Eigenfrequency Wire Alignment System for Magnet Fiducialization

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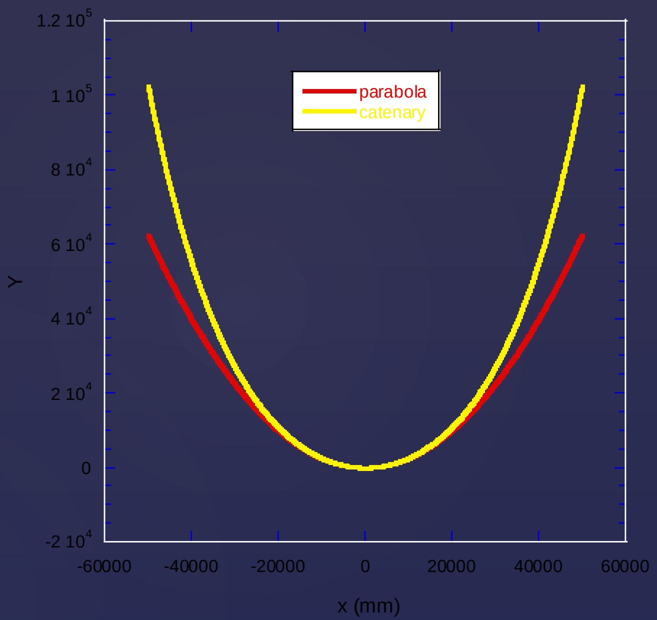
About Wire Alignment System

Problems for absolute wire measurement:
- α. determining the curve of the wire
- β. sensor linearity
- χ. sensor offset
- δ. wire straightness error

$$\text{Sag max} = \frac{\rho g}{8T} L^2$$

Curve of the wire:

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



Sag in 100 m	Diff. of parabola and catenary
1000 mm	0.13 mm
100 mm	< 1 µm
27mm *	Negligible

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

About Wire Alignment System

1. Equation of calculating maximum sag of a parabola :

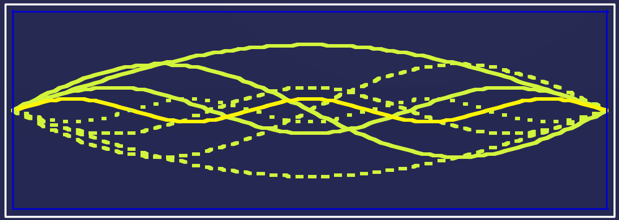
$$S = \frac{\rho g}{8T} L^2$$

ρ : density (kg/m);
T : tension (N);
L : length (m),
g : gravity acceleration.

2. eigenfrequencies of standing wave for the wire with two fixed ends :

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

n : n-order of vibration mode



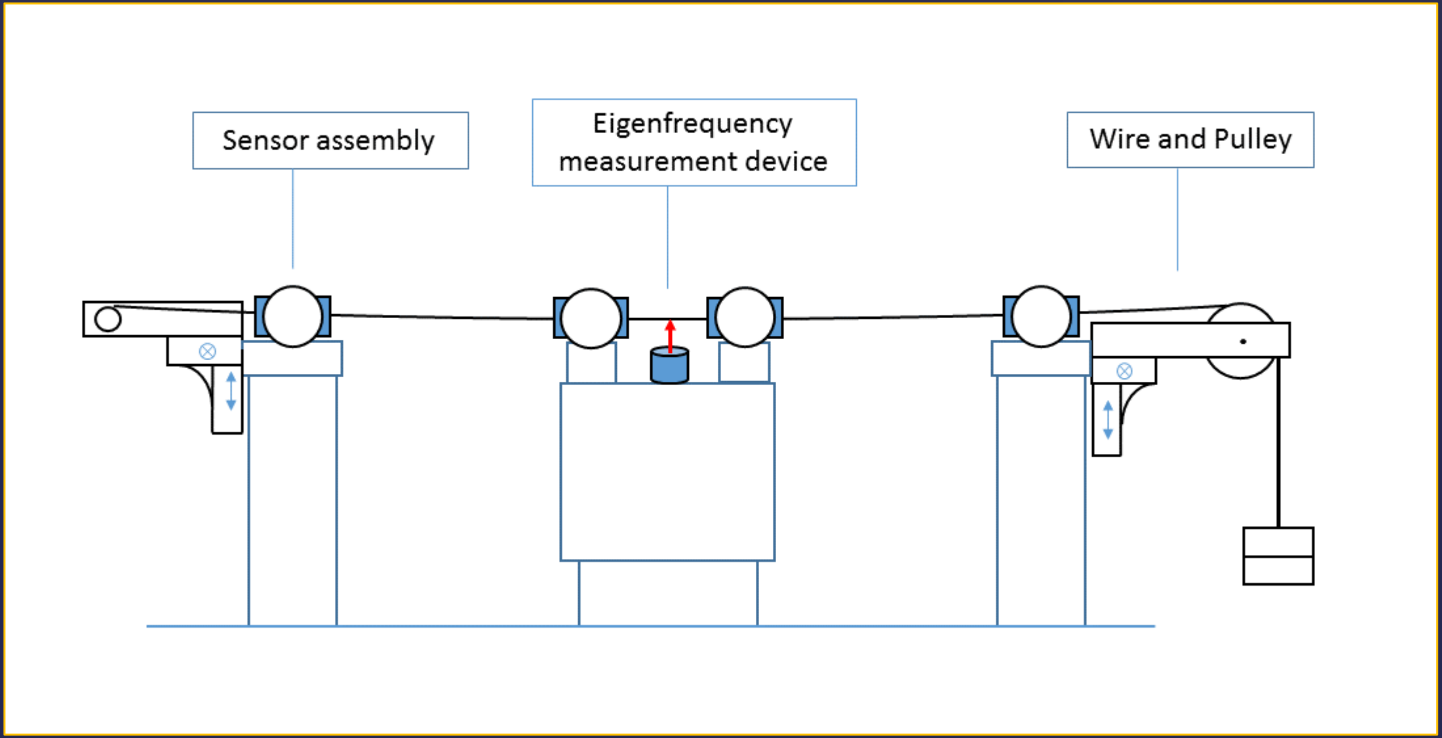
Vibration mode of fixed wire

$$S = \frac{n^2 g}{32 f_n^2}$$

α. Sag depends on eigenfrequency only;
β. Any order of vibration mode gives same value;
χ. Usually fundamental frequency is used.

