CHAPTER III

Analysis of Pulsed Wire Measurements on Bi-harmonic Undulator
1. Introduction

The measurement of undulator is an important issue in design of uniform, precise and quality undulators for synchrotron radiation and free electron laser applications. Such measurements are usually made point to point by a Hall probe. The pulsed wire method was suggested as an alternate method for field integral measurements [1]. In this method, a thin wire is stretched along the length of the undulator axis. When a current flows through the wire, a force proportional to the local transverse field component is exerted on the wire. This force evolves into a wave on the wire that propagates from the vicinity of the wire to a sensor located at the undulator ends. The sensor output versus time is the field integral versus position along the wire. The pulsed wire method has been used successfully over the years for magnetic measurement studies of undulators in close agreement with the Hall probe results. The wire sag, non uniformities of the wire and dispersion are some of the limitations of the method. Some other limitations and errors include attenuation, scattering on in homogeneities, reflection from the wire end supports, electronic and optical noise, ground and thermal vibrations that affect the accuracy and precision pulsed wire measurements of the undulator.

Pulsed wire magnetic field measurements [2] were made on a 4.3 meter long undulator. The permanent undulator has 3.56 meter period length with 120 periods. The detector was H21A1 optical interrupter switch. The CuBe wire length was 12 meter and wave velocity is 340 m/s. The CuBe wire with 76 µm diameter was used in the experiment. CuBe wire with 56 µm diameter was used with the optical switch in the pulsed wire measurement of 75 cm long Hallbach undulator [3]. The wave velocity upto 270 m/s versus wire tension was measured. The Pulsed wire system [4] used wire diameter 400 µm with a H21A3 optical switch as a detector. The wave velocity was 100 m/s and the tapered undulator was 1 meter long with 40 number of periods. The first and second field integrals were measured and the field was determined by differentiating the first integral [5]. A laser–photodiode detection system was used on a 2.7 cm tapered period wiggler. The method was applied successfully to field measurements in pulsed microwiggles [6,7]. The pulsed wire method was used for undulator magnetic field measurements [8, 9]. A CuBe wire with 100 µm diameter, 2.7 meter long was used for the measurement system. The undulator was 60 mm period length and there were 10 periods. An infrared 100 mW...
laser diode and a fast infrared 100 MHz photodiode was used for detection. The first and second field integrals of the undulator was measured with an accuracy close to that of Hall probe results. The Pulsed wire method was improved [9] by use of special thin dielectric hangers to decrease wire sag. Oil bubble dampers for damping the wave signals reflected from the wire supports were used in the experiment. The Pulsed wire method [10] was used for field integral measurements with CuBe wire of 100 µm diameter wire, 2 meter long with an optical detector. The undulator was a hybrid undulator with 9 periods with 6 cm period length each. Further developments of the Pulsed wire method for magnetic measurements and focusing strength measurements in long undulators was reported [11,12]. The effects of wire imperfections and dispersion of the acoustic wave was analzsed for a thick wire [13,14,15].The Pulsed wire method was improved with improved sensitivity of the optical switch ,H21A1 by varying the aperture of the switch[16].The undulator used for the experiment was 15 periods and each period was 10 cm long. The pulsed wire method used CuBe wire of 100 µm diameter of 4.86 meter long. The effect of the wire dispersion was discussed. Most recently the pulsed wire technique was applied for field measurement studies of table top planar undulator of 30 cm long with six periods [17, 18]. The CuBe wire diameter was 250 µm diameter .The detector was a Motorola optical switch .The pulse length requirements were discussed. The detailed theory of wave dispersion was theoretically analyzed [19]. An algorithms is derived to correct the dispersion and finite pulse width errors in the measurements of first integrals and dispersion errors in the second field integral measurements [20]. All these developments have made PWM as an attractive option for magnetic measurements in narrow gap undulators or in cryogenic environments such as superconducting undulators that stimulated researchers to apply PWM in other measurement applications. The PWM was applied for measurement of millimeter wave travelling wave tube [21] which is the new application area of pulsed wire technique. Another application, the PWM has been effectively used for magnetic axis alignment of pulsed solenoids with a resolution better than 25µm [22].

