Scientific Journal of Intelligent Systems Research Volume 7 Issue 9, 2025
ISSN: 2664-9640

Active Guided Wave Phased Array Monitoring System for Vehicle-mounted Composite Hydrogen Storage Tanks

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Abstract

To address the safety hazards caused by potential damage to the core component of hydrogen energy vehicles-the IV/V type composite hydrogen storage tank-during its service life, this paper proposes an online structural health monitoring (SHM) system based on active ultrasonic guided wave technology. The system utilizes a piezoelectric transducer linear phased array to perform periodic high-resolution scanning of the hydrogen storage tank structure. The hardware platform of the system is centered around a Zynq, complemented by a 16-channel synchronous sampling analog front end, aiming to achieve full matrix capture data acquisition and total focusing method imaging. This paper focuses on analyzing the advantages and challenges of non-dispersive shear horizontal waves compared to traditional Lamb waves in anisotropic curved structures, and determines the technical path of using shear mode transducers PZT as sensors. The research aims to provide a complete technical route and solution for the development of an intelligent monitoring system capable of adapting to complex on-board environments and achieving precise imaging of early defects in hydrogen storage tanks.

Keywords

Structural Health Monitoring; On-board Hydrogen Storage Tank; Ultrasonic Guided Wave; Phased Array; Zynq SoC; Total Focusing Method.

1. Introduction

New energy vehicles represent the primary direction for the transformation and upgrading of the global automotive industry and are a key focal point for countries to address climate change and promote green, low-carbon industrial development[1-2]. Type IV/V composite pressure vessels, due to their lightweight and high-strength characteristics, have become the preferred solution for on-board high-pressure hydrogen storage systems. However, Composite Overwrapped Pressure Vessels (COPVs), during their long-term service, are subjected to high-pressure cycles, vehicular vibrations, and potential external impacts, making them susceptible to internal damage such as matrix cracking, fiber fracture, and delamination, which pose a serious threat to driving safety[3].

Traditional periodic non-destructive testing methods are inadequate for the demands of on-board, online monitoring. Structural health monitoring technology based on ultrasonic guided waves has become a research hotspot in this field due to its large-range and high-sensitivity characteristics[4]. Currently, research on monitoring technology based on Lamb waves is extensive. However, the inherent multi-modal and dispersive nature of Lamb waves makes signal processing extremely complex in anisotropic and geometrically complex COPVs, limiting their monitoring accuracy. In contrast, the fundamental shear horizontal wave (SH_0 Wave) possesses the unique advantage of being non-dispersive, meaning its wave packet does not easily deform during propagation, providing a physical basis for achieving high-resolution imaging[5].

This paper designs a purely active guided wave monitoring system to meet the online monitoring needs of vehicle-mounted hydrogen storage tanks. The system employs advanced phased array imaging technology, aiming to validate a prototype for a structural health monitoring (SHM) system capable of high-precision damage assessment on complex curved structures, thereby providing a novel technical means to ensure the safety of hydrogen energy vehicles.

2. System Overall Design and Monitoring Principle

2.1. System Architecture

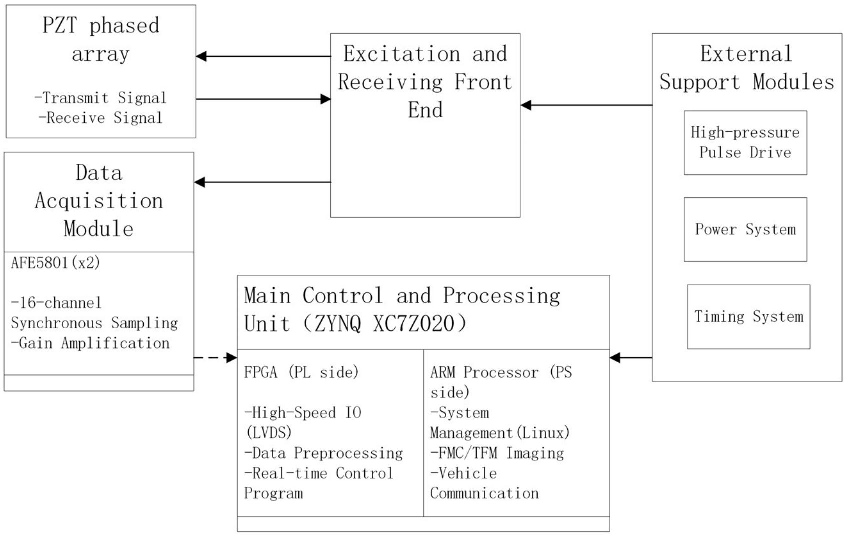

Figure 1. System Hardware Platform

This system is an independent, active guided wave monitoring system whose core operational mode is periodic inspection. The system hardware platform, as shown in Figure 1, consists of four main parts: the main control module, the data acquisition module, the excitation and receiving module, and the sensor array.

