Shock and Vibration 10 (2003) 365–377
IOS Press

Measurement of naval ship responses to underwater explosion shock loadings

Il-Kwon Park[a,*], Jong-Chul Kim[a], Chin-Woo An[a] and Dae-Seung Cho[b]
[a]*Naval Weapon Systems Test Range, Agency for Defense Development* (*ADD*), *P.O. Box 18, Chinhae, Kyungnam, 645-600, Korea*
[b]*Department of Naval Architecture and Ocean Engineering, Pusan National University, 30 Jangjeon-Dong, Kumjung-Ku, Pusan, 609-735, Korea*

Received 20 March 2003

Abstract. The shock-resistance capability of battle ships against a non-contact underwater explosion (UNDEX) is a very critical factor of survivability. In July 1987 and April 2000, we successfully conducted UNDEX shock tests for a coastal mine hunter (MHC) and a mine sweeper/hunter (MSH) of Republic of Korea Navy (ROKN), at the Chinhae bay, Korea. Test planning for conducting these shock tests included responsibilities, methods, and procedures. Test instruments were developed and tested on a drop shock machine to confirm availability in the actual shock tests with emphasis on shock resistance, remote control and reliability. All vital systems of the ships were confirmed to be capable of normal operational condition without significant damages during the explosion shot. By analyzing the test results, the tactical operational safety zone of the ships in underwater explosion environments was estimated. In this paper, we described the results of measurement of naval ship responses to underwater explosion shock loadings including test planning, sensor locations, data reduction, explosive devices, instrumentation and damage assessments of MSH.

Keywords: Underwater shock test, test instrumentation, shock loading, underwater shock analysis

1. Introduction

An underwater shock test is the controlled demonstration of the resistance of hull, machinery, and payload equipment to the hostile environments where a combatant or support ship may be exposed during its life. Underwater shock is a more potentially serious threat. A large number of weapons (e.g., mines, bombs, and torpedoes) capable of producing a shock attack can be effective at a considerable long distance because the water is a very efficient shock transmitting medium [1].

Minelaying is one of the most cost effective ways of exerting maritime power. In World War II, more than half a million mines were laid defensively and offensively in waters and made more damages than by any other weapon. Between 1939 and 1945 the U.K. lost 650 ships to mines; Germany and Italy lost over 1,100 with 600 to 800 damaged; Japan lost more than 500 with 1,000 damaged [2].

MHC and MSH may be easily exposed to an underwater shock because of the role of these ships. Especially, ROKN has taken an interest in the shock-resistance of these ships during design and construction periods.

ADD successfully conducted underwater explosion shock tests of ROKN's two ships, MHC and MSH. In July 1987, MHC was tested with five kinds of 50 sensors. At that time, shock tests with a scaled model of the ship were conducted before actual tests. Transient signals of shock response were stored in analog tape recorders and the firing system was manually controlled. In April 2000, MSH was directly tested with six kinds of 200 sensors without a pre-test with a scaled model ship. The instrumentation was set up consid-

*Corresponding author: Tel.: +82 55 540 6817; Fax: +82 55 542 3737; E-mail: ikpark@add.re.kr.

ISSN 1070-9622/03/$8.00

ering the numerically estimated shock response of the whole ship, and the operation of instrumentation was controlled and monitored from the main controller.

This paper describes the measurement of naval ship responses to underwater explosion shock loadings in ROKN MSH. In Section 2, general guidelines for the underwater shock test of ships are reviewed. In Section 3, we introduce the specially-designed test instrumentation developed by us, which has a capability of acquiring 200 channel data. In Section 4, we describe the shock tests for ROKN MSH, data reduction and analysis, and assessments of tactical operational safety zones. Section 5 presents the conclusions.

2. General guidelines for the underwater shock test of ships

Concerning the test objectives, shock test is categorized into the full-scale ship test for the ship's shock proofing, the model test for the research, the floating shock platform (FSP) and the submerged shock test vehicle (SSTV) for the large equipment development [1]. The guidelines for the underwater shock test of the ROKN MSH are summarized as follows.

2.1. Objectives

Primary objectives of a shock test are well defined in Pusey [3] and NAVSEA [4] as follows;

(a) to demonstrate the capability to operate, or fight the ship in a combat shock environment,
(b) to evaluate the shock hardening modifications that have been made and define any additional modification required for the class and for other applicable ships,
(c) to validate the shock criteria and standards specified for the class,
(d) to provide a basis for refinement of shock hardening criteria for future ships,
(e) to diagnose the causes of equipment damage or malfunction aboard the ship.

2.2. Test planning

Shock test planning begins approximately three years prior to the conduct of the test. The pretest planning such as development of a management plan, conduct of readiness reviews and training of ship's force are included. Early participation of ship's forces is very important in conducting a successful shock test because they should be familiar with guidelines concerning shock test security and be able to safely perform their responsibilities.

2.3. Shock factors

A shock factor is the relative measure of the shock intensity delivered to a ship by an underwater explosion. The shock factor is a function of the type and size of the explosive charge, the distance from the ship and the orientation relative to the ship. Ship shock test generally consists of several shots (typically three or four) with succeedingly more intense shocks. Intermediate level shots may include two shots of equal intensity but from the port and starboard sides. When it is possible, consider alternating shot sides for all shots. Generally, Keel Shock Factor (KSF) or Hull Shock Factor (HSF) are used as the shock factor, KSF is used as the shock intensity of MSH. After determination of KSF, various shock wave parameters such as maximum pressure, decay constant, impulse, energy, bubble period, and bubble radius, etc. are calculated using the empirical formula [5].

2.4. Explosive charges

According to the NAVSEA [4], three sizes of specially designed HBX-1 explosive charges are recommended to be used during shock tests. The weight of charges and the general application related to the overall length of the ship are individually 1,200 lbs for less than 425 ft (130 m), 10,000 lbs for 425 to 625 ft (130 to 191 m), and 40,000 lbs for greater than 625 ft (191 m). A smaller charge than indicated in the above may be used when less intense shock levels are required. For MSH's shock tests, four MK25 mines (1,200 lbs) of HBX-1 explosive charges which were managed in ROKN were successfully exploded by the remote firing control device.

