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Improvements of the Pulsed-Wire Method to Measure Undulators+

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***Abstract* – In this paper, we will present the Pulsed-Wire Method (PWM) for undulators measurements used for the first crossed overlapped electromagnetic undulator OPHéLIE. This method gives directly the first integral of the magnetic field by use of short current pulse and the second integral using a step current pulse through the wire. We characterized OPHéLIE by use of the second integral mode to optimize the beam trajectory in the respect of specifications. There was a good correlation between these results and those obtained from the on-beam test. We were therefore encouraged to further develop this method to determine optical performances of undulators. In order to validate this approach we compared spectrum determined by pulsed-wire technique and Hall probe scans, used as reference, applied both to the OPHéLIE prototype, which is a shorter planar version. For the PWM, we used the short current pulse according to the undulator's period (the first integral mode). An introduction of digital data processing techniques has been used to improve the signal-to-noise ratio, to minimize the effect of the background vibrations and characterize the wire's response.**

I. INTRODUCTION

OPHéLIE [1], the first crossed electromagnetic undulator, was characterized with the Pulsed-Wire Method (PWM). There was good correlation between these results and those obtained from the on-beam tests. We tried to develop this method to directly obtain the electromagnetic spectra associated with the undulators.

For an optimal performance, undulators require a fine tuning of the magnetic field, which is time-consuming in the case of Hall probe measurement. This duration is strongly reduced by the Pulsed-Wire Method.

However, this method suffers from acoustic noises and non-stationary gain brought about by the optical sensor.

Filtering and smoothing techniques have been put to work to reduce these drawbacks.

The electromagnetic spectra obtained by the PWM method are compared to those given by a Hall probe.

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II. APPLICATION TO OPHÉLIE

A. *The pulsed-wire method*

R. Warren [2] has developed a method to measure undulators. This method consists of sending a short current pulse through a wire in order to measure the magnetic field first integral.

$$x(t) = -\frac{I_o}{2\mu c}\Delta t \int_o^{ct} B(z)\,dz \qquad (1)$$

where I_o is the current injected in the wire, μ the linear mass, c the velocity of the wave along the wire. Δt is the current pulse width. This relation is valid only if Δt is smaller than the wave time period. With a longer pulse, we can directly obtain the second integral through the relation :

$$x(t) = -\frac{I_o}{2\mu c^2}\int_o^{ct} dz \int_o^{z} B(u)\,du \qquad (2)$$

The 125 µm-diameter wire of CuBe is stretched by a mass of 750 g. The current injected in the wire is 0.3 A and the pulse width 25 ms . The vibration x(t) is detected by an optical sensor (laser diode + photodiode) and visualized through a numeric oscilloscope (8-bit resolution).

The space integrals are taken over the bounded interval where the applied magnetic field is significant ; the time integral is taken over the current pulse durations.

The PWM has been used in order to fulfil the following requirements :

1. For all main field values, the photon source, supposed to be located at the middle of the undulator, must be centred within ± 40 µm in both planes which requires that the particle path remains on axis.
2. The undulator exit position must not exceed ± 40 µm in both planes.
3. The undulator exit angle must not exceed ± 40 µrad in the horizontal plane and ± 15 µrad in the vertical plane which corresponds to the maximum acceptable value of closed orbit distortion.

Requirements 1 and 2 are fulfilled by the means of correction coils located at each end of the undulator.

The requirement 3 is fulfilled by the means of the compensation coils mounted on the main poles.

Fig. 1 presents the transverse excursion of the particle beam measured when using PWM after finding an adequate balance between the currents in the correction coils. The vertical undulator current is set successively to 100 A, 150 A and 200 A for a phase-shift between Horizontal and Vertical field components. The central point of the average excursions and the exit positions remain into the required tolerances (< 30 µm on the Fig. 1).

