20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Comparative assessment of signal cable impact in differential capacitive position measurements

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Abstract – **An experimental procedure for a systematic analysis of stability, precision and noise immunity of micrometric measurements based on capacitive sensors at varying cable configurations and installation conditions is proposed. First, the measurement problem arising from the interferences introduced by the cables and a background on the capacitive sensors in use at CERN (European Organization for Nuclear Research) is presented. Then, the proposed procedure, the test design and the measurement station are illustrated, by considering different cable types. Finally, the experimental validation of the procedure is reported.**

I. INTRODUCTION

In some industrial and research applications characterized by particular environments, the need for determining the position of components within micrometric accuracy arises [1]. High-precision is achieved by means of special equipment in combination with specific precautions adequate to the measurement environment in order to minimize measurement uncertainty [1].

At European Organization for Nuclear Research (CERN), sensors based on the capacitive principle for micrometric monitoring are used in several installations in the Large Hadron Collider (LHC), and are planned to be used in the Compact LInear Collider (CLIC) – a possible future linear collider currently under study [2, 3]. In particular, the contact-free micrometric distance to an object is measured by capacitive sensors mainly. In these sensors, a change in the distance between the electrode and the target is related to a variation in the capacitance [4]. As an example, the capacitive sensors used for micrometric measurements in the LHC low-beta installations are: (i) Hydrostatic Levelling Sensor (HLS) [1, 5], where the surface of the water is the reference; (ii) Distance Offset Measurement Sensor (DOMS) [1], where the surface of a conductive plate is the reference; and (iii) Wire Position Sensor (WPS), where the stretched wire is the reference line [1, 5].

The high-radiation level in the environment where the sensors are located forces the dislocation of the transducing electronics several tenths of meters from the sensors, owing to the damaging impact of radiation on electronics [6]. On the other hand, electronics placed far away from sensors create additional signal conditioning problems. The cables can be exposed to a series of interferences that may distort the measurements. Furthermore, the cables parameters may be changed by environmental and installation conditions. Typical interferences are: (i) electromagnetic noise coming from the proximity to other equipment (especially power lines); and (ii) crosstalk from external cables or the sensor cables themselves [7].

Apart from environmental interference, other conditions can influence the cables parameters, such as: temperature, humidity, cables length [8], cableways geometry and pulling methods [9, 10], radiation and magnetic fields.

Owing to the cables length, a significant influence for capacitive measurements can arise from the intrinsic parasitic capacitance of cables as well as between adjacent cables. These parasitic capacitances cause a coupling of the electric field, which induces a current change in the circuit. Adequate shielding of the cable can reduce the effect of the parasitic capacitances but cannot suppress them [10, 11]. As an example, the typical parasitic capacitance of a coaxial cable is about 80 pF/m. In the case of the WPS sensors used at CERN, the measured capacitance range is about 0.4 pF. A resolution in position of 0.1 μm requires for 4 aF in capacitance change. Even for 1-m cables, the sensor-measured value will be hidden by the parasitic capacitance of the cable. Therefore, suppressing the effect of the parasitic capacitances is mandatory. Main solution is an active shielding [12], where the geometry is defined and outer and inner conductors are driven at the same potential by a buffer amplifier. This technique is used in remote capacitive sensors because counteracts the effects of both external interference and parasitic capacitances of the shielded cable.

The other parasitic parameters of the cables, as inductance line resistance and isolation resistance, are also not to be neglected in their possible influence on the measurement results. These parameters have a direct impact on the sensor-cable-circuit impedance and may result in a measured signal offsets.

ISBN-14: 978-92-990073-2-7

For micrometric measurements with long cables using grounded capacitive sensors, a suitable electronics is necessary for reading the value of the sensor. The conditioners used at CERN by Large Scale Metrology Section of the Machines & Experimental Facilities Group in the Engineering Department (EN/MEF-SU) are sensitive charge amplifiers with active shielding by FOGALE Nanotech [13, 14]. Other solutions exist, as an example the Sigma-Delta charge-to-digital converter AD7747 by Analog Devices, offering active shielding and resolution at the level of 20 aF in the 8 pF measurement range.

In this paper, the impact of different cable types and configurations on stability, precision, and noise immunity is assessed in micrometric measurements using differential capacitive sensors (WPS) with grounded wire as reference. In particular, main focus is given to the aspect of cables parameters variation under different installation conditions, by considering all the other components of the transducing system as a constant part.

