EIGENFREQUENCY WIRE ALIGNMENT SYSTEM FOR MAGNET FIDUCIALIZATION

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Abstract

The magnets of the SPring-8 storage ring have critical alignment tolerances and the positions of the fiducial points of magnet relating to magnetic centre need to be precisely calibrated. Recently, in renewing the magnetic field measurement device, an eigenfrequency wire alignment system is developed to replace old laser CCD-camera system. The advantage of new system is it can continuously monitor the position change of magnet during magnetic field measurement. The sag, in consequence the curve of wire is obtained by measuring the eigenfrequencies of wire. It is confirmed that the system has a resolution of 0.03μm for wire sag. And, could be used up to 50 meters range with an expected resolution of 10μm.

INTRODUCTION

To renew existing laser CCD system we have used in the Magnetic Field Measurement Device (MFMD), a wire alignment system is developed, considering it can continuously monitor the positional change of magnet during magnetic field measurement.

Alignment using wire has a long history. It was utilized in distance and offset measurement, or smoothing the magnets in the ring. Wire was tested for material, devices of reading wire position etc. [1][2]. Because of the sag, wire alignment was restricted to horizontal plane. The combination of the HLS and WPS made it possible to make absolute measurement both in horizontal and vertical planes [3]. In some particular application, electric conductive wire is used to find magnetic centre [4][5][6].

We have contrived a new method for wire alignment which determines wire sag by measuring the eigenfrequencies of wire. It is tested a simple and accurate method for absolute wire alignment.

ABOUT EIGENFREQUENCY WIRE ALIGNMENT SYSTEM

An absolute system are demanded for determination of the curve of wire, good linearity of sensor, small sensor offset and small wire straightness error.

About the cure of wire

The curve of wire is a catenary, it could be approximated with a parabola. The difference of the two depends on the amount of wire sag. Table 1 shows the estimation for a 100 meters wire. Difference is small even the sag in centimetres order. And, the sag of the carbon wire is only about 3cm, so the difference of two curves is negligible.

Table 1: Difference of catenary and parabola in height

Sag for 100m wire	Difference in height
1000 mm	0.13 mm
100 mm	< 1 μm
27 mm *	negligible

*Kevlar carbon wire
Density (kg/m) 3.22E-4
Tension (kg) 15

For a parabola one needs only to know the sag in the middle to give the curve expressed as following.

$$y = \frac{4S}{L^2}x^2 - S \tag{1}$$

where, S is maximum sag; L is the length of wire.

About the eigenfrequency of wire

The equation to calculate maximum sag of a wire is known as

$$S = \frac{\rho g}{8T}L^2 \tag{2}$$

where, ρ is density (kg/m) of wire; T is tension (N); L is length (m), g is gravity acceleration.

And, for the wire with two fixed ends, eigenfrequencies are indicated as

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{\rho}} \tag{3}$$

where, n is n-order mode.

Substituting eq. 3 for eq. 2, one gets following equation.

$$S = \frac{n^2 g}{32 f_n^2}\ [\mathrm{m}] \tag{4}$$

That is, wire sag are determined by eigenfrequencies only. And, it can be calculated using any order of vibration mode.

About eigenfrequency wire alignment system

The Eigenfrequency Wire Alignment System (eWAS) is developed for absolute straight line measurement. For the MFMD, it is composed of sensor assemblies, carbon wire and pulley, and wire frequency measurement devices. Figure 1 is the schematic figure of the system.

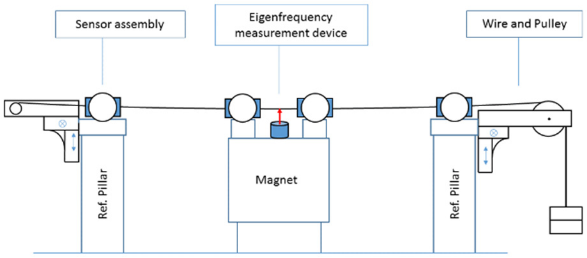

Figure 1: Schematic figure of the eigenfrequency wire alignment system

Features of the eWAS

Features of this system are firstly, wire sag is obtained by measuring the eigenfrequency of wire. Secondly, wire position sensor (FOGALE nanotech WPS) are embedded in well machined ceramic balls to translate electrical centres to physical centres.