In this chapter we apply PWM for measurement of new novel exotic type undulators. The PWM so far has been applied for magnetic measurements of planar/elliptical PPM, hybrid type and tapered undulators. However due to its increased applications, the undulator technology has been improved for new, unique
applications of undulators in the areas of synchrotron radiation and free electron laser applications. For example, there are multi frequency undulators, optical – klystron undulators, crossed undulators, crossed overlapped undulators and step tapered undulators. In this chapter as possible extension applications of PWM, we use PWM for magnetic measurements of recently reported bi-harmonic undulators [23]. The biharmonic undulators are modified planar sinusoidal undulator fields proposed to enhance free electron lasing at a desired higher harmonic. The standard planar undulator is a one peak per half period undulator field. The third bi-harmonic field is two peak per half period undulator field. As the harmonic number increases, the number of peaks per half period of the undulator is increased. The fifth, seventh and ninth harmonic undulators have three, four, five peaks in each half period of the undulator. As a consequence it requires fast detection systems to pick up multi peak oscillations of the wire in each half undulator field. In section 2, we describe the new pulsed wire bench. It is equipped with both the detection systems. An optical switch is located at one end of the undulator while the laser-photodiode sensor is used the other end of the undulator. Two wires with different diameters are used in the set up. The measurement results are discussed in section 3. It is observed that both the sensors give results in close agreement with the Hall probe results. The stiffness and dispersion of the thick wire and the multi peak wire oscillations of the wire do not affect the accuracy of the PWM but limits the range of tension in the pulley end in comparison to a planar sinusoidal field.

2. PULSED WIRE BENCH

The pulsed wire bench is set on the same vibration isolation support. Two wire diameter of 250 \( \times m \) CuBe wire having \( \rho = 4.1 \times 10^{-4} \text{ kg/m} \) and 125 \( \times m \) CuBe wire having \( \rho = 1.01 \times 10^{-4} \text{ kg/m} \) is installed for magnetic measurements. The wire length is 1.39 meter, which is more than four times the length of the undulator. Two sensors are employed for wire deflection measurements. An optocoupler is used as the sensor at the location of 148 mm away from the one end of the undulator. The optocoupler switch used for the experiment is a Motorola make Model No is MOC7811. The optocoupler switch consists of an infrared LED and a phototransistor which are molded in a plastic housing. The Optocoupler switch is mounted on a
assembly mount shown in Fig1a. The mount assembly consists of two circular rings. The outer diameter of the outer ring is 85 $mm$ and the outer diameter of the inner ring is of 60 $mm$. The outer ring is marked. The inner ring can be rotated inside the outer ring. The optical switch is fixed on the inner ring. The rotation of the inner ring allows the optical switch to measure both the horizontal and vertical field integral data. There is a slot of 12 $mm$ width for removing and inserting the wire. The drawing and schematic of the system is as shown in Fig1b. The mount assembly is attached to a post of 12 $mm$ diameter and 58 $mm$ in length and is mounted on a rail through xyz translation stages. The rail allows the switch to be fixed at minimum distance of 148 $mm$ and maximum of 560 $mm$ distance from the undulator end. The xyz stages give vertical, horizontal and height alignments to the switch. The complete installation can be viewed in Fig1c.

![Diagram of optocoupler sensor mount](image)

a. Complete assembly of optocoupler sensor mount
b. Schematics of optocoupler sensor mount.

c. Photograph of optocoupler sensor mount.

Fig 1 Optocoupler detection system
A laser - photodiode sensor is used as a detector at the other end of the undulator. The 5 \( mW \), 635 \( nm \) laser is Coherent’s Ultra Low Noise series diode laser Model No. 31-0144-000 module. The rms noise typically \( \approx 0.06 \% \). The laser spot size is 1\( mm \). The laser is fixed on a laser mount vertical facing downwards through xyz stages. The xyz stages gives a movement of 5 \( mm \) each in upward, downward and forward direction. The photodiode for the system is Newport, USA make silicon detector Model No. 818-BB-21. The 818-BB-21 High Speed silicon photo detector operates from 300 \( nm \) to 1100 \( nm \) with a 0.40 \( mm \) active diameter and has rise time less than 300 \( ps \). It is connected to Tektronix TDS2024B, 4 channel, 200 \( MHz \) digital storage oscilloscope through a 50 \( ohm \) BNC connector output. The laser - photodiode mount assembly is seen in Fig 2a and Fig 2b. The complete pulsed wire set up is shown in Fig 3. In our present measurement, with a given SNR, a current of 1.9\( A \) and 0.6\( A \) is used for wire diameters of 250 \( \mu m \) and 125 \( \mu m \) respectively.

