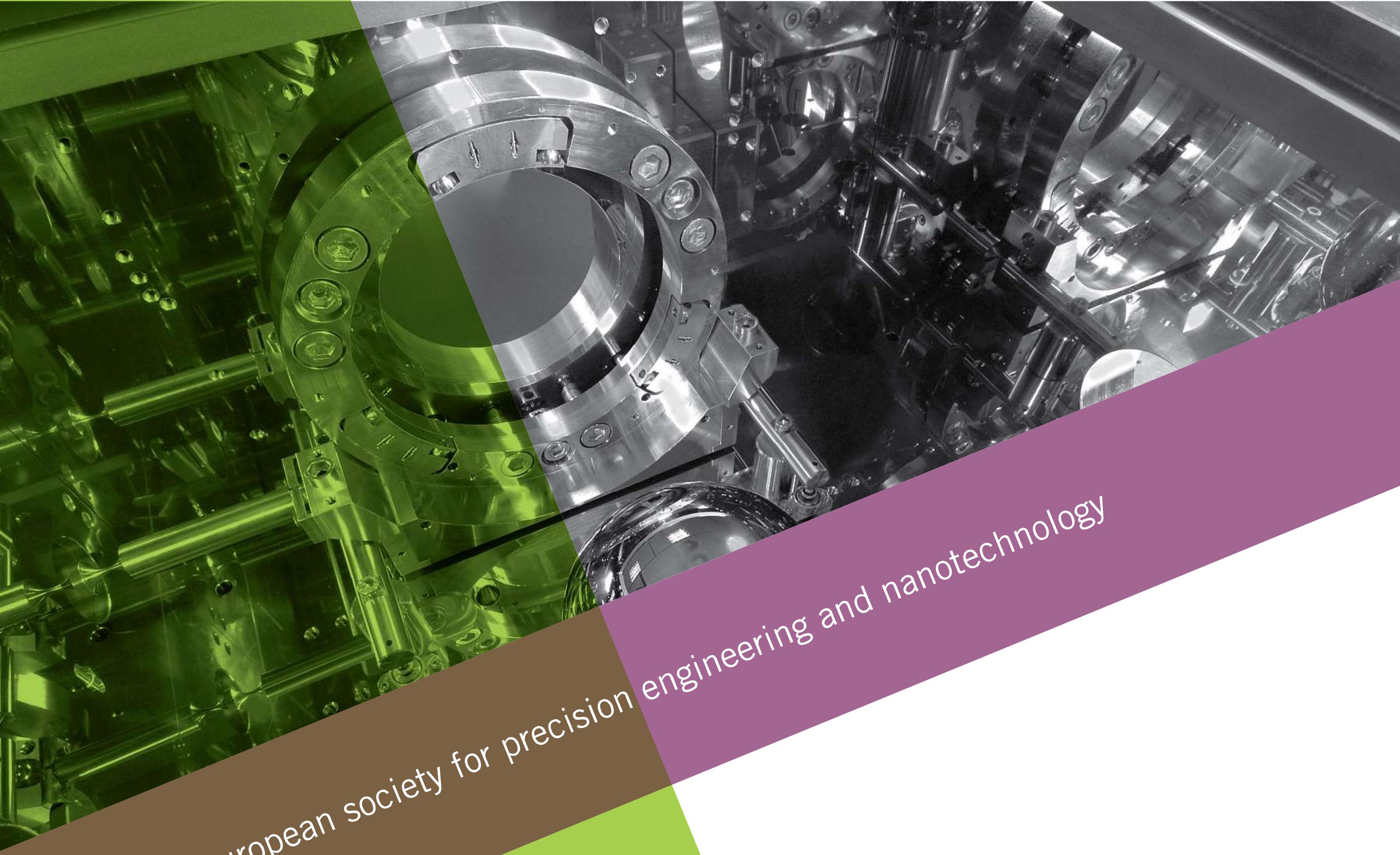

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Characterisation of positioning performances of a mechatronics device actuated via a frictionless voice-coil actuator

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Abstract
Ultra-high precision positioning is a critical feature of the micro- and nanotechnologies. Precision positioning devices are, however, generally characterized by friction, which negatively impacts their performances. The experimental set-up previously used to characterise these drawbacks is employed again in this work, but the rotary DC motor is substituted by a frictionless linear voice-coil actuator, allowing to simplify the kinematic chain. The force vs. displacement characteristics are hence measured for the actuator itself and when it is coupled to the linear guideways. It is thus experimentally proven that the frictional disturbances of the guideways become predominant. By applying a simple control typology, the performances of the mechatronics system are finally assessed proving that its positioning accuracy and precision, compared to those of the original system, clearly improve.

