Monte Carlo simulation of X-ray backscatter detection for the seam tracking when welding sandwich panels

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Abstract. The I-core sandwich panels are widely utilized in manufacturing lightweight structures in a variety of fields, such as aviation, aerospace, shipping, and so on. However, due to their structural characteristics, it is difficult to track the weld seam automatically in the welding process. At present, a detection method based on the backscattered X-rays is widely used for seam tracking of the sandwich panels. The conventional modelling based on analytical method has been applied in the simulation of X-ray backscatter detection system, but analytical method has a deviation from the actual situation under the low X-ray intensity. In this paper, a simulation model based on Monte Carlo method is proposed to simulate the X-ray backscatter detection system for the automatic seam tracking in the welding of such sandwich panels. The effect of photon energy and beam intensity on the detector counting is analysed. The result shows that the proposed method can accurately simulate the X-ray backscatter detection system for the automatic seam tracking when welding sandwich panels; the proposed simulation method can provide more accurate simulation results and more time domain information of photons at a relatively low beam intensity. The proposed method can also provide information as a basis for the optimization of the X-ray backscatter detection system at a relatively low dose.

1. Introduction
As a type of lightweight structure, as illustrated in figure 1, the I-core sandwich panels could offer high strength to weight and stiffness to weight ratios, make it available in a variety of manufacturing fields, such as rocket engine nozzle [1], aircraft wings, and ship bulkhead [2] and so on. In the sandwich structure, cover sheet is commonly welded to mid wall by laser above the cover sheet at the joint of the cover sheet and mid wall. The laser penetrates the cover sheet and reaches upper part of mid wall and the molten zone joins as it cools down. However, it is difficult to detect the location of joint of the cover sheet and mid wall during the welding process, which resulting in mismatch in location between weld and mid wall and further other quality problems. In order to reduce the occurrence of such problems, the stability of the welding process is further enhanced with an X-ray backscatter detection system, making it possible to detect the hidden mid wall behind the cover sheet [1].

At present, some scholars use analytical method to describe the X-ray backscatter detection system [3-5]. The analytical method make many simplifications and approximations of the detection system in...
the modelling process, such as the approximation of the Compton scattering with matter based on Klein-Nishina formula, estimating the absorption efficiency of the detector for X-ray photon based on experience, simplification of physics process based on the X-ray photon energy and so on. This causes the analytical method to deviate from the actual result in some situations, especially at relatively low beam intensity. Compared with traditional analytical method, Monte Carlo method which also called random sampling or statistical experimental method are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. Their essential idea is using randomness to solve problems that might be deterministic in principle. Monte Carlo method is capable of getting the approximate optimal solution on any size of samples. The high energy particle, such as X-ray photon and gamma photon, whose transportation and interaction with matters are a typical physical process described by probabilities, lends itself naturally to be simulated by Monte Carlo. Thus, the simulation based on Monte Carlo method is to acquire approximate optimal solution about the distribution of remaining photons in the space in the stochastic physical process such as photons collision, absorption, scattering and refraction at arbitrary sample sizes.

In this paper, a simulation model based on Monte Carlo method is proposed to simulate the X-ray backscatter detection system for the seam tracking of welded sandwich panels. The proposed method mainly simulates the transport process of X-ray photon in discrete form. The proposed method can more accurately simulate the interaction mechanism of collisions, scattering and absorption of X-ray photons with matter to obtain more accurate simulation results and furthermore describe the physical process under the low-size sample (low radiation dose).

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Figure 1. Welded sandwich panels.

2. Modelling

2.1. Physics process
As illustrated in figure 2, a well-collimated pencil-beam of X-rays is directed toward the workpiece, and the X-rays backscattered from the workpiece are collected by detector. In the detection process, both the photon energy and beam intensity of x-ray beam are decaying step by step. The decaying path mainly consist of the following parts: a) the attenuation of the incident beam in the workpiece; b) the backscattering of the incident beam by the workpiece; c) the attenuation of the backscattered beam in the workpiece. The attenuation of beam intensity in the air could be temporarily ignored.

