# Improvement of High Accuracy X-ray Thickness Gauge for Metal Plate

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Abstract
In order to improve the accuracy of sheet and strip thickness measurement, a kind of improved differential evolutionary algorithm based on double exponential model was proposed for data fitting. Combined with the polynomial fitting algorithm, it reduced the relative error of the measurement; combined with bidirectional voltage doubling rectifying technology, a novel phase shifted control electric zero voltage switch PWM converter was used to realize soft switch. This paper designed a high voltage power supply with 70kV adjustable constant voltage and constant current. By using alternating current non-saturated control filament current to realize constant current, it prolonged the service life of the X-ray tube, realized bi-fold voltage, and reduced level of withstand voltage. The algorithm was implemented by STM32CPU and the 0-4mm steel was measured. Within the range of 0-1mm, the accuracy of the results is 0.001mm and the reaction time is better than 5ms.
Keywords: DOUBLE EXPONENTIAL MODEL, DIFFERENTIAL EVOLUTIONARY ALGORITHM, POLYNOMIAL FITTING ALGORITHM, X-RAY

## 1. Introduction

X-ray detection technique has been widely used in fields of industrial nondestructive detection such as defecting segmentation of weld image, security inspection, exploration, archaeology, medical science, thickness measurement, and so on[1-3]. Because of the fast development of steel industry and technological level in recent years, all industries are strict in the quality of sheet and strip, especially the thickness, which is the most strict and direct factor, and has raising global concern of metallurgical industry in the world.

Compared with the uncontrollable factors of isotope and temperature influence of eddy current, X-ray can be controlled and won't be influenced by temperature. So X-ray thickness gauge can measure and control sheet thickness on roll mill production lines and is widely researched. A new nonlinear model is put forward in [4] and the exponential in mono-energetic nonlinear model is replaced by polynomial model in [5], thus the single exponential model is converted to a multiple one. This method shows good performance of accuracy and stability when standard plates are few and uneven nonlinear distributed. Although particle swarm optimization (PSO) algorithm can change the influence of technological parameters through online optimization and also improves the quality of strip steel in [6], it is easily influenced by initial weight, particle location and speed, etc. While differential evolution (DE) is a random search based global optimization algorithm which is not influenced by initial value and has no need of derivation as well as faster convergent speed than PSO [7]. The effect of alloy compensation under narrow-band mono-energetic ray is obvious, and the relative error of measurement for stainless steel decreases to 0.1% [8]. Because of the effective description of double exponential model to the typical electromagnetic pulse wave [9] and advantages of DE algorithm, DE algorithm is used in double exponential model fitting in [10]. This method shows good measurement accuracy in actual thickness gauge research. But the accuracy becomes low as the steel thickness rises.

In order to avoid that disadvantage, this paper proposes a new algorithm combining double exponential fitting and polynomial fitting with DE algorithm. The new algorithm applies increasing the calibration value and polynomial fitting to improve the accuracy when the range of increasing thickness is large. To reduce the loss of switches and improve the switch power stability, this paper designs a high voltage power supply with 70kV adjustable constant voltage and constant current using a novel phase shifted control electric zero voltage switch PWM converter which is used to realize soft switch and bidirectional voltage doubling rectifying technology.

**2. Principle of X-ray thickness gauge and improving algorithm**

X-ray detector detects the X-ray after traveling through the analyte and outputs a signal whose strength is relative to the strength of the X-ray.

As is shown in Figure 1, X-ray strength detected by X-ray detection is relative to the output current strength and can be converted to voltage signal as follows:

$$V_1 = V_0 e^{-\mu d} \tag{1}$$

Where, $V_0$, $V_1$, $\mu$ and $d$ represent the voltage with no object, voltage with object, effective attenuation coefficient of X-ray for the object and the thickness of the object, respectively. $\mu$ is relative to the density of object, atomic number, ray length, and so on.