Frictionless voice-coil actuator, compliant elements, disturbances, positioning accuracy and precision, experimental assessment

1. Introduction

Ultra-high precision positioning is one of the critical features of micro- and nanotechnological applications. Recently it was shown that, in positioning systems characterised by stochastic nonlinear frictional disturbances, nanometric positioning is achievable only if these are properly modelled via the Generalized Maxwell-slip (GMS) friction model and compensated by using suitable control typologies. In the case of a micromanipulation device guided on linear guideways, actuated by DC motor – gearhead assembly coupled to a ball screw, it was also shown that, due to reduction ratios, the frictional contribution of the actuator-gearhead set is the most significant one [1].

Building on this experience, in this work a nanometric positioning device is considered where the number of elements inducing friction is minimised by using the recently proposed frictionless linear voice-coil (VC) actuator whose moving magnet is guided by flexure-based diaphragms [2]. In fact, moving magnet actuators of this type have the advantage of eliminating the need for a ball screw, but also that there are no moving leads, and are thus nowadays increasingly used in precision applications (especially robotics) [3].

The force and displacement characteristics of the used actuator are hence experimentally assessed vs. the driving current, allowing to evaluate the performances influenced by the electromagnetic characteristic of the actuator, by the heating of the coils and by the displacements of the compliant bearings. The actuator is then coupled to the linear guideways, whose frictional contribution becomes clearly predominant. By applying a simple control typology, the performances of the mechatronics system are hence experimentally assessed in terms of the achievable positioning accuracy and precision and compared to those of the original system driven by the DC actuator.

2. Experimental set-up

The considered high-precision system is guided on MINIRAIL MN7 Schneeberger guideways mounted on an anti-vibration table (Fig. 1). A Heidenhain MT60k linear incremental encoder, coupled with a EXE-102 interpolation unit, allowing to attain a 25 nm resolution, is used as a feedback sensor. The system is actuated by using the H2W Technologies cylindrical NCM02-17-035-2F frictionless VC actuator [4]. In fact, the moving magnet of the actuator with mass m_m = 115 g is supported and guided via a pair of symmetric and monolithic compliant bearings. The actuator enables to achieve continuous forces of F = 15.6 N and peak forces of F_{max} = 46.7 N on a motion range d = 5.6 mm. The system is controlled by using a NI MyRIO 1900 hardware and the LabVIEW 2015 software.

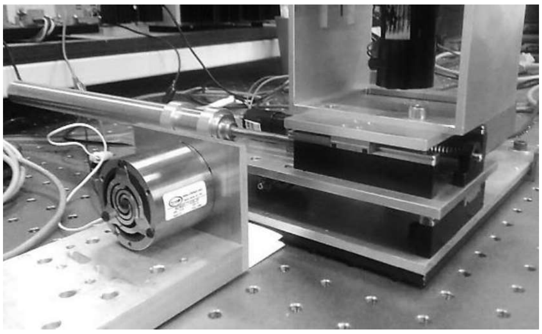

Figure 1. Experimental set-up.

The model of the system is hence defined by its mechanical (equation (1)) and electrical (equation (2)) part and implemented in the MATLAB/Simulink environment:

$$(m_m + m_s)\cdot\ddot{x}(t) + k_s\cdot x(t) + F_{fr} = k_f\cdot i(t) \quad (1)$$

$$L\cdot di/dt + R\, i(t) - k_b\cdot\dot{x}(t) = u(t) \quad (2)$$

Here x is the linear displacement, m_s = 3 kg is the movable mass supported on the linear guideways, k_f = 22.5 N/A is actuator's force constant, k_s is the spring constant of the parallelly connected compliant elements – to be determined via experimental measurements, k_b = 22.5 N/(Vs) is the back-EMF constant, $i(t)$ is the current, $u(t)$ the voltage, while L = 4.35 mH and R = 22 Ω are, respectively, the inductance and the resistance of the coil [4]. The term F_{fr} represents, in turn, the friction induced by the linear guideways, which is modelled by using the GMS friction model with six Maxwell-slip blocks whose parameters were previously experimentally determined [1].

3. Characterisation of performances

The first set of measurements performed on the experimental set-up is carried on with the actuator alone in an open-loop configuration. Since the actuator is frictionless, the generated force F vs. the resulting displacement x can be used to determine the stiffness of the compliant diaphragms [2]. In this frame, the displacement of actuator's movable shaft is measured by using the high-resolution encoder, while the current I absorbed by the coil is controlled by slowly ramping actuator's input voltage and concurrently measured via a Fluke 116/EUR precision multimeter. F can thus be determined by multiplying I with k_f. In Fig. 2 are shown the hence obtained experimental as well as the results obtained via the MATLAB/Simulink model. The spring constant is thus determined to be k_s = 2362.5 N/m. It can also be observed that in the considered displacement range the F vs. x characteristic is linear, i.e. that the influence of the electromagnetic nonlinearities of the motor and the geometric nonlinearities of the compliant members is negligible.