2.5. Methods of support

In order to obtain the desired shock factor in the test, the depth of the charge and the distance from the ship must be closely controlled. Ship should not be moored during the tests to allow all systems and equipments to be normally operated. The bridle method and the parallel method are generally used. For MSH, the bridle method was applied to obtain the proper distance between the ship under test and the explosive charge, and a pontoon was used to suspend the explosive charge at the desired depth.

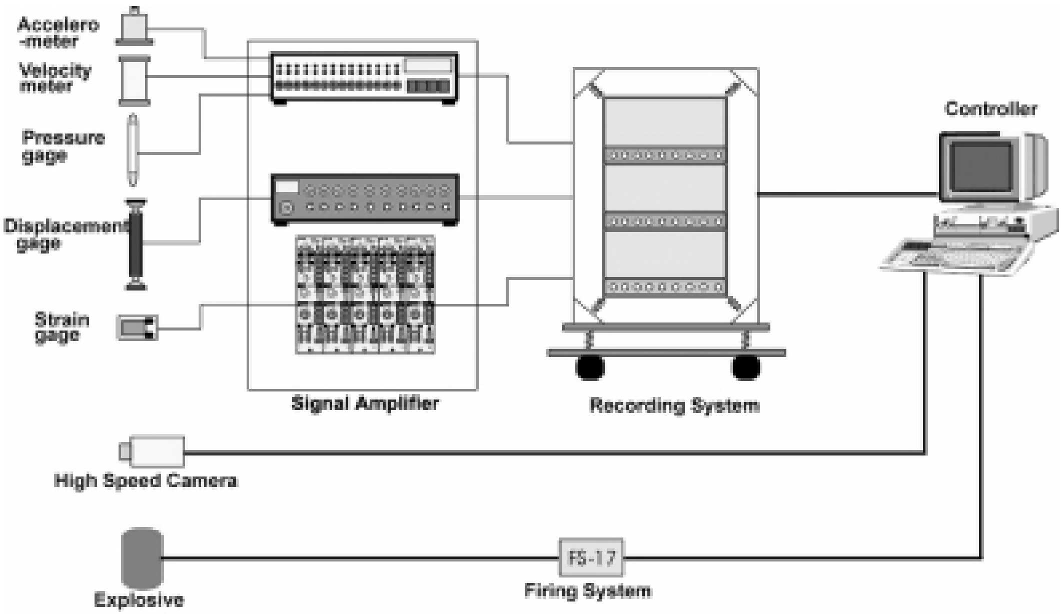

Fig. 1. Schematic diagram of test instrumentation.

Table 1
Characteristics of sensors

Type	Model	Range
Accelerometer	PCB305A05	2500 g
Displacement gage	GE-4.01	6 inch
Pressure gage	PCB138A10	10,000 psi
Strain gage	M/M CO.	50,000 $\mu\varepsilon$
Velocity meter	GE-2.75	20 ft/s
High speed camera	KODAK HG2000	1,000 fr/s

2.6. *Target ships for the test*

Generally, the crew and basic hull possess an inherently high degree of shock resistance compared to the payload equipments aboard the ship. The use of highly sophisticated and complex systems aboard the ship has tended to increase the susceptibility of equipment to high shock loadings.

For combatant ship construction programs, a ship of the class will be recommended to undergo a shock test. The lead ship of a class is usually designated to undergo a shock test so that shock-hardening modifications can be incorporated into the following ships during construction. For non-combatant ships, a representative ship of each class is selected in the same manner as above. Service craft and small landing craft normally don't need shock tests.

Shock tests are highly recommended to be performed just prior to the Post-Shakedown Availability (PSA), so that any damage can be repaired and shock-hardening modifications can be installed during PSA.

2.7. *Test ranges*

No special range facilities are required for shock tests. A requirement is sufficient water depth to reduce the effect of the reflected shock wave. In general, water depth of 100 fathoms (180 m) is required in NAVSEA [4].

Tests must be conducted in an area where swimmers and divers can be cleared from the waters to a distance of 20 miles from the point of test explosions. It is necessary to avoid conducting trials in shipping lanes or in commercial fishing areas. The waters must be checked in advance to be satisfactory with respect to sea and weather conditions, environmental factors.

2.8. *Sensors*

Six kinds of sensors are attached throughout the ship according to their purposes. Specially designed, size of 60 × 60 × 10 mm, aluminum accelerometer mounts are positioned and tightly glued with GRP resin on the hull bottoms to adequately obtain transient signals.

The primary purposes of the sensors are as follows;

– pressure gages for recording underwater shock environments,
– strain gages for structural and material response evaluations,
– displacement gages for relative motions of equipment foundations,

Table 2
Characteristics of controller

Type	Specification & Capability
Hardware	○ Rugged PC (Pentium Pro) ○ 64 MB RAM Memory/Super VGA card ○ Equipment control/data communication interface card ○ Recorder, high-speed camera and firing system interface card
Software	○ Control of recorder, high-speed camera and firing system ○ Countdown, timer and display ○ Checking the synchronous operation of recording system and display ○ Monitoring measurement system ○ Data back-up, play back and analysis

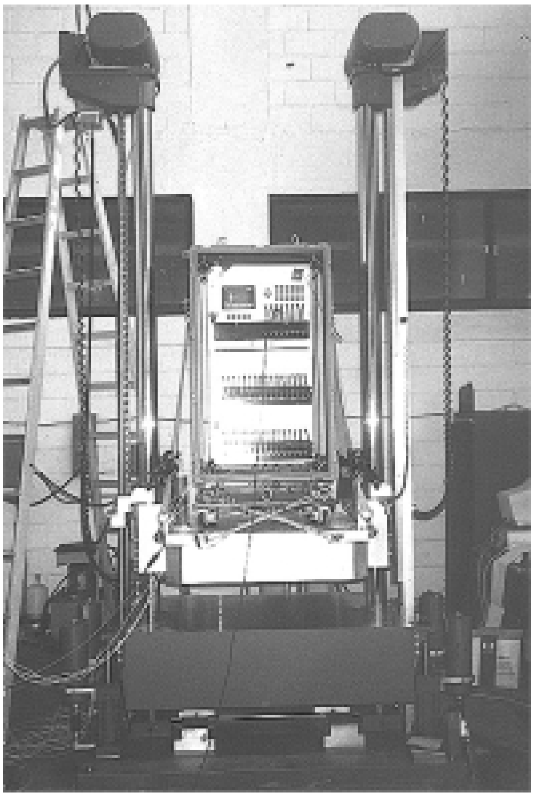

Fig. 2. View of drop shock test.

