

# Acceleration Measurements on Naval Vessels Undergoing Explosive Shock Testing

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## SUMMARY

When shock testing naval vessels, the structural response to a dynamic load is usually measured by accelerometers positioned at selected locations throughout the vessel. The complexity of the structure under test presents a formidable task in identifying key measurement locations. The aim of this paper is to present the issues raised in choosing such locations.

## 1. INTRODUCTION

In shock testing a naval vessel many accelerometers may be located on board the vessel to measure its response from the underwater blast wave. Accelerometers are positioned on the structure at locations such as the outer hull plating, bulkheads and superstructure. Other locations include ship's equipment such as the power plant, control systems and electronic instrumentation. It is a difficult task to identify suitable locations for measurements because of the large size of the naval structure and the complex behaviour of the structure arising from the interaction of the blast wave with the vessel.

The aim of this report is to present some of the work undertaken at DSTO-Materials Research Laboratory (MRL) on acceleration measurements, and to discuss the issues raised in selecting accelerometer locations.

The selection of accelerometer locations begins with recommendations by naval architects, but the decision as to which locations are most suitable involves further refinements that depend on considering the instrumentation requirements. This report is confined to the instrumentation considerations; it discusses the selection of locations by considering the limitations of the accelerometers used, the manner in which they are mounted, and the nature of the signal recorded.

Acceleration measurements are only a small part of our work on shock testing. Other current activities include measurements of underwater blast waves, vibration analysis, and the shock loading of materials. However accelerometer measurements are important because they provide valuable information on the vessel's response in the most extreme operational environment. This response is difficult to predict in detail owing to the structural complexity of such a vessel.

## 2. BACKGROUND

Shock testing the structure and equipment of a naval vessel is part of the shock qualifying process that ensures that the vessel has met its design specification and identifies deficiencies in the design or construction of the vessel. The performances under shock loading of equipment, such as the propulsion unit, the navigation system and combat systems are evaluated. The shock test parameters are defined by the shock standard to which the vessel was designed.

The test, as performed by MRL in conjunction with the RAN, consists of a series of experiments conducted at sea using explosives to generate underwater shock waves. A typical experimental configuration consists of mooring the vessel at a defined stand-off distance from the explosive charge of known yield located on the sea bed (Figure 1).

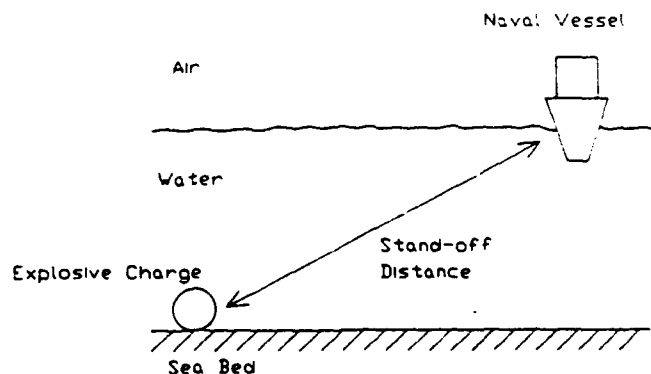
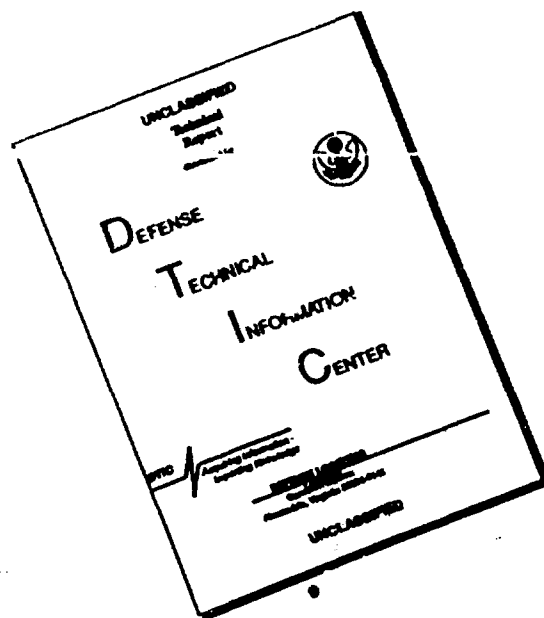


Figure 1: A typical experimental configuration for shock testing a naval vessel. The vessel is moored at a defined stand-off distance from the explosive charge of a known yield.