Eigenfreqency Wire Alignment System (eWAS)

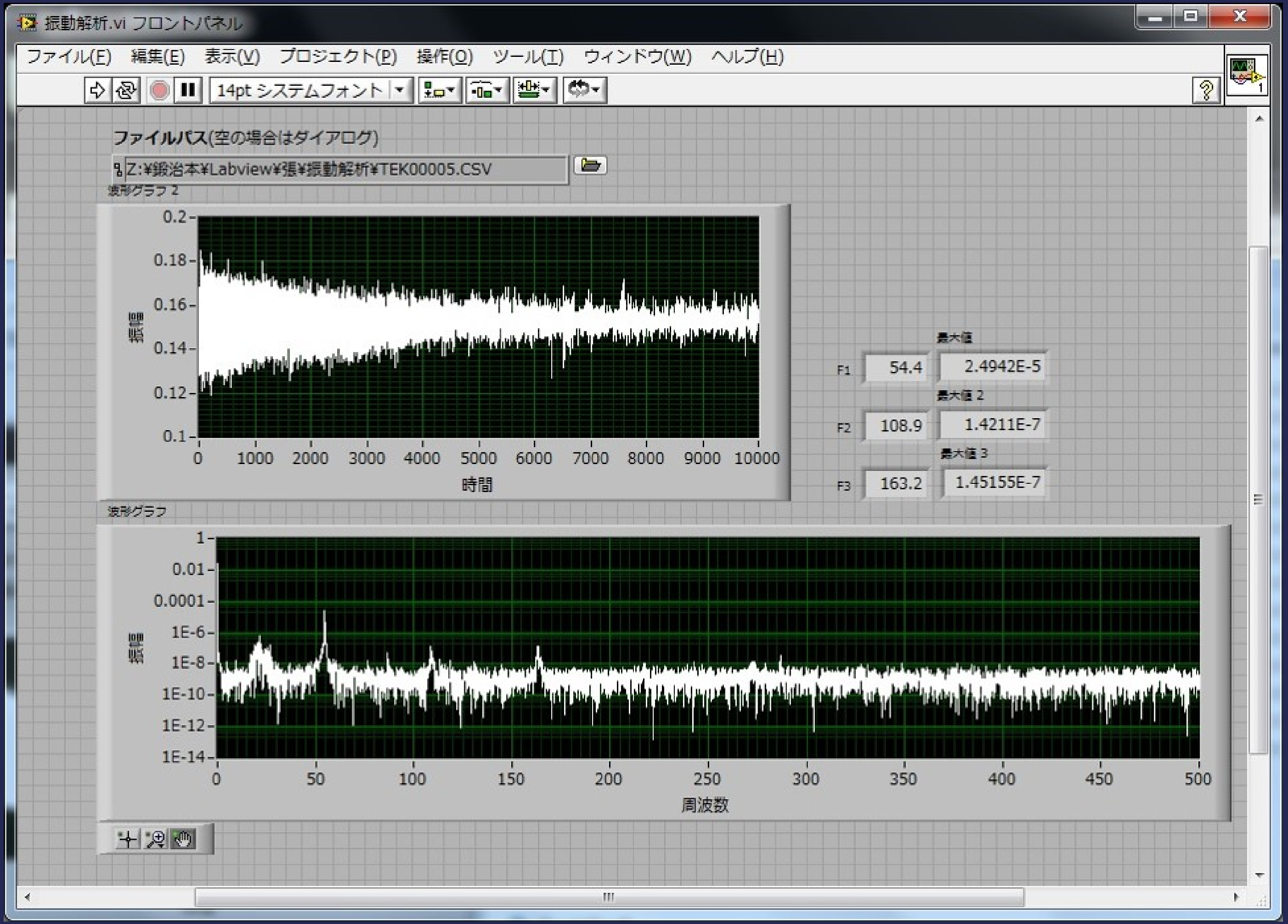
eWAS is developed for absolute measurement. For magnet fiducialization it is composed of four sensor (WPS) assemblies, carbon wire, and wire eigenfrequency measurement devices.



Schematic figure of the eWAS for magnet fiducialization

Features of the eWAS

The sag of wire is calculated by measuring the eigenfrequency of wire.