II. BACKGROUND

A capacitive measurement system converts a change in a position or in the properties of the dielectric material into an electrical signal. The capacitive sensors under investigation or use ??at CERN are two-dimensional WPS.

Initial studies have been carried out in 2007 [16] using HLS. These results on the one-dimensional, single electrode HLS are the basis of current WPS tests.

A. Hydrostatic Levelling Sensor

A HLS (Fig.1) is used to determine the level of water with respect to the sensor electrode [1]. Using several HLS and a hydraulic network (Fig.2), based on the communicating vessels principle, the height differences between electrodes can be determined. The sensor electrode and the targeted reference water surface make up a capacitor (Fig.1).

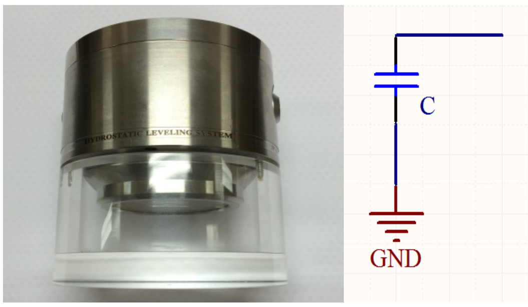

Fig.1. HLS (left) and equivalent electrical circuit (right)

The HLS, considering the FOGALE Nanotech sensor-cable-conditioner configuration, has an operating range of 5 mm, a precision of ±1 µm, and a resolution of 0.2 µm (laboratory conditions).

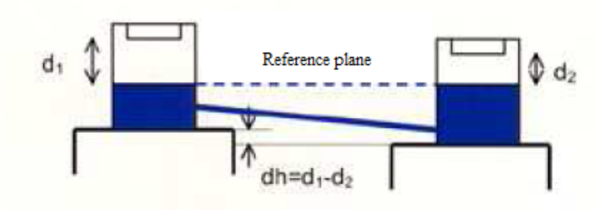

Fig.2. HLS network operating principle (from Santos, 2007 [16])

B. Wire Position Sensor

The WPS (Fig.3) is a differential capacitive sensor and is designed for monitoring objects with respect to a stretched wire representing a reference line [1]. It has two electrodes per axis facing each other, which makes a total of four electrodes as shown in Fig.3.

The sensor can be treated as a pair of double capacitors in differential configuration.

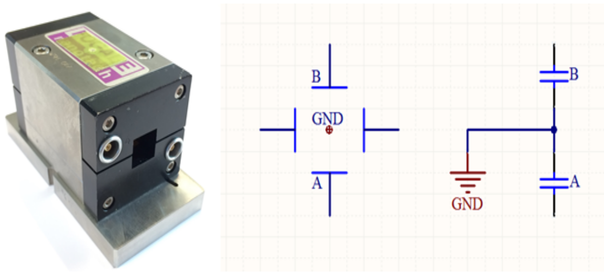

Fig.3. WPS (left) and equivalent electrical circuit (right)

The position of the wire in the centre can be considered as sensor's ''0''. Fig. 3 right shows the equivalent circuit. The WPS has a *X-Y* working range of 10 mm by 10 mm. The FOGALE Nanotech sensor-cable-conditioner configuration has a precision of ±1 µm and a resolution of 0.1 µm (laboratory conditions).

III. MEASUREMENT PROBLEM

Difference in cables configurations and installation conditions can have an impact on position measurements precision and output signal drift. In the following paragraphs, the main factors producing the interferences introduced by the cables are illustrated.

A. Cable length

The variation in the cable length can introduce: (i) a change in cable stray parameters as inductance, capacitance, as well as in line and isolation resistances; and (ii) the increase of electromagnetic noise impact, as bigger length is exposed to electromagnetic radiation.

B. Cable coiling

Coiling can cause cable performance variation due to the produced self-inductance and mutual inductance (among cable wires).

A varying electric current in an inductive circuit induces a proportional voltage opposing to the change in current (self-inductance). The varying field in this circuit may also induce an electro-magnetic field in neighbouring circuits. Coiling multiline signal cables could cause crosstalk increase among the wires of the same cable [15].

C. Cable bending

The bending can affect the internal dimension of cables. This can result in a change in cable stray parameters. It is important to consider also this possible uncertainty source in the CERN critical applications mentioned above, where a resolution in position of 0.1 µm requires a capacitance change of 4 aF.

