ESTIMATION OF MAGNET ALIGNMENT ACCURACY FOR SPRING-8 UPGRADE USING RESONANCE-FREQUENCY TRACKED VIBRATING WIRE

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Abstract

SPring-8 major upgrade, SPring-8-II, is being designed. The new storage ring requires alignment errors of 25 [μm] (1σ) or less for multi-pole magnets on a straight line between adjacent two bending magnets [1]. Using a test bench consisted of five multi-pole magnets with typical field gradients, we have demonstrated an alignment of these magnets by introducing a vibrating wire method (VWM) without conventional fiducialization. A resolution was better than 1 [μm] for a measurement of a magnetic center, however, systematic errors caused by a wire-sag, and caused by background fields, were negligibly small. The background fields were canceled by counter dipole and quadrupole magnets. In order to observe a drift of the magnetic center caused by a temperature rise of a water-cooling magnet, and caused by a deformation after installation, etc., we developed a resonance-frequency tracked vibrating wire for a sustainable measurement. Actual accuracy of our alignment procedure, including the drift, will be described in this paper.

INTRODUCTION

Low emittance storage rings are being constructed at synchrotron radiation facilities in the world [1]–[5]. Because an alignment tolerance is one of most important issues, high alignment precision of micro-meter order enhances flexibility in the design of the low emittance ring. For the SPring-8-II, multipole magnets between adjacent two bending magnets will be installed on a common girder, and will be aligned out of the machine tunnel. After the alignment, the magnets fixed on the common girder will be transported to the machine tunnel, and will be installed. Therefore, it is necessary to suppress a total error, including a change and a drift of the magnetic center caused by a transportation and a deformation.

A vibrating wire method (VWM) has been used for such a high precision alignment [6]. A tensioned wire excited with AC current is placed along a longitudinal direction. A field profile of a multi-pole magnet in the vicinity of its magnetic center can be measured by detecting a vibration of the wire at its resonance frequency.

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The resonance frequency easily drifts due to a change in an ambient air temperature. To trace the resonance frequency at all times, we developed a frequency feedback system. It is necessary to trace the resonance even if the wire is placed in the vicinity of the magnetic center, where the magnetic field is nearly zero. Here, we propose to install one additional tensioned wire parallel to the original wire. Using the system, we aim to establish an *in-situ* alignment procedure with actual accuracy of micro-meter order.

PRINCIPLE

When a tensioned wire is supplied with AC current in a magnetic field, vibrations of the wire in horizontal and vertical directions are generated by a vertical flux component B_y, and a horizontal flux component B_x, respectively. An amplitude $A_n(\omega)$, and a phase $\phi_n(\omega)$ of the vibration near its resonance frequency are shown as [7],

$$A_n(\omega) = \frac{a_n}{\sqrt{(\omega^2 - b_n^2)^2 + c_n^2\omega^2}}, \tag{1}$$

$$\phi_n(\omega) = \tan^{-1}\frac{c_n\omega}{\omega^2 - b_n^2}, \tag{2}$$

where n is mode number, b_n, and c_n are resonance frequency [rad/s] and damping constant [s^{-1}], respectively. Magnetic field at the wire is estimated by coefficient a_n [m/s^2] [8]. The frequency of the AC current is always fixed to the resonance frequency (ω=b_n), the field is estimated by only one amplitude A_n(=a_n/b_nc_n) without a fitting by Eq. 1.

FREQUENCY TRACKING

Change in the resonance frequency can be estimated by measuring the phase of the wire vibration because the phase is $\pi/2$ [rad] at the resonance [9]. From Eq. 2, the change in the resonance frequency $\Delta\omega$ [rad/s] is expressed as following equation.

$$\Delta\omega \cong \frac{c}{2\tan\phi(\omega)}. \tag{3}$$

Set frequency of the supplied current was traced to the resonance frequency by controlling the phase of itself using Eq. 3. We shall call this process “basic feedback”.

When the wire is set in the vicinity of the magnetic center, the signal strength is not enough for the basic feedback. In addition, a polarity of the phase is frequently changed in the position. Second wire was installed in parallel to the above the signal wire as a designated wire for the feedback, which we shall call "feedback wire". Distances between the signal wire and the feedback wire were 5 [mm] in horizontal and vertical directions. The set frequency of the supplied current of the signal wire was traced to the resonance frequency by controlling the phase of the feedback wire. We shall call this process "advanced feedback".