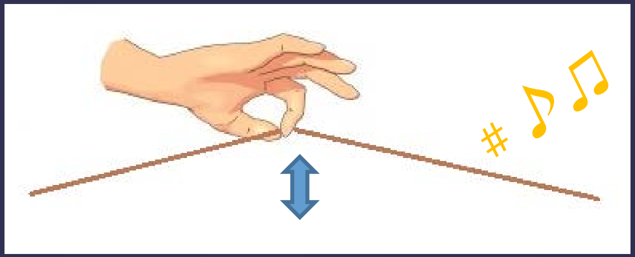


LabVIEW FFT analysis of wire vibration

Test wire:
Mat: Cu-Be
Dia: ϕ0.2mm
Len: ~2.2m
Ten: 1.5kg

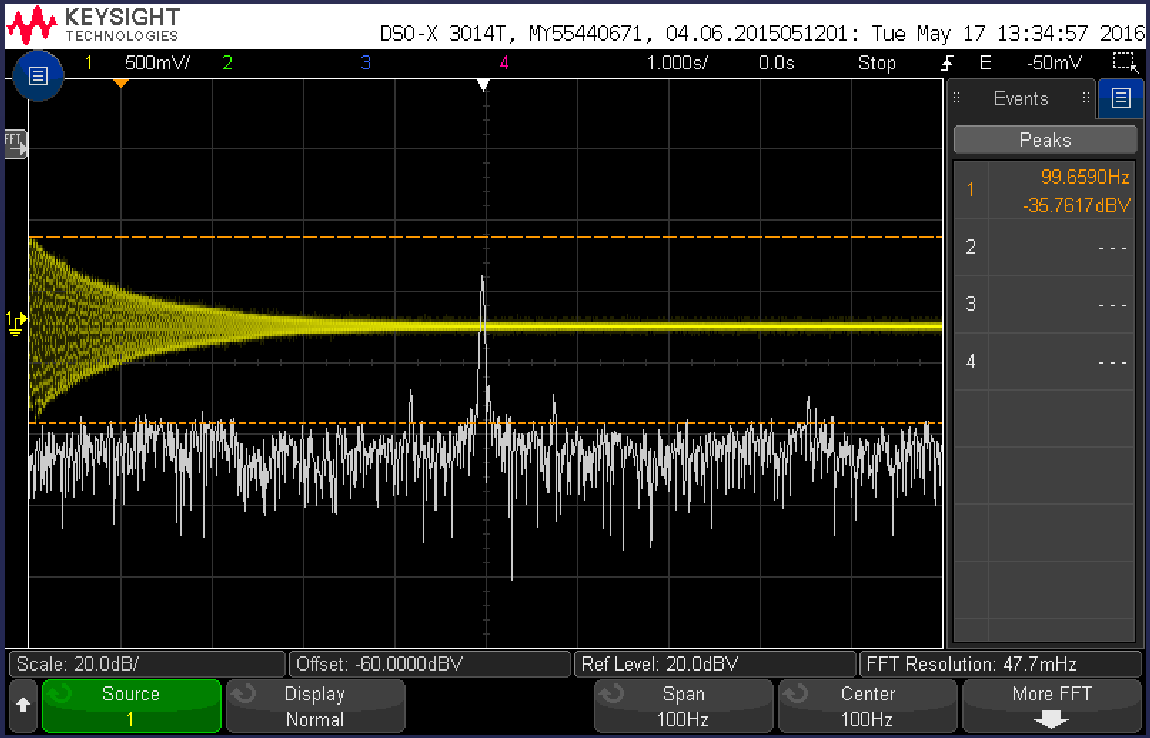
Features of the eWAS

1. Hold up wire then release it, to make wire free oscillation.



2. The oscillation is measured with a laser displacement sensor and a oscilloscope.

3. FFT gives the peaks of vibrations and eigen-frequencies are used to calculate wire sag.



Features of the eWAS

The sensors are embedded into well machined ceramic balls, to translate electrical centres to physical centres.

Photo of the sensor assembly

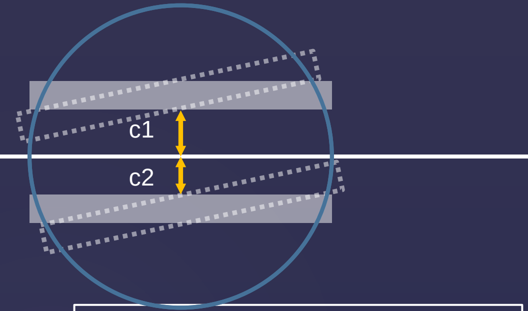
Sensor Assembly :
- Sensor (FOGALE) :
  - Resolution: 0.2 μm
  - Linearity: ±2 μm @±1mm
  - Mea. Range: ±5 mm
- Wire :
  - Material: Kevlar carbon
  - Dimeter: 0.5 mm
  - Density: 3.22e-4 kg/m (measured)
- Ball (KYOCERA) :
  - Material: ceramic
  - Dimeter: 76.2 mm
  - Sphericity : ±7 μm

Features of the eWAS

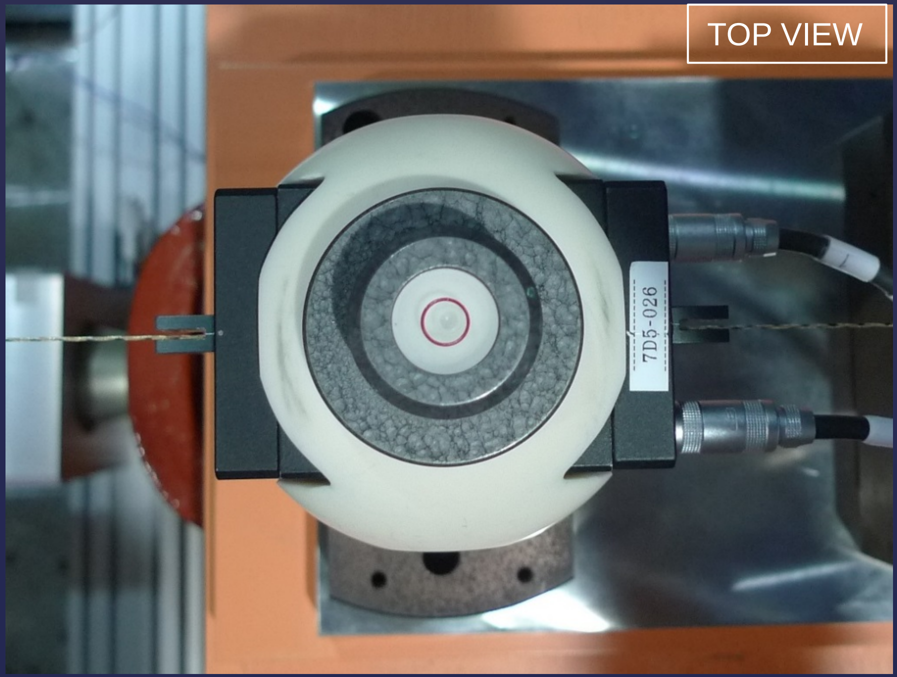
Could wire position sensor be used in this way?
The WPS measures