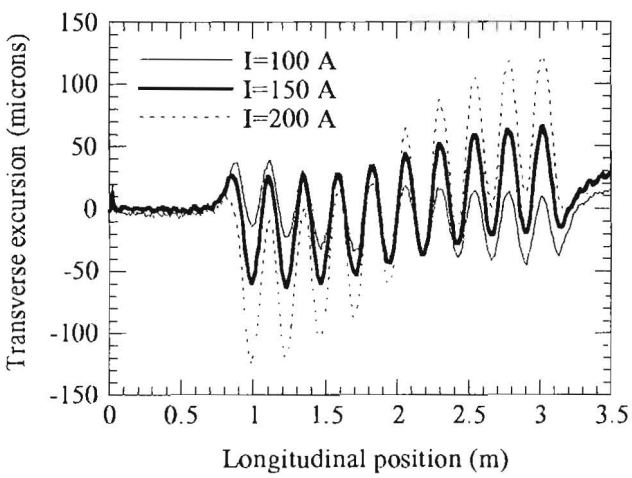

Fig. 1.

B. Improvement of the method

If we neglect the loss induced by air friction, the dynamic system is governed by the following equation.

$$\frac{\partial^2 x}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 x}{\partial t^2} = -\frac{1}{\sigma} B(z) I(t) \qquad (3)$$

$$\text{where } c = \sqrt{\frac{\sigma}{\mu}}$$

where σ is the tension and µ the mass per unit length of the wire. Considering the wire as infinite the solutions are :

For a short pulse current :

$$x(t) = -\frac{I_o}{2\mu c}\,\Delta t \int_o^{ct} B(z)\, dz \qquad (4)$$

For a short length magnetic field :

$$x(t) = -\frac{B_o}{2\mu c}\,\Delta z \int_o^{t} I(u)\, du \qquad (5)$$

where B_0 is the magnetic field and Δz the field length.

As we can see, the role of the current and the magnetic field are fully interchangeable.

This property was used to improve the pulsed wire method.

C. Introduction of an adaptive filtering

Compared to the Hall probe scans, the PWM is much faster. But this increase in speed goes along with a degradation in the signal-to-noise ratio.

One of the methods to reduce noise is to increase the current in order to have bigger signal amplitude. Another is to average the signal which means that we inject a few current pulses through the wire, waiting between each pulse for the wire to stop moving.

As the response of the optical detector is non linear on the whole range, both methods can introduce significant distortion of the signal.

Our approach was to inject small currents in order to remain in the local linear area of the detector and introduce adaptive filtering to improve the signal-to-noise ratio.

We decided to use a Wiener filter. The procedure is decomposed in two steps. The first one called the learning phase where the algorithm calculates the coefficients of the kth order filter in order to have its output as close as possible to a reference signal (Fig. 2). The second one is the smoothing phase where we applied the filter calculated previously to the measured signal representative of the integral of the magnetic field.

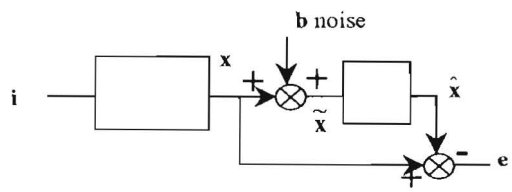

Fig. 2. Principle of the adaptive filter.

The learning phase has been achieved by introducing a permanent magnet, considered as a short length magnetic field, around the wire, far enough from the undulator. The current **i**, flowing through the wire is delivered by a wave generator. Introducing this current and the magnetic field in (5) the response of the wire **x** is the integral of the current. We used the algorithm to calculate the optimal filter according to the minimization of the average quadratic error J :

$$J = \Sigma\,[\mathbf{x} - \hat{\mathbf{x}}]^2 \qquad (6)$$

Where $\hat{\mathbf{x}}$ is the estimated vibration signal elaborated by the Wiener filter from the noisy measured signal $\tilde{\mathbf{x}}$ supplied by the position sensor.

Therefore, $\hat{\mathbf{x}} = \mathbf{w}^T * \tilde{\mathbf{x}}$ (7) * : convolution product.

Then the average quadratic error was :

$$J = \Sigma(\mathbf{x} - \mathbf{w}^T * \tilde{\mathbf{x}})^2 \qquad (8)$$

The error J should be minimum when its partial derivatives with respect to all the filter's coefficients **w** are zero :

$$\frac{\partial J}{\partial w_i} = 0 \qquad \text{for } i=0,1,\ldots,k$$

In order to obtain these conditions, the coefficients **w** of the filter must verify the Wiener relation :

$$\mathbf{w} = R^{-1}.\,\mathbf{p} \qquad (9)$$

where R : autocorrelation matrix of $\tilde{\mathbf{x}}$

p : covariance vector of $\tilde{\mathbf{x}}$ and **x**.

