

## Virtual Source Multi-mode Method for Ultra-thick Weld Full-section Inspection

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**Abstract:** Full-section inspection of ultra-thick welds (UTW) is crucial for the nuclear power industry. The extensive weld section and the nearly vertical groove geometry pose significant challenges for flaw characterization. This paper presents a virtual source multi-mode total focusing method (VSMM-TFM) inspection method. The VS method not only enhances the emission energy but also simplifies multi-mode path calculations. Multi-mode decoupling enables full-section imaging at a single scanning position. Simulation and experiment on a 120-mm workpiece demonstrate that the VSMM-TFM method exhibits significant advantages in terms of inspection sensitivity, data volume, and imaging efficiency.

**Keywords:** Ultrasonic imaging, Virtual source, Multi-mode, Ultra-thick welds, Full-section inspection

### Introduction

Ultra-thick narrow-gap weld (UTW) is widely employed in critical components such as pressure vessels that operate under extreme temperature and pressure conditions[1]. The J-shaped groove features a high aspect ratio, with angles typically ranging from 2° to 6°[2]. This type of groove helps reduce filler material consumption and improve production efficiency[3]. However, narrow-gap welding (NGW) is prone to the lack-of-sidewall-fusion (LOSWF) flaws, which are typically oriented nearly perpendicular to the weld surface [4]. Flaws can significantly compromise structural integrity, fatigue resistance, and service life. Therefore, ultrasonic non-destructive testing (NDT) of UTW holds substantial engineering importance.

Phased array ultrasonic testing (PAUT) is widely used for weld inspection and among it, the total focusing method (TFM) achieves point-by-point focusing, significantly enhancing resolution[5]. However, TFM has some limitations in the inspection of UTWs. Firstly, the single-element excitation mode results in low emission power[6]. As illustrated in Fig.1, the interface reflection of the wave caused by the wedge further weakens the energy transmitted into the UTWs. In addition, TFM requires the storage and processing of a large volume of full matrix capture (FMC) data. This challenge will become more pronounced in UTW, where more A-scan sampling points are needed to ensure full-section inspection. In order to improve the emission energy and reduce the time of image reconstruction, Plane Wave Imaging (PWI) has been

introduced [7]. However, due to the narrow beam spread of plane waves, multi-angle acquisitions are essential to ensure a good imaging quality[8].

To address this issue, a group of elements can focus the emitted waves on a point, which is known as the Virtual Source (VS) method[9]. VS enables high signal-to-noise ratio (SNR) flaw inspection while reducing the number of emission events[10]. Sumana et al. simulated the inspection of flaws in 200 mm thick components using the VS method, demonstrating its suitability for thick-wall structures[11]. LOSWF flaws are frequently occur at near-vertical angles along the groove, resulting in directional echo patterns. The directional nature of echoes and the extensive weld section necessitate multiple array scanning positions to inspect the entire weld, as shown in Fig.1. Multi-mode TFM is typically employed to inspect such flaws[12]. However, current VS research primarily focuses on direct-mode imaging and has not been extended to multi-mode imaging, particularly involving mode conversion[10]. Therefore, applying the VS approach to the UTWs inspection still presents challenges.

To this end, this study proposes a Virtual Source Multi-Mode TFM (VSMM-TFM) for full-section inspection of UTWs. The VS method is used to enhance emission power and the VS imaging is extended to multi-mode imaging, incorporating back-wall reflections and mode conversions. Various skipping modes of longitudinal and shear waves are decoupled to reconstruct flaws throughout UTWs from top to bottom at a single scanning position. Virtual sources are po-

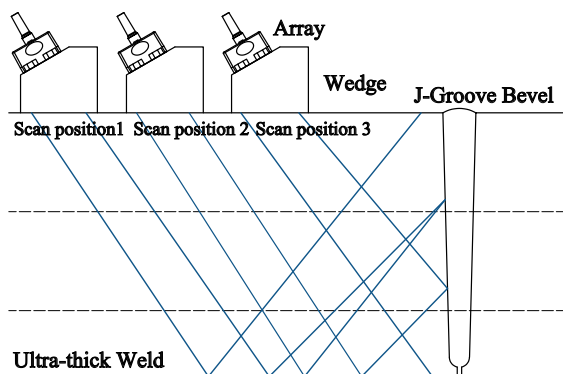


Fig. 1: Schematic diagram of the inspection for ultra-thick welds.

sitioned at the interface between the wedge and the weld surface. Mode conversions are designed to occur during the emission process. Under this configuration, the computational dimensionality of the multi-mode wave propagation model is reduced by one, which significantly improves the efficiency of the time of flight (TOF) calculation. VSMM-TFM achieves flaw imaging with fewer emission events, improving the efficiency.