a. Schematic of Laser sensor
b. Schematic of the laser-photodiode sensor mount

Fig 2 Laser-photodiode detection system

Fig 3 Complete pulsed wire set up
The transverse motion equation in the wire is given by

\[ \frac{\partial^2 x}{\partial z^2} + \frac{1}{v^2} \frac{\partial^2 x}{\partial t^2} = -\frac{B_u(z)I(t)}{T} \]  

(1)

where \( v = \sqrt{T/\mu} \) is the wave velocity. \( T \) is the tension on the wire. \( I(t) \) is the current in the wire and \( B_u(z) \) is the magnetic field at a location \( z \). For a short pulse of the first field integral is given as

\[ x_1(t) = -\frac{I_0}{2\nu} t^{\nu} \phi(z)dz \]  

(2)

For a longer pulse the second field integral is given by,

\[ x_2(t) = -\frac{I_0}{2\nu} z^{\nu} \phi(z) + B_u(z)du \]  

(3)

\( I_0 \) is the current injected to the wire. The first and second field integral i.e. Eq. (4) and Eq. (5) in the pulsed wire method is measured by an appropriate pulse width. The field integral data obtained from the pulsed wire method is compared with Hall probe data.

3. Measurement Results and Discussion

In this section, we study the experimental results of pulsed wire method on biharmonic undulators. The biharmonic undulators are fabricated by putting shims along the length of the undulators. The measurements are taken by two detection systems located at both ends of the undulator. Both the sensors are located at a distance of 148 mm from the end of the undulator. The CuBe wire is fixed at one end and the other end of the wire hangs over a pulley with a weight. Before current is applied to the wire, the wire was scanned across the sensor in order to determine the voltage versus displacement calibration curve. The two calibration curves are plotted in steps of 20 \( \mu \)m in Fig 4 for two wire diameters of 250 \( \mu \)m and 125 \( \mu \)m. Pinhole diameter of 250 \( \mu \)m is used for opto-coupler sensors for both the wire diameters. It is placed on the source side. The laser sensor is a combination of laser and photo diode and a pinhole diameter of 300 \( \mu \)m is placed at the laser face for our measurements. The working principles of the two sensors are inverse to each
other. The opto coupler works on the principle of current flowing in the circuit by photo illuminated transistor and the principle of operation is represented by [17],

\[ V_{CE} = V_{CC} - I_{CE} R \]  

(4)

When the wire blocks the LED light path, no light falls on the photo transistor and the current flowing is zero i.e \( I_{CE} = 0 \) and \( V_{CE} = V_{CC} \) is the supply voltage recorded is maximum when the light path is interrupted. As the wire moves away from the center, the light path is opened up and allows the light to fall on the photo transistor. A current flows and reduces the recorded voltage. The voltage versus distance curve for the optocoupler is shown in Fig4a. The slope of the curve is the sensitivity of the sensor. The sensitivity of the two output curves are calculated in the linear portion of the curve and is 8 mV/µm (250 µm wire) and 6 mV/µm (125 µm wire) respectively. The laser–photodiode detector works on the principle of interception of a Gaussian distribution of intensity. The un-interrupted light through a wire is given by [24],

![Fig 4 calibration curve for a) opto coupler detector b) laser-photodiode detector](image-url)
\[
P(x) = \frac{2P}{\pi x} \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} dx e^{-\frac{y^2}{w^2}} e^{-\frac{x^2}{r_w^2}}
\]

where \(2r_w\) is the wire diameter and \(w\) is the laser beam spot size. When the wire is located at the center of the laser beam, the power not blocked by the wire is minimum. It is seen from Fig 4b, that the minimum voltage occurs when the wire completely blocks the laser light. At the center, the intensity of the laser is maximum, the interrupted light is maximum hence this corresponds to minimum voltage. As the wire moves away from the center, more and more light falls on the photodiode and the output voltage rises. The laser used has a spot size of 1000\(\mu m\). A number of pinhole diameter was used to reduce the beam spot size and the pinhole diameter of 300 \(\mu m\) is placed to reduce the laser spot and gives a sensitivity same as that of the optocoupler. Thus sensitivity of the laser-photodiode with the 300 \(\mu m\) pin hole is 8 \(mV/\mu m\) (250 \(\mu m\) wire) and 6 \(mV/\mu m\) (125 \(\mu m\) wire) respectively.