$$\Delta C = C_1 - C_2$$

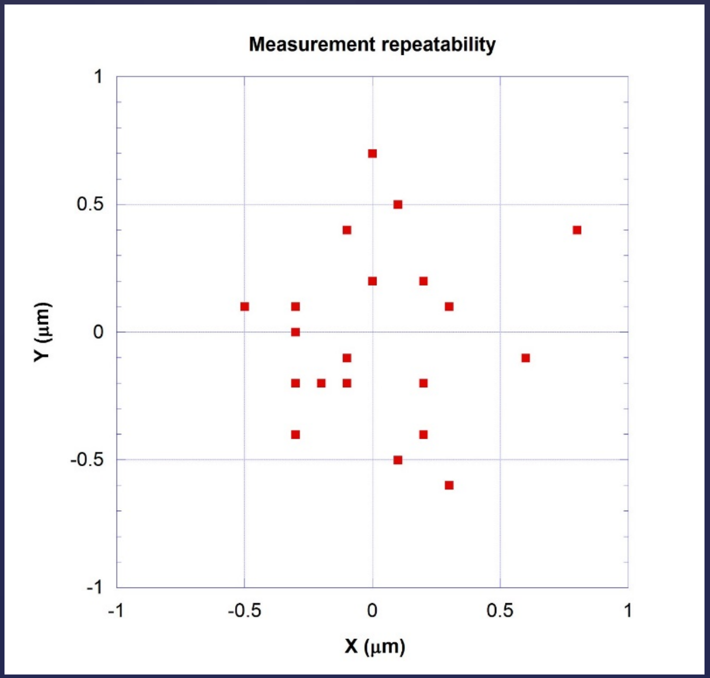
The error of ΔC, proportional to the product of wire offset and rotation angle of plates, is small.



Schematic graph of plates



Adjustment of sensor tilts with the level and slits



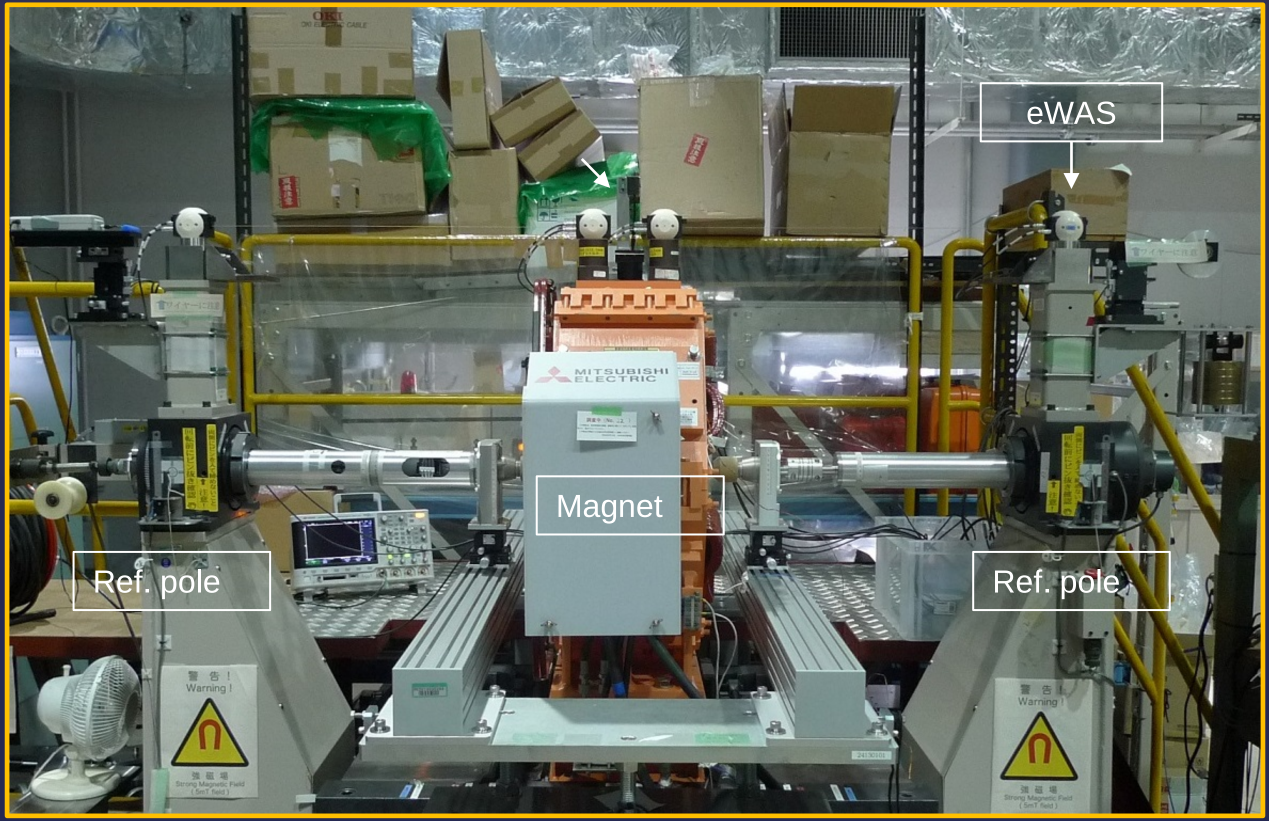
Reproducibility of the sensor center

eWAS for Magnetic field measurement device

Wire system for magnet field measurement device :

α. Distance : 2.2 m

β. Wire fundamental frequency : 99.8 Hz



Wire alignment system for magnet fiducialization of magnet field measurement device.