- accelerometers for structural and equipment shock response motions,
- velocity-meter for structural shock response motions at keel position.
- In addition, high-speed motion cameras with lights for structural motion behaviors are installed at selected positions.

2.9. Underwater shock analysis

Pre-shot analyses for the whole ship are performed to obtain measuring ranges and to assess the integrity of target ship. Comparisons between test and analysis are performed as post-shot evaluation. The details of software utilized by ADD for shock analyses are as follows;

- ASRA for the approximate ship shock response analysis due to shock wave (ADD code),
- SSRA3D based on the DAA(Doubly Asymptotic Approximation) for the 3D ship shock response analysis due to shock wave (ADD code),
- Filtering, FFT and shock response spectrum software for the analysis of test results [6].

Table 3
Characteristics of recorder system

Type	Capability
Recording type	Digital recording (SRAM)
Storage memory	200CH*2MByte/Ch.
A/D converter	12 bit resolution
Sampling frequency	200 kHz (variable/channel)
Anti-aliasing filter	10 k, 20 k, 80 kHz (variable in steps)
Input range	10V (variable in steps)
Model (40ch/set)	PSO5570C+PSO9000*2ea

3. Instrumentation

3.1. Test instrumentation

Specially-designed test instrumentation capable of acquiring 200 channel data, composed of various sensors, signal and control cables, signal conditioning unit, digital tape recording unit and controller were installed prior to the tests.

A central control instrumentation for recording and firing control device was located on the 02-deck of MSH with an awning stanchion to prevent sea water splashing on near explosions.

The schematic diagram of test instrumentation is shown in Fig. 1 and principal characteristics of test instrumentation are summarized in Tables 1–4.

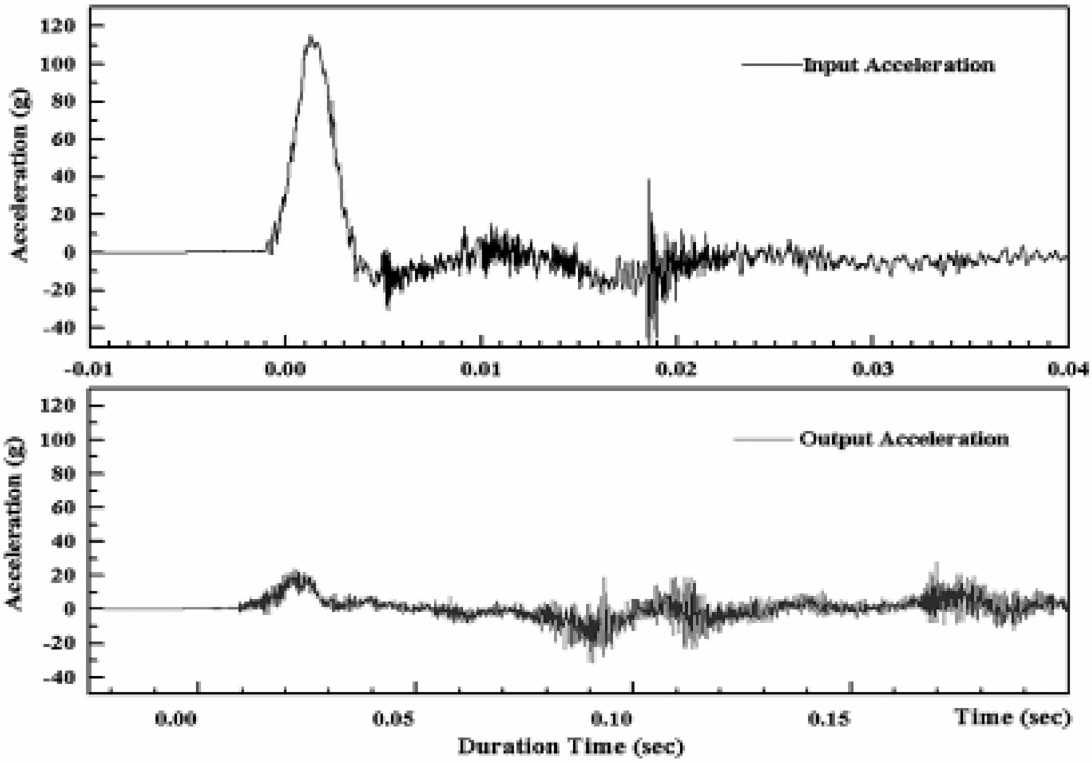

Fig. 3. Input-output response characteristics of test instrumentation.

Table 4
Characteristics of signal conditioner

Type	Model	No. of Ch.	Freq. Range (kHz)
Acceleration	PCB584A	120	0.05–100
Pressure	PCB584A	10	0.05–100
Strain	MM2310	60	DC-65
Displacement	DGPS10073	10	–

3.2. Shock-resistance capability of instrumentation

Shock test of instrumentation developed by ADD was performed to confirm the shock resistance capability by using a drop shock machine. A half-sine wave was used as the input signal of the drop shock machine as defined in MIL-STD-901D [7].

The view and the characteristics of the drop shock machine test are described in Figs 2 and Table 5. Instrumentation rack was specially made of three-layered shock mounts and urethane-foam cases to absorb severe shock impulses. To confirm its shock-resistance capability, input-output acceleration was measured below and above shock mounts, and inner parts of the instrumentation rack, respectively. Measured input-output response characteristics of instrumentation rack are shown in Fig. 3, and the shock machine test results show that the maximum allowable input shock level is 177 g due to the duration time of 4msec.