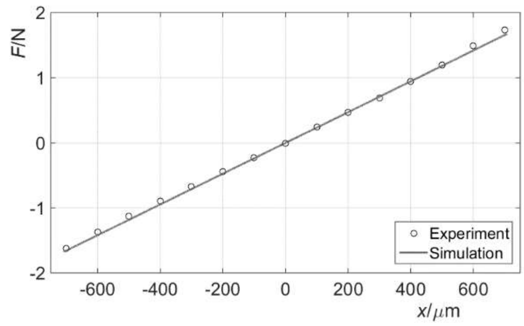

Figure 2. F vs. x characteristics of the actuator.

The next set of experiments is conducted with the aim of determining the rise of coils' temperature for a constant absorbed current. In fact, generated heat and the resulting expansion of the mechanical components could decrease the positioning performances [3]. It has to be noted here, however, that, if compared to moving coil voice-coils, the actuators with a moving magnet, where the coils are mechanically coupled with actuators' housing, are characterised by a superior heat rejection. In fact, the performed experimental measurements allow establishing that, when a constant current $I \approx 80$ mA is applied, the temperature rise $\Delta\vartheta$ of the coils, measured via a K-type thermocouple and recorded on the used multimeter, saturates in ca. one hour to about $\Delta\vartheta = 0.5$ K, so that its influence on the air-isolated moving magnet is negligible.

In the following step, the actuator is coupled to the linear positioning system whose frictional properties were previously thoroughly validated [1]. The described experimental procedure for the open-loop configuration is followed again, and the obtained experimental results, as well as the results predicted via the MATLAB/Simulink model, are reported in Fig. 3. It can thus be observed that the used mechatronics devise is in the pre-sliding motion regime for actuating forces of up to ca. 1 N. What is more, considering the marked stochastic variability of friction (up to ~ ± 15 %) [1], experimental results are matching excellently the modelled ones.

A simple digital PID controller with a 3.3 µs sampling time is finally employed to obtain the closed-loop response of the considered mechatronics system. The parameters of the controller are optimised via developed model so that a phase margin of 45° and a gain margin of 30 dB are assured, resulting in PID gains of $K_P = 0.1$, $K_I = 1 \cdot 10^{-4}$, $K_D = 100$. A control bandwidth of ~ 250 Hz characterises hence system's behaviour. Tracking of sinusoidal excitations with varying amplitudes and frequencies is hence validated. Based on the obtained results, compared also to those when the system is driven via a DC motor-gearbox-ball screw chain, the positing performances of the system actuated with the frictionless VC are clearly better, with some residual motion reversal glitches, that could be eliminated with a more elaborated control typology (Fig. 4) [1].

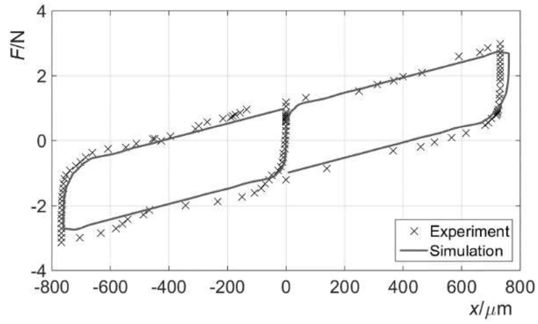

Figure 3. F vs. x for the actuator coupled to the linear guideways.

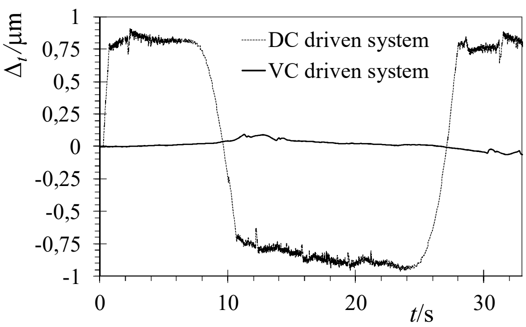

Figure 4. Comparison of tracking errors of DC and VC driven system.

4. Conclusions and outlook

A frictionless VC actuator is used in this work to drive an ultra-high precision mechatronics device. This configuration allows eliminating from the kinematic chain several mechanical elements inducing friction, thus making the frictional disturbances of the linear guideways clearly predominant. It is also established that the heating induced in the coils is small and its influence, even without thermal compensation, is negligible. By tracking a sinusoidal excitation of the thus obtained mechatronics system controlled via a simple PID controller, it is established that the positioning performances are significantly better than those of the same system driven by a DC actuator.

In the prosecution of the work, the developed mechatronics system will be coupled to closed-loop control based on an STR controller that allows to adapt on-line and in real-time the PID gains so as to compensate the disturbances acting on the system [1]. A Koopman-based model predictive control will also be implemented, since it allows not only "lifting" the nonlinear system's dynamics into a higher dimensional space where its behaviour can be accurately predicted by a linear system, but also eliminating steady state errors while being characterised by very small overshoots and reduced settling times [5].

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