Thermal hysteresis of travelling inductance standards

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***Abstract*—The international comparison CCEM-K3.2018 "Inductance at 10 mH and 1 kHz" is under preparation. To verify the uncertainty claims of the participant institutes, travelling standards of unprecedented level of stability are required. INRIM and PTB characterised several General Radio 1482 inductance standards versus large temperature steps that may occur during air carrier transportation. This work reports on the unexpected thermal hysteresis manifested by these standards which may impact on the uncertainty of the reference value of the K3 comparison.**

***Index Terms*—Metrology, International System of Units, inductance measurement, calibration, measurement uncertainty.**

I. Introduction

The Consultative Committee for Electricity and Magnetism (CCEM) of the International Committee for Weights and Measures (CIPM) has identified *electrical inductance* as a *key quantity*, at the specific value of $10\,\mathrm{mH}$ [1]. For key quantities, CCEM organises *Key Comparisons* (KC) to sustain the worldwide compatibility of measurements. At present, the comparison CCEM-K3.2018 "Inductance at $10\,\mathrm{mH}$ and $1\,\mathrm{kHz}$" is running and is in its organisational stage.

Travelling standards employed in KCs must be stable against time, mechanical shocks, and wide swings in the ambient parameters occurring during transportation.

This summary reports about the investigations performed at INRIM and PTB on the effects of wide temperature swings, which may occur during the necessary intercontinental transportation, on metrology-grade inductance standards.

II. Inductance standards

The most popular series of metrology-grade inductance standards is the General Radio 1482, originally developed in 1952 [2] and still commercially available at the time of writing. These standards are composed of a copper winding over a non-ferromagnetic core, embedded in a soft insulating material (cork granulate). Electrically, they are configured as three-terminal impedances (high terminal H, low terminal L, shield G).

The specified inductance temperature coefficient of the 1482 standards is $30 \times 10^{-6}\,\mathrm{K}^{-1}$. The dc series resistance of the inductor has a temperature coefficient of $3.94 \times 10^{-4}\,\mathrm{K}^{-1}$, that of pure copper.

To reduce the dependence over ambient temperature, dedicated thermally-stabilised enclosures were developed [3]. In previous comparisons, performed more than 20 years ago, it was possible to transport the standards with the thermostat switched on [4], [5]. With modern air freight regulations this is no longer possible. Therefore, the existence of possible thermal hysteresis effects deserves investigation.

Fig. 1. General Radio 1482 toroidal inductance standard, configured as a two-terminal impedance.

III. Measurements at INRIM

INRIM performed measurements on a General Radio $10\,\mathrm{mH}$ 1482-H, serial number 16617, bought for the purpose of this work on the secondhand market. The measurements were performed at a frequency of $1\,\mathrm{kHz}$ and a current of $10\,\mathrm{mA}$, using a fully-digital four-terminal-pair bridge [6]. The reference impedance was a $100\,\Omega$ ac-dc resistor. The measurement standard uncertainty is 4.8×10^{-6} ($k = 1$).

The standard was placed in a thermostated air bath (Kambic TK-190 US) at $23.00\,^{\circ}\mathrm{C}$ for 70 days and then cooled down to $15.00\,^{\circ}\mathrm{C}$ for 6 days. The temperature was then reset to $23.00\,^{\circ}\mathrm{C}$.

Fig. 2 shows the temperature evolution in the air bath and in the winding, the latter monitored by measuring the inductor dc resistance. The delay due to the limited heat exchange from the surface to the bulk of the inductor is evident.

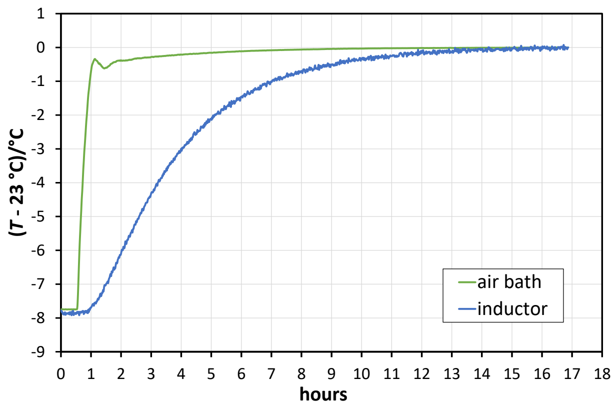

Fig. 2. Temperature evolution of the air bath (green) and of the winding (blue) after a positive step of the air bath temperature setting. A negative step (not shown) has similar time constants.

