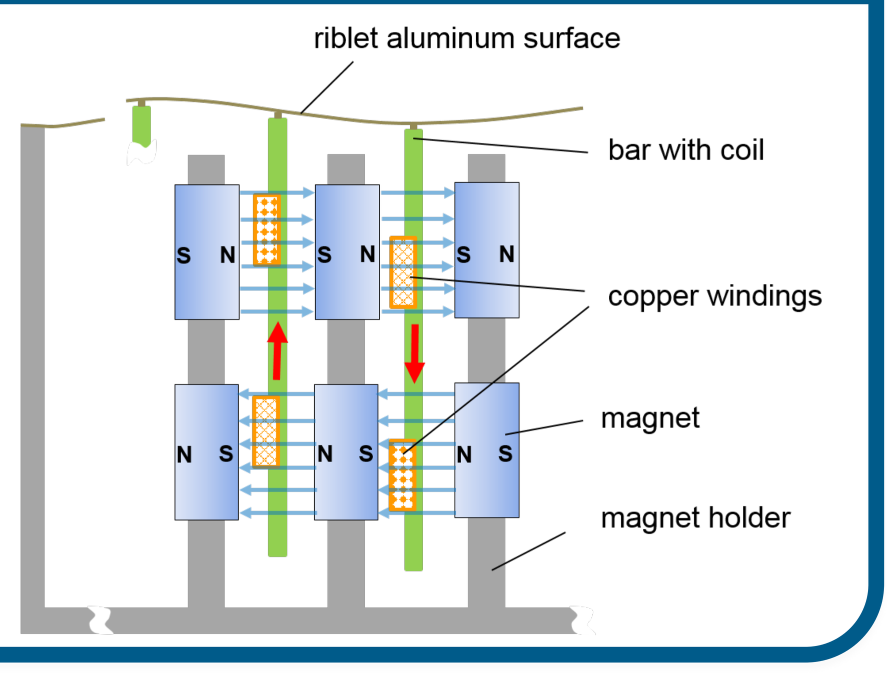
Control of Nonlinear Coupled Electromagnetic Actuators for Active Drag Reduction in Turbulent Flow

F. Seidler, J. Trabert, M. Dück, S. van Waasen, M. Schiek (Forschungszentrum Jülich),
D. Abel (RWTH Aachen), E. B. Castelan (Federal University of Santa Catarina)

Introduction

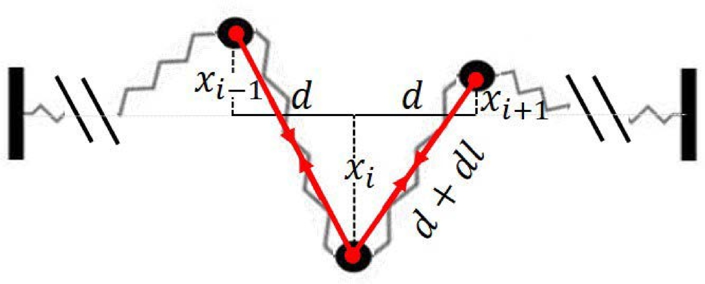
The research group FOR1779 "active drag reduction via wavy surface oscillations" develops robust methods for reduction of turbulent friction drag by flow control. Its focus on unsteady flow conditions requires control of the in-house developed electromagnetic actuator system generating the transversal surface waves in wind tunnel experiments.
A schematic of the system is shown on the left. Elastic deformation of the aluminum surface is facilitated by sending current through copper coils placed inside the magnetic field of Neodymium permanent magnets. The PCBs carrying the coils are guided by ball bearings (not shown). Main challenges in control design for this system are:

- Nonlinear reset force and coupling between actuators via aluminum surface
- Bearing friction and magnetic field inhomogeneity
- Real time communication between actuators, sensors and the central flow control unit



Mechanical Model

The actuator system can be approximately modelled as a system of coupled, damped, driven, one dimensional oscillators with strong nonlinear coupling.