EXPERIMENT

Sag Correction and Kink Survey

Vertical position of a tensioned wire is shown a catenary curve in longitudinal direction. A sag, *S(s)*, which is defined as a vertical displacement from the both end of the wire, becomes maximum at the center of the wire. The maximum sag S_{max} is expressed by the fundamental resonance frequency ω_1 as [7],

$$S_{max} = \frac{g}{32(\omega_1/2\pi)^2}, \tag{4}$$

where, g [m/s^2] is the acceleration due to gravity. Therefore, the sag can be corrected by measuring the resonance frequency.

In order to confirm, vertical position of a wire was measured by a Hydrostatic Leveling System (FOGALE, HLS), and a Wire Positioning System (FOGALE, WPS) on a precise stone surface plate [10]. Wire length was 4.433 [m]. One end of the wire was fixed on the surface plate. Two kinds of tensions, 1.75 [kgw], and 2.00 [kgw], were applied. Nominal maximum sag were 0.36 [mm], and 0.32 [mm], respectively. Two sensors of the HLS were placed on the surface plate to measure a figure error of the surface plate. One sensor was fixed as a reference point at the center of the surface plate in longitudinal direction. The other sensor was placed just below the tensioned wire. To measure a relative height of the wire, a sensor of the WPS was put on the top of the other sensor of the HLS. A moveable unit of the sensors are shown in Fig. 1. The unit was moved statically along the wire, and then, relative heights of the wire were measured at seven points in longitudinal direction.

A s-axis was defined along the wire in longitudinal direction, and the center of the wire was defined as *s*=0. A height reference line, *y*=0, was defined as a line passing through two wire positions at *s*=±1.8 [m]. A difference of absolute height between the two points is not important. Even if the difference is equal to 5 [mm], a change in the theoretical sag due to the difference are less than 2.1×10^{-4} [μm]. In case of the test, the absolute height at the two points were roughly corresponded within 1 [mm].

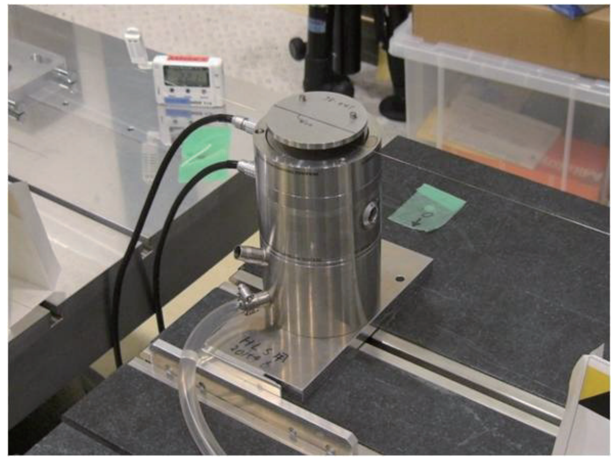

Figure 1: Moveable unit of sensors of HLS and WPS placed on a precise stone surface plate. Two sensors of the HLS were prepared. One more sensor of the HLS was fixed as a reference point (out of the figure).

Measurement of Magnetic Center

Three quadrupole magnets and two sextupole magnets were prepared as test magnets. Outline of the test magnets and a common girder are shown in Fig. 2. A 4.871-[m] long Be-Cu wire with 0.2-[mm] diameter was prepared as a field signal wire. One end of the wire was fixed through a pulley. A load of 2.00 [kg] was hung at the other end of the wire through a pulley. A ball-bearing pulley was adopted at the loaded end to keep the tension. Nominal fundamental resonance frequency is $2\pi\times28.3$ [rad/s].

Wire girders at the both ends was made of a super-invar material to suppress a change in the position due to a fluctuation of the girder temperature. At the both end of the wire girder, the pulleys were placed on x-y stages with a resolution of 0.1 [μm] to scan the wire in a transverse plane. The wire was moved in parallel using these stages. In order from the loaded end, the test magnets are called Q_1, S_2, Q_3, S_4, *and* Q_5. Symbols *"Q"* and *"S"* indicate quadrupole and sextupole magnets, respectively. Specifications of these magnets are listed in Table 1. In this table, l_p is the pole length and l_e is the effective length, which is defined Eq. 7.