In Fig 5a and Fig 5b, we plot the second field integral and the magnetic field calculated from hall probe data and PWM data for wire diameter of 250 \(\mu m\) for the planar undulator.
In Fig 5c and 5d the measurements are shown for the 125 µm wire diameter. The measurements are done at the undulator gaps of 24 mm, 27 mm and 30 mm respectively. All the plots corresponds to average data obtained from the wire.

Fig 5b Magnetic field for planar undulator from pulsed and hall probe method

Fig 5c Second field integral for planar undulator from pulsed and hall probe method
Fig 5d Magnetic field for planar undulator from pulsed and hall probe method

The third harmonic undulator measurements are shown in Fig 6a – Fig 6d. The fifth harmonic undulator measurements are shown in Fig 7a-7d.

Fig 6a Second field integral for 3rd bi-harmonic undulator from pulsed and hall probe method
Fig 6b Magnetic field for 3rd bi-harmonic undulator from pulsed and hall probe method

Fig 6c Second field integral for 3rd bi-harmonic undulator from pulsed and hall probe method
Fig 6d Magnetic field for 3rd bi-harmonic undulator from pulsed and hall probe method

Fig 7a 2nd field integral for 5th bi-harmonic undulator from pulsed and hall probe method
Fig 7b Magnetic field for 5th bi-harmonic undulator from pulsed and hall probe method

Fig 7c 2nd field integral for 5th bi-harmonic undulator from pulsed and hall probe method
Fig 7d Magnetic field for 5th bi-harmonic undulator from pulsed and hall probe method

The PWM data is plotted in Fig 8 and Fig 9 for the seventh and ninth harmonic undulator collected from the two sensors for the two wire diameters. The measurements are taken at shim gap of 4 mm, 7 mm and 10 mm respectively. The data for the second field integral is double differentiated to get the magnetic field profile. The results for the seventh harmonic undulator with 250 µm wire diameter is plotted in Fig 8a and fig 8b. The results for the seventh harmonic undulator with 125 µm wire diameter is plotted in Fig 8c and fig 8d respectively. The magnetic measurement results for the ninth harmonic undulator with 250 µm wire diameter is presented in Fig 9a and Fig 9b. The magnetic measurement results for the ninth harmonic undulator with 125 µm wire diameter is presented in Fig 9c and Fig 9d respectively.
Fig 8a 2\textsuperscript{nd} field integral for 7\textsuperscript{th} bi-harmonic undulator from pulsed and Hall probe method

Fig 8b Magnetic field for 7\textsuperscript{th} bi-harmonic undulator from pulsed and Hall probe method
**Fig 8c Second field integral for 7th bi-harmonic undulator from pulsed and Hall probe method**

**Fig 8d Magnetic field for 7th bi-harmonic undulator from pulsed and Hall probe method**
2nd integral of magnetic field (in tesla*m)

9th harmonic

Tension 3.3N
wire dia 250+ m
shim gap 4mm

OC
HPM
LS

Distance along the length of the undulator(in meter)

Fig 9a 2nd field integral for 9th harmonic undulator from pulsed and Hall probe method

Fig 9b Magnetic field for 9th harmonic undulator from pulsed and Hall probe method

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Fig 9c Second field integral for 9th harmonic undulator from pulsed and Hall probe method

Fig 9d Magnetic field for 9th harmonic undulator from pulsed and Hall probe method
The PWM data for the magnetic field is compared with the Hall probe data in Fig 10a for a shim gap of 4mm (i.e. undulator gap 24mm) for all the harmonic undulator including the planar undulator results. The results are shown for the Brms versus tension over the pulley with wire diameter of 250µm. The optocoupler sensor shows the best matches results with the Hall probe data. The disagreement is 0.27% at a tension of 4.14N. For a 5% disagreement with the Hall probe data the tension range is found to be 2.49N to 7.24N. The laser photo-diode sensor gives 3% disagreement with the Hall probe data at 4.55N and the tension range is 2.49N to 6.82N for a 5% disagreement with the Hall probe data. The third, fifth and seventh harmonic undulator measurements show best matching results in a tension range of 2.48N to 5.19N whereas for the ninth harmonic undulator the range is around 3.3N to 5.62N. The measurements are repeated with the 250µm diameter wire for a shim to shim gap of 7mm and similar observations were seen for a gap of 7mm. The optocoupler and laser – photodiode sensors gives best matching results at 3.3N with 1.5% and 6% disagreement with the Hall probe data. The overall tension range is from 2.88N to 7.24N for both the sensors. The tension range is limited for all other higher harmonic undulator measurements. For undulator gap at 30mm (shim to shim gap of 10mm) the planar undulator measurements shows best results in 3.71N to 5.62N range. For biharmonic undulator measurements good agreement with the Hall probe data is obtained in the range of 3.71N to 4.82N. In Fig 11, we plot the comparative results for all the harmonic numbers. The measured data gives a disagreement of 62 Gauss and 97 Gauss at 24mm measurements at the 5th harmonic with the Hall probe data. At 27mm gap, the measurement gives a disagreement of 134Gauss and 245 Gauss at the third harmonic with laser photo diode and optocoupler sensor respectively. At this gap the 7th harmonic measurement disagree with the Hall probe data upto 200 Gauss with both the sensors. At a gap of 30mm, the PWM data disagrees with the Hall probe data by 66 Gauss and 252 Gauss with the optocoupler and laser sensor respectively for the planar undulator. For the ninth harmonic measurements the maximum disagreement is 152 Gauss by the optocoupler sensor. All these measurements give an important conclusion that the PWM data is close to the Hall probe data upto 250 Gauss maximum in our measurement setup.
Fig 10a: BRMS versus tension