We first derive an expression from the shown geometry assuming the aluminum surface behaves like a Hookian spring and the actuators like point masses. The force exerted by x_i on x_{i-1} is:

$$F(x_i, x_{i-1}) = -\frac{EQ}{d}\left(1 - \frac{1}{\sqrt{1 + \frac{(x_i - x_{i-1})^2}{d^2}}}\right)(x_i - x_{i-1})$$

Since the target amplitude of 1 mm is small compared to the spacing d = 10 mm of the actuators we use Taylor expansion to simplify the initial expression. After linearization and Laplace transformation we find:

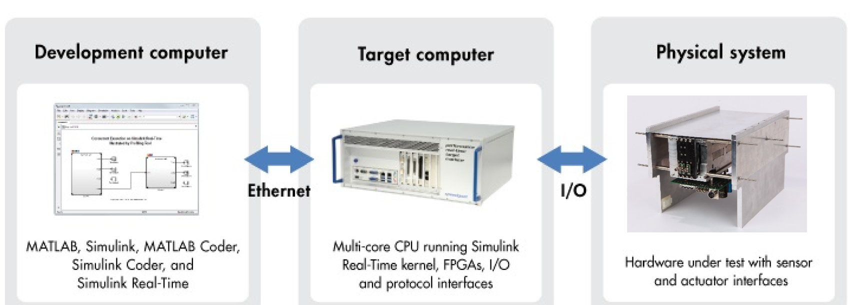
$$\frac{x(s)}{U(s)} = \frac{C_e}{C_e^2 s + (ms^2 + rs + k)(R + Ls)}$$

m	Mass of the actuators and the moving aluminum surface
k	Spring constant
r	Pure viscous friction term
L	Inductivity of the coil
R	Ohmic resistance of the coil
C_e	Coil constant (current → force)

This transfer function can be used to tune standard linear feedback controllers (e.g. PID) within a small amplitude range for which k does not significantly change due to nonlinearity.

Parameter Identification

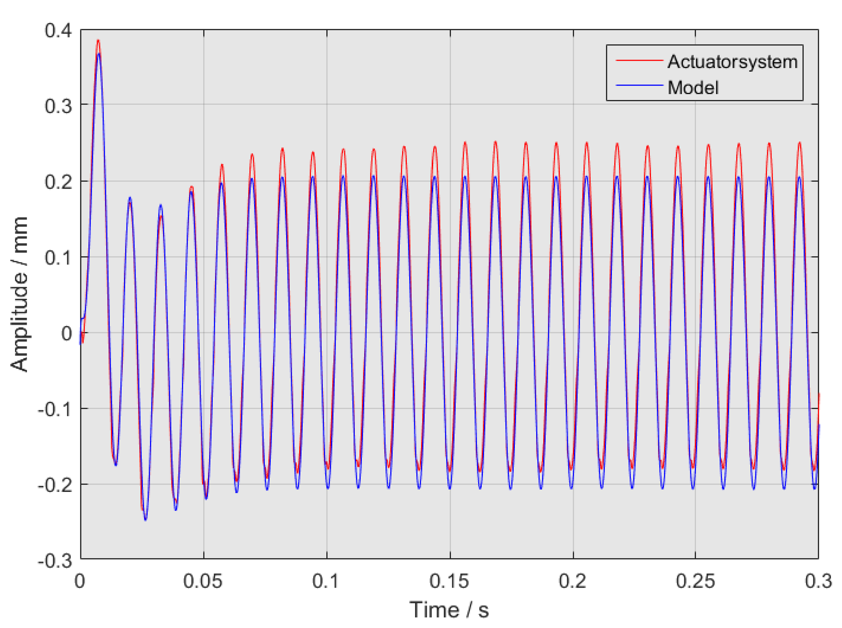
We use a Simulink Real-Time set up as shown (left) to examine and control the actuators. The versatility of this system significantly speeds up development.