In order to confirm the shock-resistance capability of instrumentation due to the variation of shock duration time, transfer functions are extracted from the measured input-output data of the shock machine test. From these measured data, theoretical transfer function is estimated. The estimated results compared with the measured results are shown in Fig. 4. The shock-resistance capability of test instrumentation due to the variation of duration time and the peak acceleration levels of shock input are also shown in Fig. 5. The test instrumentation was confirmed to be available in real shock tests considering the duration time and the magnitude of the estimated shock response of MSH.

4. Conduct of shock tests

Naval Weapon Systems Test Range (NWSTR), ADD in association with ROKN conducted the underwater explosion shock test of MSH in April 2000 as shown in Fig. 6. ADD commenced a test project in early 1998, prepared the test plan, and performed readiness

Table 5
Characteristics of shock machine

Type	Specification
Shock table	95 cm × 95 cm (longitudinal)
Shock wave & acceleration maximum level	Sine wave: 1,000 g
	Pulse wave: 130 g
	Saw tooth wave: 200 g
Shock duration time	0.5 ∼ 65 msec
Maximum test weight	2,500 lbs
Maximum velocity	25 ft/sec

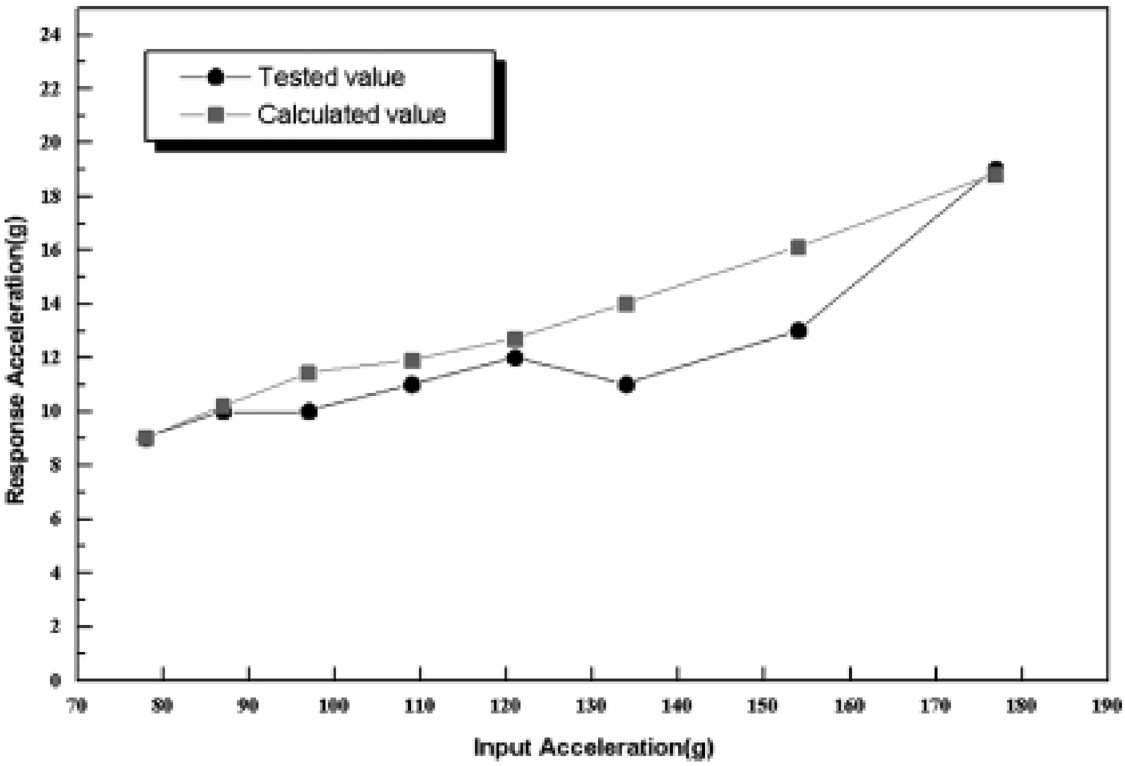

Fig. 4. Comparison of estimated and tested results.

reviews, pre-test inspections, crew's training and ship preparations, etc.

MSH made of glass reinforced plastic (GRP) material was designed and constructed by Kangnam shipyard under ROKN's supervision. The principal dimensions of MSH are; length between perpendiculars (55.6 m), length overall (59.4 m), breadth (10.5 m), draft (3.0 m), and displacement (880 ton).

4.1. Schedule of shock tests

Four shots on MSH were scheduled at an interval of one week, but delayed a few days due to the weather conditions. After each shot, a detailed survey of MSH was performed to identify any malfunctions of the ship's equipment and to determine the readiness of the ship for the next test. MSH's ballast and fuel tanks were kept in a normal load condition. The standoff-distance was measured by using three fixed distance wires.

The actual schedule of underwater shock tests on MSH in 2000 is;

(a) Ship preparations (22 March to 5 April) for installation, calibration and interface check-up of sensors, cables, instrumentation, firing system and explosive, training and pre-test inspection.
(b) Four shots were individually performed on 6 April, 18 April, 25 April and 2 May.