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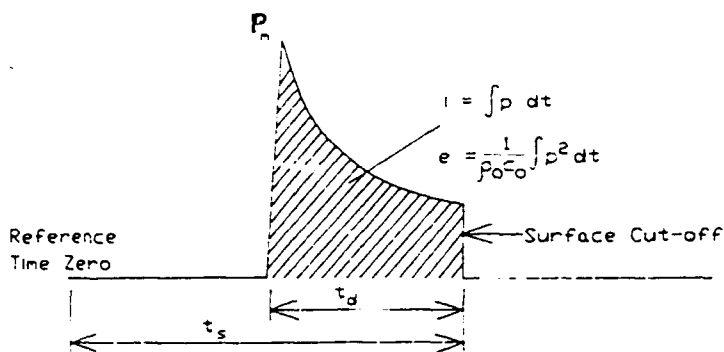


Figure 2: A typical shock profile from an underwater explosion. Important parameters of the profile are the peak pressure,  $P_m$ , the rise time of the signal, the duration,  $t_d$ , the surface cut-off time,  $t_s$ , the impulse,  $i$ , and the energy flux density,  $e$ . Note  $\rho_0$  and  $c_0$  denote the density and acoustic velocity of the water, respectively.

The dynamic load on the vessel caused by the shock profile can be quite complex. Its shape depends on the explosive geometry and the propagation of the shock wave. Interface boundaries where there are differences in density, such as the surface of the water, give rise to reflection and refraction of the shock wave. Typical features of the shock profile include a very rapid pressure rise to a peak value, followed by an exponential decay until it drops sharply depending on the distance from the free surface of the water (Figure 2). The peak pressure, decay time (time constant), duration, impulse, energy and time to surface cut-off are parameters that characterise the pressure profile. Therefore the pressure profile is measured by underwater pressure transducers placed in the vicinity of the vessel in order to determine these characteristics.

The dynamic load, defined by the parameters of the pressure profile, provides the controlled condition of the experiment. Similitude equations which predict the shock wave parameters [1] can be used to calculate the amount of explosive and stand-off distance of the vessel required for the desired dynamic load. The load, defined in this manner, complies with the shock standard.

### 3. ACCELEROMETER CHARACTERISTICS AND MOUNTING

Accelerometers located on board measure the response of the vessel to underwater shock. The choice of the type of accelerometer and its location on the naval vessel is a vital decision determining the validity of the results. The accelerometer must have suitable characteristics to faithfully record the signal. The short duration and intensity of the signal place demands on the accelerometer's characteristics such as the sensitivity, linearity and response. Furthermore, the accelerometer must be mounted at a location representative of the manner in which the vessel responds to the load. For example, locating the accelerometer on components not rigidly mounted would yield meaningless results on the vessel's structural response.

We have found that piezoresistive accelerometers are most suitable for these measurements. The accelerometer consists of silicon strain gauges mounted

on a small cantilever [2]. The cantilever has two slits at one end and is rigidly attached to the accelerometer base at the other (Figure 3). The strain gauges are located across the slits; with one strain gauge in tension and the other in compression. The strain gauges are part of a wheatstone bridge and form a half bridge.