Verification of the resolution for sag measurement

By the equation

$$S = \frac{g}{32f_1^2}$$

f_1 : fundamental frequency

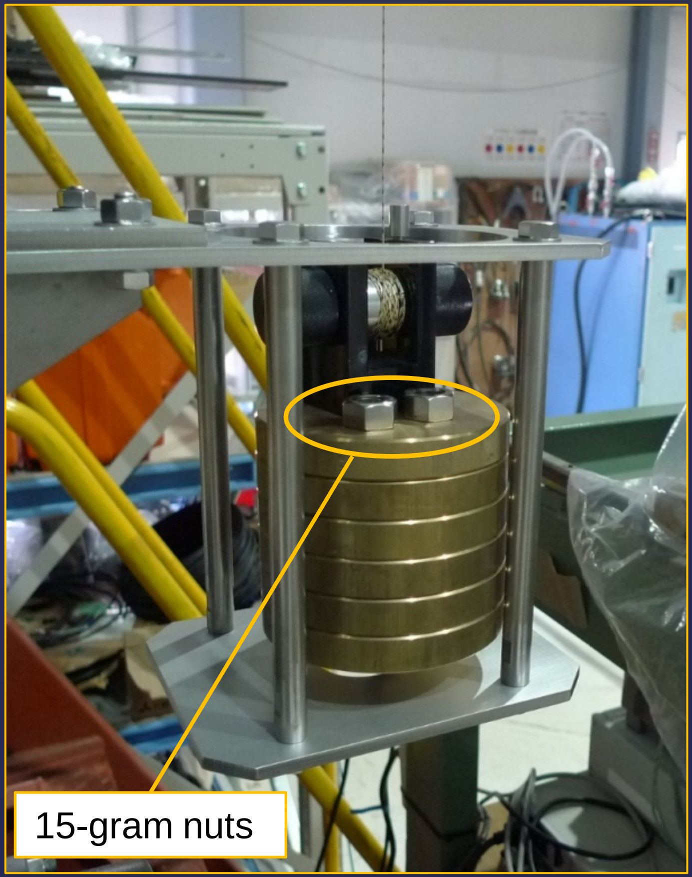
the resolution of sag is:

$$\Delta S = \frac{g}{16f_1^3}\Delta f_1$$

It is ~0.03 μm for our system.

(@ f_1 = 100Hz, Δf_1 = 50mHz)

To verify the resolution, the tension was added with nuts one by one, each weighted about 15 grams , corresponding to 0.12Hz frequency or 0.07μm sag increment.

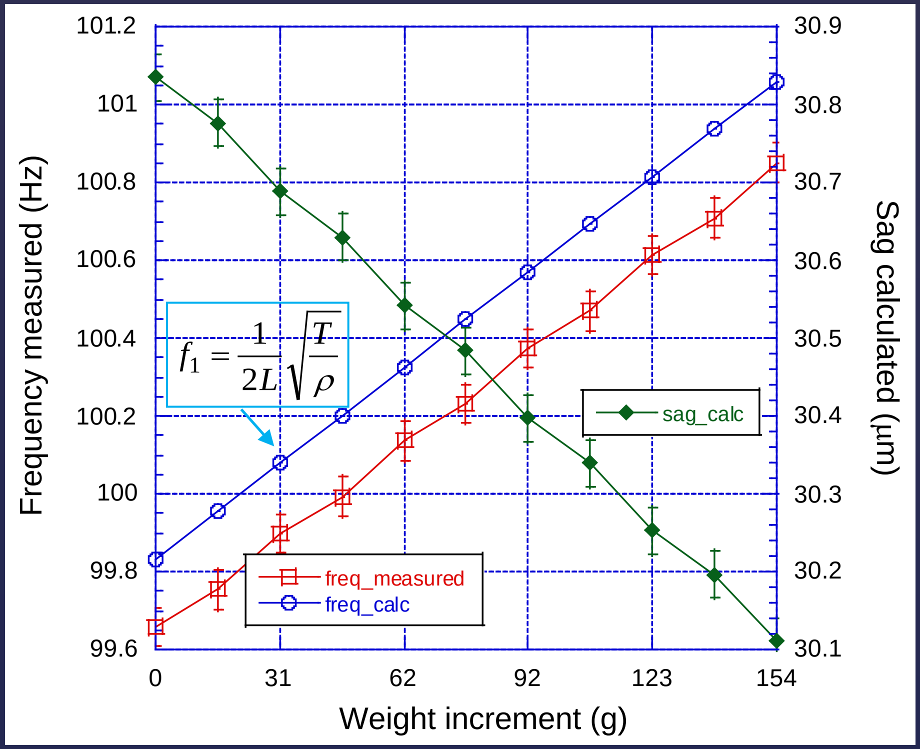


Experiment of the frequency and sag resolution

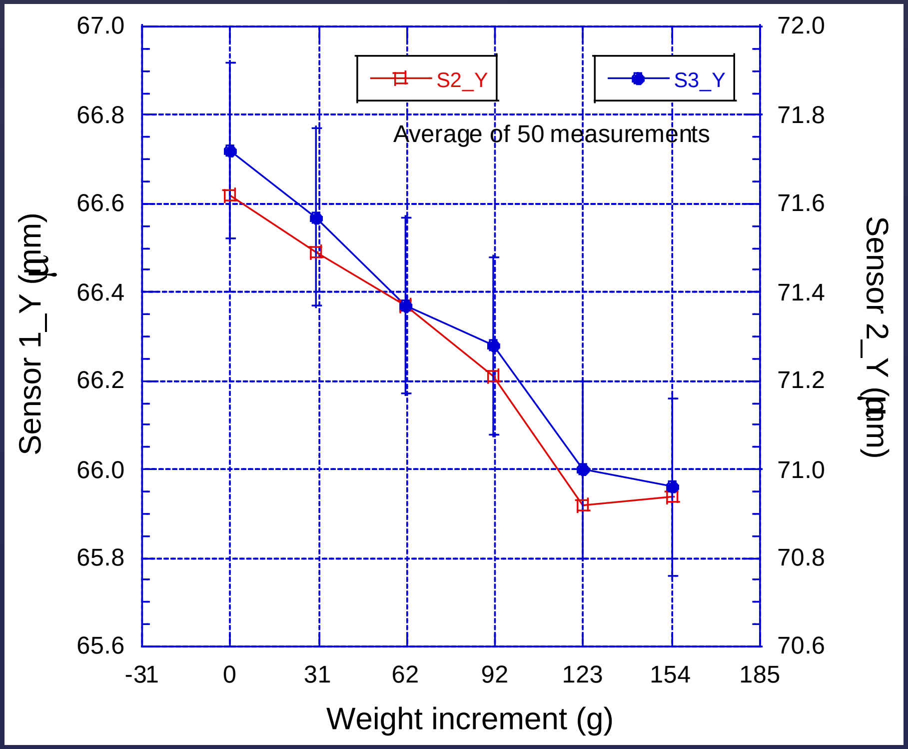
Experiment results of sag measurement

α. Measured frequency and calculated sag agree with calculation. And, resolution of sag is tested better than 0.1μm.