In the following chapter, a procedure for assessing the effects of the cable effects and wiring factors on the micrometric measurements is presented.

IV. TEST PROCEDURE

The objective of the tests is to compare the conditioners measured output signal changes for different types of cables and their installation conditions (cable length and cable path geometry – section III A-C) in non-industrial environment.

The types of cables under test are: MULRAD 2 (twisted pair, single shielded), MBB6 (3x twisted pair, each pair shielded and external cable shielding), and CAD50 and CB50 (coaxial cables with 3 mm and 5 mm of diameter, respectively). Each cable type is grouped in a cable set providing the connection between the conditioner and the WPS sensor. All the cable sets are prepared in 5 different lengths of 5, 10, 17, 27, and 40 m.

The tests are carried out with a stable sensor and wire position. Due to different types of cables (coaxial-shielded, twisted pair-shielded) the two types of WPS sensors are used as reference: (i) 4 connectors WPS for coaxial cables, and (ii) 2 connectors WPS for twisted cables. Also two types of signal conditioners having similar parameters are used (Fig. 4).

The sensor is installed on the test bench (Fig. 5) with constant wire position, to provide stable reference. For each test (cable length, installation configuration - section III A-C), each cable set is measured during 10 minutes with a frequency of 4.5 Hz after the stabilization of the conditioner signal (preheating of electronics). Two measurements for each cable (the second one after disconnection and reconnection again to verify if reconnection not create the change of measured value) are carried out.

As the measured signal (absolute position) value for each measurement is stable due to constant test bench capacitances, the change of the cables length or configuration may have impact for measured position offset and noise level.

To assess the signal stability between each sets of appropriate measurements - the RMS value of conditioner output signals (X, Y) are taken and compared. The ΔRMS equal to position offset is taken as signal stability assessment factor. Accordingly the measured signal standard deviation (STDEV) is used to assess noise level change.

Finally, the results are compared to evaluate which parameters of the cables and what installation precautions have to be considered as the most important for capacitive micrometric measurements.

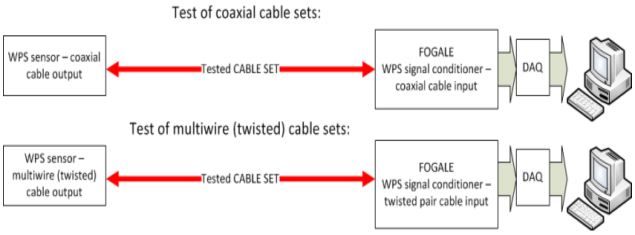

Fig.4. Measurements schematic

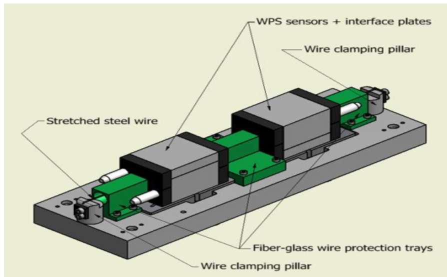

Fig.5. WPS test bench

In addition, the possible uses of other type of cables as an alternative to those provided by the manufacturer and the suitability of their performance have to be assessed. Concerning the last point, the measurements are important also to optimize the impact of the costs of the cables for future installations.

V. EXPERIMENTAL RESULTS

In the following paragraphs, the outcomes of the tests of the above procedure are reported for assessing the effects on the cable (A) *length,* (B) *coiling*, and (C) *bending.*

A. Cable length

This test is important to assess the cable length influence on the measurements precision of the sensor. The results show that the cable length affects the measured signal value (Figs. 6 and 7).

Coaxial cable with bigger diameter shows better signal stability, namely ΔRMS of 50 µm in case of CB50 and

100-400 µm of drift for CAD50 over change of cable length). The reason may be that parasitic capacitance of the CB50 is lower and does not have a high impact on the conditioner.

An unexpected change of the signal value for the specific cable length of 27 m was observed, possibly arising from interferences of conditioning electronics with specific cable impedances close to this length.

The noise level of the coaxial cables measured signal (STDEV) is less than 2 µm over all lengths of cables, although it increases according to the length.

The multicore cables results show that the noise level increase according to the length and for the MULRAD cables is bigger than for the MBB6 (1µm vs. 0.5µm for l=40m – Fig.7).

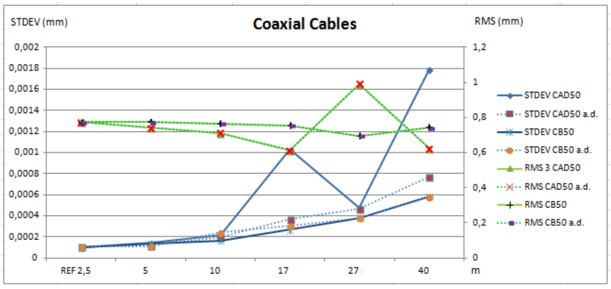

Fig.6. Cable length test: coaxial cables results.

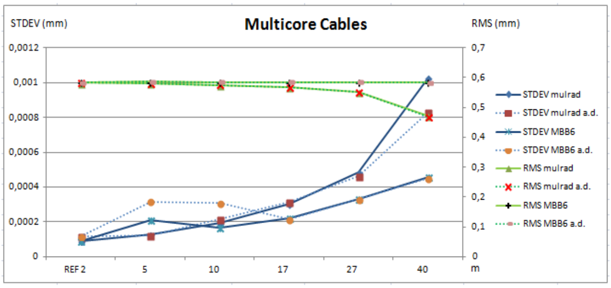

Fig.7. Cable length test: multicore cables results.

For MBB6 cables, the length has a negligible impact on the RMS value change. Furthermore, any significant drift of RMS value (less than 3 µm) is observed over the whole range of cable lengths.

Conversely, for the MULRAD cables, the drift of the RMS value was significant (about 100 µm). The better behaviour of the cable MBB6 can be explained by the lower impedance and mutual inductance of the cable due to its twisted structure.

B. Cable coiling

This test is important to assess the impact on the measurements of sensors with different lengths of rolled cable sets in stable environment. The tested cable was coiled with a diameter of 0.4 m.

Coaxial cables with bigger diameter (Fig. 8) show better signal stability, namely ΔRMS of 50 µm in case of CB50 and 100-400 µm of drift for CAD50 over change of cable length. Coiling of the cable CAD50 dumps excitation of the electronics with a length of 27 m. The reason can be the change of cable impedance for rolled cable and its possible interference with signal conditioner for this impedance value. The noise level of the signal (STDEV) is less than 1 µm over all the lengths of cables, although it increases according to the length.

The results for the multicore cables (Fig. 9) have shown that the increase in noise according to the cables length is bigger for the MULRAD than for the MBB6, although still very small (below 1µm).

A small drift (3 µm) of RMS value for MBB6 cable was observed over the whole range of cable lengths. Coiling of the MULRAD cable enlarges the RMS value shift (position offset) for lengths over 17 m.

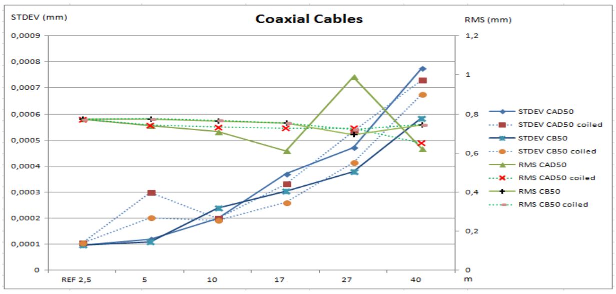

Fig.8. Cable coiling test: coaxial cables results.

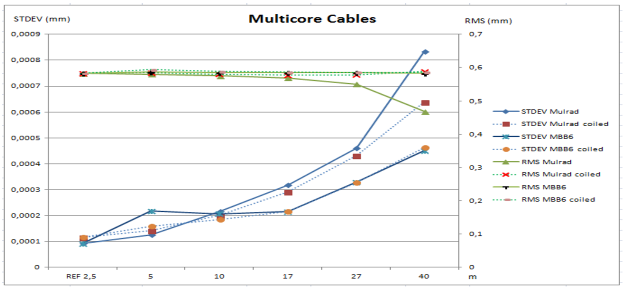

Fig.9. Cable coiling test: multicore cables results.

The reason can be that increase of the cable impedance affects the electronics behaviour.

The noise of the signal (STDEV) is less than 1 µm over all lengths of cables, although it increases according to the length.

C. Cable bending

This test is important to assess the impact on the measurements of cable bending. All the tested cables were bended with the minimal radius specified by the producer. Only the two lengths of 17 and 27 m of each cable were tested with a number of bends of 10 and 20.

For the coaxial cables (Fig. 10 and 11), the bending has an impact for the cable CAD50, namely a ΔRMS of 70-150 µm. The cable CB50 shows lower shift of RMS signal value (ΔRMS of 30 µm). Coaxial cables with bigger diameter show better signal stability.

The noise of the signal (STDEV) is less than 1 µm over all the lengths of cables.

For the multicore cables (Fig. 12 and 13), the RMS changes are very small (ΔRMS of 5-20 µm) but not negligible. The RMS change for MBB6 (~5µm) is lower than for MULRAD (~20µm).

The better behaviour of the cable MBB6 can be explained by its lower impedance and mutual inductance due to its twisted structure.

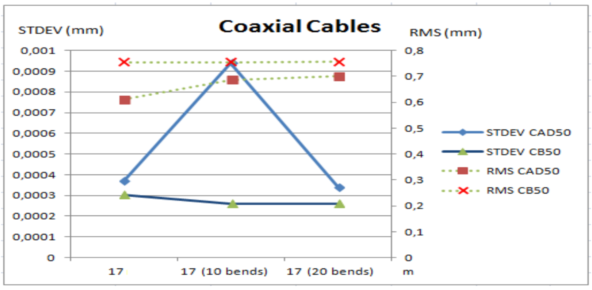

Fig.10. Cable bending test: 17 m coaxial cables results.

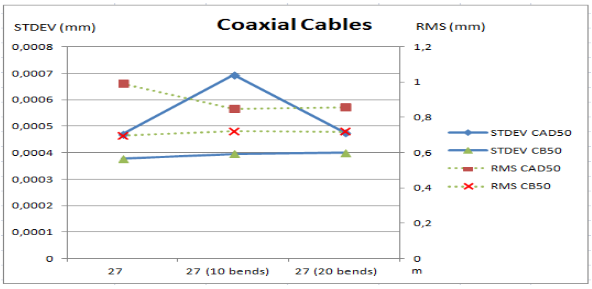

Fig.11. Cable bending test: 27 m coaxial cables results

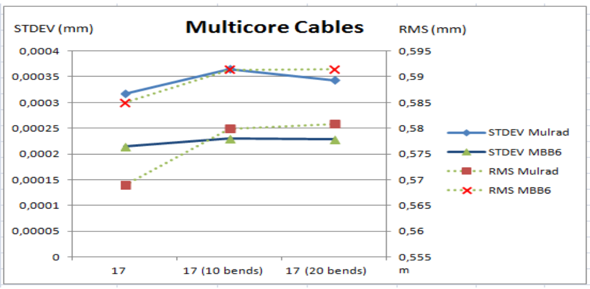

Fig.12. Cable bending test: 17 m multicore cables results

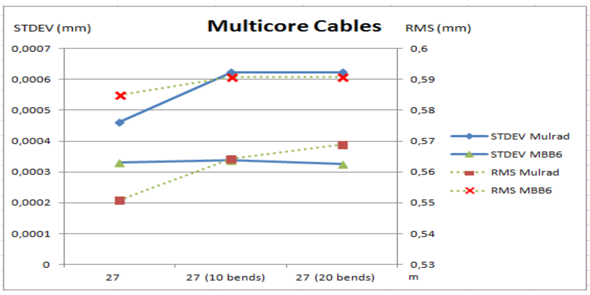

Fig.13. Cable bending test: 27 m multicore cables results.

VI. CONCLUSIONS AND FUTURE TESTS

The results on WPS have confirmed that cables of different lengths have an influence on micrometric measurements increasing according to the length.

The coaxial cables, the CB50 with bigger diameter show a better stability when the length increases. This effect may be explained by lower cable impedance change for different length/configurations when the cable diameter is bigger.

Concerning the multicore cables, the MBB6 is more stable when the length increases. The twisted structure of the cable guarantees the best noise immunity and independence of measurements, according to installation and environmental variations. Moreover, twisted structure minimizes the mutual inductance of the cable and the EM noise impact.

The interesting problem is that for some of cable configurations the noise level changes nonlinearly with an increase of the cable length (i.e. increase of noise for 17m CAD50 cable in length test and bending tests). This may suggest the interference between certain cable impedance values and excitation of conditioning electronics. As currently the signal conditioners are considered as "black boxes", the future investigations will be taken to understand deeper the problem.

In addition to the current tests, the future tests will be carried out to characterize the impact of crosstalk and temperature change.

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