Taking logarithm of both sides in formula (1), we can get the following formula.

$$\ln V_1 = \ln V_0 - \mu d \tag{2}$$

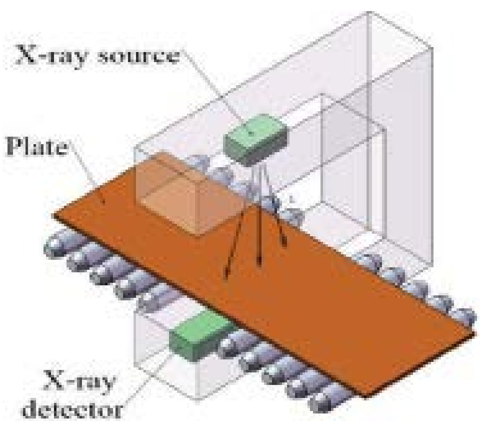


**Figure 1.** Schematic diagram of X-ray measuring

From formula (2), we can know that $\ln(V_1/V_0)$ is proportional to $d$ in mono-energetic X-ray measurement. Better measurement effect can be achieved by correcting multi-energy spectrum effective attenuation coefficient of X-ray $\mu$ with negative exponent [11]. Double exponential model can effectively describe electromagnetic pulse and can describe target values of corresponding parameters more accurately than single exponential model. So four-parameter double exponential model is used for data fitting and here is the form.

$$\begin{aligned} & y = ae^{-bx} + ce^{-dx} \\ & s.t. \quad y, x \ge 0 \end{aligned} \tag{3}$$

Where $y$ is 1000 times of the sampled voltage and $x$ is the object thickness.

In order to reduce the influence of the initial value on the global optimal solution, DE algorithm is used for double exponential fitting. First, formula (3) is transformed to constrained nonlinear optimization problem as follows

$$\begin{aligned} & \min \sum_{i=1}^{n} (ae^{-bx_i} + ce^{-dx_i} - y_i)^2 \\ & s.t. \quad y|_{x=0} = a + c \,\&\, b, d > 0 \end{aligned} \tag{4}$$

Then DE algorithm is used to fit $a$, $b$, $c$, $d$ in formula (4) and the improved constrained optimization problem is

$$\begin{aligned} & \min f(z_1, z_2, \ldots, z_D) \\ & s.t. \quad z_j^L \le z_j \le z_j^U \end{aligned} \tag{5}$$

Where D is dimension of solution space and the value is 4. $z_j$ represents $a$, $b$, $c$, $d$ and j=1, 2, 3, 4. $z_j^L$ and $z_j^U$ represent upper and lower bounds of the $j$th parameter. From formula (4) we can know that the sum of $a$ and $c$ is constant so that four parameters are simplified as three parameters thus the computational complexity is reduced effectively. DE algorithm fitting mainly consists of three steps.

Initialization

$$Z(0) = \{z_i(0) \,|\, z_{i,j}^L \le z_{i,j} \le z_{i,j}^U\} \tag{6}$$

Where $i$ and $j$ represent the number of individual and parameter, respectively. $z_{i,j}(0)$ represents the $jth$ parameter of the $ith$ individual in 0 generation species Z(0) ($i \in$[1, 2,…, N], $j \in$[1, 2, 3]) and is randomly produced by the following formula.

$$z_{i,j}(0) = z_{i,j}^L + rand()(z_{i,j}^U - z_{x,j}^L) \tag{7}$$

Where rand() is a random function and can produce data distributed uniformly between 0 and 1.

2) Reproduction

New individuals are generated through performing variation and cross operation to individuals in population, so as to realize local searching and global optimization and therefore avoid local optimization is avoided. Difference operation are made between two random selected individuals to fix individual for variation, namely

$$v_i(g+1) = z_i(g) + F(z_{r1}(g) - z_{r2}(g)) \quad (8)$$

Where $r1$ and $r2$ represent sequence number of two selected individuals. $F$ is mutation factor and $g$ represents generation number. Variation avoids local optimization and can search for global optimization. Cross operation can realize diversity of parameter interference. When running local research, formula (9) can be applied to perform cross operation to individuals in population with the probability of $Cr$ so as to create new individual population.

$$u_{i,j}(g+1) = \begin{cases} v_{i,j}(g+1), & rand() \le Cr \\ z_{i,j}(g), & otherwise \end{cases} \quad (9)$$

3) Selection

By using target evaluation function to make greedy selection for individuals, the next population individuals are generated.

