Hardware-in-the-loop Simulation with Acoustic Coupling for Underwater Acoustic Detection System

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Abstract—**How to supply the transducer array in detection system with acoustic signal is considered for testing and evaluating underwater acoustic detection system. In this paper, we present a particular approach to address this problem. A hardware-in-the-loop (HIL) simulation environment is developed for testing and evaluating the existing underwater acoustic detection system. In the presented HIL simulation, a target signal simulator with acoustic coupling device is introduced into the simulation for providing acoustic signal for receiving array in detection system. With the HIL simulation by using acoustic coupling, testing and validation of underwater acoustic detection system can be performed in air condition, which reduces the testing times in underwater environment. Experiments with the developed HIL simulation are carried out and simulation results verify the feasibility and effectiveness of the HIL simulation obtained with acoustic coupling for underwater acoustic detection system.**

Keywords—hardware-in-the-loop; acoustic coupling; under-water; acoustic detection; target signal simulator

I. INTRODUCTION

Acoustic detection has received considerable attention for target detection in underwater applications [1-4]. As testing and validation of underwater acoustic detection system has become more and more important in the design and development process, the need to minimize the time of development with low cost has also become greater.

It is well known that computer simulation is an effective approach for designing and testing the actual system in laboratory. Currently, extensive research is being carried out in the development of simulation platforms for underwater acoustic detection system [5-8]. As the modeling and simulating of acoustic target is vital for acoustic detection, there have been two simulating paths for the target acoustic signal generation and supply for acoustic detection system. One is supplying the signal processing subsystem in acoustic detection system with the generated electrical signal. The other path of obtaining the desired signals is to make actual acoustic signals in anechoic water tank. The main drawback of the prior is that the transducer array is out of consideration in the testing and simulating process and the simulation accuracy is limited by the inconsideration of acoustic characteristics. The method of water tank suffers from the tremendous challenges of expensive cost for underwater experiments.

Hardware-in-the-loop simulation is a technique for performing testing and evaluating actual system in a comprehensive, cost effective and repeatable manner [9]. It has been proved to be a reliable, effective, and nondestructive method in the design, development, and testing of various industrial systems. HIL simulation refers to the simulation which simulates one part of the whole system with computer modeling while uses physical modeling or actual system for the other part. HIL simulation technology has been widely applied to high investment and high risk areas such as aviation, aerospace, underwater vehicles, and large complex control systems [10-13], etc. On one hand, HIL simulation solves difficulties of system model abstraction and the problems that simplified models can not effectively simulate the real system in pure digital off-line simulation, and on the other hand, it avoids long cycle and repetitive work of actual system development and reduces development costs and risks efficiently.

In this paper, a HIL simulation obtained by means of acoustic coupling is presented for underwater acoustic detection system. First, the actual apparatus of transducer array is introduced into the underwater acoustic detection simulation to resolve the problem of hardness and complexity of modeling transducer array, and then the detection system are supplied with the actual acoustic signals by means of acoustic coupling in air condition rather than water tank. As the key part of the presented HIL simulation, a type of target signal simulator with acoustic coupling device is specially designed for underwater acoustic detection system. The presented HIL simulation achieves low cost and can perform the functions of the underwater acoustic detection in air condition.

II. ARCHITECTURE OF HIL SIMULATION WITH ACOUSTIC COUPLING

The HIL simulation with acoustic coupling for underwater acoustic detection system comprises three parts of target signal simulator, acoustic coupling device, and acoustic detection system. Fig.1 illustrates the schematic diagram of HIL simulation.

Supported by the Northwestern Polytechnical University Foundation for Fundamental Research (NPU-FFRJC201226)

978-0-933957-40-4

A. Target Signal Simulator

Target signal simulator is responsible for generating the simulated target signals with analog mode for acoustic detection system. In active detection mode, the generated target signal comprises target echo, reverberant, ambient sea noise, and interfering signals. In passive detection mode, the target signal comprises target radiant noise, ambient sea noise, and interfering signals.

B. Acoustic Coupling Device

Acoustic coupling device overall serves the purpose of acoustically coupling the target signals for the treatment of source supply to the receiving transducer array in air condition. The target signals generated with the signal simulator are introduced into the acoustic detection system through the coupling device. The acoustic coupling device for use with the receiving array in the HIL simulation consists of an acoustic array, called acoustic coupling array, and a layer of acoustic coupling material which is between the coupling array and the receiving array.