This paper is structured as follows: Section 2 describes the method, which is validated through the CIVA simulation and experiment in Section 3. Finally conclusion is summarized in Section 4.

**VSMM-TFM Inspection Method**

A set of sub-elements is excited to generate a virtual source focused at the interface between the wedge and the UTW, as illustrated in Fig.2. The waves propagating into the UTW from  $P_{VS}$  can be regarded as a finite extension of the focused waves. Within a certain angular range these waves can be considered as cylindrical waves. For each VS focusing event, data is required by all elements, forming an  $M \times N$  FMC dataset, where  $M$  and  $N$  represent the number of VSs and elements, respectively. The TOF between the imaging point  $P$  and elements are calculated for each transmission and reception. All FMC data are then coherently summed to achieve synthetic focusing, yielding the pixel amplitude at point  $P$ :

$$I_{VS}(P) = \left| \sum_{i=1}^M \sum_{j=1}^N \tilde{s}_{ij}(T_i(P) + T_j(P)) \right| \quad (1)$$

where  $T_i$  represents the TOF of the emission process.  $T_j$  denotes the travel time of the scattered wave from imaging point to the receiving element.  $\tilde{s}$  is the Hilbert transform of the signals.

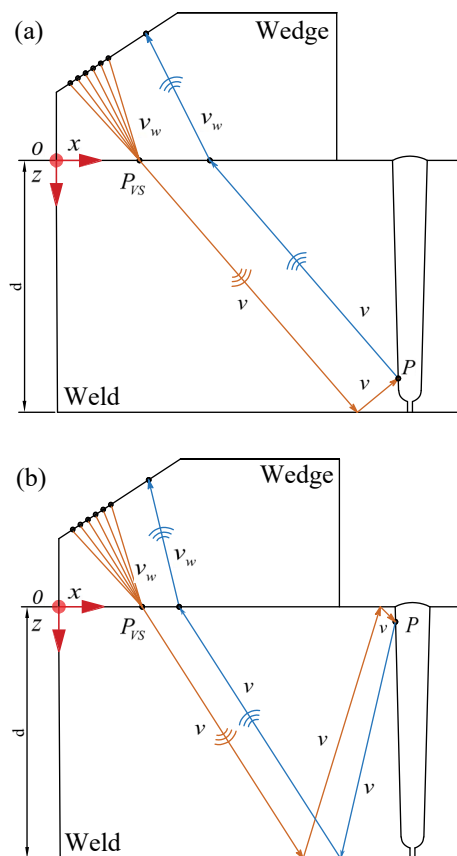


Fig. 2: Virtual source multi-mode TFM ray path: (a) half-skip modes (b) multi-skip modes.

The TOF in emission can be divided into two parts: the delay from the sub-elements to VS and from VS to imaging point. The TOF in reception can be calculated using the Fermat's principle. In VSMM-TFM, various skipping modes of longitudinal (L) and transverse (T) waves are decoupled to imaging flaws throughout the weld from top to bottom at a single scanning position. Mode conversions are designed to occur during the emission process. Under this case, the computational dimensionality of the multi-mode wave propagation model is simplified, which significantly improves the efficiency of the TOF calculation. The modes employed in inspection are shown in Table 1.

Tab. 1: Inspection modes.

Inspection Region	Inspection Modes
Top	TTT-TT
Middle	TL-L
Bottom	LL-L

## Simulation and Experiment

Simulations were conducted on a 120 mm thick weld using CIVA software to evaluate the method. As shown in Fig.3, notches with a length of 5 mm are machined at three locations on the steel test block. VSMM-TFM inspection was performed using a 5 MHz, 64-element, 0.6 mm pitch linear phased array with a wedge of  $16.2^\circ$ . The element number in VS array is 21, and the pitch is identical to above. The sampling frequency is set to 25 MHz. Additionally, under the same configuration, TFM inspection was also simulated.

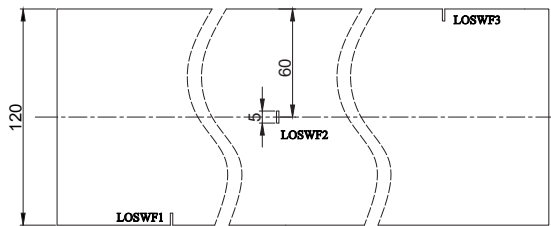


Fig. 3: Schematic diagram of the simulated test block and flaws distribution.