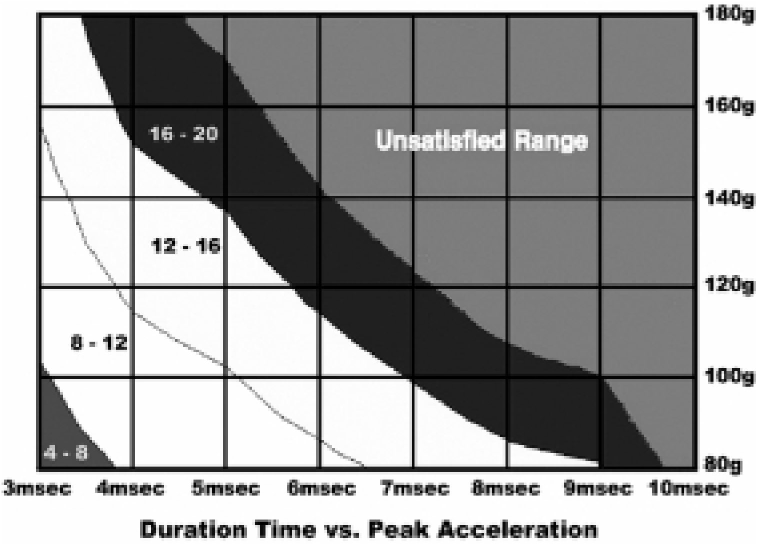

Fig. 5. Shock response level of instrumentation due to duration time and peak acceleration.

Fig. 6. View of MSH shock test.

4.2. Test sites

Two test sites, the Chinhae bay and the Namhyung Island, were reviewed considering shock test conditions, but finally the Chinhae bay was selected due to sea weather conditions and efficient logistic supports, off the distance of 10 miles from the ROKN commanding post.

ROKN and coast guard patrol boats supported on-site operations during shots. A helicopter was also assisted in the sea area surveillance and served as a photo platform.

4.3. Locations of sensors

During four shots, all data were obtained as time-history recordings of acceleration, displacement, strain and pressure through test instrumentation installed aboard the ship. Six kinds of 200 sensors were installed according to their purposes throughout the ship.

The number and locations of sensors are;

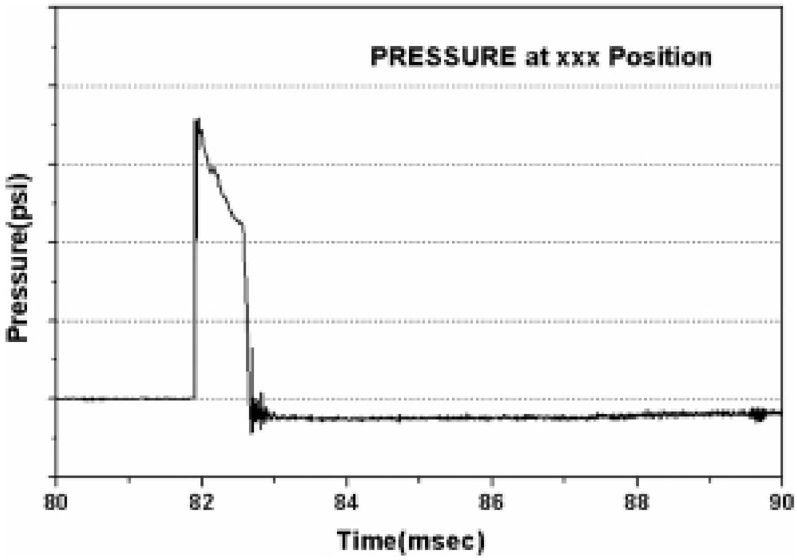

Fig. 7. Shock pressure profile at outside hull.

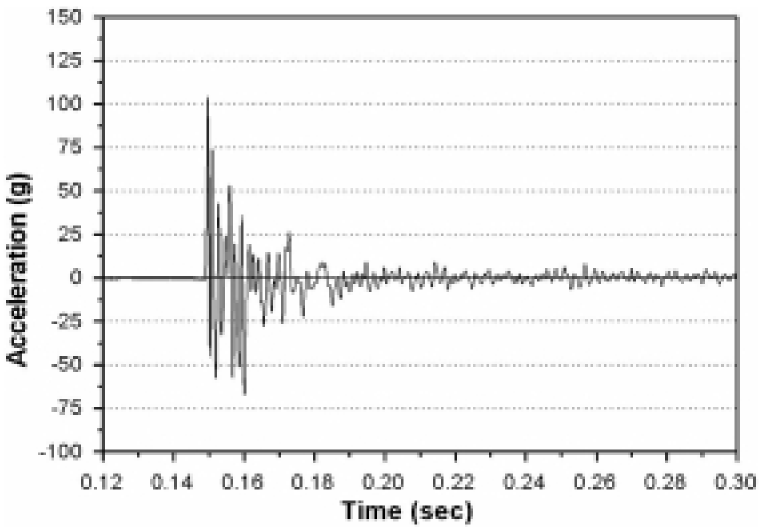

Fig. 8. Filtered(2.5 kHz) time-history signal.

(a) one hundred fifty accelerometers for main equipments and foundations of shock grade A, B, and each deck plate,
(b) ten displacement gages between main equipments and their foundations,
(c) thirty strain gages for main equipment foundations, deck plates, mast and local position of hull structure,
(d) ten pressure gages for shock wave measurements,
(e) one velocity-meter for structural shock response motions at keel position,
(f) and three high speed motion cameras for motion of mast, swimmer delivery vehicle (SDV), gas turbine generator.

4.4. Acquisition of shock response data

Firing system to synchronize the start of transient recorders, and high-speed cameras was located in the instrumentation camp on 02-deck of MSH. Every channel signal, which was synchronous with high-speed camera, was stored on SRAM memory of the transient recorder. The operation of these devices was controlled