Table 1: Specification of test magnets

Name	**Bore dia. [mm]**	**Max. gradient [T/m] or [T/m^2]**	**Length l_p, l_e [mm]**
Q_1	85	17.0 @536[A]	310, 138
Q_3	85	17.6 @552[A]	970, 954
Q_5	85	17.4 @544[A]	470, 222
S_2	92	420 @300[A]	270, 211
S_4	92	420 @300[A]	270, 224

Supplied current of the wire was generated by an arbitrary waveform generator. An amplitude of the current was 98 [mA$_{rms}$]. Wire positions in horizontal and vertical di-

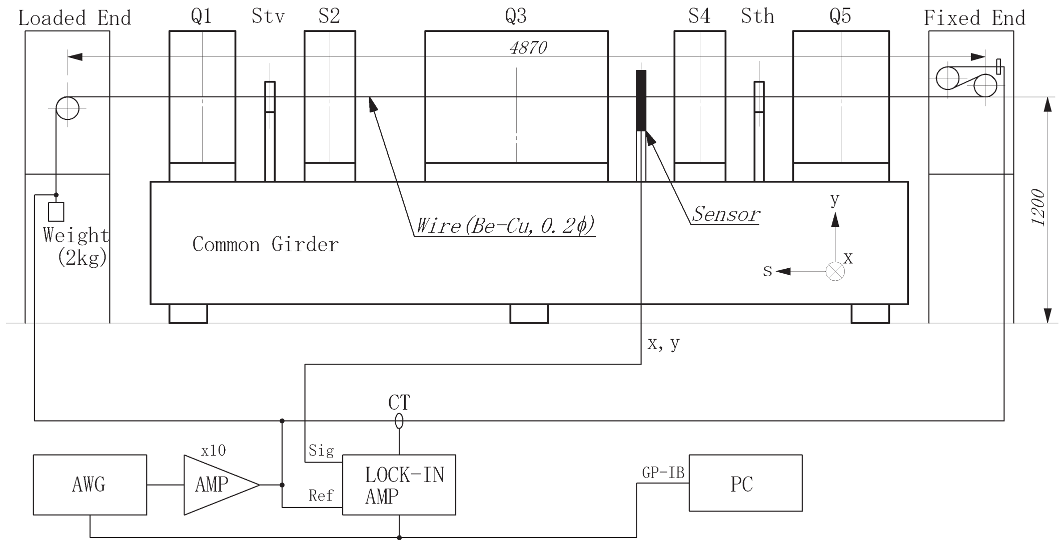

Figure 2: Outline of the test magnets and test common girder. The wire is fixed through a pulley at one end. A load is hung through a pulley at the other end. These pulleys are placed on x-y stages to scan the wire. The "signal wire" and the "feedback wire" were tensioned in parallel with a distance of 5 [mm] in *x* and *y* directions. The *x* and *s* axes point to the north and the east. Wire length is 4.871 [m]. Tension is 2.00 [kgw]. Maximum sag is 0.383 [mm]. Nominal fundamental resonance frequency is 28.3 [Hz] Bottom of figure is shown block diagram of vibration amplitude measurement.

rections were measured by laser sensors (KEYENCE Ltd, LS-9000D) placed at the longitudinal position of 1.83 [m] from the fixed end. The amplitude and the phase of the vibration at the set frequency were picked up by a lock-in-amplifier. To cancel a background field, e.g., geomagnetism, a pair of counter-dipole magnets (*Sth*, and *Stv*) were installed. Maximum integrated field of these magnet are 1.5 [mTm].

Using only a fundamental resonance frequency, flux densities in the test magnets were estimated by measuring the amplitude at the resonance frequency. Magnetic centers of quadrupole and sextupole magnets were measured by scanning the wire position in horizontal and vertical directions. Definition of coordinate axes are also shown in Fig. 2. Only a target magnet for the measurement was excited.

Quadrupole Magnet The magnetic center of a quadrupole magnet in transverse direction (x_0, y_0) is defined by the point, where the horizontal dipole and vertical dipole are zero. Horizontal and vertical distributions of integrated flux densities $B_x l_e$ and $B_y l_e$ [Tm] in the magnet are expressed as,

$$B_x(y)l_e = G_q(y - y_0)l_e, \qquad (5)$$

$$B_y(x)l_e = G_q(x - x_0)l_e, \qquad (6)$$

where, G_q [T/m] is a gradient of a quadrupole magnet. The length l_e is an effective length considered a sensitivity of the vibration to the field, which is defined as,

$$l_e \equiv \int_{s_u}^{s_d} sin(\frac{n\pi s}{L})ds, \qquad (7)$$

where, *L* [m] is the wire length, s_u and s_d [m] are longitudinal positions of upstream and downstream edges of the magnet, respectively. The effective lengths for the fundamental resonance are also listed in Table 1. Background field components of $\delta b_x L$ and $\delta b_y L$ [Tm] are added to Eq. 5 and Eq. 6. These components were canceled by *Sth* and *Stv*.