$$z_i(g+1) = \begin{cases} u_i(g+1), f(u_i(g+1)) \le f(z_i(g)) \\ z_i(g), \quad otherwise \end{cases} \quad (10)$$

DE algorithm can reach global optimal convergence without derivation and has a faster derivation speed than PSO algorithm [9]. Polynomial fitting through formula (11) is used to improve accuracy when the thickness increment is high.

$$d = a_0 + a_1(\ln V) + a_2(\ln V)^2 + \cdots + a_n(\ln V)^n \quad (11)$$

**3. X-ray high-voltage power supply**

In order to generate stable X-ray strength, the phase shifted control zero voltage switch PWM converter which is used to realize soft switch and bidirectional voltage doubling rectifying technology are used. So the stability of power voltage is improved and the ripple size is reduced [12, 13]. To improve the stability of power supply and reduce the volume of power supply, technologies such as Royer resonance, proportional integration differential (PID) control, slope design of linear gradient can be used [14, 15]. Anode of X-ray tube power is supplied with 24V voltage and converted to positive and negative square-wave signal of a 24V voltage through half-bridge inverter. Then this signal is sent to primary part of the high frequency step-up transformer. And then the output signal of it is a positive and negative square-wave signal with about 4000V voltage. This high voltage square-wave signal is converted to 70KV direct current signal by 10 times plus and minus bidirectional voltage doubling rectifying. ARM processor gets the output voltage by voltage sampling module and voltage A/D conversion module. D/A conversion module controls the output duty ratio of the PWM phase shift module and adjusts the output voltage to make the change rate better than 0.1%.

X-ray tube filament is powered by 24V voltage through power system and converted to positive and negative square-wave signal of a 24V voltage through half-bridge inverter. Then this signal is converted to sine wave signal of about 4V through isolation transformer. ARM processor gets the filament current by current sampling module and voltage A/D conversion module. D/A conversion module controls the output duty cycle of the PWM phase shift module and adjusts the output voltage as well as the filament current combining the anode power to make the change rate better than 0.1%.

The power block diagram is shown in Figure 2 and the entity of X-ray power is shown in Figure 3. The system main circuit is powered with 24V voltage. In order to make less voltage bias ensure constant current, LM7824 is used for voltage stabilizing.

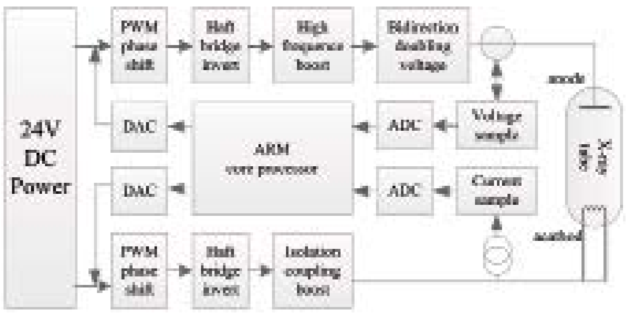


**Figure 2.** Block diagram of X-ray power

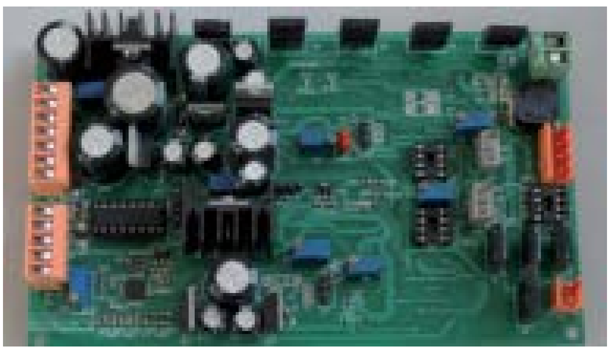

**Figure 3.** Entity of X-ray power

SG3525 is used as the phase shifted control module of PWM and the control circuit is shown in Figure 4. Soft start capacitor of the input soft start pin is 47*uF*. SG3525 starts work when the capacitor is charged and the soft start pin voltage is high.