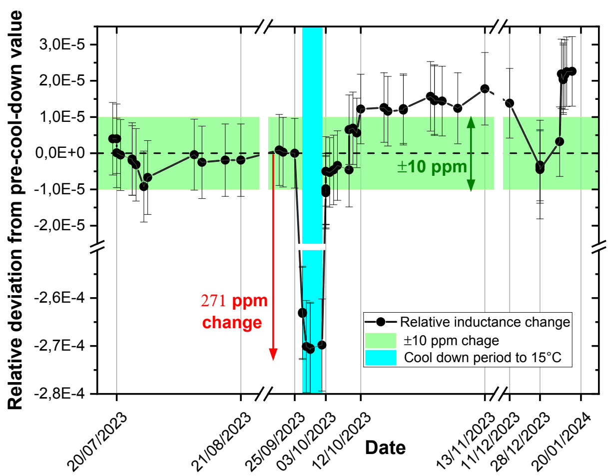

Fig. 3. Time evolution of the inductance of the INRIM $10\,\mathrm{mH}$ standard before, during and after the temperature step event. The uncertainty bars correspond to a $k = 2$ coverage factor.

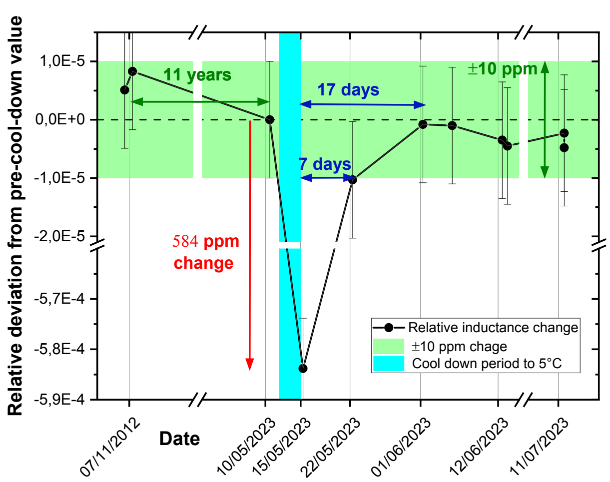

Fig. 4. Time evolution of the inductance of the PTB $100\,\mathrm{mH}$ standard before and after the temperature step event. The uncertainty bars correspond to a $k = 2$ coverage factor.

Fig. 3 shows the evolution of the inductance value before, during and after the cooldown event.

IV. Measurements at PTB

PTB performed measurements on a General Radio $100\,\mathrm{mH}$ 1482-L, serial number 1279, with the PTB Maxwell-Wien-Bridge [7]. The complete measurement uncertainty for this bridge is 5×10^{-6} ($k = 1$). For $k = 2$, this uncertainty corresponds to the expanded uncertainty of PTBs CMCs for impedance. The measured inductance standard showed a good stability in the past. Since the last measurements in 2012 the inductance value was reduced by less than 10×10^{-6}.

The $100\,\mathrm{mH}$ standard was cooled down to $5.0\,°\mathrm{C}$ for 3 days. Fig. 4 shows the inductance evolution before, during and after the cooldown event.

V. Discussion and Outlook

Fig. 2 shows that the thermal settling time of the inductors is around $12\,\mathrm{h}$, hence small with respect to the observation timescale of Figs. 3 and 4.

Both INRIM and PTB measurements show that the inductor value is stable before the cooling event, which induces for its duration a value shift compatible with the specified temperature coefficient of the 1482 series of $30 \times 10^{-6}\,\mathrm{K}^{-1}$.

Both INRIM and PTB measurement series show that the inductance value displays significant aftereffects related to the cooling event. The PTB standard recovered the original value (to within $\pm 10 \times 10^{-6}$), but only after several days. The INRIM standard suffered of a series of step changes that occurred in the following two months of observations.

Although the behaviours of the two inductors are different, both are incompatible with the requirements of an international intercomparison aiming at a determination of the degrees of equivalence with an uncertainty below 10×10^{-6}, as expected from CCEM-K3.2018.

Further measurements will be performed and reported at the Conference.

References

[1] Consultative Committee for Electricity and Magnetism (CCEM), “Strategy 2020-2030,” https://www.bipm.org/en/committees/cc/ccem, 2021, CCEM 32nd meeting.

[2] H. W. Lamson, “A new series of standard inductors,” *General Radio Experim.*, vol. XXVII, no. 6, pp. 1–4, nov 1952.

[3] L. Callegaro, V. D’Elia, F. Francone, and D. Serazio, “100 mH travelling standard for the EUROMET 607 pilot intercomparison,” in *Conference Digest Conference on Precision Electromagnetic Measurements*, 2002, pp. 352–353.

[4] H. Eckardt, “International comparison of 10 mH inductance standards at 1 kHz,” https://www.bipm.org/kcdb/comparison?id=38, Jun. 2001, CCEM WGKC/2001-15.

[5] A. Kölling, “Final report on EUROMET comparison EUROMET.EM-K3: a 10 mH inductance standard at 1 kHz,” *Metrologia*, vol. 48, no. 1A, p. 01008, jan 2011.

[6] M. Marzano, V. D’Elia, M. Ortolano, and L. Callegaro, “Primary realization of inductance and capacitance scales with a fully digital bridge,” *IEEE Trans. Instr. Meas.*, vol. 71, pp. 1–8, 2022.

[7] R. Hanke, A. Kolling, and J. Melcher, “Inductance calibration in the frequency range from 50 Hz to 1 MHz at PTB,” in *Conference Digest Conference on Precision Electromagnetic Measurements*, 2002, pp. 186–187.