The vibration amplitude A_x and A_y are in proportional to integrated flux densities, $B_y l_e$ and $B_x l_e$, respectively. By scanning the wire in horizontal and vertical directions, the coordinates of the magnetic center were found out. The amplitudes, A_x and A_y, at the magnetic center are equal to zero. A scan step was 2 [μm] in the range of $\pm$10 [μm] in both directions. Excitation current of all the target magnets was 300 [A]. Nominal gradient of the target magnet was 9.6 [T/m].

Sextupole Magnet The magnetic center of a sextupole magnet in transverse direction (x_0, y_0) is defined by the point, where the normal quadrupole given by dB_x/dy(=dB_y/dx) and the skew quadrupole given by dB_x/dx(=-dB_y/dy) are zero. Horizontal and vertical distributions of integrated flux densities, $B_x l_e$ and $B_y l_e$ [Tm], in the magnet are expressed as,

$$B_x(x,y)l_e = G_s(x - x_0)(y - y_0)l_e + \delta B_{x,0}l_e, \qquad (8)$$

$$B_y(x,y)l_e = \frac{G_s}{2}[(x-x_0)^2 - (y-y_0)^2]l_e + \delta B_{y,0}l_e, \qquad (9)$$

where, G_s [T/m^2] is a gradient of a sextupole magnet, and $\delta B_{x,0}l_e$ and $\delta B_{y,0}l_e$ [Tm] are dipole components at the magnetic center. The background field, $\delta b_x L$ and $\delta b_y L$, are also added to Eq. 8 and Eq. 9.

A difference of the component B_x between two vertical offset positions, y=y+y_f and y-y_f, is defined as $\Delta B_{x,yf}$. The difference is shown as,

$$\Delta B_{x,yf}(x) l_e = 2 G_s y_f (x - x_0) l_e. \qquad (10)$$

Similarly, a difference of the component B_x between two horizontal offset positions, x=x+x_f and x-x_f, is defined as $\Delta B_{x,xf}$. The difference is shown as,

$$\Delta B_{x,xf}(x) l_e = 2 G_s x_f (y - y_0) l_e. \qquad (11)$$

A vibration amplitude difference between two vertical offset positions is defined as $\Delta A_{y,yf}$, and that between two horizontal offset positions is defined as $\Delta A_{y,xf}$. The amplitude differences, $\Delta A_{y,yf}$ and $\Delta A_{y,xf}$, are in proportional to the difference, $\Delta B_{x,yf} l_e$ and $\Delta B_{x,xf} l_e$, respectively. By scanning the wire in horizontal and vertical directions at above four offset positions, the coordinates of the magnetic center were found out. The offsets, x_f and y_f, were set to 1 [mm].

In the group of multipole magnets, a background field gradient, δgL [T], generated by remanent fields of other quadrupole magnets was not negligible. An error field, $2y_f\delta gL$ [Tm], is added to Eq. 10. To cancel the background gradient, the Q_1 magnet excited oppositely as a counter-quadrupole magnet. Consequently, the amplitude differences, $\Delta A_{y,yf}$ and $\Delta A_{y,xf}$, are equal to zero at the magnetic center. A scan step was 20 [μm] in the range of $\pm$100 [μm] in both directions. Excitation current of all the target magnets was 300 [A]. Nominal gradient of the target magnet was 420 [T/m^2].

Alignment Test

For all the test magnets, two fiducial points were prepared on the top. Using these fiducial points, positions of mechanical centers of all the magnets were pre-aligned by a Laser Tracker System (Leica, AT402) and a water level. A sub-reference line was defined as a line passing through two positions of mechanical centers of the Q_1, and Q_5. Then, the mechanical centers of other magnets were adjusted to the sub-reference line by the Tracker. Yaw angles of these magnets were also corrected by the Tracker. Pitch and roll angles of these magnets were corrected by the water levels.

Next, positions of the magnetic center of the Q_1, and Q_5 were measured. A reference line was defined as a line passing through the two positions. Displacements of the magnetic centers from the reference line were measured for other magnets. For the Q_3, the horizontal position of the magnetic center was adjusted to the reference line on a basis of the vibration amplitude.