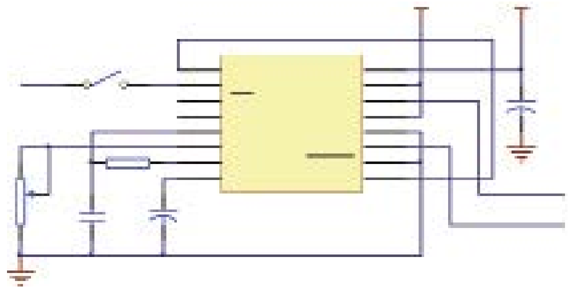

**Figure 4.** PMW control circuit

The control power with positive and negative bidirectional voltage doubling rectifying circuit is shown in Figure 5. The basic principle of it is as follows. When the input voltage Vi is in its positive half cycle, C47 is charged to the peak of Vi by current ID11 through D11. When the input voltage Vi is in its negative half cycle, C48 is charged by peak value of Vi plus voltage across C47. Voltage across C48 reaches twice of Vi voltage when charged by ID12 through D12. The positive and negative procedures repeat continually. The final result is that voltages across C48, C50, C52, C54, C56 reach twice voltage of Vi and the left side is positive and voltages across C38, C40, C42, C44, C46 also reach twice voltage of Vi and the left side is positive. The left side of C48 is earthed and the left side of C46 acts as high voltage output. The output voltage is sum of absolute value of positive and negative voltage and the value can reach 70KV.Pulsation coefficient is the sum of vector and the positive and negative value cancel out. So the system output ripple is very low.

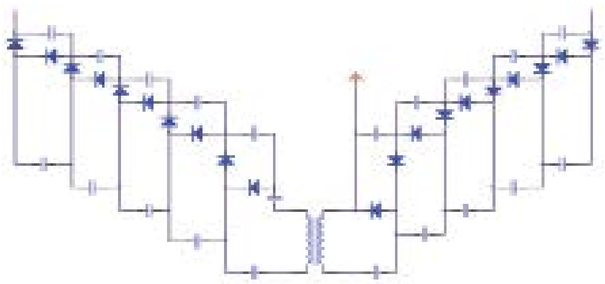

**Figure 5.** Bi-directional doubling voltage rectifing circuit

High voltage power influences the system a lot and can make nonreversible damage if it is out of work. So this module is separately tested. Agilent 34401A avometer with high accuracy of 6.5 bits is used to inspect the voltage and the test result is showed as Table 1.The result shows the power stability is good.

**Table 1.** Stability test of high voltage power

| Voltage of X-ray cube | 32500V | 65000V | 72000V |
|---|---|---|---|
| Intrinsic error | 0.30% | 0.40% | 0.42% |
| Repeatability | 0.05% | 0.06% | 0.08% |
| Long time drift(8h) | 0.08% | 0.11% | 0.12% |

**4. Analysis of measured results**

Small signals collected by X-ray detector are sent to serial communication module by STM32CPU after being amplified and converted by A/D conversion. Accuracy of model meets command when the thickness-voltage samples are sufficient. So adequate testing is made to thickness detecting module by different voltages of X-ray tube and the test results of steel plate are compared to copper plate. As is shown in Figure 6, the measured voltage and sheet thickness fit the exponential relation estimated by (2).

Voltage of X-ray tube also influences the measured value from Figure 6. In macroscopic view, work voltage decrease makes measured voltage decreasing evidently. Increase of sheet thickness and decrease of work voltage make environmental error increase on account of inherent electromagnetic noise interference in space. Given that increasing work voltage of X-ray can cause bad influence on human health, environment radiation safety and equipment life, voltage should be reduced as possible among the range of measure error. In addition, different materials absorb different degrees of X-ray by comparison of copper testing result. So sampling points data should be rebuilt when the measured material changes.

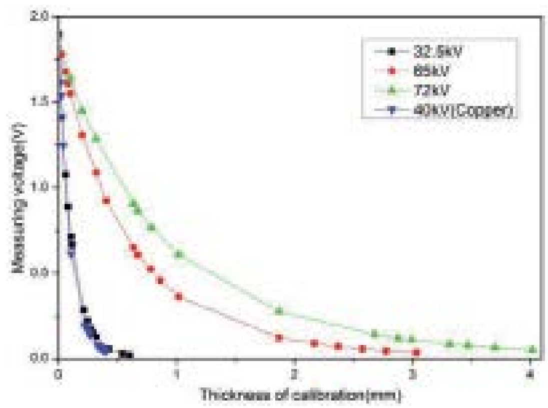


**Figure 6.** Relationship between thickness of plate and measurement voltage

The results of the steel plate thickness measured by double exponential model obtained through fitting the above sampling values of steel plate is shown in Figure 7.

