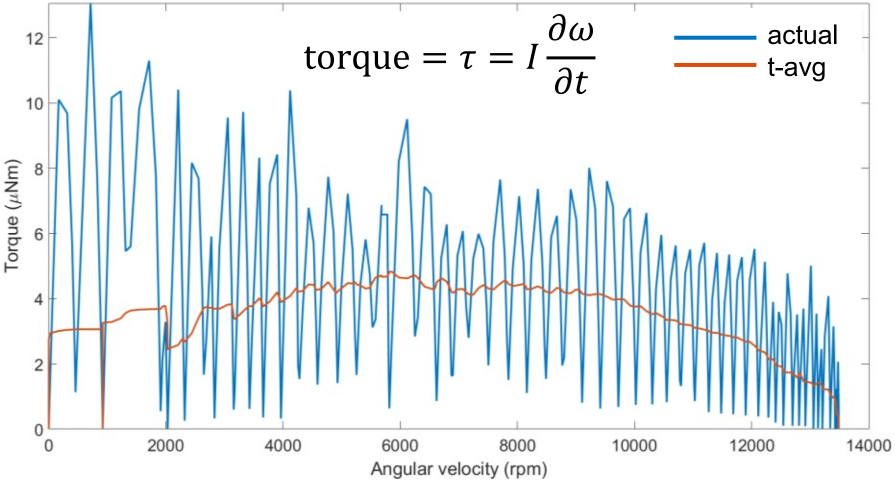


Performance – static friction

- $\mu = 0.4$
- $\omega_{steady} = 13500 \text{ rpm}$
- $\tau_{max} = 4 \text{ μNm}$
- $P_{max}^{mech} = 4 \text{ mW}$