Frequency Tracking and Drift of Magnetic Center

For both of the signal wire and the feedback wire, the amplitude and the phase were continuously measured in 24 [hours] with the basic feedback and without any feedbacks near the fundamental resonance to compare a stability. The amplitude in both directions were set to 0.1 [mm] by the *Sth* and *Stv*. The background gradient was canceled by the counter quadrupole magnet. A sampling cycle was 3 [sec]. In case of the basic feedback, the feedback cycle was 2.5 [min] using averaged phase by 20 data just before the feedback timing. A correlation between resonance frequencies of the two wires obtained from the measurement. Using the correlation, the same continuous measurement was carried out with the advanced feedback.

To observe drifts of the magnetic centers of the Q_1 and Q_3, the vibration amplitudes were continuously measured in 50 [hours] just after the excitation with the advaced feedback. The signal wire was set to the magnetic center, (x,y)=(x_0,y_0), at the start of the measurement. The feedback wire was placed at (x,y)=(x_0+5[mm],y_0-5[mm]). The current of the feedback wire was 640 [μA$_{rms}$] for the Q_1 and 98 [μA$_{rms}$] for the Q_3. Changes in the amplitude of the signal wire were converted to changes in the position of the magnetic center.

RESULT

Wire Sag

Measured wire heights in longitudinal direction are shown in Fig. 3 with the wire tension of 2.00 [kgw]. Calculated height using measured fundamental resonance frequency is also shown in this figure. A difference between measured height and calculated one was 1.0 [μm] at the center of the wire. The maximum difference was 8.5 [μm]. In case of the height with the tension of 1.75 [kgw], the difference at the center and the maximum difference were 2.1 [μm] and 9.6 [μm], respectively.

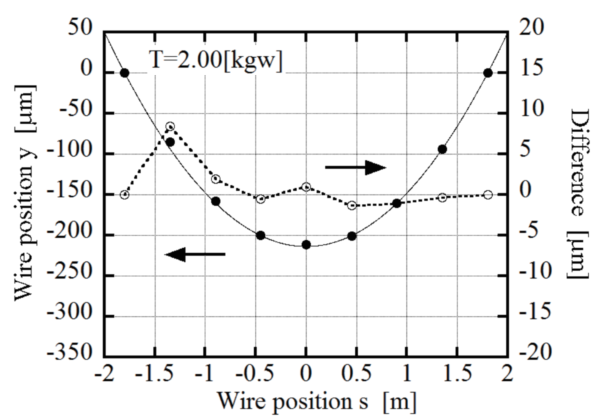

Figure 3: Wire height distribution in longitudinal direction with the tension of 2.00 [kgw]. Closed circle indicates measured height by the HLS and the WPS. Solid line indicates calculated height by measured fundamental resonance frequency. Open circle and dashed line indicates a difference between the measured height and the calculated one.

Magnetic Center and Alignment Test

As an example for the quadrupole magnet, the vibration amplitudes versus the wire positions for the Q_3 are shown in Fig. 4. The wire positions indicate the displacements from the reference line. The vertical displacement was corrected by the calculated sag. The displacements in horizontal and vertical directions were (-28.47±0.07, +53.23±0.07) [μm]. After the magnetic center was adjusted to the reference line in horizontal direction, the displacements became (-2.59±0.07, +60.12±0.04) [μm] (See Fig. 4, closed circle).

As an example for the sextupole magnet, the amplitude differences versus the wire positions for the S_2 are shown in Fig. 5. The displacements were (+28.8±0.8, +11.8±0.7) [μm]. Similarly, for the S_4, the displacements were (+36.0±0.7, +11.1±0.9) [μm].

About the measured displacements are not discussed further in this paper because distances between the magnetic center and the mechanical center are unknown for the Q_1 and the Q_5. For all the quadrupole magnets, fitting errors of the magnetic center measurement were less than 0.1 [μm]. For all the sextupole magnets, the fitting errors were less than 1 [μm]. A detection limit of an integrated field was estimated to be less than 0.1 [μTm].