β. Change of the sag is confirmed by the measurement of WPS.



Experiment results of frequency measurement and sag resolution.



Changes of wire sag measured with the WPS

Resolution for 30 meters wire

Sag resolution calculated using fundamental frequency:

$$\Delta S = \frac{g}{16 f_1^3} \Delta f_1$$

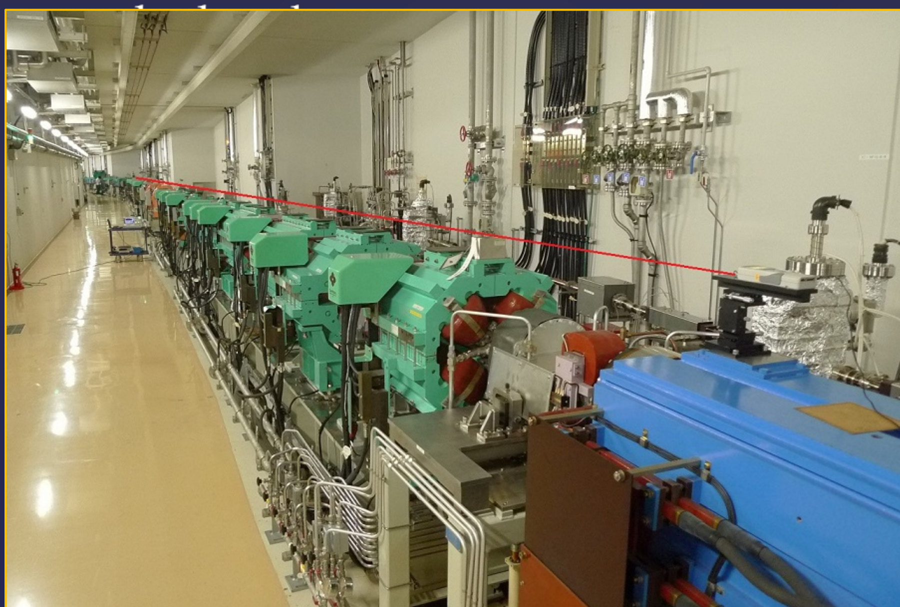
It is low for a 33-m wire.

(~50µm @ f_1 = 8.4Hz, Δf_1 = 50mHz)

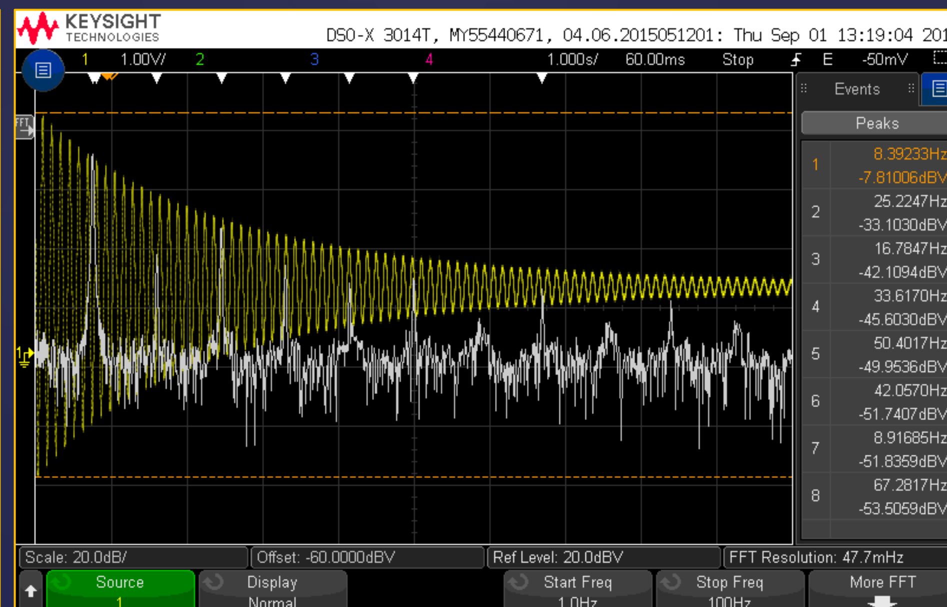
Resolution using high order mode frequency:

$$\Delta S = \frac{g}{16 n f_1^3} \Delta f_n$$

it is n times high than 1-order mode.



Experiment for 33 meters measurement

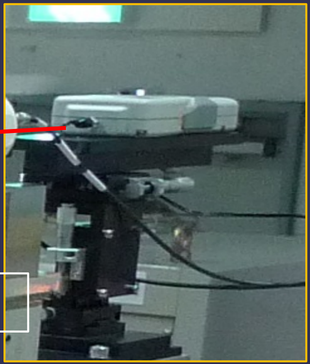


Excited eigenfrequencies up to 10-order modes for a 33-m wire *.