In the detection process, the forms of interaction of X-ray photon with matter include: Photoelectric Effect, Compton Scattering, pair production, Rayleigh scattering, Bremsstrahlung, Ionisation, MultipleScattering. As X-ray backscatter detection system typically use relatively low energy X-ray (10keV~100keV), the predominant modes of photon interaction at relatively low photon energies would be Photoelectric Effect and Compton Scattering. Compton Scattering is the most dominant interaction mechanism in this tissue.
2.2. Set-up for simulation
As illustrated in figure 3, the X-ray backscatter detection system consists of X-ray Source, workpiece and detector. During the detection process, a pencil-beam of X-rays is directed toward the workpiece, then X-rays are backscattered from the workpiece to the detector which receives the backscatter signal, the model in the simulation process is depicted as figure 3.

2.2.1. Workpiece. As illustrated in figure 3, the I-core sandwich panels are composed of cover sheet and mid wall, which are both made of Ti6AlV with a size of 200mm*100mm and a thickness of 3mm, the main composition of Ti6AlV is summarized in table 1.

|   | Ti | Fe | C | N | H | O | Al | V |
|---|----|----|---|---|---|---|----|---|
|   | balance | ≤0.30 | ≤0.10 | ≤0.05 | ≤0.015 | ≤0.020 | 5.5~6.8 | 3.5~4.5 |

2.2.2. X-ray source. It is primarily to define two parameters of X-ray source: photon energy and beam intensity. Photon Energy is the energy of single photon in the X-ray beam produced by X-ray source. X-ray beam intensity is the amount of photons make up the beam [6].

X-ray photon Energy is a measurement of the penetrating power of the X-ray beam. In order to ensure the sufficient beam intensity which detector could receive, the incident beam must have enough energy to overcome the attenuation of cover sheet at least. In this paper, we need to detect the mid wall through the 3mm thick cover sheet, thus, the incident beam must overcome the attenuation of the 3mm thick cover sheet to the intensity of incident beam and backscattered beam at the same time. The attenuation of beam intensity in the cover sheet is calculated for different incident photon energies.
summarized in table 2, the linear attenuation coefficient of the material in the table is derived from the reference [7].

| Primary Photon Energy (keV) | 30  | 40  | 50  | 60  | 70  | 80  |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| Linear attenuation Coefficient of incident beam (cm⁻¹) | 22.9 | 10.0 | 5.4 | 3.44 | 2.3 | 1.82 |
| attenuation length of incident beam in the cover sheet (mm) | 3  | 3  | 3  | 3  | 3  | 3  |
| Penetration ratio of incident beam (%) | 0  | 5  | 19.8 | 35.6 | 50 | 58 |
| Photon Energy of scattering angle of 135 (keV) | -  | 35 | 42 | 50 | 57 | 63 |
| Linear attenuation Coefficient of backscattered beam (cm⁻¹) | -  | 15 | 8.6 | 5.4 | 3.8 | 3  |
| attenuation length of incident beam in the cover sheet (mm) | -  | 3/cos135˚ | 3/cos135˚ | 3/cos135˚ | 3/cos135˚ | 3/cos135˚ |
| Penetration ratio of incident beam (%) | -  | 0.17 | 2.6 | 10 | 20 | 28 |

As illustrated in table 2, the X-ray beam with photon energy of 30 keV is not capable of penetrating the cover sheet made of Ti6AlV. Meanwhile, the intensity of the remaining intensity reaching the detector of 40 keV is too small to cause the detector to obtain effective backscatter signal. Therefore, in order to ensure the intensity of the backscattered beam reaching the detector, we setup the photon energy of the X-ray source to be above 50keV.

In the case of constant photon energy of incident beam and scattering angle at which the detector receive the backscattered x-rays, the greater the intensity of the beam emitted by the X-ray source, the backscattered intensity of the backscattered beam detector could receive from the workpiece would be greater. The effect of the statistical error of detector counting on the detection accuracy would be less, the detection accuracy would be higher. Hence, this paper set the intensity of 1*10⁸.