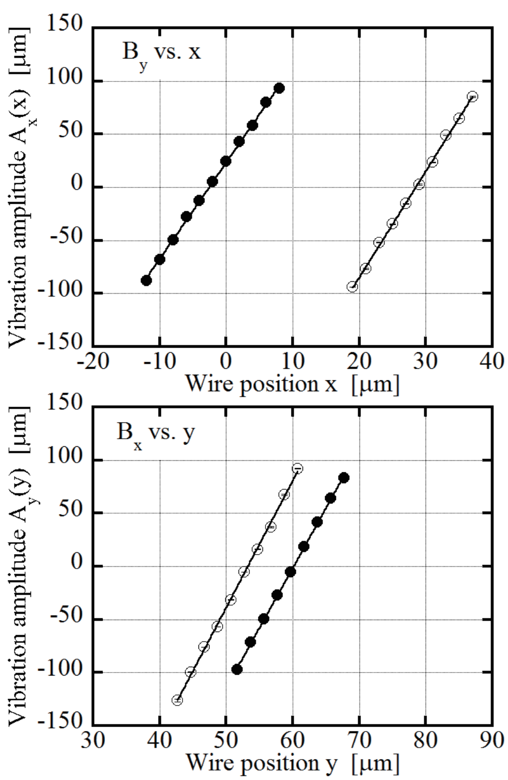

Figure 4: Vibration amplitudes versus wire positions for the Q_3. Open and closed circle indicate the amplitudes before and after adjustment by VWM, respectively. Error bars indicate one standard deviation of ten measurement. Solid lines indicate results of the least squires fitting.

Temporal changes in the Magnetic Center

Time dependences on the vibration amplitude and the phase are shown in Fig. 6 in horizontal direction without

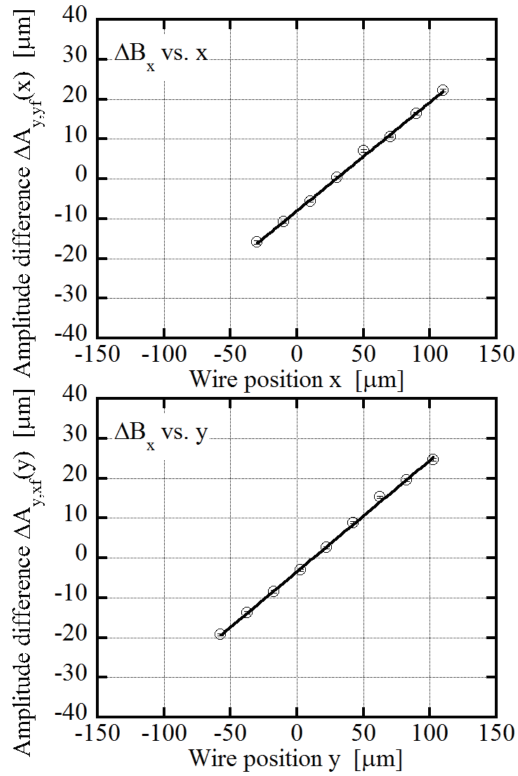

Figure 5: Vibration amplitude differences versus wire positions for the S_2. Error bars indicate one standard deviation of ten measurement. Solid lines indicate results of the least squires fitting.

any feedbacks and with the basic feedback. The amplitude was decreased by -16 [%] from the original amplitude in 10 [hours] without any feedbacks. A correlation between the ambient air temperature and the phase was observed clearly with a correlation coefficient of 0.89. Temperature coefficients was 29 [deg/K].

On the other hand, the amplitude and the phase were kept using the basic feedback with one standard deviation of 1.6 [%] and 1.7 [deg], respectively. A correlation between the ambient air temperature and the resonance frequency was observed with a correlation coefficient of 0.69. Temperature coefficients was 0.02 [Hz/K]. The resonance frequency of the signal wire, f_s, was strongly correrated with that of the feedback wire, f_f, with a correlation coefficient of 0.99.

From the correlation, for the advanced feedback, a relation between the frequency change of the signal wire, Δf_s and that of the feedback wire, Δf_f was determined as Δf_s=0.905Δf_f. The amplitude and the phase were similarly kept with the advanced feedback using the relation with one standard deviation of 1.5 [%] and 1.8 [deg], respectively.

Temporal changes in the magnetic center for the Q_3 is shown in Fig. 7 after starting of excitation. Temperatures of the yoke and an ambient air are also shown in this figure. Correlation between the vertical center and the yoke temperature was observed clearly. However, the yoke temperature was not achieved constant during 2 [days]. The yoke temperature was changed due to a fluctuation of the ambient air temperature. It is necessary to stabilize the air temperature to estimate a time constant of the drift of the magnetic center.