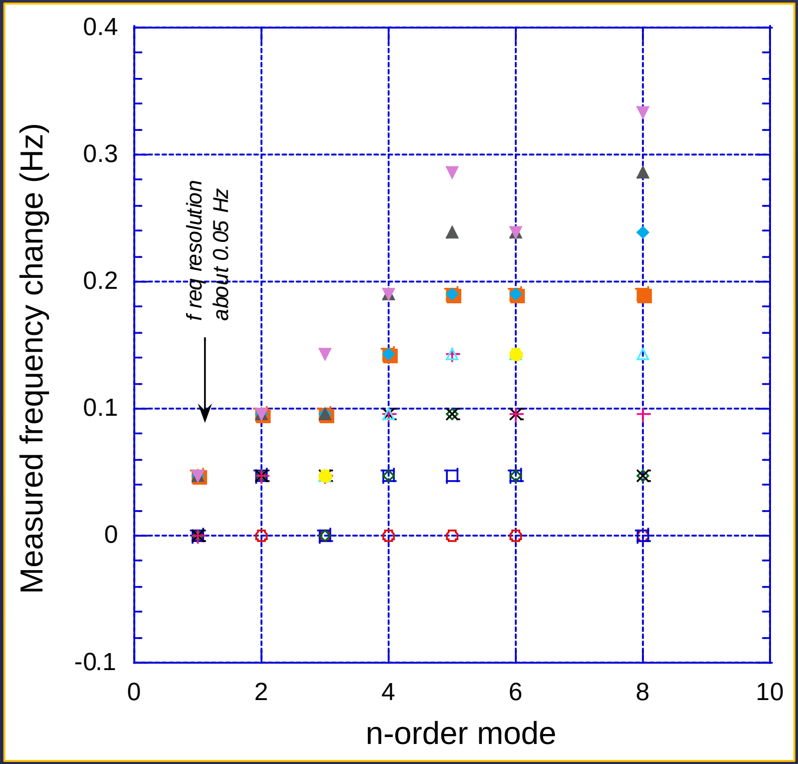
* Kevlar carbon wire, tension 10 kg

Resolution for 30 meters wire

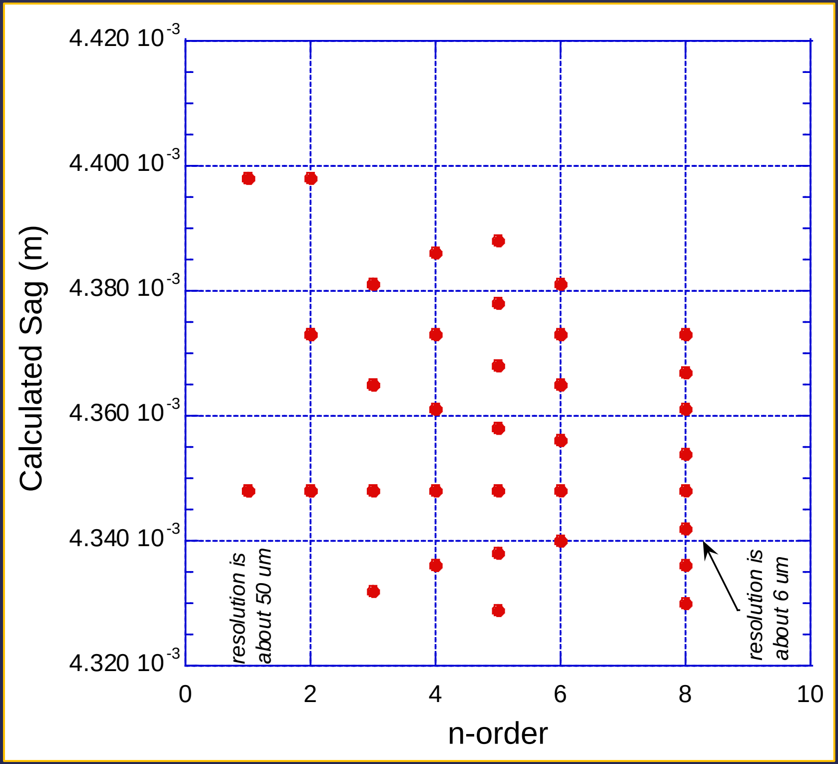
A digital force gauge stretches the wire, and increases tension by 10 grams each step, which corresponding to 4μm increment of wire sag.



Force gauge



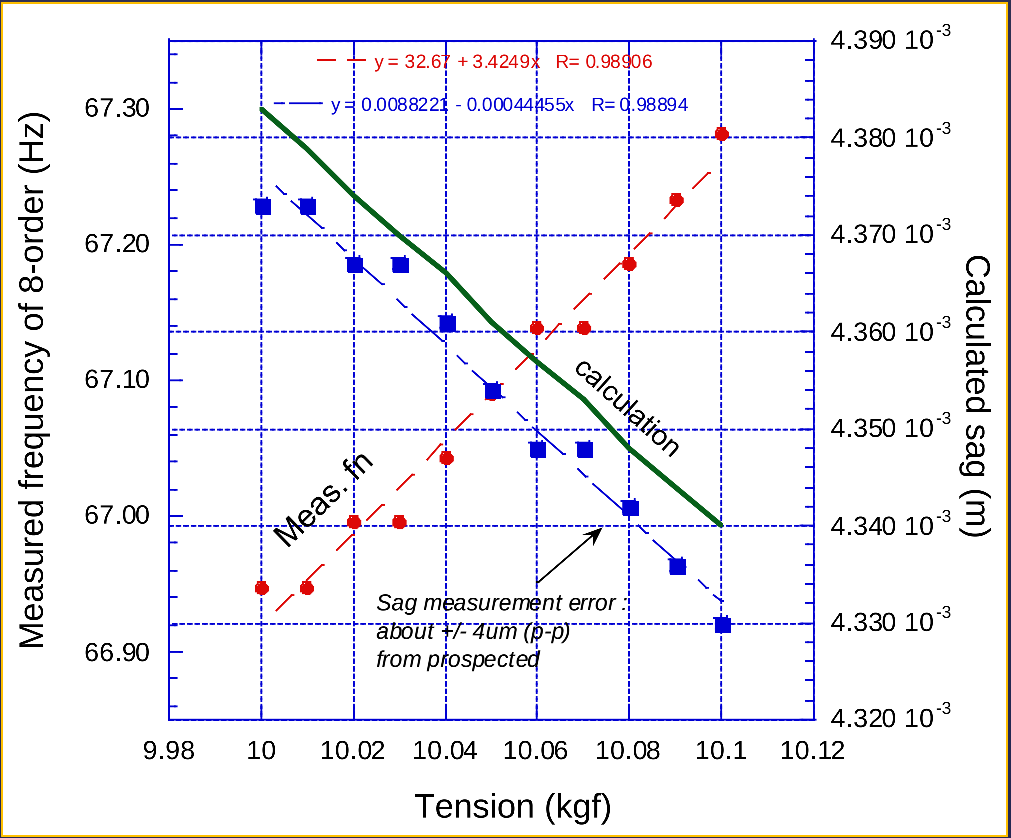
Measured frequency changes for each vibration mode



Calculated sags from frequencies for each mode

Result of 30 meters wire

It is estimated that when utilizing 8-order frequency, resolution of the sag is 6 μm, and measurement error is ~ 4μm. Measurement results well agree with prospected.