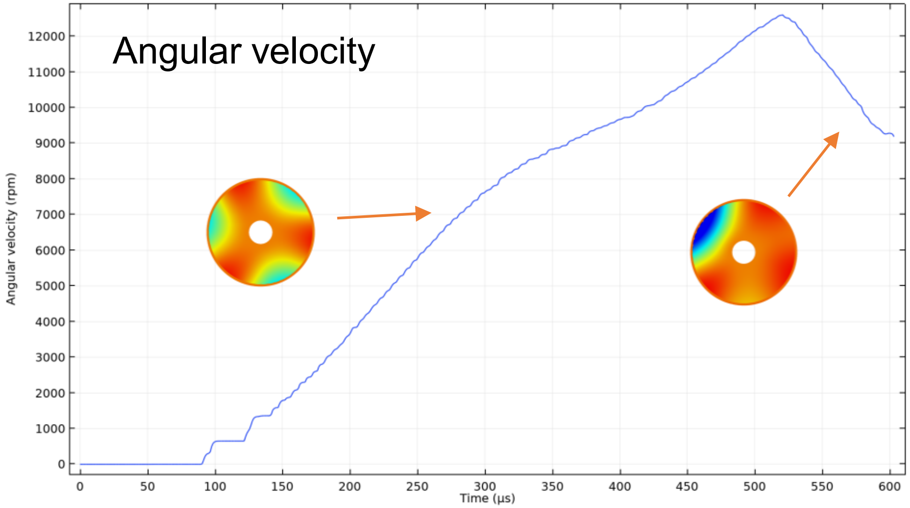


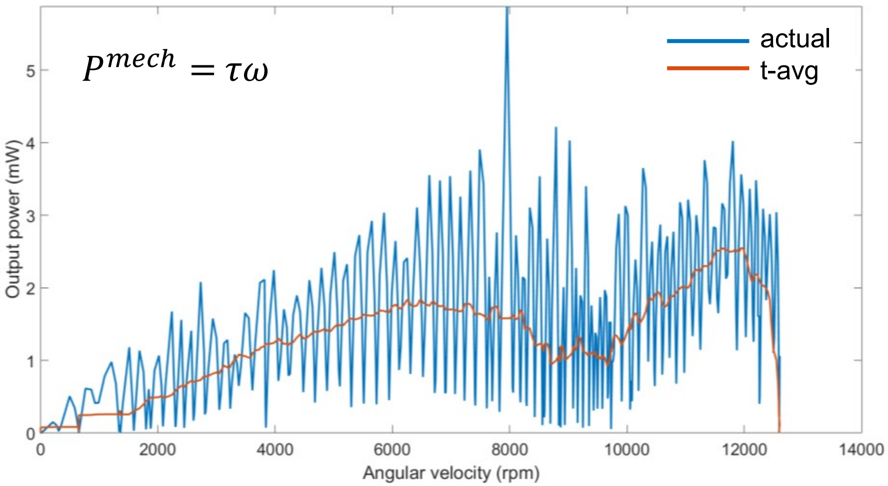




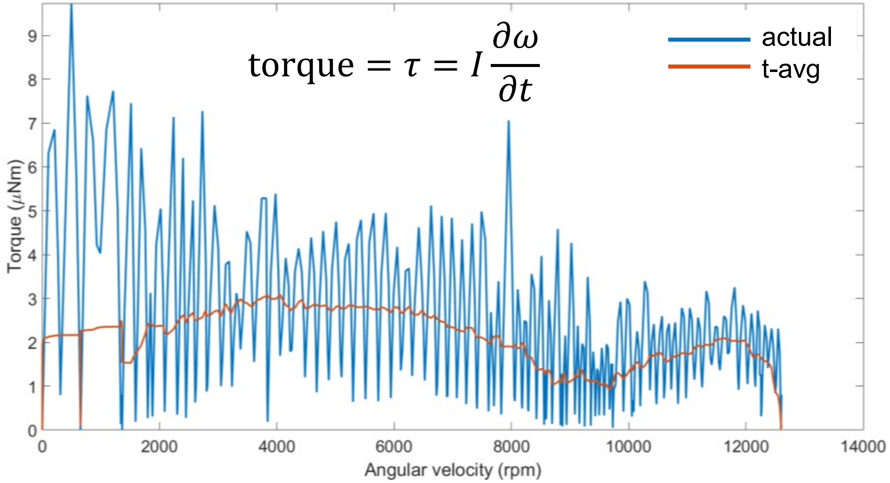
Performance – dynamic friction

- $0.2 \leq \mu \leq 0.4$
- $\omega_{max} = 12500\text{rpm}$
- $\tau_{max} = 3\ \mu\text{Nm}$
- $P_{max}^{mech} = 3\ \text{mW}$





$$P^{mech} = \tau\omega$$

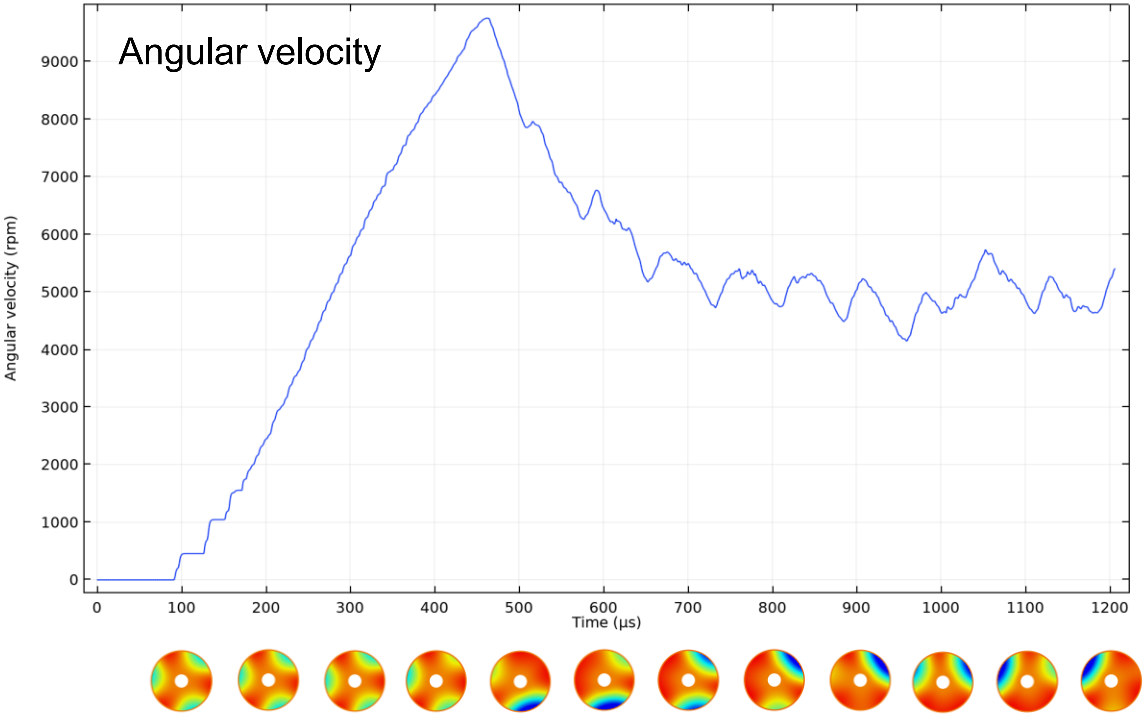


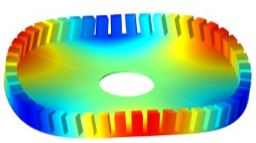
$$\text{torque} = \tau = I\frac{\partial\omega}{\partial t}$$