The two major reasons for using piezoresistive accelerometers are that they have DC response and a stable zero baseline. We evaluated piezoelectric accelerometers and found that in this environment the baseline drifts. This drift arises from heat exposure

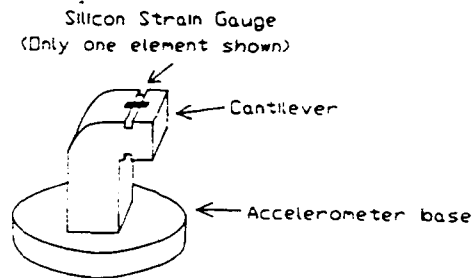


Figure 3: Schematic of an Endevco piezoresistive accelerometer.

but, more importantly, from the amplitude linearity characteristics of the piezoelectric crystal [3]. Increasing the acceleration level increases the sensitivity of the accelerometer. The relationship is linear depending on the accelerometer design and crystal used. A spurious DC signal is produced in the acceleration record. This is highly undesirable because the results are integrated numerically to obtain velocity and displacement. The baseline drift introduces an offset that appears in the integration as a ramp and parabolic error, respectively.

To ensure that the accelerometer faithfully measures the dynamic load it must be mounted rigidly on the surface [4]. Although the accelerometer is small and light, minimising material mismatching, precautions are needed in mounting the accelerometer. These include applying the correct torque on the accelerometer mounting screws, using mechanical filters, and avoiding locations that have high local resonance. Applying the correct torque ensures that the accelerometer and the component under test are an integral part so that the entire system responds as one. Mechanical filters are used to isolate the accelerometer from unwanted frequencies. For example, measurements on a steel panel contain a high frequency resonance which is not representative of the structural response of the vessel and should be eliminated.

Isolating the accelerometer from vibration requires an understanding of the modes and frequencies of vibration of the ship. As an example, a merchant ship undergoes several vibration modes in its normal operational environment [5]. These include hull vibration (1-6 Hz), vibrations at interfaces between the hull, bulkhead and/or ship's equipment (3-12 Hz), superstructure vibration (7-14 Hz) and local vibration of plates and

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frames (10-40 Hz). Vibration is caused by propulsion induced forces and the surrounding water. The frequencies of interest during shock testing are in the range of 0-300 Hz [6]. During the shock test ship induced vibrational effects are of secondary interest.

The accelerometers can be mounted in three orthogonal axes but are commonly mounted either in the vertical direction or horizontal plane (Figure 4). We have used the vertical direction to study the structural response of the vessel. The horizontal mounting technique is used on ship's equipment such as electronic systems and the propulsion system. However, both usually are required at the same location.

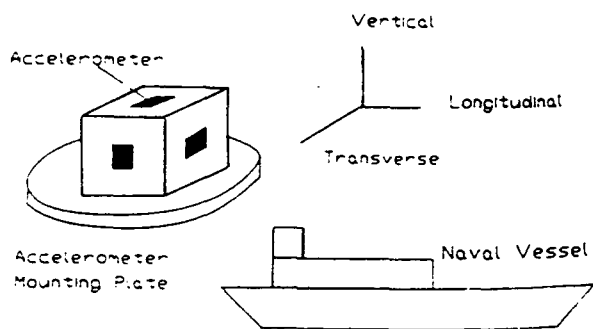


Figure 4: Possible mounting orientations of an accelerometer on board a naval vessel.

#### 4. SELECTION OF ACCELEROMETER LOCATIONS

Shock testing of naval vessels is a complicated field and requires the understanding of many aspects of shock waves and dynamic loading. For example, in designing the shock test, hydrodynamics, shock wave physics and explosives' science are used to predict the load on the vessel and understand the propagation and interactions of the shock wave. Studying the response of the vessel requires knowledge of materials science, and structural and vibration engineering. Because measurements involve the use of electronic instrumentation, metrology, computer science and numerical analysis, an understanding of these branches is needed when selecting transducer locations.

Our preliminary approach in the selection of suitable locations has been to review all of the results from previous shock experiments. These are categorised according to the magnitude of the dynamic load and correlated to the accelerometer locations. Comparisons between results show that the acceleration levels and frequencies are dependent on the geometry of the

structure and the location of the accelerometer on board the vessel. By these comparisons we estimate the levels and select the appropriate accelerometer and mounting configuration. At present this is the only quantitative means used to estimate acceleration levels and to determine the suitability of a particular location.