Calculation and measurement results for 33 meters wire

Expectation of resolution * :

Distance	n-order	Frequency	Sag	Resolution
(m)		(Hz)	(mm)	(μm)
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

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

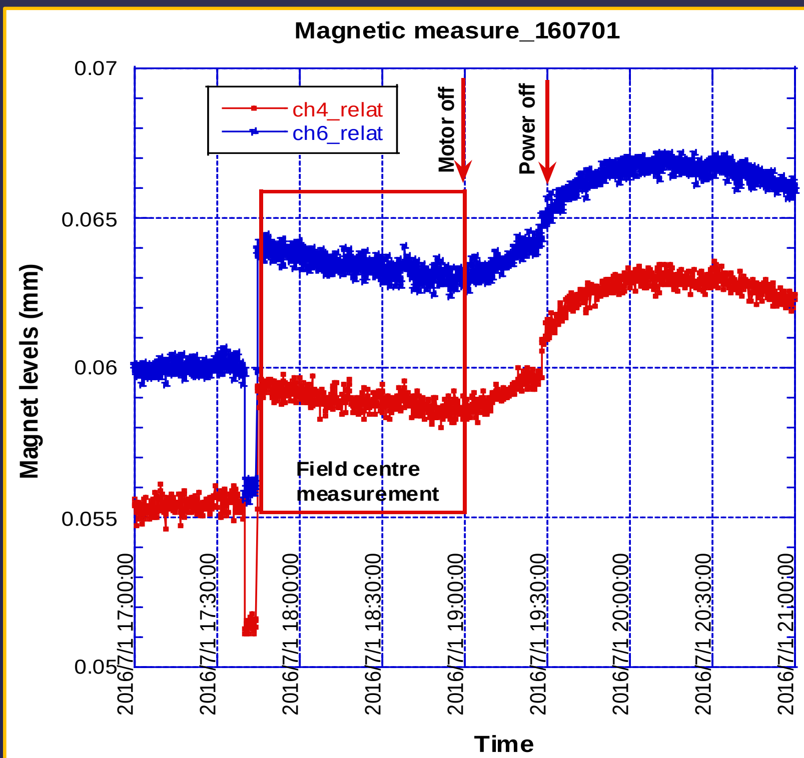
eWAS for Magnetic field measurement device

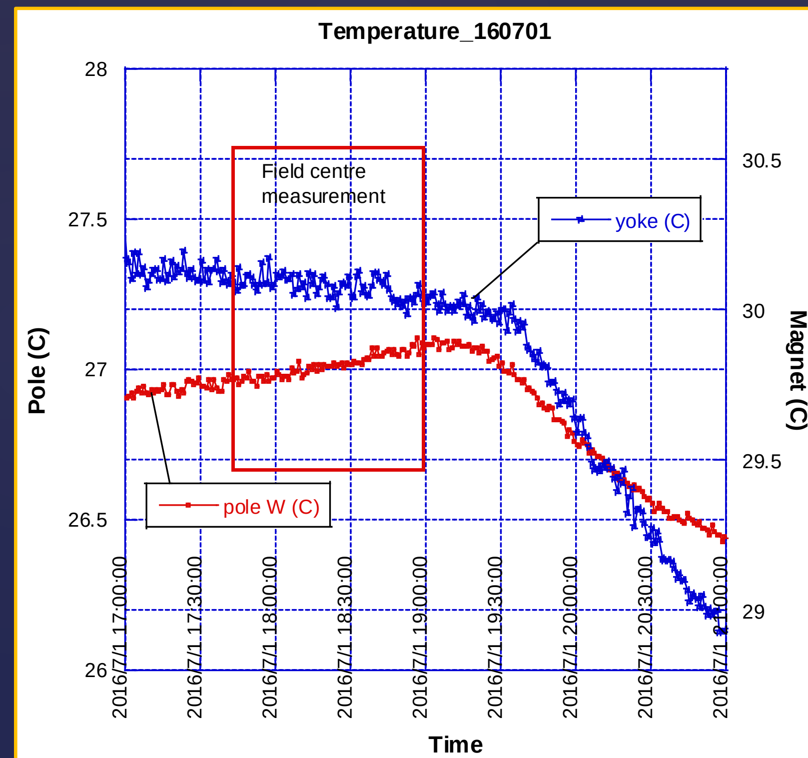
Capacities of the wire system for magnetic field measurement device :

α. Resolution of the sag : 0.03μm

β. Centre reproducibility : 0.5 μm

χ. Measurement stability : 1 μm/day @ ΔT=1°C





Temperatures of magnet and reference pole during magnetic field measurement.

Change of relative position between magnet and poles during magnetic field measurement.

Conclusion

a. Eigenfrequency wire alignment system is developed for absolute measurement.
b. Features of this system are firstly, wire sag is calculated from the eigenfrequencies of free vibration. Secondly, WPS sensors are embedded into well machined ceramic balls, to translate electrical centres to physical centres.
c. Resolution of sag measurement is tested better than 0.1μm in several meters range. And, utilizing 8-order frequency, it is 6 μm for 30 meters wire.
d. This system can be used in 50 meters with an expected resolution of 10 μm.