In addition, the scattering probability of single photon by workpiece is related to photon energy. The lower energy cause the bigger scattering probability. Therefore, we set the low energy on the premise of overcoming the attenuation of the workpiece. At the same time, X-ray is a result of ionizing radiation, with a certain degree of radioactivity, it is necessary use relatively low energy X-rays on the premise of the detection requirement.

| Table 3. The detailed parameters of X-ray backscatter detection system. |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| X-ray source              | X-ray beam direction | (0,-1,0)     | X-ray source location     | (0,106,0)  | X-ray beam intensity | 2*10⁷/5*10⁷/7*10⁷/1*10⁸ |
| Workpiece                 | Cover sheet(material) | Ti6AlV     | Cover sheet(dimensions)   | 200mm*100mm*3mm | Mid wall(material) | Ti6AlV  |
|                          | Mid wall(dimensions) | 200mm*100mm*3mm | The gap between cover sheet and mid wall | 1mm   | detector                | material | NaI crystal |
|                          |                  |                  |                          |                  | dimensions      | 50mm*50mm*30mm |
|                          |                  |                  |                          |                  | The distance between source and focal spot | 106mm   |
|                          |                  |                  |                          |                  | The distance between detector and focal spot | 120mm   |
|                          |                  |                  |                          |                  | The cut-off value for photon energy | 0.1mm   |

In summary, this paper set the photon energy in the range of 50 ~ 80keV, beam intensity of 1 *10⁸ and the distance between X-ray source and focal spot of 106mm. Detector. As illustrated in figure 3,
the detector is a NaI crystal with a size of 50mm*50mm and a thickness of 30mm. The detector is located at a distance of 120mm from the focal spot position as shown in figure 3. The detector is located at angle of 135° relative to the incident photon direction.

The detailed parameters of X-ray backscatter detection system are shown in table 3.

3. Results and discussion

In this paper, Geant4 simulation software was used to model and simulate X-ray backscatter detection system, and the effect of X-ray photon energy and beam intensity of X-ray on detector counting was analysed. Geant4 is a Monte Carlo-based high-energy particle transport simulation software toolkit developed by the CERN [8]. The simulation model for the detection system is shown as figure 4, the line represents the track of single photon until ‘death’, the points on the line represent the interactions with matter in the track process.

![Figure 4](image)

**Figure 4.** The schematic of Monte Carlo simulation model.

3.1. Simulation results

As illustrated in figure 3, the X-ray backscatter detection system is consist of X-ray Source, workpiece and detector. During the detection process, a pencil-beam of X-rays is directed toward workpiece, then X-rays are backscattered from workpiece to the detector which receive the backscatter signal, the model in the simulation process is depicted as figure 4.

X-ray intensities are measured by counting photons \( N \pm \sqrt{N} \) and the precision obtainable is limited by standard deviation \( \sqrt{N} \). Therefore, as long the detector counting increase, the relative uncertainty would decrease [6]. This paper acquires the detection results under different energy and intensity of X-ray beam based on the Monte Carlo simulation and evaluates the detection results according to the following parameters about the detector counting: 1) The target counting \( N_s \). Define the detector counting value when the mid wall is detected as the target counting. 2) Background counting \( N_b \). Define the detector counting value when no mid wall are detected as the background counting.

The following table 4 shows the detector counting under different photon energy using the Monte Carlo method and the analytical method in reference [3] while the beam intensity of the source is constant 1*10^6.

When the difference between the target counting and the background counting is within the standard deviation of the background counting, the detector may not be able to obtain effective backscatter signals from the mid wall.

