Sensors and Actuators A 238 (2016) 266–275

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

External mechanical disturbances compensation with a passive differential measurement principle in nanoforce sensing using diamagnetic levitation

Margot Billot, Emmanuel Piat**, Joël Abadie*, Joël Agnus, Philippe Stempflé

Femto-ST Institute, Univ. Bourgogne Franche-Comté, Univ. de Franche-Comté/CNRS/ENSMM/UTBM, Besançon, France

ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 27 October 2015
Accepted 23 November 2015
Available online 3 January 2016

Keywords:
Micro and nano force sensor
Magnetic spring
Diamagnetic levitation
Kalman filtering
Unknown input estimation
Passive disturbances compensation

ABSTRACT

Nanoforce sensors using passive magnetic springs associated to a macroscopic seismic mass are known to be a possible alternative to force sensors based on elastic microstructures like Atomic Force Microscopes if the nanoforces that have to be measured are characterized by a bandwidth limited to a few Hertz. The estimation of the unknown force applied to the seismic mass is based on the deconvolution of the noisy measurement of the mass displacement which has an under-damped dynamic. Despite their high performances in terms of linearity, resolution and measurement range, such force sensors are extremely sensitive to low frequency environmental mechanical disturbances, like the angular variations of the anti-vibration table supporting the device or the residual seismic vibrations that are not filtered by the table. They are also sensitive to the temperature evolution of the ambient air. The evaluation, modeling and compensation of such environmental disturbances have to be specifically studied in the context of magnetic springs associated to a macroscopic seismic mass because of their important negative effects in terms of low frequency drifts and oscillatory disturbances. This article presents an estimation and a passive compensation strategy of the low frequency and non-stationary mechanical disturbances that is based on a differential principle. This approach is applied to a nanoforce sensor based on diamagnetic levitation developed in the last decade. It does not necessitate to add new types of sensors in the measurement chain such as very high resolution and low frequency inclinometers or accelerometers in order to estimate the mechanical disturbances. In term of performances, the force estimation error remains in the nanonewton level over periods of time of several minutes when external temperature remains constant.

1. Addressed problem

1.1. Introduction

Achieving progresses in the measurement of micro and nanoforce remains a necessity in domains like material sciences at micro and nano scales or micro and nanorobotics. For instance, in the first case, it is often necessary to characterize, in terms of adhesion and friction, functionalized and/or structured surfaces at micro and nanoscales. In the second case, performances of micro and nano-objects manipulation during micro-assembling should be improved if the forces applied on the objects are directly taken into account in the control loops driving the micro-actuators. Such progresses concern both force sensors embedded in microrobotics devices and force sensors embedded in dedicated measurement platforms. Whatever is their final use, all micro or nanoforce sensors use a transducer to convert the force into a measurable effect. In many force sensors, this effect is related to the displacement x of a force–displacement transducer. Most classical designs are based on elastic microstructures with one or several degrees of freedom which have a high resonant frequency: AFM based microforce sensors [1,2], piezoresistive microforce sensors [3,4], capacitive microforce sensors [5], piezoelectric microforce sensors [6]. Another important challenge that leads to original development of micro and nano force sensors is present in the field of metrology of small forces (below the mN). The strategies used by National Metrology Institutes (NMIs) to try to establish traceable measurements of small forces are varied. The simplest consists in calibrating the sensor using a dead weigh which is possible when the

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** Corresponding author.
* Principal corresponding author.

E-mail addresses: margot.billot@femto-st.fr (M. Billot), emmanuel.piat@ens2m.fr (E. Piat), joel.abadie@femto-st.fr (J. Abadie), joel.agnus@ens2m.fr (J. Agnus), philippe.stempfle@ens2m.fr (P. Stempflé).

http://dx.doi.org/10.1016/j.sna.2015.11.032
0924-4247/

measurement direction is vertical. This restrictive approach has the major disadvantage that the uncertainty associated with the weight, in mass metrology, increases gradually as the latter decreases [9]. In terms of alternatives, many micro and nanoforce sensors are based on elastic microstructures. Some works have been done by NMIs to develop traceable low forces sensors using piezoresistive MEMS [10] or capacitive cells (comb-drives) [9]. Another measurement principle is the mass comparators. Schematically, a comparison of mass acts via an elastic structure (micro or macro) which is moved along an axis to mechanically load an artefact with an unknown force. This artefact is itself in contact with an electromagnetic balance which generates an opposite electromagnetic force adjusted by a current. This current is controlled in order to generate a controlled displacement of the loaded artefact. When a null displacement is reached, the electromagnetic force is then the opposite of the unknown loading force. The electromagnetic balance is previously calibrated with dead weights, which allows to know the electromagnetic force versus the current and thus the force applied to the loaded artefact. In such designs, the electromagnetic balance is an active force sensor. The measured output value that has to be controlled is a displacement, the associated reference is a null displacement, the controller output is a current and the known generated force is a known function of the current. Different mass comparators have been developed to measure vertical forces using masses of 1200 g [11], 210 g [12], 41 g [13] (PTB, Germany) and 5 g [14] (KRISS, Korea). These comparators reach different working ranges (from a few hundred nanoNewton to Newton) and resolutions (minimum 1 nN) [10]. An original electromagnetic balance using a reference death weight of 1000 g is also developed to measure the horizontal forces that exceed the micronewton [15]. Controlling the force orientation during micro-nano force measurement is particularly difficult. Thus, if a sensor is designed to measure the force in only one direction, an error in the orientation of the applied force leads to a measurement error. This error can be either estimated or not. If it is estimated, the force measurement can be corrected. This is for instance the case with the previously referenced mass comparator which has a tilting sensitivity. Tilting angle must be inferior to 0.1 μrad to guarantee an 1 μN accuracy. This tilting error is measured with a high-resolution inclinometer. If the error is not corrected it should be bounded and included in the uncertainty calculation. For instance, the uncertainty associated to the vertical force sensor described in [9] needs a cosine correction factor as the force applied is never strictly vertical. The temperature is also known to be a source of disturbance in the field of metrology and the force sensors developed by NMIs are always controlled in temperature (generally with 0.01° accuracy) over long periods of time [13,16] in order to establish a traceability of micro-nano-force to International System of Units standards.