Therefore, the coefficients of the filter characterize the wire and sensor system and they were used for the smoothing phase to suppress the noise.

D. Application to the first integral measurement

In order to verify the validity of the filtering, we characterize an undulator and try to deduce its optical power spectrum. This undulator is a 5-periods one and it is the shorter planar version of OPHéLIE with $B_o = 0.095$ T and $\lambda_o = 0.12$ m.

First, we measured it by usual Hall probe scan and deduced the associated optical spectrum. We ompared this spectrum with the one obtained through our wire method.

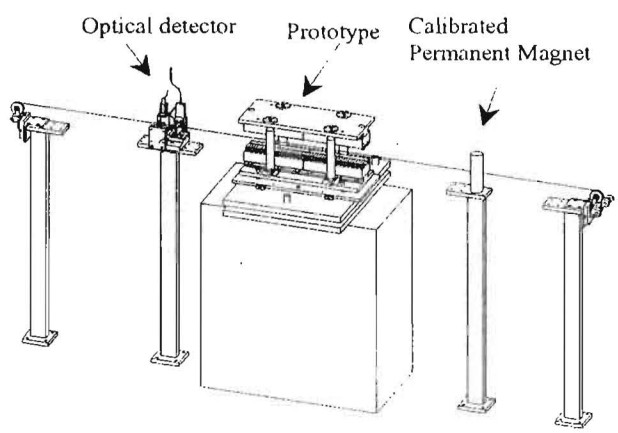

Fig. 3. Arrangement of the PW gear.

To stimulate the wire system under realistic conditions, the current (Fig. 4), is proportional to the magnetic field computed by a 3D model of the undulator with OPERA 3D [3].

The first part of the current wave is used to calculate the filter's coefficients (learning phase) and the second part (smoothing phase) to measure the undulator field integral.

The delay between these two stimulations is about 9 ms and we assumed that the wire's parameters remain stable during this delay.

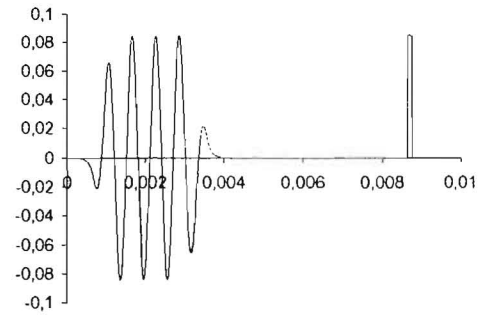

Fig. 4. Current (A) versus time (s).

In Fig. 5, we show the filtered response of the wire stimulated by current shown in Fig. 4. The first part of the signal is the integral of the cross-correlation between the undulator magnetic field and the sinus-like current. The second part (extracted for spectrum calculations) is the integral of the undulator magnetic field. The last part is the integral of the sinus-like current.

The different parameters of the experiment are :

$I_o = 85$ mA, $\Delta t = 100$ µs, $\mu = 0.101.10^{-3}$ kg/m, $c = 200$ m/s, $I_{max} = 17.10^{-4}$ Tm where I_{max} is the amplitude of the integral of the magnetic field

Under these conditions the amplitude of the wire deflection was about 0.36 µm. This small amplitude insures that the consequences of the wire stiffness may be neglected.

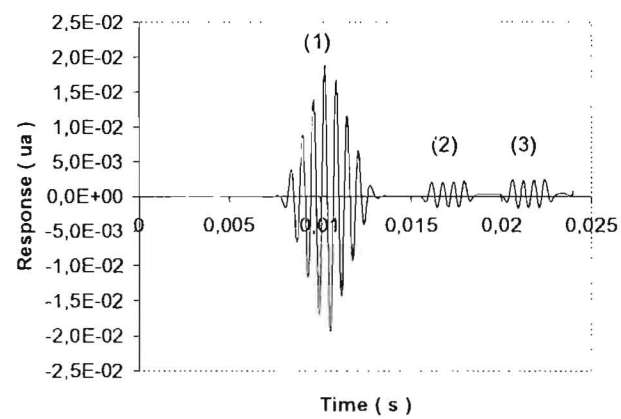

Fig. 5. System response.