The following table shows the effect of different beam intensity on the detector counting while the photon energy is constant 60 keV.
Table 4. The detector counting under different photon energy using the Monte Carlo method and the analytical method.

| X-ray Photon Energy (keV) | Monte Carlo method | Analytical method |
|--------------------------|--------------------|-------------------|
|                          | $N_s$ | $N_b$ | $N_s-N_b$ | $\sqrt{N_s}$ | $N_s$ | $N_b$ | $N_s-N_b$ | $\sqrt{N_s}$ |
| 50                       | 411   | 405   | 6         | 20.1         | 392.7 | 388.9 | 3.86      | 19.72        |
| 60                       | 3013  | 2731  | 282       | 52.3         | 2974.1 | 2798.6 | 175.5     | 52.9         |
| 70                       | 5112  | 4359  | 753       | 71.5         | 5091.3 | 4571.9 | 519.4     | 67.6         |
| 80                       | 6678  | 5596  | 1082      | 74.8         | 6761.7 | 5716.4 | 1045.3    | 75.6         |

3.2. Discussion
As illustrated in table 4 and figure 5, in terms of current parameters setup, the deviation of the counts of detector obtained by the Monte Carlo method and the analytical method is basically within the range of standard deviation and the simulation results are relatively close.

![Figure 5](image_url). The Effect of X-ray energy on the counts of detector.

On the other hand, as illustrated in table 4 and figure 5 while the X-ray photon energy is increased from 50 keV to 80 keV, the target counting of the detector is increased from 411 to 6678 and the background counting of the detector is increased from 405 to 5596. Under normal circumstances, with the greater the thickness of the workpiece increase, the cumulative effect of backscattered x-rays become stronger, result in increasing the backscatter signal of detector. As reaching a certain depth (limit thickness), the X-ray photons backscattered from matter in this depth are not able to penetrate the matter and reaches the detector, Backscatter signals remain stable without increasing. Thus, the larger photon energy lead to a larger limit thickness, stronger cumulative effect of the backscatter signal and certainly the larger counts of detector.

However, as the photon energy increase, the photon tends to be forward scattered instead of backscatter, and the proportion of the backscatter beam intensity decreases. As shown in figure 5, as the photon energy of the X-ray increases, the rate of increase of the detector counts becomes slower.
As illustrated in Table 5 and Figure 6, when the X-ray intensity increases from $2 \times 10^7$ to $1 \times 10^8$, the target count of the detector increases from 862 to 3013 and the background count increases from 804 to 2731. But the discrepancy between the Monte Carlo method and the analytical method probe count is the difference between the lower ray intensity target count and the background count. This paper mainly uses low-energy radiation (60keV), and makes some simplifications to its physical process when it is calculated by analytical method. This simplification has little effect on the result data when the radiation intensity is large, but when the radiation intensity decreases, the analytical method and the description of the actual physical process may be larger deviations, resulting in greater fluctuations in the results of the data.

Table 5. The detector counting under different beam intensity using the Monte Carlo method and the analytical method.

| X-ray beam Intensity ($10^8$) | Monte Carlo method | Analytical method |
|-------------------------------|-------------------|-------------------|
|                              | $Ns$  | $Nb$  | $Ns-Nb$ | $\sqrt{Ns}$ | $Ns$  | $Nb$  | $Ns-Nb$ | $\sqrt{Ns}$ |
| 0.2                           | 862   | 804   | 58      | 28.3      | 815.1 | 769.2 | 46.0     | 27.7     |
| 0.5                           | 2017  | 1903  | 114     | 44.9      | 1874.9| 1771.4| 103.5    | 42.1     |
| 0.7                           | 2620  | 2451  | 169     | 51.2      | 2419.9| 2292.1| 127.8    | 47.8     |
| 1                             | 3013  | 2731  | 282     | 54.9      | 2974.1| 2798.6| 175.5    | 52.9     |

4. Conclusions
The method and important findings of this paper can be summarized as follows.
A Monte Carlo simulation method of X-ray backscatter detection is proposed for the seam tracking of welded sandwich panels. Based on the proposed model, the effect of X-ray photon energy and beam intensity on the counts of detector is analyzed. The results indicate that the proposed method can accurately describe the interaction mechanism both at high and low beam intensities. The proposed method can track the X-ray photon during all of lifetime from generation to disappearance and acquire the physical process that experienced. The proposed method can acquire the accurate moment of each particle entering the detector, and it can also judge photons reaching the detector, which backscattered by the mid wall. The proposed method can provide a reference for the implementation of the detection system in the aerospace and shipbuilding.

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