C. Acoustic Detection System

Underwater acoustic detection system is to determine by underwater sound the presence, location or nature of targets in underwater. Detection system works in two modes of active detection and passive detection. It involves transducer array and signal processing system. The signal processing system comprises signal conditioner, beamformer, detection/ estimation statistics processor, etc [14, 15]. In the presented acoustic detection system, the transducer array is only used for receiving and the two types of mode are considered in target signal simulator.

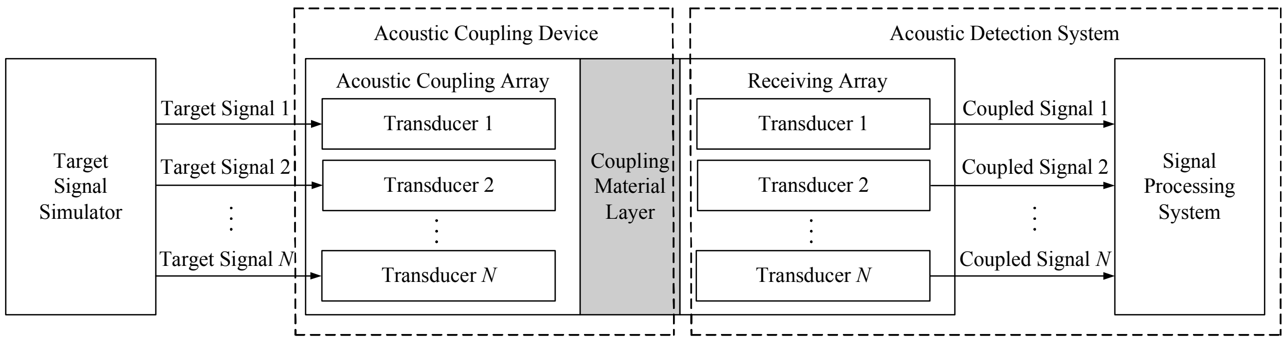

Fig. 1. Schematic diagram of HIL simulation with acoustic coupling

III. TARGET SIGNAL SIMULATOR

Target simulator is an important supporting test equipment of sonar system, and its basic function is to generate various simulated signals which target echoes or emits for sonar probe hydrophone array to receive, but also to provide these signal to the sonar system for the purpose of sonar function testing or performance testing.

The early target simulator is application developed on the DOS operating system, which function is very poor. With the rapid development of computer technology, CPU speed has been greatly improved, the simulator which originally can only be achieved on an external circuit, can now be directly implemented using computer simulation technology.

With the appearance of high performance DSP, real-time signal processing system has found widespread applications. In this paper, the designs of target signal simulator include hardware part and software part. The parallel processing system with multi-DSP is used as the hardware platform in the presented target signal simulator, which is based on industrial personal computer with a DSP board [16] and a D/A conversion board. In this paper, a set of application software is introduced mainly.

A set of application software for the target signal simulator with bottom-up layer style by means of module design comprises a main control software for the main control board, a DSP software for the DSP board, and a D/A conversion software for the D/A converter board. As up layer of management, the main control board software provides system management while DSP software and D/A conversion software perform system functions as bottom layer of task. The module design of the set of application software is described in Fig. 2.

A. Main Control Software

Main control software offers the parallel processing system management and control to initial system, load DSP programs, interact with DSP board, and provide operating visualization. The general workflow of the main control software is depicted in Fig. 3.

B. DSP Software

DSP software is the key part to support parallel processing. According to the module design of the DSP software and the structure of DSP array, the generation of each type of target signals is map to each DSP, in order to achieve distributed parallel processing obtained with DSPs' cooperative working.

DSP software has three steps in data flow. The first step is to calculate the direction angle of target or jamming in certain location with underwater acoustic detection system, and then each type of target signals is generated respectively, where the target echo(or target radiant noise) and jamming signal is obtained with the direction angle, and others are isotropic. In the last step, these signals are added to form the received target signal. In the above, the task in the second step can also be performed simultaneously. Thus, the target generation with

DSPs can be obtained with three pipelines. Fig. 4 illustrates the workflow of the target generation with combination of pipelining and parallelling.