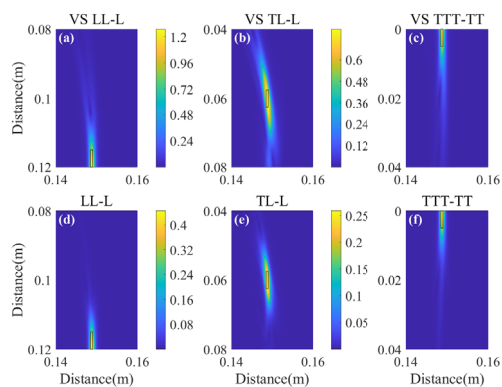


Fig. 4: Flaw reconstruction Results: (a)-(c): VSMM-TFM imaging results; (d)-(f): TFM imaging results.

The comparative results are shown in Fig.4. The results are not normalized, and all images are presented in linear scale. Fig.5 shows the maximum flaw indication amplitudes for each mode under both methods. The inspection sensitivity of VSMM-TFM is significantly higher than that of TFM, increasing by a factor of 2.77 (on average). TFM requires a dataset size of  $64 \times 64$ . In contrast, only 21 VSs are configured in VSMM-TFM, resulting in a dataset size of  $64 \times 21$ . This represents a 3.05-fold reduction in data volume. On a desktop computer equipped with an Intel Core i7-13700KF CPU and an NVIDIA GeForce RTX 4070 GPU, the computation time for the VSMM-TFM TOF matrix using MATLAB R2021b is 21.80s. Compared to TFM's 655.86s, this represents

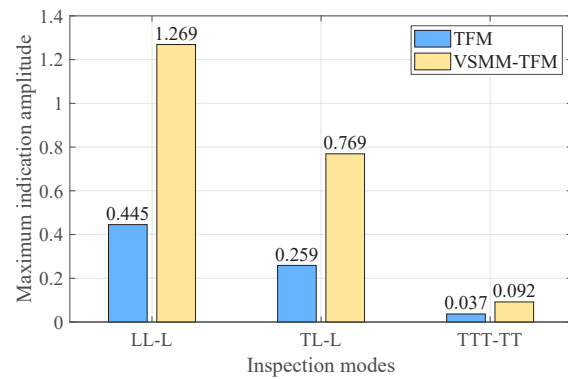


Fig. 5: Comparative inspection sensitivity of two imaging methods for flaws at different parts.

a 30.09-fold speedup (for a pixel grid of  $601 \times 101$ ). The average imaging time for TFM is 0.56s, while for VSMM-TFM it is only 0.15s, representing a 3.73-fold improvement in efficiency. From the results, VSMM-TFM enables full-section inspection of UTWS at a single scanning position and the flaw indications align perfectly with the actual flaw positions.

Experimental validation was conducted using the same parameters as in the simulation, targeting the LOSWF2 and LOSWF3 (10 mm in length), as shown on the Fig.6. The results are presented on the right side of Fig.6. In both methods, a vector coherence factor was applied to suppress noise. The indication area of the LOSWF2 reconstructed by VSMM-TFM is noticeably larger than that of TFM. VSMM-TFM method achieves a high SNR image of the LOSWF3, which is missed in the TFM image.

These results demonstrate that the VSMM-TFM method is highly suitable for multi-mode imaging of ultra-thick welds, as it enables stronger flaw characterization with higher imaging efficiency.

## Conclusions

This paper presents a virtual source multi-mode TFM based full-section inspection method for ultra-thick weld. VSMM-TFM enables stronger flaw characterization in UTWs with higher imaging efficiency. The VS approach not only enhances the emission energy but also simplifies multi-mode path calculations while reducing data volume. Multi-mode decoupling enables full-section imaging at a single scanning position. CIVA simulation and experiment results demonstrate that the VSMM-TFM method exhibits significant advantages over TFM in terms of inspection sensitivity, data volume, and imaging efficiency. In VSMM-TFM images, flaw indications are 2.77 times those of TFM, while the TOF matrix calculation time and imaging time are reduced by 30.09 and 3.73 times respectively. In the experiment, VSMM-TFM successfully inspec-