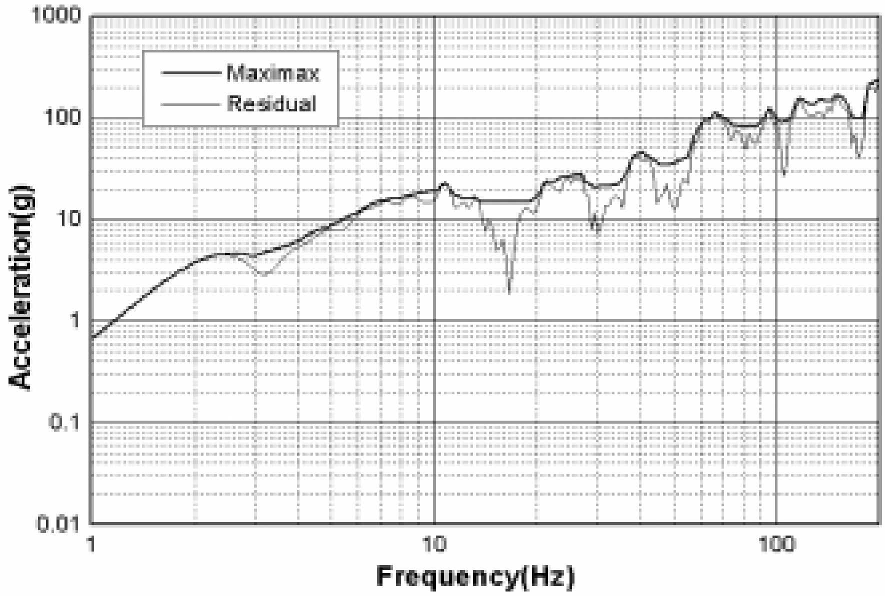

Fig. 9. Shock Response Spectrum at the foundation of main equipment.

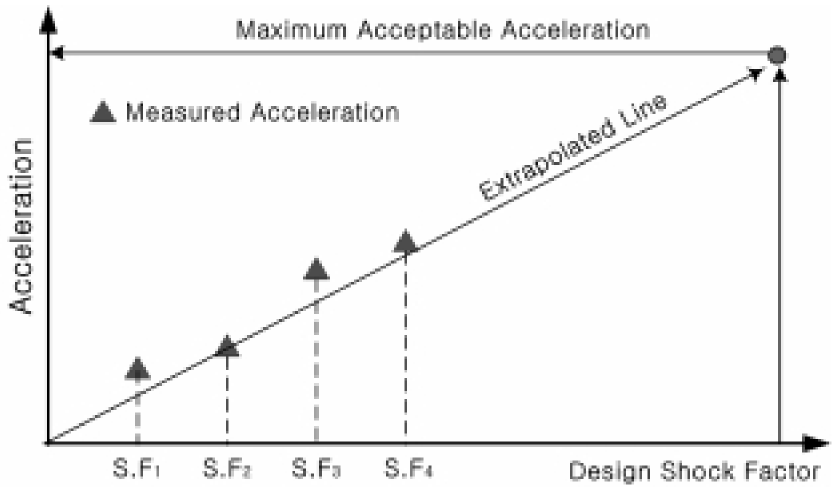

Fig. 10. Estimation of maximum acceptable acceleration.

and monitored from the main controller in the instrumentation camp. In the bridge, the operation status and the countdown clock on a computer monitor were displayed.

For reliable data acquisition, the input-ranges of signals in transient recorders should be adjusted to proper values. The instrumentation was set up considering the numerically estimated peak values of the whole ship analysis. Accordingly, reliable data were measured on every shots.

4.5. Data reduction and analysis

Shock factors of the real tests are reviewed by using the shock pressure wave profile of the underwater explosion as shown in Fig. 7. For data reduction of acceleration, strain, velocity, and displacement signals, primary time-history signals are filtered by 2.5 kHz low-pass filter as shown in Fig. 8. From the analysis for shock response spectra of the main equipments and the hull structure, the peak responses during the pulse are estimated as shown in Fig. 9. The principal normal

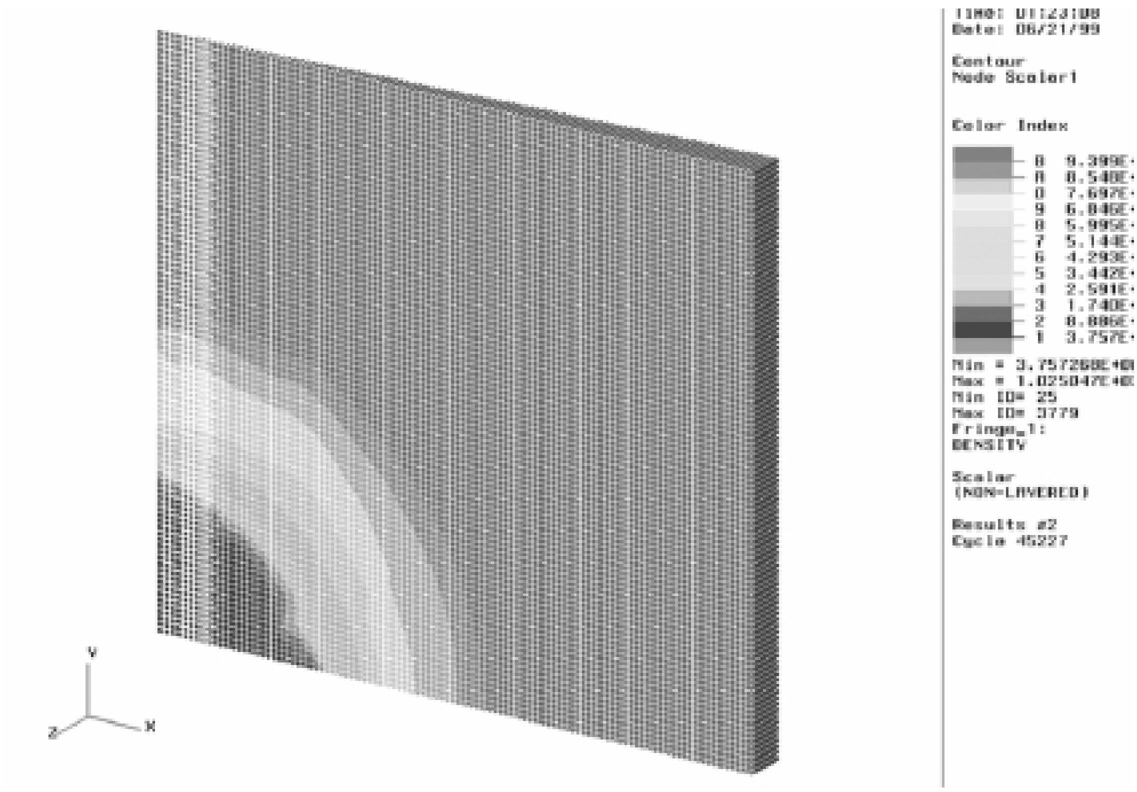

Fig. 11. Modeling of shock input loading using JWL equations (after time of 8 msec).