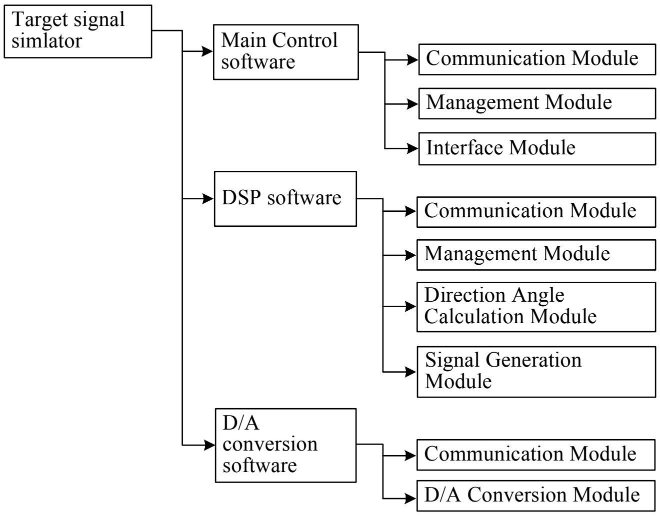

Fig. 2. Architecture of set of target signal simulator softwares with modules

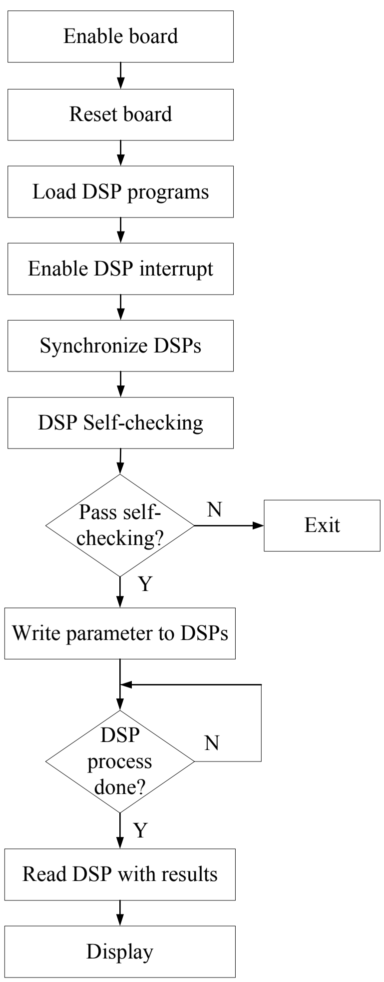

Fig. 3. Workflow of main control software

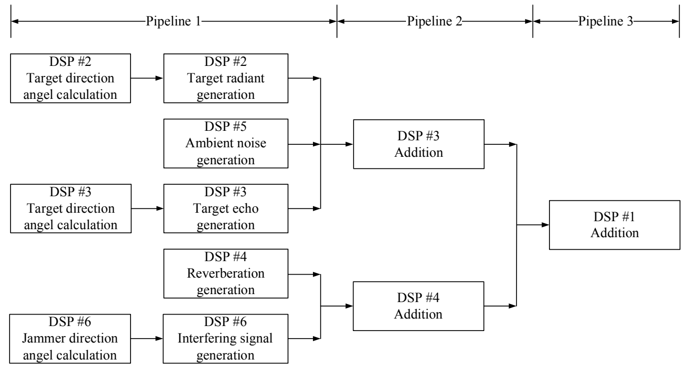

Fig. 4. Workflow chart of target signal generation with combination of pipeling and parallelling

IV. ACOUSTIC COUPLING DEVICE

A. Acoustic Coupling Array

Acoustic coupling array is supplied with electrical signals and arranged to provide acoustic signals with acoustic coupling for the receiving array of the detection system.

As an acoustic signal provider with one by one element, the coupling array is designed with the same distributed elements as the receiving array firstly. In this way, the target signal of radiation is incident on the surface of the receiving array in a normal direction, in order to reduce the effects of mutual radiant impedance between elements. In additional, transducers with small radiant surface are used as elements of the coupling array.

To keep coupling thoroughly, the coupling surface of the coupling array must conform to the surface of the receiving array. In the presented HIL simulation, the surface of the receiving array and therefore the coupling surface are both plane. The coupling device is attached closely to the receiving array by mechanical support, as shown in Fig. 5 schematically.