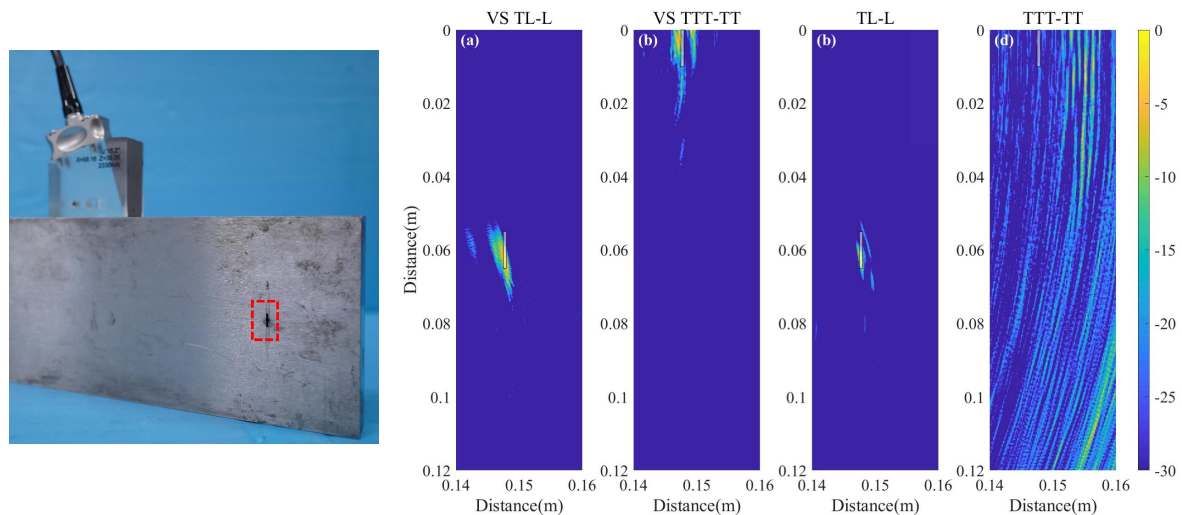


Fig. 6: Experimental setup and test block (left) and corresponding imaging results (right): (a) VSMM-TFM TL-L, (b) VSMM-TFM TTT-TT, (c) TFM TL-L, (d) TFM TTT-TT

ted the top flaw that was missed by TFM. In summary, the VSMM-TFM effectively addresses the insufficient energy issue of conventional TFM in UTW inspection while demonstrating superior inspection efficiency.

#### References

- [1] U. K. Mohanty et al. 'A Resource-Efficient Process Design for Heavy Fabrication: A Case of Single-Pass-per-Layer Narrow Gap Welding'. In: *Sustainable Materials and Technologies* 33 (2022), e00488.
- [2] E. Nicolson et al. 'Dual-Tandem Phased Array Method for Imaging of near-Vertical Defects in Narrow-Gap Welds'. In: *NDT & E International* 135 (2023), p. 102808.
- [3] H. Xu et al. 'Imaging X70 Weld Cross-Section Using Electromagnetic Testing'. In: *NDT & E International* 98 (2018), pp. 155–160.
- [4] E. Nicolson et al. 'Towards an In-Process Ultrasonic Phased Array Inspection Method for Narrow-Gap Welds'. In: *NDT & E International* 144 (2024), p. 103074.
- [5] B. W. Drinkwater and P. D. Wilcox. 'Ultrasonic Arrays for Non-Destructive Evaluation: A Review'. In: *NDT & E International* 39.7 (2006), pp. 525–541.
- [6] L. Le Jeune et al. 'Plane Wave Imaging for Ultrasonic Non-Destructive Testing: Generalization to Multimodal Imaging'. In: *Ultrasonics* 64 (2016), pp. 128–138.
- [7] X. Xu et al. 'Data Fusion of Multi-View Plane Wave Imaging for Nozzle Weld Inspection'. In: *NDT & E International* 141 (2024), p. 102989.
- [8] T. Gantala, S. P.L. and K. Balasubramaniam. 'Improved Imaging Technique for Nondestructive Evaluation Using Arbitrary Virtual Array Source Aperture (AVASA)'. In: *NDT & E International* 138 (2023), p. 102869.
- [9] E. Hoyle et al. 'Virtual Source Aperture Imaging with Auto-Focusing of Unknown Complex Geometry through Dual Layered Media'. In: *NDT & E International* 98 (2018), pp. 55–62.
- [10] J. Wang et al. 'Virtual Source Total Focusing Method for Crack Detection in Complex Curved Structure'. In: *NDT & E International* 140 (2023), p. 102968.
- [11] Sumana and A. Kumar. 'Phased Array Ultrasonic Imaging Using Angle Beam Virtual Source Full Matrix Capture-Total Focusing Method'. In: *NDT & E International* 116 (2020), p. 102324.
- [12] M. V. Felice and Z. Fan. 'Sizing of Flaws Using Ultrasonic Bulk Wave Testing: A Review'. In: *Ultrasonics* 88 (2018), pp. 26–42.