Guidance on suitable accelerometer locations is also provided by qualitative considerations of materials science and structural engineering. For example, the shock wave causes local motion, which occurs as deformation of hull plating, and overall structural motion, which results from inertial effects. The accelerometer must faithfully record both types of motion. Locations of the accelerometers are determined by considering their suitability for providing information on these motions.

Consideration is also given to the nature of the signal. A typical result is shown in Figure 5. The general feature of an acceleration signal is its oscillatory and dissipative nature; that is, it resonates at a particular frequency and decays quickly with time ( $\approx 80$  ms). The signal is complex and difficult to analyse and exhibits recurrence (ie. there is a reappearance of the signal after some time has elapsed). By analysing the signal, the validity of the results is determined and the suitability of the accelerometer location and mounting are evaluated.

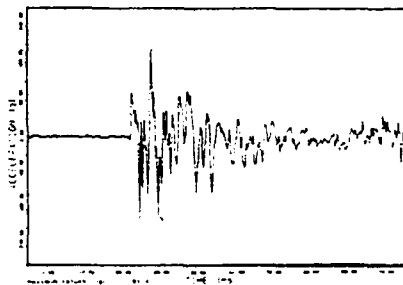


Figure 5: A typical acceleration signal from a dynamic load due to an underwater explosion.

#### 5. FUTURE DIRECTIONS

Another aspect to be considered is the need to develop tools to identify measurement locations so that the selection procedure is quantitative and consistent, and acceleration levels for a given shock configuration are predictable. A quantitative selection procedure would identify measurement locations and would provide a systematic selection procedure. The prediction of acceleration levels would ensure that the locations chosen would represent the severest loading conditions on the vessel.

The development of an acceleration predictive capability is made possible by the availability of relatively powerful and cheap computers. To predict the acceleration levels on the vessel, finite element and boundary element codes can be used [7] which are now relatively accessible. Major disadvantages are that these codes

are complex and need to be calibrated by using representative measurements from shock experiments.

A further development that can improve the selection procedure is the availability of an extensive shock induced acceleration data base. Shock experiments are expensive and a limited amount of data is currently available at MRL. The data base can be increased without the need for expensive full scale shock experiments. To study the local effects on components and ship's equipment, results can be obtained from laboratory experiments using high impact shock machines [8] and small scale shock experiments [9]. These results would indicate acceleration levels for full scale shock tests.

To obtain data on the structural effects, it may be possible to use slamming experiments in which the vessel undergoes dynamic loading in rough sea conditions. Slamming experiments also give rise to hull whipping [10]. In fact, studies have shown that the whipping component is of much lower amplitude and frequency than the dynamic load (in this case the slamming force) and persists over a longer period of time. The load, on the other hand, has a much higher frequency and amplitude but decays very rapidly. It is recommended that investigations should be undertaken to determine the validity of comparisons between results from slamming experiments to results from shock tests.

Data obtained by these techniques can be compiled together with the limited data available from shock tests. Models and/or guide lines can then be developed to identify suitable locations for instrumentation in future shock trials.

## 6. CONCLUSION

Selecting locations for accelerometers on board naval vessels begins with recommendations by the naval architects on possible locations of interest. The actual locations chosen take into consideration the accelerometer type, mounting and the nature of the acceleration signal. In choosing the locations, data are used from previous shock experiments and the suitability of the location is based on these measurements. Qualitative considerations are also used to identify items on the vessel that are prone to damage.

It is recommended that computational tools be developed to quantify the selection procedure and enable the prediction of acceleration levels. The availability of

relatively powerful and cheap computers make it possible to use finite element and boundary element codes to achieve this. These can be supplemented by experimental data from laboratory experiments using shock machines and small scale shock tests. It may be possible to obtain further data from slamming experiments under conditions that simulate the structural response of the vessel from shock tests. The feasibility of such comparisons requires further investigation.

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