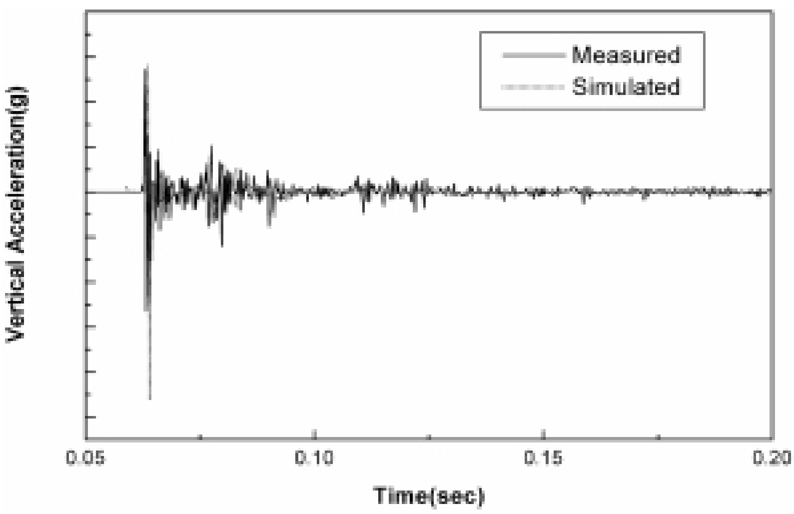

Fig. 12. Comparison of measured and simulated vertical acceleration at bottom structure.

stresses in ship's structure are calculated by using the measured data of 0°/45°/90° rosettes type strain gages.

The shock hardening criteria of ship's structure and equipments are validated by extrapolation, curve fitting and regression methods using the processed data of shock tests as shown in Fig. 10. Test result data are summarized to database as forms of time histories and shock spectra.

Prior to the tests, numerical shock analyses were performed. ADD used their analysis code, which is based

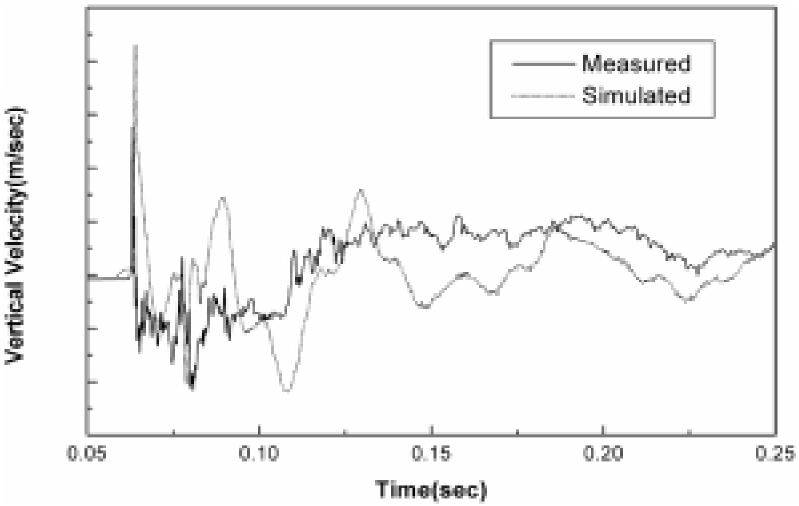

Fig. 13. Comparison of measured and simulated vertical velocity at bottom structure.

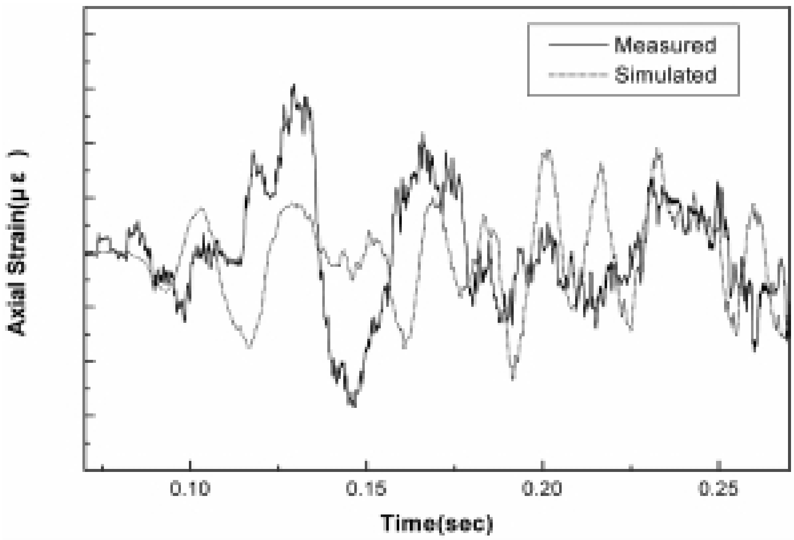

Fig. 14. Comparison of measured and simulated axial strain at mast pipe.

on the DAA method and adapted to the surface ship problems, to calculate the ship shock response. Pressure wave was calculated by empirical-exponential formula. In case of having no empirical-exponential formula, pressure waves were calculated by hydro-code using the Jones-Wilkins-Lee (JWL) equations. Figure 11 shows the pressure profile from the results of the hydro-code.

In Figs 12–14, shock responses from the DAA method are displayed with measured data. On 41 positions of ship, Russell's error factors were calculated within the time durations of 250 ms for the purpose of comparison study [8,9]. The magnitude error factors were below 0.3 for 60% of comparison positions. The phase error factors were below 0.5 for most comparison positions. Correlations between the measured data and the analysis results were satisfactory comparing the magnitude error factors of 0.2 by the Russell's laboratory experiments. Figure 15 shows sampled stress distribution from the calculation using the DAA method.