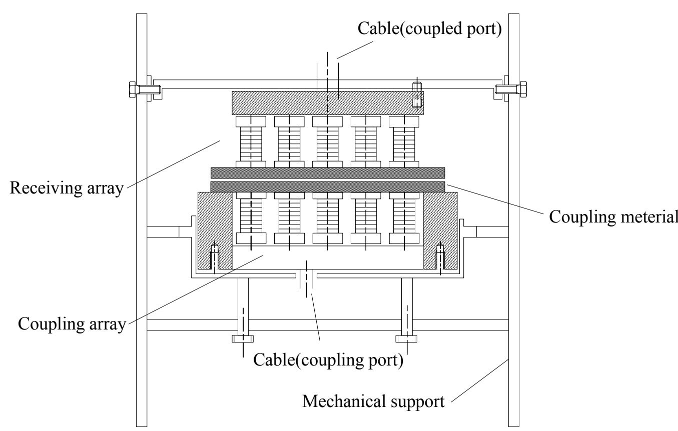

Fig. 5. Schematic diagram of assembly of coupling device

B. Acoustic Coupling Material

Between the surfaces of the coupling array and receiving array is a layer of acoustic coupling material, which is the propagation medium for the acoustic signals in air condition.

Two problems need to be considered for the coupling material layer. One is the type of the coupling material and the other is the thickness of the layer. The first is to provide that the acoustic impedance of the coupling material at least essentially coincide with seawater, since no reflection then occur at the boundary surface between the coupling array and the receiving array. The layer is preferable of a thickness which helps to coupe thoroughly and makes the buffering purpose when applying pressure on the coupling array and receiving array.

1) Acoustic impedance

As illustrated in Fig.5, target signals of acoustic radiant pass from the coupling material into the sound permeable membrane of the receiving array. That is, the acoustic waves propagate in two mediums of the coupling material and the sound permeable membrane. Assume the thickness of the coupling material layer is described as D and its acoustic impedance is

$$R_2 = \rho_2 c_2 \tag{1}$$

where ρ_2 is the density of the coupling material and c_2 is the velocity of propagation in the coupling material. The acoustic impedance of the sound permeable membrane is

$$R_1 = \rho_1 c_1 \tag{2}$$

where ρ_1 is the density of the sound permeable membrane and c_1 is the velocity of propagation in the sound permeable membrane.

Hence, sound intensity permeability coefficient t_1 [17] is given as

$$t_1 = \frac{4}{4\cos^2 k_2 D + \left(R_{12} + R_{21}\right)^2 \sin^2 k_2 D} \tag{3}$$

and sound intensity reflection coefficient r_1 [17] can be written as

$$r_I = 1 - t_I \tag{4}$$

where $R_{12} = R_2 / R_1$, $R_{21} = R_1 / R_2$, and k_2 is the wavenumber of the acoustic signal in the coupling layer.

Let $t_1 \approx 1$ or $r_1 \approx 0$, we can obtain

$$R_2 \approx R_1 \tag{5}$$

That is, the acoustic impedances of the coupling material and the sound permeable membrane are the same. As polyurethane rubber is commonly provided as material of the sound permeable membrane to coincide with seawater and therefore the same type of rubber is considered for the choice of coupling material. In this way, the layer has acoustic impedance being substantially the same as seawater, provided a reasonable velocity math with seawater.

2) Thickness of the Layer

Besides obtained with (5), the maximum of t_1 also occurs approximately when the item of $\sin k_2 D$ is a minimum, i. e.

$$\sin k_2 D = 0 \tag{6}$$

Thus,

$$D = n\lambda_2 / 2, \quad n = 1, 2, \cdots \tag{7}$$

if $n = 1$, then

$$D = \lambda_2 / 2 \tag{8}$$

This is, in order to achieve total transmission we require the thickness of the coupling material layer is approximately the half wavelength of acoustic radiant in coupling medium.

V. EXPERIMENTS AND RESULTS

Simulation experiments are carried out with the developed HIL simulation for underwater acoustic system. In the experiments, the simulated target signals are generated with target signal simulator, and then the receiving array is supplied with the generated target signal by means of acoustic coupling through coupling material layer and the coupled signals are processed with signal processing system in receiving system.

Figure 6 shows the combined target signals from target signal simulator in active mode. As huge data volume, only the first four channels of the target signal waveforms are displayed in Fig. 6 and also extracted on the scale of 100:1. As shown in Fig. 6, the reverberation is arrived first, and the target echo follows.