To measure the eigenfrequencies, the wire is lifted up perpendicularly with hand at the middle, and then released to excite the wire free vibrating. The oscillation of wire is measured with a laser displacement sensor and an oscilloscope for 10 seconds, with frequency resolution of 0.05 Hz. Then, frequency analysis is performed by FFT. The peak in fig. 2 indicates the fundamental frequency of the wire.

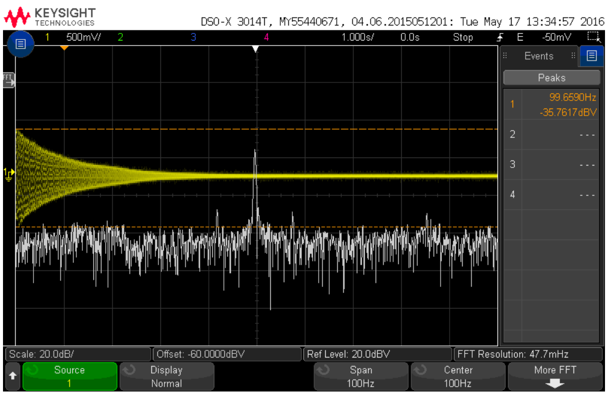

Figure 2: The oscillation of wire, measured with a laser displacement sensor, and the peak of FFT analysis.

Figure 3: The sensor assemblies

The sensor assembly is shown in fig. 3. And, its parameters are listed in table 2.

Table 2: Parameters of the sensor assembly

Sensor (FOGALE)	
Resolution:	0.2 μm
Linearity:	±2 μm @±1mm
Meas. Range:	±5 mm
Ball (KYOCERA)	
Material:	ceramic
Dimeter:	76.2 mm
Sphericity:	7 μm
Wire	
Material:	Kevlar carbon
Dimeter:	0.5 mm
Density (measured)	3.22e-4 kg/m

The measurement of WPS sensor is usually sensitive to tilts. While, it is confirmed that if the tilts of sensor, or the wire offset from ball centre is small, measurement repeatability will be good enough. To control sensor's tilts, a 2mm/m level is used to adjust the rolling and pitching, and two slits are used to indicate the yawing (fig. 4). Measurement repeatability is tested 0.5 μm (p-p) both in x and y directions.

(TOP VIEW)

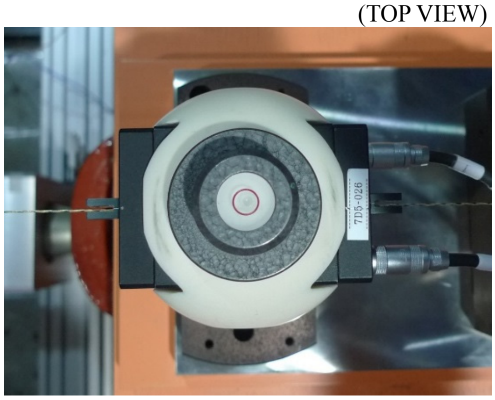

Figure 4: Sensor's tilts are adjusted with a level and two slits.

VERIFICATION OF THE RESOLUTION OF WIRE SAG

Resolution of wire sag

According to eq. 4, the resolution of wire sag can be deduced from the resolution of frequency measurement as following, using the fundamental frequency.

$$\Delta S = \frac{g}{16 f_1^3} \Delta f_1 \qquad (5)$$

where, f_1: fundamental frequency of wire, around 100 Hz in our case. The frequency measurement device we are using has a frequency resolution of 0.05 Hz. Consequently, the resolution of wire sag is estimated ~ 0.03 μm.

The verification of such small resolution is not easy. In the experiments, wire tension was increased by adding nuts one by one to the weight (6kg), each nut weights about 15 grams, corresponding to 0.12Hz frequency or 0.07μm sag increment. The results are shown in fig. 5. Measured frequency agrees well with the calculation. Calculated sags from the frequency measurements also agree with the estimation, having a 0.07μm increment each step and ±0.02 μm measurement uncertainty. And, Changes of the sag are confirmed by two WPS sensors. Although the resolution of the WPS (~0.2 μm) is not good enough to track the change for each step, the averages of 50 times gives the trend and total amount of sag changes.