To conclude this short review of micro and nanoforce sensors, all sensors are subject to external disturbances that affect their dynamic and that should be estimated and compensated if their bandwidth and amplitude corrupt the force that has to be estimated. A possible categorization of such environmental disturbances and their domains of influence can be found in [7,8]. Their estimation and active or passive compensation in micro and nanoforce sensors remains an open research problem.

1.2. Nanoforce sensors using magnetic springs

Nanoforce sensors with low resonant frequency that are based on low stiffness magnetic springs associated to a macroscopic seismic mass (from milligramme to gramme) are a possible alternative to classical designs based on elastic microstructures to measure low frequency forces or quasi static forces. The unknown force is applied on a macroscopic seismic mass connected to a passive magnetic spring and induces a displacement response of the mass. Because of the macroscopic size of the force–displacement transducer, these force sensors, developed in the last decade, are commonly used in force measurement macroscopic platforms with one [17] or several degrees of freedom [18]. Indeed, they have been used for instance with success to characterize the mechanical behavior of human ovocytes whose stiffness is commonly below 0.01 N/m [19]. Contrary to sensors based on micro elastic structures, very long range of force amplitude can be measured without any risk of breaking the force–displacement transducer, linearity also remains excellent over classically ±1 mm displacements of the transducer and a nanonewton resolution can be reach thanks to the low stiffness of the sensor that can easily be adjusted by varying the magnets configuration of the device. Moreover, the mechanical part manufacturing is a low cost processing and does not necessitate any complex machining. As the transducer mass can be measured with a micro balance, its second-order behavior can be identified (including the stiffness corresponding to the steady state behavior) using a zero-input response [17]. These is no parametric indetermination during calibration like for micro-nano force sensors whose mass is hard to determine. When the mass is unknown, the calibration requires thermal noise measurement or indirect methods with additional hypotheses that are generally difficult to verify.

If only one Degree of Freedom is considered and under the assumption that the environmental disturbances are completely negligible, their force–displacement dynamic is a second-order under-damped transfer because of the inertia of the macroscopic mass, the very small viscous friction applied on the mass and the absence of dry friction. When an adequate design of the magnetic spring is used, if a force $F^x(t)$ is applied along an axis $\vec{x}$, the linear displacement $x(t)$ obtained corresponds to the following dynamic in a global inertial reference frame R_0 attached to the laboratory:

$$m\ddot{x} + K_v^x\dot{x} + K_m^x x = F^x \tag{1}$$

where m, K_v and K_m are the mass, the viscous damping coefficient of the mass and the magnetic stiffness of the transducer. Thus, classical open-loop steady-state equation:

$$F^x = K_m^x x, \qquad K_m^x > 0 \tag{2}$$

cannot be used to determine the force $F^x(t)$ because the evolution of the successive derivatives of the mass displacement x is absolutely not negligible over long periods of time. That is why, the force estimation becomes in this context an open-loop deconvolution problem of a noisy output signal whose principle is shown in Fig. 1. The force $F(t)$ applied on the transducer is corrupted by environmental disturbances. The resulting displacement dynamic is measured with a sensor corrupted by measurement noises and gives the measurement signal x_k^m, sampled at a period T_s. Knowing this signal, it is necessary to compute at each sampling time the estimation $\hat{F}_k$ of the real force $F(kT_s)$ applied on the transducer, thanks to a real-time deconvolution.

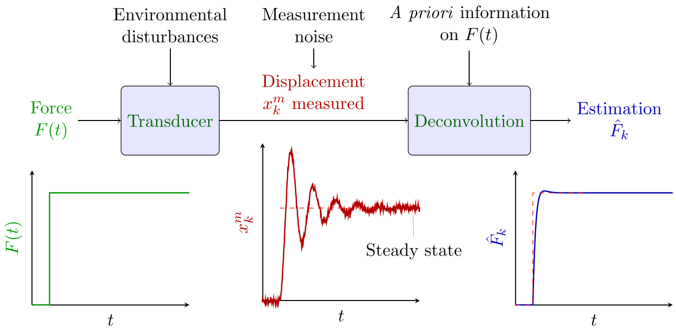

Fig. 1. Force estimation using a deconvolution approach.