For example, we can interface with the Matlab System Identification toolbox. It allows us to fit our model to data collected using a sine signal as voltage input including transient oscillations at the beginning (below). Combining with direct measurements we obtain for the operating point 40 Hz, 250 µm:

Known before fit	
m	70 g
R	14 Ohm
C_e	0.032 Vs/mm

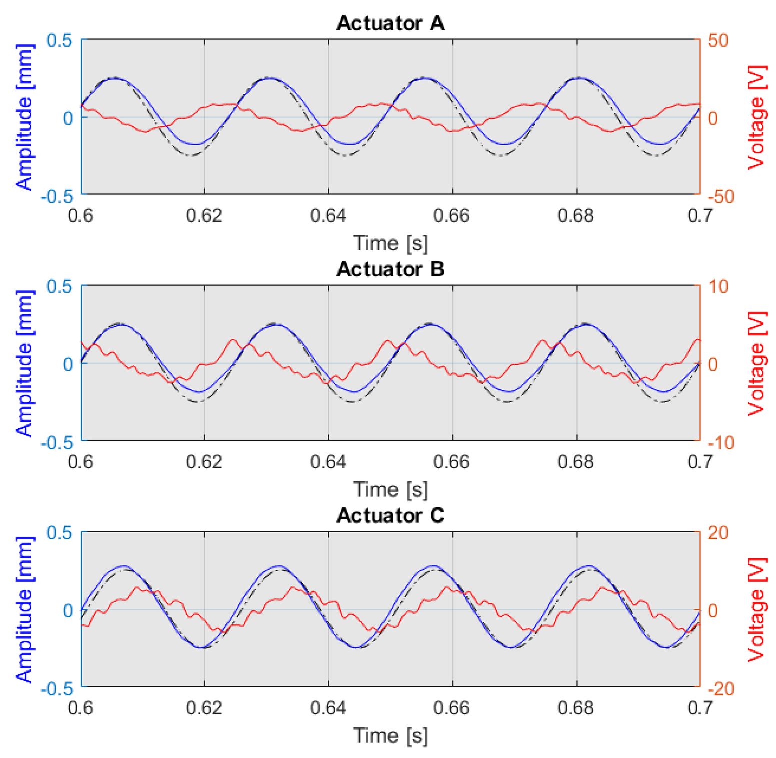
From fit	
k	13.4 N/mm
r	245 kg/s
D	1 (damping measure)
L	23.4 mH