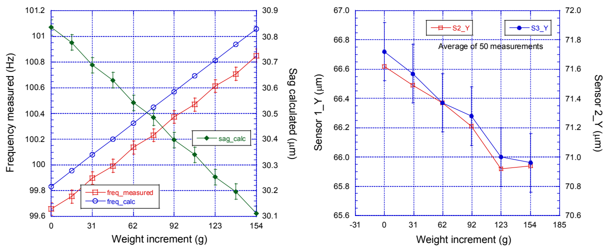

Figure 5: Left: measured frequency against tension increment agrees well with the calculation; Right: changes of sag are confirmed by two WPS sensors.

Resolution of 30-meter wire

To investigate the possibility of using eWAS method in long distance, a 33 meters wire was setup in the tunnel of the SPring-8 storage ring.

According to eq. 5, the resolution of sag become low as wire length increases, by a factor of frequency cube. It is estimated that it will drop to 50μm for a 33-m wire when using fundamental frequency, which is 8.4Hz for a tensile strength of 10 kg.

To the problem of the low resolution of long wire, the solution is utilizing high order mode eigenfrequencies. From eq. 4, the resolution using high order mode can be deduced as

$$\Delta S = \frac{g}{16nf_1^3}\Delta f_n \qquad (6)$$

Comparing to eq. 5, it is understood that the resolution using n-order mode is n-times high than fundamental mode.

So, it is better to measure the eigenfrequencies as high order as possible. Figure 6 shows the oscillation signal and the FFT peaks of a 33-m Kevlar carbon wire. It is seen that the eigenfrequencies up to 10 orders have been excited.

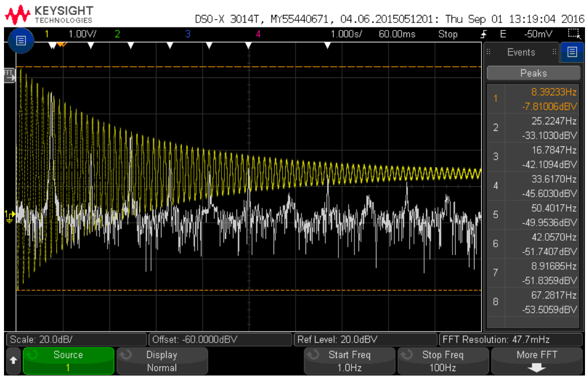

Figure 6: Excited eigenfrequencies up to 10-order modes for a 33-m wire.

To test the resolution of a 33-m wire, a digital force gauge stretches the wire to 10 kg, and increases tension by 10 grams each step, which corresponding to 4 μm sag changes by calculation. Frequencies of each mode was measured. It is confirmed that the frequencies of high orders are more sensitive to the tension than low order. The resolution of sag using 8-order mode is 6μm, in comparison to 50 μm when using fundamental mode (fig. 7). The reason that it was not 4μm as prospected is because the frequency resolution was still insufficient.

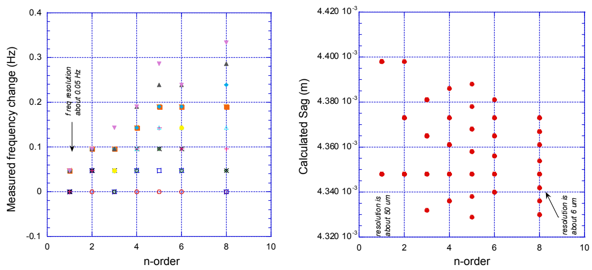

Figure 7: Left: frequencies of high orders are more sensitive to the tension than low order. Right: resolution of sag using 8-order mode is 6 μm, in comparison to 50 μm when using fundamental mode.

Results of 30-meter wire and other expectations

It is confirmed that for a 33 meters wire the calculated sag from measured frequency has a resolution of 6 μm and an uncertainty of ±4μm (p-p) when utilizing 8-order eigenfrequency. The results agree well with calculation. Thereof, it could give the expectations of the resolution for other distances as listed in table 3.