In order to directly display the measured accuracy, relative error of the measured steel thickness is calcu-

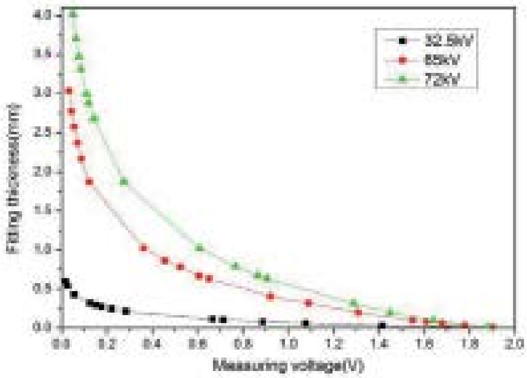


**Figure 7.** Relationship between measurement voltage and fitting plate thickness

lated. The result shows that the error increases obviously when the work voltage is as low as 32KV and the sheet thickness is larger than 0.2mm. The error increases until the thickness increases to 2mm when the work voltage is high. In order to improve the accuracy, this algorithm increases the calibration value and applies polynomial fitting. The measured relative error compared with the double exponential model is shown in Figure 8.

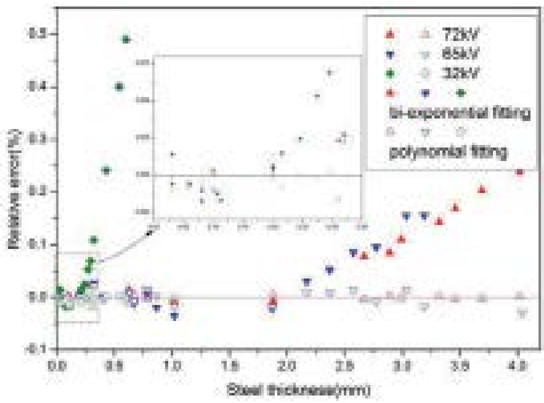


**Figure 8.** Relative error of thickness of measurement

Increase of the calibration value brings large cost of human and material resources at the same time. So polynomial fitting is only used for correcting when the thickness is large. The relative measurement error is less than 0.05% after revision. We use A/D converter from Texas Instruments company to realize high speed A/D conversion and the concrete type is ADS1191 Σ-Δ which has a 16 bit sampling accuracy and 8Ksps conversion speed [16]. The result shows that the accuracy can reach 0.001mm when the thickness is among 0-1mm, and the response time is less than 5ms.

**Conclusions**

Based on the double exponential model, an improved differential evolution algorithm combined with the polynomial model is used for data fitting which has been proved to reduce relative error measured by X-ray thickness gauge with the measurement precision better than 0.05%. To design a high voltage power, a novel phase shifted control zero voltage switch PWM converter is used to realize soft switch. Combined with bi-directional voltage doubling rectifying technology, a 70kV power with adjustable constant voltage and constant current is realized. Thus it prolongs the service life of the X-ray tube. The algorithm is implemented with STM32CPU. Measurement made on steel with thickness among 0-4mm and the results show that the accuracy can reach 0.001mm and the response time is less than 5ms when the thickness is less than 1mm.

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# An Experimental Study: Effect of Technological Parameters on Cutting Force in Processing Hetian Jade by Ultrasonic Grinding

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Abstract
Jade is hard to be processed into jewelry, and it is even more difficult for the Hetian jade that produced in Xinjiang, China. In a conventional processing technology, the cutting force can hardly be controlled precisely, which would result in a low level of product quality. With taking into account of Hetian jade's characteristics, the ultrasonic vibration grinding, a processing method, is used in our experimental study in this article, in which, the effect of different processing parameters on cutting force has been controlled. Experimental results show that changes of