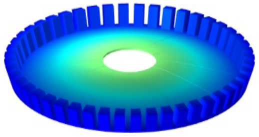
NB: only solutions with positive acceleration are considered to compute the torque and output power

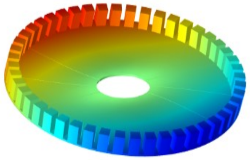
Performance – dynamic friction & damping

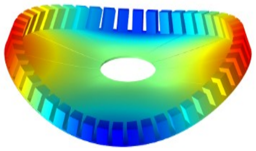
- $0.2 \leq \mu \leq 0.4$
- Damping
- $\omega_{max} = 9800 \text{ rpm}$
- $\omega \sim 5000 \text{ rpm}$
- Unstable velocity due to interference with other resonant modes
- Nonlinearities
- Contact-induced vibrations
- Simplified damping description
- Voltage actuation




49kHz

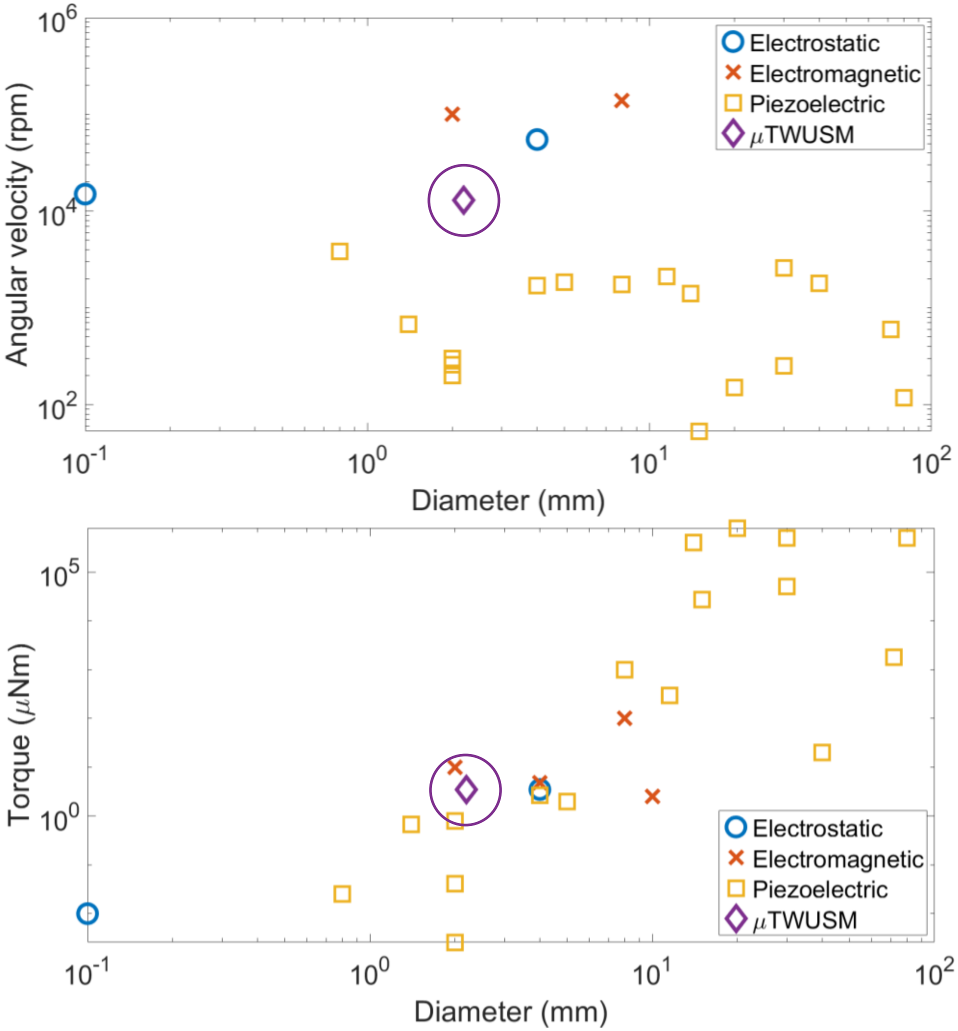

20kHz


19kHz


26kHz

Conclusions

- Extremely competitive if compared with other devices (2019).
- Design refinement needed to further improve the performance.
- Microfabrication and assembly issues to be faced.



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Acknowledgments

This work has been carried out during a Politecnico di Milano master student internship within STMicroelectornics.

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