Comparison PD to ILC

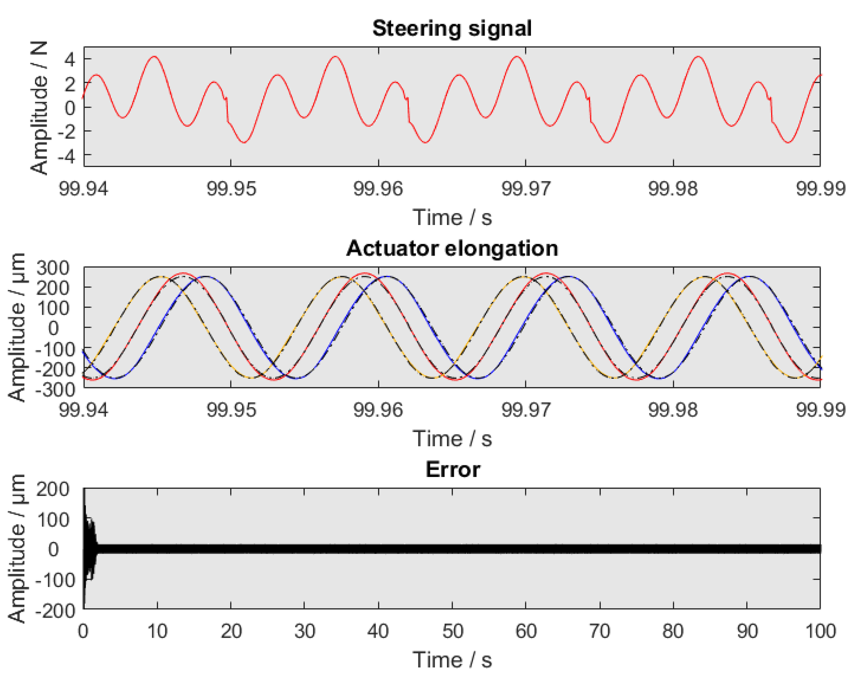
PD on hardware

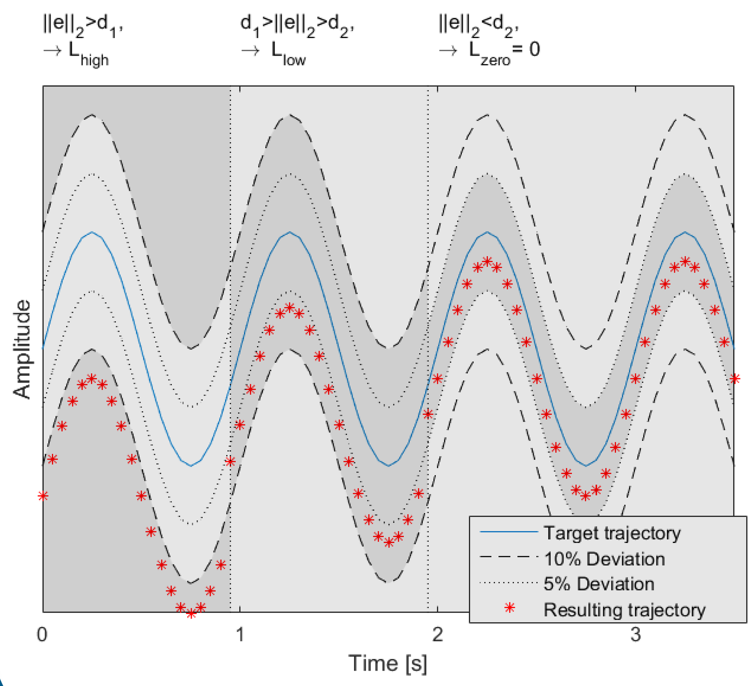
From the parameters of the identified model we derive the tuning for a PD controller and apply this to our test system using Simulink Real-Time toolbox. This control strategy neither takes into account the coupling between nor the nonlinear reset force of the actuators. Despite this it can achieve phase shifts up to 15° between the control inputs. Unfortunately, this is insufficient for our purpose.



ILC in simulation

In addition other control schemes, especially iterative learning control, are evaluated to improve over the result obtained with PD control. In simulation a PD-type ILC can achieve a 45° phase shift as shown to the right.





However the basic PD-type ILC is not stable and converges slowly. To overcome these problems we use switching ILC [4] and adapt the learning gain for fast convergence in stage 1 and switch to slower but more reliable convergence in stage 2. Learning is switched off as soon as the error is within acceptable range. This ensures stability.

Outlook

We are hoping to implement ILC soon, possibly combining with PID for better disturbance rejection. Improvements to model and system identification also seem promising, especially the addition of a more sophisticated friction model and nonlinear system identification. A sufficiently precise model can enable deadbeat control with ILC i.e. reaching steady state after one period.

Publications

[1] Dueck, M. ; Schloesser, M. ; Waasen, S. van ; Schiek., M.: Ethernet based time synchronization for Raspberry Pi network improving network model verification for distributed active turbulent flow control. In: Control Theory and Technology 13 (2015), May, Nr. 2, S. 89–95. DOI 10.1007/s11768–015–4143–1

[2] Dueck, M. ; Voelkel, S. ;Waasen, S. van ; Schiek, M. ; Abel, D.: Entwicklung einer echtzeitigen Aktuator-Ansteuerung mit Transienten-Glättung in LabVIEW Real-Time zur Strömungsregelung durch transversale Oberflächenwellen. In: Automation 2015, Benefits of Change - the Future of Automation, VDI-Berichte 2258, 11.-12. Juni 2015, Baden-Baden, VDI Verlag, 2015. – ISBN 978–3–18–092258–4, S. 203–212

[3] Dueck, M. ; Schloesser, M. ; Waasen, S. van ; Schiek, M.: Deterministic Transport Protocol Verified by a Real-Time Actuator and Sensor Network Simulation for Distributed Active Turbulent Flow Control. In Proceedings of 3rd International Conference on Advanced Computing, Networking and Informatics (ICACNI). Smart Innovation, Systems and Technologies, Bd. 44. Springer India, September 2015. ISBN 978–81–322–2528–7, 29-38

[4] M. Dueck, D. Abel, S. van Waasen, and M. Schiek. Transversal surface wave control by gain switching iterative learning improving research on active turbulent flow control. In Control Conference (AUCC), 2015 5th Australian, November 2015. ISBN 978-1-9221-0770-1, 300-305