Figure 7 shows the beam signals from signal processing system in underwater acoustic detection system. Split beamforming is used in the signal processing system. As shown in Fig. 7, the first two channels are signals of left beam and right beam in horizontal direction and the last two channels are signals of up beam and bottom beam in vertical direction. Meanwhile, the improvement obtained with beamforming is achieved obviously.

In Fig.6, the coordinates of the target and the carrier of the acoustic detection system are as follows: target (-1588.72, -5, -6349.82) m and carrier (-1404.93, -7.03, -5488.64) m. The current course of the target and the carrier is 270 deg and 186.85 deg. The real value of the horizontal angle, vertical angle, and relative distance of the target calculated in terms of the coordinates of the target and the carrier are 5.20 deg, 0.13 deg, and 880.58 m, respectively. The real value of relative velocity of the target calculated according to the velocity and course of the target and the carrier is 48.90 kn.

As shown in Fig. 7, the estimated values of the horizontal angle, vertical angle, relative distance, and relative speed are 2.49 deg, 0.09 deg, 894.72 m, 40.77 kn, respectively. Considering the reasonable error of estimation, experimental results show that the developed HIL simulation with acoustic coupling for underwater acoustic detection system is validate and verify the feasibility of HIL simulation by means of acoustic coupling.

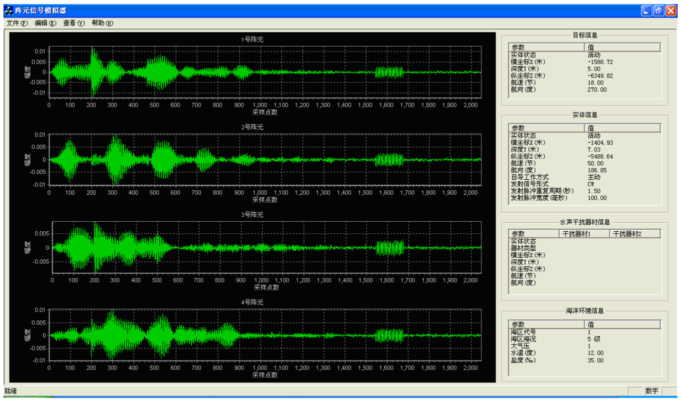

Fig. 6. Waveforms of generated target signals with target signal simulator

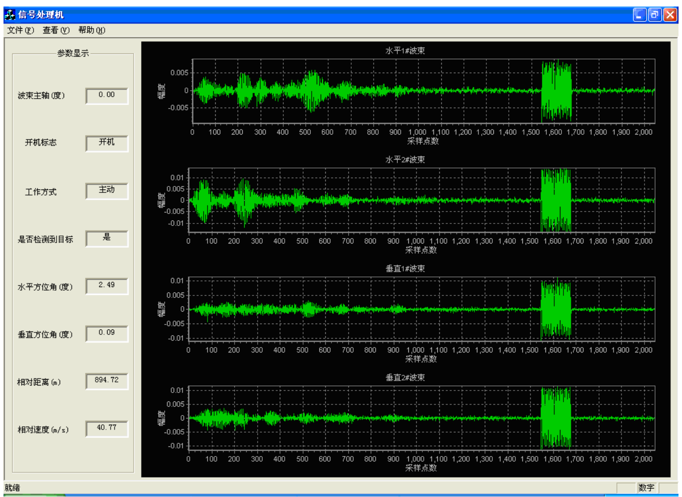

Fig. 7. Waveforms of beam signals with signal processing system

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we present a HIL simulation with acoustic coupling for underwater acoustic detection system. A particular approach is described to provide the receiving transducer array with acoustic signal in air condition. The underlying idea is to introduce a target signal simulator with acoustic coupling device into the simulation and therefore the receiving array can be supplied with the coupled acoustic signal from acoustic coupling device. The developed HIL simulation with low cost can minimize the time of research on actual acoustic detection system and provide valuable reference in other underwater acoustic applications.

So far the acoustic coupling array with a fixed grid of element spacing is implemented in the presented HIL simulation for corresponding to the determined tested receiving array in detection system. To provide an acoustic coupling device for generic use, further improvement is under investigation and design of adjustable spaced transducer array for acoustic coupling device, in order to match the requirement of supplying arbitrary receiving array.

ACKNOWLEDGMENT

This work was partially supported by the Northwestern Polytechnical University Foundation for Fundamental Research (NPU-FFRJC201226).

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