(1) Main Control Module: A Xilinx Zynq SoC is selected as the central processing unit. The Zynq is a heterogeneous multi-core embedded processor from Xilinx, fully named Zynq-7000 All Programmable SoC (System on Chip). It innovatively integrates programmable logic with a processor core on a single chip, combining the flexibility of hardware with the programmability of software. Its unique heterogeneous computing architecture tightly integrates a Processing System (PS) based on an ARM core and Programmable Logic (PL) consisting of a Field-Programmable Gate Array (FPGA). The PL side is responsible for handling high-speed, parallel, and timing-critical low-level data acquisition and excitation control tasks. The PS side runs an embedded operating system, implements complex high-level imaging algorithms, manages the system, and communicates with the vehicle's CAN bus.

(2) A highly integrated 16-channel synchronous sampling analog front-end solution is chosen. To balance performance and cost, the system will use a mid-to-high-speed Analog Front-End (AFE) chip, such as the low-power TI AFE5801 series, designed specifically for non-destructive testing or medical ultrasound applications. This chip integrates a Low-Noise Amplifier (LNA), a Programmable/Variable Gain Amplifier (PGA/VGA), and a high-speed Analog-to-Digital Converter (ADC) in a single package. This significantly simplifies the design of the front-end analog circuitry and optimizes the overall system cost while ensuring signal conditioning quality and channel consistency.

(3) Excitation and Receiving Module: The excitation front-end consists of an FPGA-controlled high-voltage analog multiplexer, which flexibly excites each element of the array via a high-voltage pulse driver in the peripheral support module. The receiving circuit employs a high-impedance voltage amplifier scheme, ensuring performance while maintaining design simplicity and cost-effectiveness.

(4) Sensor Array: A single, compact linear phased array layout is used. The array is composed of multiple piezoelectric transducer (PZT) units that can efficiently and purely excite and receive the non-dispersive fundamental shear horizontal wave.

2.2. Monitoring Principle and Imaging Method

The system utilizes advanced phased array imaging principles. During the data acquisition phase, the Full Matrix Capture (FMC) mode is employed. In this mode, each element i (i=1,...,N) in the array acts sequentially as a transmitter, while all other elements j (j=1,...,N) act simultaneously as receivers. This process captures a "full matrix" of data containing N×N sets of signals, $s_{ij}(t)$.

In the data processing phase, the Total Focusing Method (TFM) is used for image reconstruction. This algorithm grids the monitoring area in software. For any pixel point $P(x,y)$ within the area, its imaging intensity $I(x,y)$ can be calculated by coherently summing the full matrix data. This process can be viewed as a virtual post-processing focusing, with the core calculation formula as follows:

$$I(x,y) = \left|\sum_{i=1}^{N}\sum_{j=1}^{N} s_{ij}\left(t_{ij}(x,y)\right)\right| \tag{1}$$

where $s_{ij}(t)$ is the original time-domain signal from transmitting element i to receiving element j, and $t_{ij}(x,y)$ is the theoretical time-of-flight from transmitter i, scattered by pixel $P(x,y)$, to receiver j. For an isotropic medium, this time-of-flight can be calculated by:

$$t_{ij}(x,y) = \frac{\sqrt{(x_i-x)^2+(y_i-y)^2}+\sqrt{\left(x_j-x\right)^2+\left(y_j-y\right)^2}}{v_g} \tag{2}$$

where (x_i,y_i) and (x_j,y_j) are the coordinates of the transmitting and receiving elements, respectively, and v_g is the group velocity of the guided wave. By iterating through all pixel points and calculating their corresponding intensity $I(x,y)$, a high-resolution, full-field focused damage image is ultimately generated[6].

3. Key Technologies and Challenges

3.1. Selection and Implementation of Monitoring Waveform

The core technical decision of the project lies in the choice of the monitoring waveform. The SH_0 wave is chosen for its excellent performance in monitoring composite structures due to its non-dispersive nature. In an isotropic medium, the displacement field u_3 of an SH wave only has a component parallel to the plate surface and perpendicular to the direction of propagation. Its wave equation can be simplified to:

$$\frac{\partial^2 u_3}{\partial x_1^2} + \frac{\partial^2 u_3}{\partial x_2^2} = \frac{1}{c_T^2}\frac{\partial^2 u_3}{\partial t^2} \tag{3}$$

where CT is the bulk shear wave velocity, which does not vary with frequency. This is in sharp contrast to the complex dispersion equations of Lamb waves. However, a standard thickness-mode PZT cannot effectively excite the SH_0 wave. Therefore, the key challenge is to implement a shear mode transducer. Drawing on related research[7], a design can be adopted where an ordinary, thickness-poled annular piezoelectric ceramic is divided radially. One side is flipped so that the polarization directions of the two parts are opposite. An electrode is placed in the middle. Applying a voltage to this electrode causes the transducer to produce shear deformation along its radial normal plane, thereby generating an omnidirectional SH_0 wave.