4.6. Assessments of tactical operational safety zones

The damage criteria of a ship are classified into three grades of Kill (K), Mission Aborted (M) and Commu-

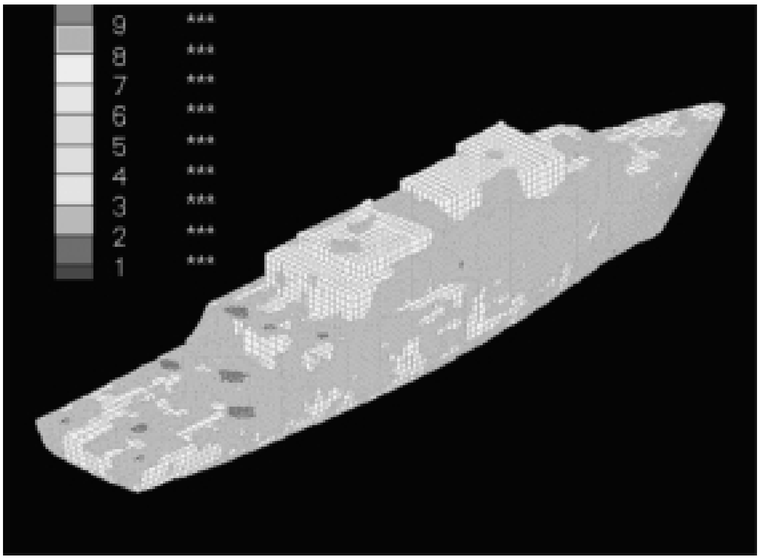

Fig. 15. Simulation results of whole structure's stress.

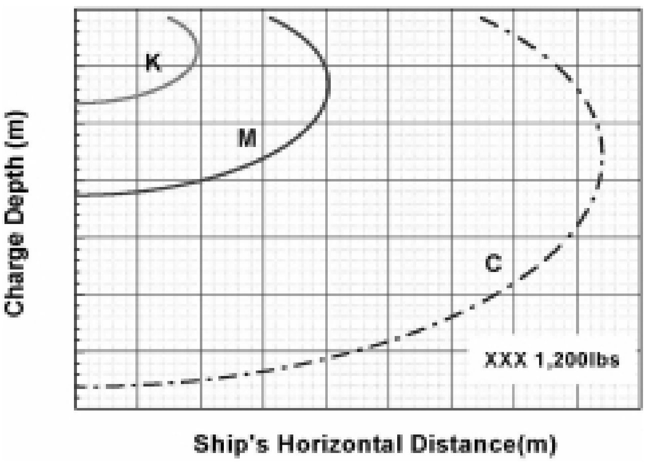

Fig. 16. Damage estimation due to charge weight and depth.

nication Impaired (C) by US Navy Standard [10]. The damage criteria K, M, C of MSH due to various charge depths and explosive types are estimated by analyzing the post-processed data of shock test results which are extracted from the extrapolation, curve fitting and regression methods. Then, we evaluate MSH's tactical operational safety zones considering the shock hardening criteria of ship's structures and the technical data of onboard equipments supplied by makers. Sample result is shown in Fig. 16.

Assessments of ship's safety zones due to charge depths and types are very critical factors to confirm her safety in tactical operating environments. Detailed test results of MSH are described in the classified ADD technical report [11].

5. Conclusions

ADD successfully conducted underwater explosion shock tests of two ROKN ships, MHC in July 1987 and MSH in April 2000, respectively. The responsibilities, methods, and procedures for conducting these shock tests have been continuously developed including test instrumentation, test operations, damage assessment, numerical analysis method for structure and reporting requirements.

In order to adequately estimate the operational safety zone of MSH in the shock environment, shock response spectra of structure and equipments are broadly extracted from the acquisition data. Even though there are still many problems which remain to be solved, the capability of performing underwater shock tests for ships was validated through the experiences of underwater explosion shock tests of two ROKN ships. Besides, the applications of modeling and simulation to shock test fields, and the developments of more advanced numerical analysis techniques equivalent to the level of real data should be continued through making the best use of these test results.

Acknowledgements

The shock tests of MSH and MHC were successfully performed under the full support of ROKN and Kangnam shipyard. We would like to express our many thanks to them. We are also grateful to ADD members who participated in the shock tests for their sincere cooperation.

References

[1] NAVSEA, *Guide for Planning and Managing Shock Trials of Surface Ships*, NAVSEA 0908-LP-000-0010, April 1989.
[2] R.J. Daniel, Mine Warfare Vessels and Systems, *Int. Symposium on Mine Warfare Vessels and Systems, RINA* **I**(1) (Jun. 1984).
[3] H. Pusey, *Underwater Shock Measurement*, Shock and Vibration Digest, Dec. 1989, pp. 9–11.
[4] NAVSEA, *Ship Post-Delivery Tests and Trials Guidance Manual*, NAVSEA 0900-LP-095-3010, Rev.1, Chap.13, Aug, 1989.
[5] Y.S. Shin, Thomas L. Geers, *Response of Marine Structures to Underwater Explosion*, Lecture Notes, Feb. 1993, pp. 3.24–3.25.
[6] C.W. An et al., *A Study on the Ship Structure Shock Response Analysis (I), ADD NSDC-513-991203*, Dec. 1999.
[7] MIL-S-901D, *Shock Tests, High Impact Shipboard Machinery, Equipment, and Systems, Requirement for*, March 1989.
[8] D.M. Russell, *Error Measures for Comparing Transient Data: Part I: Development of a Comprehensive Error Measure*, Proc. of 68th Shock & Vibration Symposium, 1997, pp. 175–184.
[9] D.M. Russell, *Error Measures for Comparing Transient Data: Part II: Error Measure Case Study*, Proc. of 68th Shock & Vibration Symposium, 1997, pp. 185–198.
[10] NAVSEA, *Operational Characteristics of Standard US Naval Mines*, (Vol. I,II), OP2637.
[11] I.K. Park et al., *Underwater Explosion Shock Test Report of MSH*, ADD NSDC-313- 000928C (Classified), Oct. 2000.


Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
International Journal of Distributed Sensor Networks
Advances in Civil Engineering
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Journal of Control Science and Engineering
Journal of Robotics
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration