WIRE SCANNERS AND VIBRATIONS – MODELS AND MEASUREMENTS

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Abstract

The new fast wire scanner foreseen to measure small emittance beams throughout the LHC injector chain will have a wire travelling at a speed of up to 20 m.s^{-1}, with a requested wire position measurement accuracy in the order of a few microns. The vibration of the thin carbon wires used has been identified as one of the major error sources on the wire position accuracy. One of the most challenging and innovative developments in this project has been the work to quantify the effect of wire vibrations and fork deformation. The measurement strategy for the former is based on the piezo resistive effect of the wire itself, while the deflection of the fork supporting the wire has been measured by semiconductor strain gauges. Dynamic models of the wire and fork have been created to predict the behaviour of the fork-wire assembly and will be used for its optimisation. This contribution will discuss the measurement setup and the model development as well as their comparison. In addition it will show that this technology can easily be implemented in current operating devices without major modifications.

INTRODUCTION

A wire scanner is an electro-mechanical device which measures the transverse beam profile in a particle accelerator by means of a thin wire moving rapidly across the beam [1]. The intersection of the wire and the beam generates a cascade of secondary particles. Those particles are intercepted by a scintillator, coupled with a photomultiplier, which measures the intensity of the light generated by the crossing particles (Fig. 1). The wire position is typically measured with a precision rotary potentiometer. By synchronising the digitised potentiometer and the scintillator photomultiplier signal it is then possible to reconstruct the transverse beam profile.

In order for the wire to reach a suitable speed when it crosses the beam, the actuator has to provide a motion which consists of an acceleration phase, a constant speed plateau and a deceleration phase (Fig. 2).

The peak acceleration values will vary depending on the peak speed required, the length of the fork, the angular travel available for the complete motion and the motion pattern parameters.
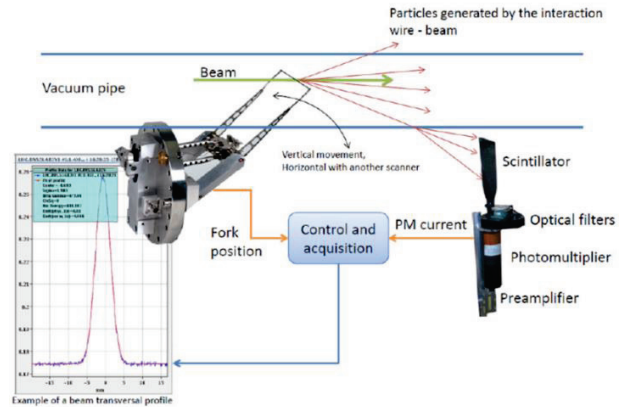

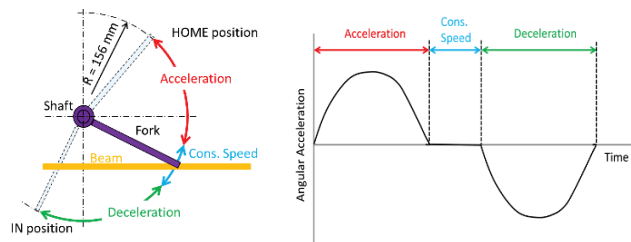Figure 1: Schematic of the wire scanner instrument.

Figure 2: Typical scan cycle (left) and motion pattern (right).

The strong initial acceleration required induces deflections and vibrations in the mechanics (shaft, fork and wire), which result in discrepancies between the true position of the wire midpoint (P) and the position measured by the angular sensor (R) (Fig. 3) [2]. Due to the variation in the acceleration, these deflections cause oscillations, thus increasing the uncertainty of the wire position even further [3].
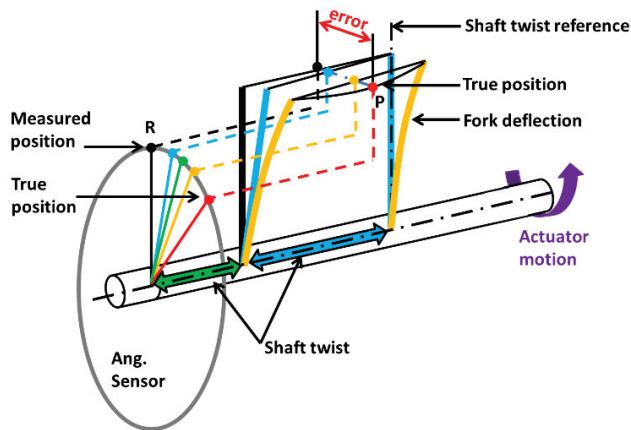
Figure 3: Typical deflections on a conceptual wire scanner instrument.

For the new CERN wire scanner the specified position accuracy is 2 μm (see Table 1 for the complete list of requirements). A new wire scanner design has therefore been developed which improves the performance of the existing device, overcoming many of its drawbacks [4]. However, acting only at the level of the design would not guarantee that the requirements would be met. A specific system for vibration measurement was therefore developed to allow the motion of the scanner to be optimizing for the final device.

Table 1: Requirements and Performances, New CERN Vacuum Wire Scanner

Peak speed	20 m/s
Fork length	156 mm
Peak angular speed	128.20 rad/s
Peak angular acceleration	6700 - 10000 rad/s^2
Tangential acceleration	95 – 159 g
Normal acceleration	260 g
Position accuracy	2 μm

VIBRATION MEASUREMENT SETUP

The vibration measurement system was developed using one of the existing proton synchrotron (PS) fast wire scanners. The fork of the scanner was equipped with high sensitivity semiconductor strain gauges, strategically located in different regions of the fork in order to record its dynamic deflection during the scan. Fig. 4 shows the location of the strain gauges. Gauges G4 and G8 mainly sensitive to the twist of the shaft; gauges G2, G3, G6 and G7 are sensitive to the deflections in X direction (transversal deflections); and gauges G1 and G5 are sensitive to the deflections in the Z direction (longitudinal deflections) (Fig. 5).
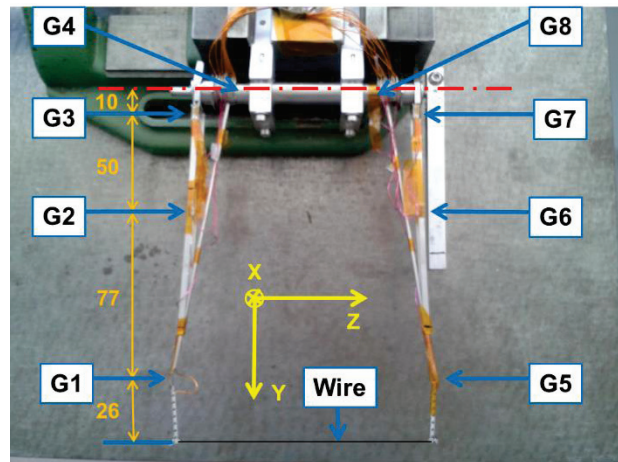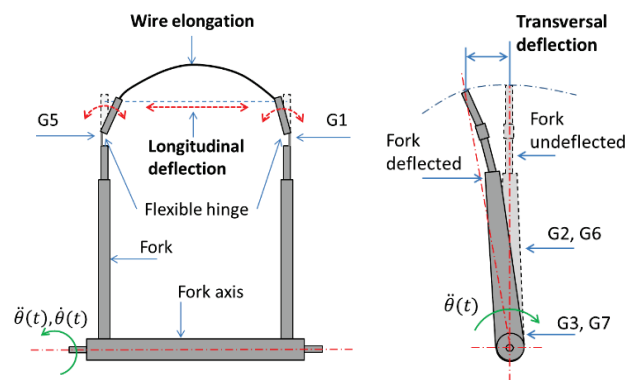
Figure 4: Gauge locations on the fork.

Figure 5: Schematics of the measurable parameters.

An electronic circuit based on a Wheatstone bridge and an amplifier was developed to measure the strain gauges and wire resistance variations. The amplified voltages produced were read-out using an oscilloscope. This acquisition system also records the angular position of the fork by means of the angular sensor of the actuator (Fig. 6).
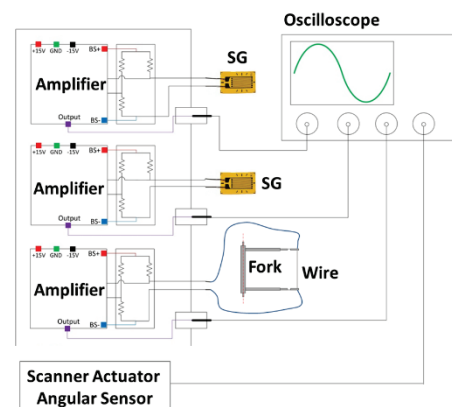

Figure 6: Schematics of the data acquisition system.

An accurate calibration is required in order to quantify the X and Z deflections of the fork arms and the wire elongation from the measurement of the voltage variations recorded by the acquisition system. The strain

gauges were calibrated using both experimental measurements and finite element analysis (FE) models. The calibration factors for the strain gauges and the wire can be seen in Table 2.

Table 2: Calibration Factors

Sensor	Factor [mm/V]	Measured parameter
G1	0.140	Tip longitudinal deflection
G2	1.329	Tip transversal deflection
G3	0.652	Tip transversal deflection
G5	-0.158	Tip longitudinal deflection
G6	1.329	Tip transversal deflection
G7	0.652	Tip transversal deflection
wire	-0.350	Wire elongation

MODELS

A modal analysis of the fork-wire system has been performed through an FE model. The first two natural vibrational modes associated with the Z-deflection of the fork are shown in Fig. 7. The first Z-mode has a frequency of 151 Hz corresponding to the symmetrical Z-deflection of the fork tips (SZ-mode). In this case, the wire maintains a constant length.
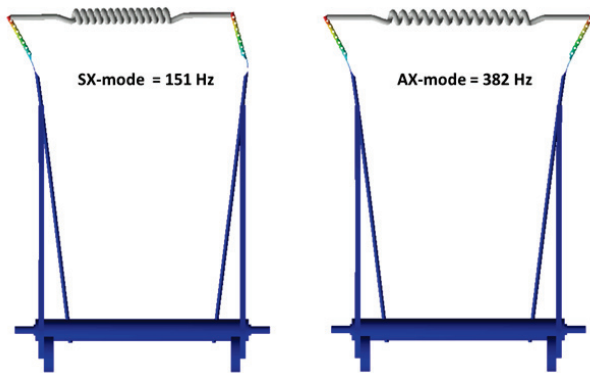

SX-mode = 151 Hz   AX-mode = 382 Hz

Figure 7: Symmetric (left) and Antisymmetric (right) Z-modes of vibration obtained through the modal analysis performed with ANSYS.

The second Z-mode is located at 382 Hz and corresponding to an asymmetrical Z-deflection of the tips (AZ-mode). This mode may lead to an instability of the wire generating parametrically-driven transverse oscillations.

RESULTS

The Fast Fourier Transform (FFT) performed on the signal of G1 and G5 (Fig. 8) clearly show the two frequencies which correspond to the first and second natural modes of the fork-wire system (~150 Hz and ~400 Hz).

Figure 9 shows the FFT performed on the wire signal. Only the second mode at ~400 Hz appears, as the first mode at ~150 Hz does not provoke wire elongation.
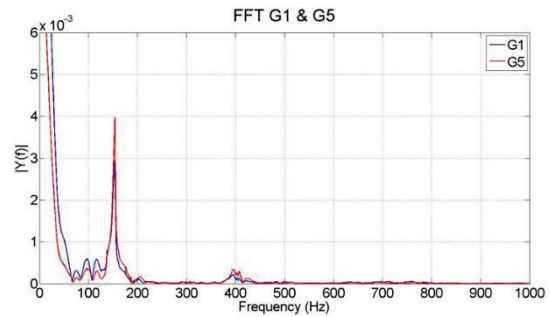

Figure 8: Frequency spectrum of the G1 and G5 signals.

The wire length (S_m) is calculated form the wire electrical tension variations and the wire elongation calibration factor. The distance between tips (L_m) is calculate from the electrical tension variation of gauges G1, G5 and their respective calibration factors. The values of L_m and S_m show the same trend (Fig. 10).
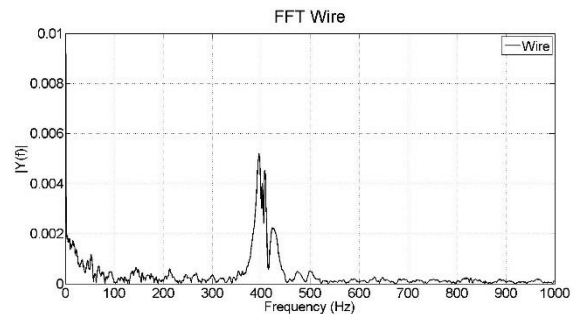

Figure 9: Frequency spectrum of the wire elongation.

The transversal gauges measurement with their respective calibration factors allows the quantification of the fork transversal displacement which is on the range 0.5 mm (Fig. 11). Wire transversal displacement estimated from the values of S_m and L_m are in the range of 10 um.
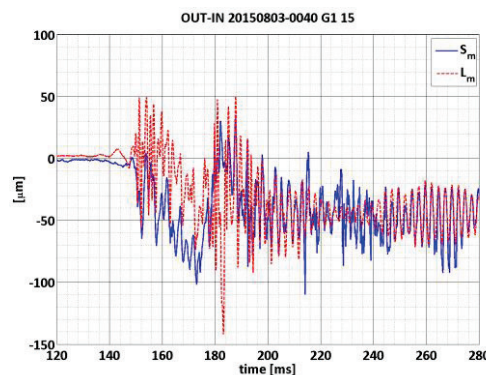

Figure 10: Comparison between wire elongation and tips separation. Motion occurs from ~ 135 to 185 ms.

The conceptual design of the PS fork, because of the flexible hinges feature, is prone to vibrate at relatively low frequencies with important amplitudes (~150 Hz and 0.6 mm for the SZ-mode, ~400 Hz and 0.1 mm for the AZ-mode), although this vibrations are in the wire longitudinal direction, which in essence would not affect

the measurement accuracy, parametric vibration can appear depending on the wire initial tension. This parametric vibrations, under the inertial forces, results in significant transversal wire oscillation, which would greatly affect the accuracy of the measurement. This transversal oscillation could even cause wire to break.
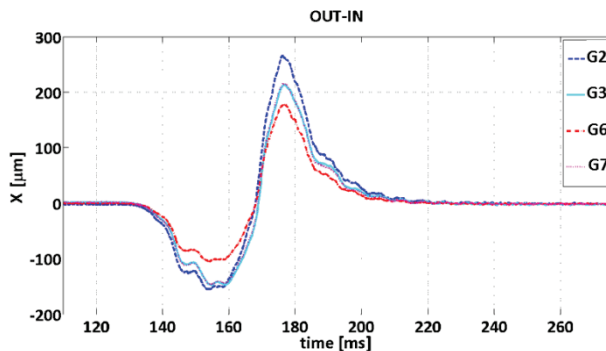

Figure 11: Tip transversal displacement results from gauges G2, G3, G6 and G7. Motion occurs from ~ 135 to 185 ms**.**

The oscillations of the kinematic chain, which link the actuator and the fork shaft, induce traversal oscillations on the fork tips which directly affect the measurement accuracy. This oscillations and the play of this kinematic chain disrupt the actuator control system performances and consequently the accuracy of measurement.

CONCLUSION

A vibration measurement system has been developed and tested for use with CERN wire scanners. The results show that this system allows the vibrational behaviour of the wire and fork to be clearly visualised.

A hybrid calibration procedure using experimental measurements and FE calculations has been developed in order to overcome the difficulty of calibration under a dynamic and nonlinear acceleration field.

It has also been proven that measurements based on the piezo-resistive effect of the wire provide consistent information allowing the vibrational behaviour of such a system to be determined. Such system can easily be implemented in existing wire scanner devices as only an additional external signal measurement system is required. This implementation would provide valuable information about the device vibrational behaviour. This information can be combined with the profile measurement in order to apply suitable experimental correction factors to the measurement. Additionally monitoring the wire vibrations along the scanner live time, allows to evaluate the aging of the system (especially wire, fork and bearings) and prevent unexpected failures. Vibration monitoring also would serve as an indicator to modify initial motion pattern parameters according to the wear or aging of the system and therefore minimize the wire position uncertainty. Also any unexpected change on the wire configuration (like a tension variation) would be easy detected and corrective actions could be applied.

For the first time the piezo resistive effect is used for wire vibrations measurements during the scan.

As a general conclusion, this work suggests that the use of a rigid fork is preferable to a flexible one, to avoid the risk of generating high wire amplitudes associated with a possible parametric resonance. This should be taken into account when designing the new scanner.

Future work will be focused on the implementation of the vibrational measurement system in the new wire scanner design. More accurate models will also be developed to verify the hypothesis of parametric excitation in the wire oscillations.

RFERENCES

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