3.2. Correction for Anisotropy and Curvature

Even for the non-dispersive SH_0 wave, its propagation velocity in a composite material varies with the propagation direction due to the different fiber winding directions, i.e., $v_g = v_g\,(\theta)$. Therefore, the time-of-flight calculation formula in the TFM imaging algorithm must be corrected:

$$t_{ij}(x,y) = \int_{i\to P} \frac{ds}{v_g(\theta_1)} + \int_{P\to j} \frac{ds}{v_g(\theta_2)} \tag{4}$$

In this equation, the integration path is the geodesic line along the curved surface of the structure, and $v_g\,(\theta)$ is the direction-dependent wave velocity function. To ensure positioning accuracy in anisotropic curved structures, a model correlating wave velocity with propagation direction must be established beforehand through finite element simulation or experimental calibration. This model can quantitatively describe the variation of wave velocity with propagation direction. The imaging algorithm must call this model during the delay calculation process to achieve precise correction of the wave propagation time in the anisotropic curved structure.

4. System Engineering Implementation

The software design of this system fully utilizes the heterogeneous computing architecture of the Zynq SoC. The software system is divided into two main parts: the low-level real-time control system running on the PL, and the high-level application management system running on the PS. The system structure and workflow are shown in Figure 2.

4.1. PL Side Software Architecture

The PL side firmware is developed using the hardware description language Verilog. It is responsible for executing all high-speed, timing-critical tasks to ensure the real-time performance and accuracy of data acquisition. Its main modules include:

(1) Excitation Timing Controller: Precisely generates the timing signals that control the high-voltage pulse driver and multiplexer, triggering each PZT element in the sensor array sequentially according to the FMC mode.

(2) AFE5801 Interface Controller: Receives parallel sampling data at high speed from the 16-channel AFE chip via an LVDS interface.

(3) Data Pre-processing and Buffering Module: Performs initial processing on the raw data, such as data frame encapsulation and formatting.

(4) DMA Controller: Efficiently transfers large amounts of data collected by the PL side directly to the PS side's DDR memory via the AXI bus, without CPU intervention, making it available for high-level algorithms.

4.2. PS Side Software Architecture

The PS side software is responsible for running complex imaging algorithms, system management, communication, and human-machine interaction. By deploying an embedded Linux operating system on the PS side's ARM processor, high-level applications are developed in C/C++. The main modules include:

(1) System Management Service: Responsible for system initialization, sensor array parameter configuration, periodic scheduling of monitoring tasks, and power management.

(2) TFM Imaging Algorithm Engine: Reads the FMC full matrix data transferred from the PL side from DDR memory and executes the core TFM imaging algorithm. This module includes the computational logic for correcting for anisotropy and curvature based on the pre-calibrated wave velocity model.

(3) Data Management and Storage Module: Responsible for storing historical monitoring data and generated damage images, providing a basis for analyzing damage evolution trends.

(4) Vehicle Communication Interface (CAN Bus): Enables communication with the vehicle's control unit, periodically reporting the health status of the hydrogen storage tank and issuing warnings when suspected severe damage is detected.