Table 3: Resolution expectation

Distance	n-order	Frequency	Sag	Resolution
(m)		(Hz)	(mm)	(mm)
2	1	168.9	0.011	0.01
5	3	202.7	0.067	0.03
10	5	168.9	0.268	0.2
30	8	90.1	2.415	3
50	10	67.6	6.708	10

* Wire: Density (kg/m) 3.22E-4
Tension (kg) 15

eWAS FOR MAGNET FIDUCIALIZATION

The eWAS used in the MFMD for magnet fiducialization has four sensor assemblies, two are set on reference pillars and the others on magnet (fig. 8). The frequency measurement devices are using KEYENCE IL laser displacement sensor and KEYSIGHT DSOX3000 oscilloscope. The length and fundamental frequency of the wire are 2.2 m and ~100 Hz respectively.

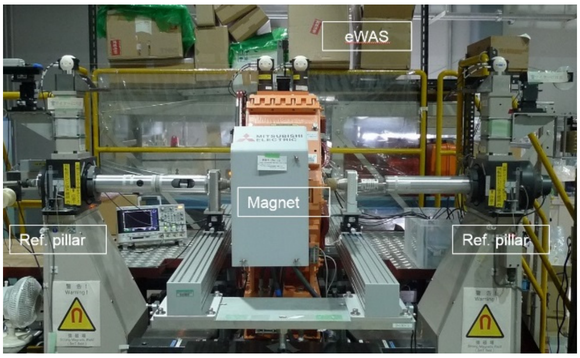

Figure 8: Wire alignment system for magnet fiducialization on the magnetic field measurement device.

Measurement stability

Test results for the measurement stability on a 1.5-m table at the magnetic field measurement hall show that the noise level of measurement is ~0.2 μm. Long-term drift is about 1 μm/°C, even though room temperature varied 0.5-1 °C per day (fig. 9). Reason of the drift is considered because of the different thermal expansion between the supports of measuring points.

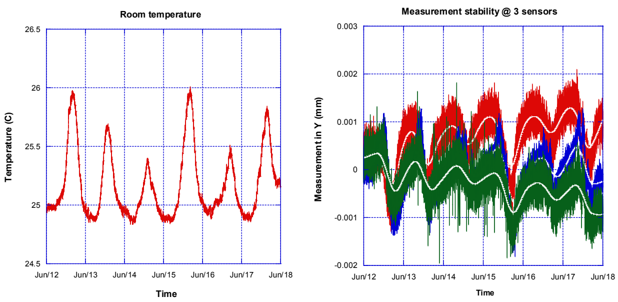

Figure 9: Measurement stability of the wire system for six days.

Examples of eWAS measurement

Owing to the high precision of the wire system, we found some facts we didn't know before.

For examples, as shown in fig. 10, there is a relative movement between the magnet and reference pillars, about 5 μm (p-p) a day. It is considered coming from their different expansions because of different thermal capacities. And, during the magnetic field measurement, the fiducial points drifted about 2 μm. It is because of the thermal extension of one pillar that has a coil driving motor inside.

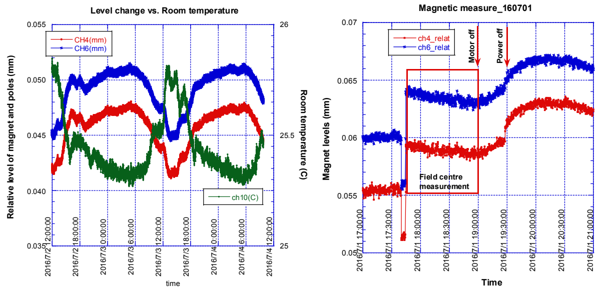

Figure 10: Left: the magnet is observed a daily movement relative to reference pillars. Right: the drift of fiducial points because of the thermal extension of one pillar.

Problem remained

The straightness of carbon wire still remains a problem. It is found that exchanging wires or shifting wire position along longitudinal direction will lead a difference of about 10 microns in measurement. Other experiment [7] convinces that the straightness of the Kevlar carbon wire is not good comparing to Cu-Be metal wire.

CONCLUSION

The eigenfrequency wire alignment system is developed for absolute measurement. Features of this system are firstly, the wire sag is calculated from the eigenfrequencies of wire. Secondly, WPS sensors are embedded into well machined ceramic balls, to translate electrical centres to physical centres. The resolution of wire sag is tested better than 0.1μm in several meters range. And, it is 6 μm for 33 meters wire utilizing 8-order eigenfrequency. This system could be used in 50 meters with an expected resolution of 10 μm.

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