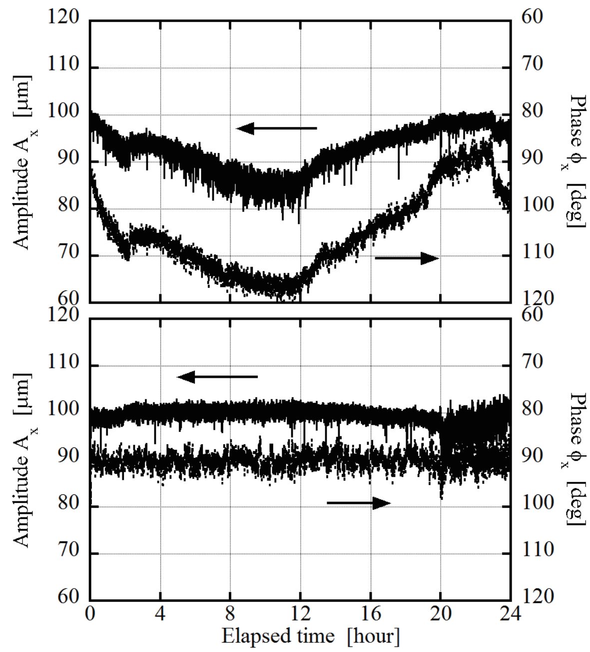

Figure 6: Amplitudes and phases of the wire vibrations versus time in horizontal direction without and with feedback.

DISCUSSION

Error budget

Major error factors are arranged bellow in order making the largest contribution in the alignment error.

Displacement from theoretical sag We are planning that the sag is calculated by measuring only the fundamental resonance in the regular alignment procedure without any measurement of the height distrubution wire by wire. In this case, the difference of an actual wire position from the theoretical curve is contributed directly to the alignment error. The difference, included any kinks, will be observed from now on.

Since the sag continuously varying along s-axis in a magnet, an effective sag S_e considered a sensitivity of the vibration should be corrected. The effective sag is defined as,

$$S_e \equiv \frac{1}{l_e}\int_{s_u}^{s_d} S(s)sin(\frac{n\pi s}{L})ds, \qquad (12)$$

Because the effective sag differ from the sag at the center of the magnet, the sag is changed due to the pitch angle. The change is remarkable for a long magnet, and for a magnet placed near the end of the wire. For the test magnets, maximum amount of the change is 2.2 [μm] for the Q_5 with the pitch angle of 0.1 [mrad].

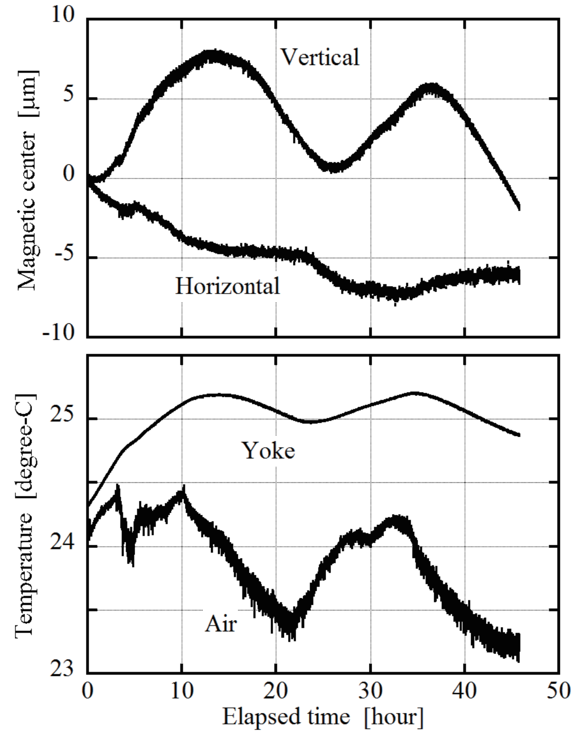

Figure 7: Example of temporal change in the magnetic center for the Q_3. Temperature of the yoke and an ambient air are also shown.

Dynamic error caused by drift and deformation The magnets should be aligned at their actual excitation current after temperatures of their yoke become stable. To estimate a time constant of the drift of the magnetic center, an ambient air temperature of the measurement room will be stabilized within 0.1 [K]. And then, the error due to the drift is suppressed to less than 1 [μm] by matching the timing and by shortening of the measurement. In addition, we will observed a change of the magnetic center caused by transportation to the machine tunnel and a drift of that caused by deformation after the installation.