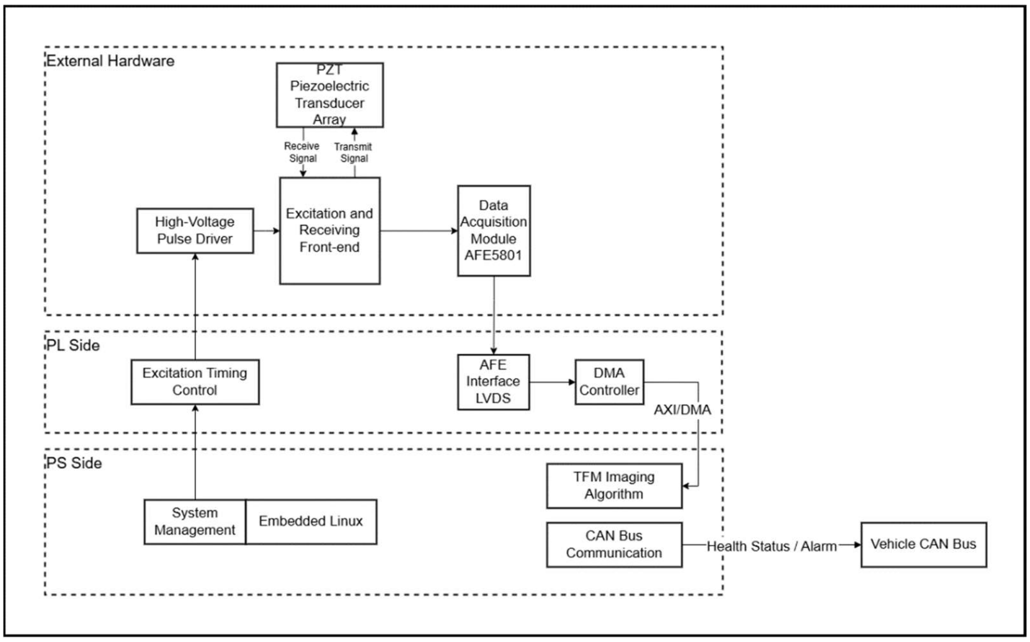

Figure 2. System Architecture and Data Flow

4.3. Data Processing Flow

The system's workflow clearly reflects the synergy between hardware and software:

Task Trigger: The system manager on the PS side initiates a monitoring task based on a preset strategy (e.g., vehicle start-up self-check, fixed time intervals, or receiving an external command).

Low-level Acquisition: The PS sends control commands to the PL via the AXI bus. The PL firmware begins to strictly follow the FMC timing sequence, controlling the excitation module to fire each PZT one by one and synchronously controlling the AFE to acquire echo signals from all channels.

Data Transfer: The PL writes a complete N×N full matrix dataset directly into the shared memory area of the PS via DMA.

Image Reconstruction: Upon completion of the DMA transfer, the PL sends an interrupt signal to the PS. The TFM algorithm engine on the PS side is activated, reads the data, performs the focusing imaging calculation, and ultimately generates a two-dimensional image reflecting the structural integrity of the hydrogen storage tank.

5. Conclusion and Outlook

5.1. Conclusion

This paper proposes a structural health monitoring system solution based on an active guided wave phased array to address the potential safety hazards of on-board composite hydrogen storage tanks during service. The system, centered on a Zynq SoC and combined with a highly integrated AFE data acquisition module, achieves multi-channel high-speed acquisition in Full Matrix Capture (FMC) mode and efficiently transfers data to the PS side's memory via DMA. Concurrently, it employs the Total Focusing Method (TFM) for image reconstruction to generate high-resolution two-dimensional damage images. This system design fully leverages the advantages of PS/PL synergy: the PL side handles high-speed, timing-critical excitation and acquisition tasks, while the PS side undertakes complex imaging calculations and system management, balancing monitoring real-time performance with imaging accuracy.

In terms of monitoring methodology, this paper analyzes the propagation characteristics and advantages of the fundamental shear horizontal wave (SH_0 wave) in composite structures, pointing out its strong application potential in anisotropic curved structures and proposing a correction approach for the direction-dependent wave velocity. The research findings provide a theoretical basis and a technical path for the early damage detection of composite hydrogen storage tanks and lay a methodological foundation for the application of guided waves in complex structures.

Overall, this paper has completed the system architecture design, key technology path analysis, and monitoring methodology construction, forming a relatively complete monitoring system plan. However, as the research is still in the design and simulation phase, physical fabrication and experimental validation have not yet been carried out.

5.2. Outlook

The current research work has several areas for improvement. Future work will be carried out in the following aspects:

(1) Further refine the software architecture design, focusing on DMA buffer management, real-time task scheduling, and data fault tolerance mechanisms to enhance the system's stability and reliability in the complex on-board environment.

(2) Explore the optimal balance between resolution and propagation distance by addressing issues such as the frequency selection of SH_0 waves and transducer structure improvements, combined with finite element modeling and experimental calibration.

(3) On the basis of the TFM algorithm, attempt to introduce sparse reconstruction methods, wavelet-based multi-resolution imaging, and deep learning-based imaging enhancement strategies to improve the damage localization accuracy and computational efficiency in anisotropic curved structures.

(4) Gradually carry out finite element simulations and laboratory prototype validation to evaluate transducer performance, signal quality, and imaging effects. Simultaneously, focus on the challenges of the on-board application environment, such as temperature fluctuations, mechanical vibrations, electromagnetic interference, and the long-term service reliability of the sensors.

(5) Through the research outlined above, the proposed active guided wave monitoring system is expected to be continuously improved and eventually achieve engineering application, providing effective technical support for the safe operation of hydrogen energy vehicles.

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