Fig 10b: BRMS versus tension
The biharmonic measurements are repeated for the wire diameter of 125 $\mu m$. The PWM data are taken at 24 mm, 27 mm and 30 mm (Fig 12a, Fig 12b and}
Fig 12c respectively) for all the harmonic undulators. For a good agreement with the Hall probe data the tension range do not change appreciably for both the planar and biharmonic undulator measurements. Fig 13 gives a summary of all measurements. The optocoupler sensor shows a perfect matching results with the Hall probe results. The laser photo diode sensor data disagree with the Hall probe data. The disagreement is 210 Gauss and 250 Gauss for the 5th harmonic at a gap of 24 mm and 27 mm respectively. For the undulator gap of 30 mm, the laser sensor data disagrees from the Hall probe data by 80 Gauss and 34 gauss at the 3rd and 5th biharmonic undulator. At these harmonic undulator measurements, the optocoupler sensors data provide a discrepancy of 205 Gauss and 119 Gauss from the Hall probe results.

Fig 12a $B_{\text{RMS}}$ versus tension
Fig 12b $\text{BRMS}$ versus tension

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A pulsed wire system for magnetic measurements has been built and successfully tested with bi-harmonic undulators. The experimental results verify the applications and ability of the PWM to measure multi peak magnetic field profiles. To ensure the reliability and repeatability of the results, two detection systems with different principles are used in the set up. Two wires of different diameters are used. The results prove that the stiffness and thickness of the wire do not affect the PWM accuracy to detect multi peak sinusoidal magnetic field profiles. The 250 \( \mu \text{m} \) wire diameter and 125 \( \mu \text{m} \) wire diameter reproduce PWM data with an accuracy of 250 Gauss with that of The Hall probe data. Second, the 250 \( \mu \text{m} \) wire diameter and 125 \( \mu \text{m} \) wire diameter measurements gives another important observations on biharmonic measurements. The two wire gives good matching results at optimum tension. A variation from this value introduce errors in the measurements. The 250\( \mu \text{m} \) wire diameter gives good agreement with the hall probe data in a limited tension range in comparison with the planar undulators. This is not observed in the case of 125\( \mu \text{m} \) wire diameter. The biharmonic field undulator is represented as

\[
B = \sum_{h=1}^{N} B^n \sin (k_1 h z)
\]

In the biharmonic undulators the wire oscillates at two frequencies i.e. at the primary frequency and at the harmonic of the fundamental frequency. The wave velocity dispersion in the thick wire gives a narrow tension window for bi...
harmonic undulator measurements in comparison to the planar undulator measurements. This effect is not observed in the case of 125 µm wire diameter as the dispersion effect is proportional to the square of the wire diameter. Third, The laser sensor and the optocoupler works on different principles of light interception, however gives equal results at equal sensitivities. The measurement results are encouraging and as a further application of the PWM method, we intend to use the method for measurement of other novel undulators such as optical klystron undulator, step tapered undulator, crossed, crossed overlapped undulator. In the optical klystron undulator, two section of the undulator are separated by a dispersion section. The step tapered undulator is a two section undulator at different gaps. Crossed undulators are two different polarized undulators separated by a drift section. When the two crossed undulators are overlapped, it is termed as crossed overlapped undulator. Magnetic measurements of the field profiles of these type of undulators will increase the application of the PWM method.

REFERENCES