E. Spectrum calculations

J.-M. Ortéga [4] has proposed a way to calculate the optical power spectrum (OPS) directly from the field first integral.

$$\mathrm{OPS}(\omega) = \frac{e^2}{4\pi^2 c}\omega^2 \left| \int \beta_x(z) e^{\frac{i\omega}{2c}\left(\frac{z}{\gamma^2} + w_x(z)\right)} dz \right|^2 \qquad (10)$$

with $\beta_x(z) = \frac{1}{B\rho}\int_0^z B(u)\,du$ where $B\rho$ is the magnetic rigidity of the beam and $w_x(z) = \int_0^z \beta_x^2(u)\,du$.

Fig. 6 and Table. 1 illustrate the comparison between OPS from Hall scan and PWM.

The major difference between these two measurements comes from the acquisition time : 13 min for Hall probe and 30 s for PWM (both including spectrum calculations). The result obtained from both methods are very similar in terms of OPS. The difference between all the main quantities in which we are interested is less than 5 %.

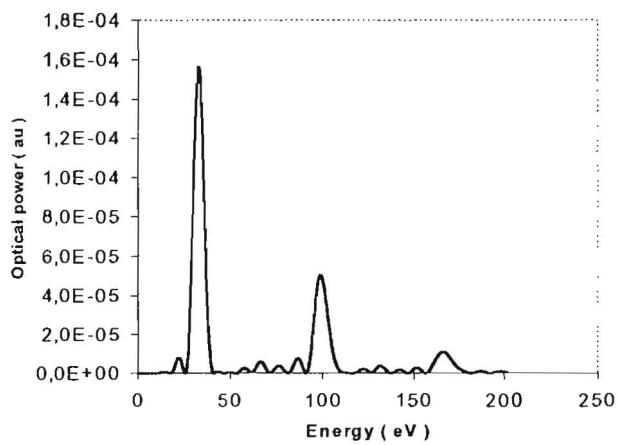

Fig. 6. Spectrum from PWM.

	Hall probe		PWM	
	Energy (eV)	OPS ($x10^{-4}$)	Energy (eV)	OPS ($x10^{-4}$)
Harm #1	32.842	15.65	33.126	15.70
Harm #3	98.770	5.08	99.217	5.17
Harm #5	166.278	1.11	165.965	1.13

Table 1. Comparison of spectra from Hall probe and PWM for different harmonics (Harm)

In Fig. 7, we introduced a local reduction of the gap by inserting a soft-iron thin sheets. The result is the disappearance of the fifth harmonic

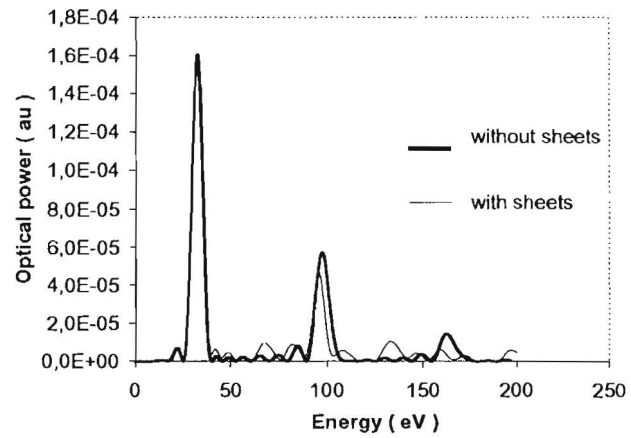

Fig. 7. Spectrum with localized reduction of the gap.

III. Conclusion

The PWM predicted efficiently the electromagnetic spectrum of the OPHéLIE prototype. In order to certify the wire method, it has to be tested on a longer, stronger undulator as well as on minigap.

IV. Acknowledgments

We would like to acknowledge Amor Nadji and Philippe Peaupardin for their helpful discussions.

V. References

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