Systematic error caused by background field The background field components, b_xL and b_yL, were estimated to be -17 and -16 [μTm], respectively. Without cancellation the background, the measured magnetic center of a quadrupole magnet is displaced by b_yL/G_ql_e in horizontal and by b_xL/G_ql_e in vertical directions. In case of the Q_1, whose effective integrated gradient is minimum of all the test quadrupole magnets, these displacements are 12 and 13 [μm], respectively. To detect the magnetic center with an accuracy of micro-meter order, it is necessary to reduce the background to less than 1/10.

The background field gradient, δgL, was estimated to be 42.6 [mT]. The value is equivalent to 0.25 [%] to Q_3, which has maximum effective integrated gradient of all the test quadrupole magnets. Without cancellation the background gradient, the measured magnetic center of a sextupole magnet is displaced by $\delta gL/G_sl_e$ in horizontal direction. In case of the S_2, whose effective integrated gradient is minimum of all the test sextupole magnets, the displacement is -480 [μm]. The displacement is smaller than the value in a strong sextupole magnet for the low emittance rings [1]-[5]. However, to detect the magnetic center with an accuracy of micro-meter order, it is necessary to reduce the background to less than 1/100. This reduction is not easy by any magnetic shield. But, it can be realized by a counter quadrupole magnet using a conventional technique.

Repeatbilities When the tension was released once, and was applied again using same wire, the displacements of all the magnets were consistent with the original values within 10 [μm]. However, when the wire was removed once, and then, new wire was tensioned again, differences in vertical direction exceeded above value. Maximum difference was 16 [μm] at the Q_3. There is a possibility that a sag was changed even though the sag was corrected. From now on, we are identifying the cause.

Resolution The fitting errors of the magnetic center measurement were much better than aimed accuracy. Optimization of the node number and of the applied current, etc., any more improvement is not needed.

The ambient air temperature of the wire are changed during a scanning period, measured amplitude is devitated. The temperature coefficient of the phase is strongly depended on a friction at the pulley of the loaded end. If the pulley was fixed, the coefficient appriximately three times as large as the present value. Even if the temperature is suddenly changed by 1 [K] without the feedback, an error of the magnetic center is estimated to be less than 1 [μm] for the present coefficient. In case of the measurement for the magnetic center, the feedback is not required.

Why B_x was chosen for sextupole

The position of the magnetic center of a sextupole magnet is also determined using B_y distributions. The vibration amplitude A_x both in the horizontal and vertical directions follow a parabolic function (see Eq. 9). For the S_2, the amplitude versus the wire positions are shown in Fig. 8.

The position of the magnetic center was obtained with an error of 2 [μm]. However, a deviation of the amplitude was much larger than the deviation in the case of B_x (Fig. 5). It is necessary to widen the scan step and the scan range to suppress the deviation. In addition, it is unsuitable a *in situ* alignment on the basis of the vibration amplitude.

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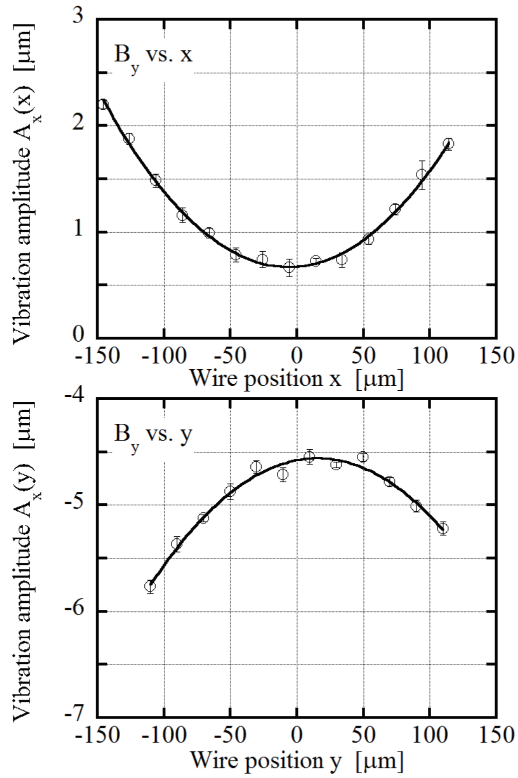

Figure 8: Vibration amplitudes, A_x, versus wire positions for the S_2. Error bars indicate one standard deviation of ten measurement. Solid lines indicate results of the least squires fitting.

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