

SHOCK DESIGN OF THE MK 49
SHIP'S INERTIAL NAVIGATION SYSTEM (SINS)

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ABSTRACT

The Sperry Marine MK 49 Ship's Inertial Navigation System (SINS) is now in production for marine surface and subsurface applications. This system has been selected as the standard NATO SINS equipment and is the only marine inertial navigator which utilizes ring laser gyros. In order to serve the NATO community, the system must withstand a variety of shock stimuli (STANAG 4141, STANAG 4142, BR3021, etc.). Sperry Marine has shock hardened the system enclosures and developed a shock isolation system for the Inertial Measurement Unit (IMU) using tension-compression liquid spring/dampers in a hexapod configuration, thereby providing the shock attenuation and precision angular alignment returnability necessary to meet the above specifications. This paper addresses the design process to shock harden the IMU and the system enclosures and presents experimental results.

INTRODUCTION

The Sperry Marine MK 49 Ship's Inertial Navigation System (SINS) is the world's first production marine navigator that uses dithered ring laser gyro technology. This system provides position, heading and attitude data to other shipboard systems such as fire control, steering, velocity logs, and so forth. Thus, it serves a vital role in military ship's operations and must continue operating and navigating during and after any imposed shocks.

During the development of the MK 49, various dynamic analyses and experiments were performed as an aid to designing specific components. Guidelines for selecting components for analysis were based on component criticality, shock sensitivity and similarity to previously tested equipment. Three components or assemblies, which will be fully described in this paper, were chosen for analysis and/or experimental testing: the upper and lower enclosures of the single enclosure system, the electronics unit in the dual enclosure system, and the Inertial Measurement Unit (IMU).

The cabinets were chosen because; a) they must support considerable loading during shock, b) they represent a new design and no previous test results for similar equipment exists, and c) the potential exists for expensive rework resulting from a failure during shock tests.

The IMU was chosen because previous shock tests of the ring laser gyros, three of which are contained in the IMU, showed that gyro performance can be affected by shock levels exceeding 56 g's. Since the MK 49 is designed to operate in shock environments exceeding 200 g's, a shock isolation system was devised to protect the gyros. The analysis aided selection of parameters necessary for the design and procurement of the shock isolation system.

DESIGN REQUIREMENTS

Beginning with the initial development stages, the MK 49 was intended to serve the navigation needs of a variety of military customers. Because each navy may have its own shock specification, a survey of these specifications was required to determine which requirements represented the most extreme environment.

For the U.S. Navy, MIL-S-901 is the appropriate specification with the test being performed on the Medium Weight Shock Machine. This requirement does not specify the shock pulse levels or duration, but only dictates the hammer drop height for a given equipment weight. However, Sperry Marine's previous experience in developing equipment to survive this test has shown that this machine usually generates approximately 150 g's for equipment similar in weight to the MK 49.

There are a variety of specifications that must be satisfied because our NATO SINS customers represent four different countries: United Kingdom, The Netherlands, Canada and Spain. Because the details of these specifications are restricted, their characteristics will be discussed only in a general sense.

The standard NATO SINS shock requirements are STANAG 4141 and STANAG 4142. Both of these specifications identify a shock spectrum (acceleration versus frequency) that must be survived. STANAG 4141 is a test specification, while STANAG 4142 is an analysis requirement.

The shock levels of STANAG 4141 are generally greater than those of MIL-S-901. However, the shock spectrum of STANAG 4141 can be generated by the Medium Weight Shock Machine if hammer heights are increased beyond those specified by MIL-S-901. The direction of the shock is also important. STANAG 4141 specifies that the vertical shock shall be the full level, while the athwartships and longitudinal directions are one-half and one-quarter of the vertical shock respectively.

STANAG 4142 specifies shock levels that are greater than those of STANAG 4141. However, since it is recognized by the NATO authorities that development of a machine to test to these levels is prohibitive, this specification allows the equipment to be qualified to these increased levels by analysis. As is the case for STANAG 4141, the direction of the shock is a factor in the magnitude of the shock levels imposed by STANAG 4142.

Additional shock requirements are also imposed by specific NATO countries. The United Kingdom requires that their systems meet the shock levels imposed by BR3021, Grade Curves C and G, while The Netherlands require that their systems meet 1.5 times STANAG 4142, which, in the vertical direction, is generally equivalent to BR3021, Grade Curve G.

BR3021 specifies a set of velocity versus time curves whose magnitude and temporal characteristics vary according to the type of vessel and the installation location. Grade Curve C is similar in magnitude to MIL-S-901, while Grade Curve G is much more

severe. In addition, BR3021 shock levels are not reduced on the basis of direction, i.e., all three axes are subjected to the full shock levels.

A careful assessment of these shock specifications shows that this wide variety of shocks can be consolidated into a few specifications used to design and test the MK 49. The chosen shock design requirements for the MK 49, which are based on two different system configurations (to be discussed) are: 1) the single enclosure system designed to 1.5 times STANAG 4142 and tested to STANAG 4141, and 2) the dual enclosure system designed to 1.5 times STANAG 4142 and tested to BR3021 Grade Curve G.

Other design requirements that affect the shock design are vibration per MIL-STD-167-1, structureborne noise per MIL-STD-740-2, and highly accurate (measured in arc-seconds) attitude requirements for the IMU platform.

ENCLOSURE DESIGN AND ANALYSIS

As mentioned before, there are two configurations of the MK 49, a single enclosure system and a dual enclosure system. The single enclosure configuration houses the entire system in a single cabinet as shown in Figure 1. The dual enclosure configuration splits the system into two cabinets -- an electronics cabinet and an Inertial Measurement Unit, as shown in Figure 2.

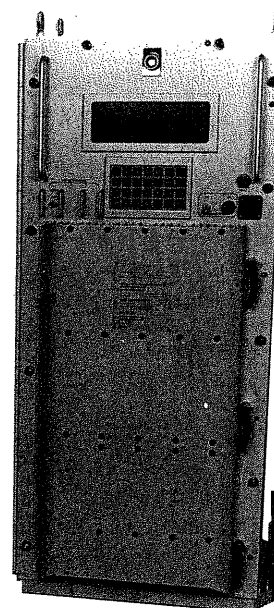
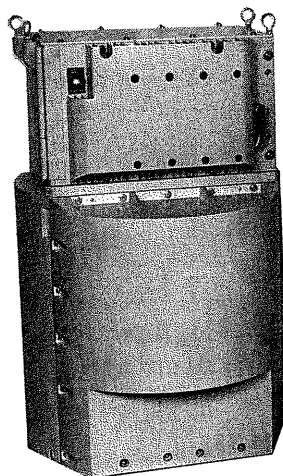
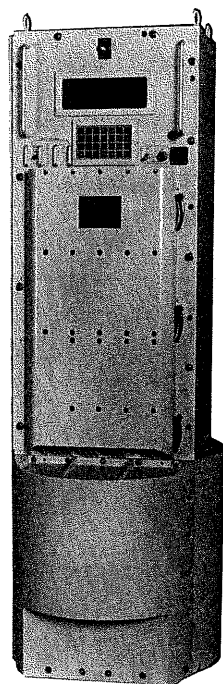


Figure 1. MK 49 Single Enclosure System

Figure 2. MK 49 Dual Enclosure System

The single enclosure version is designed to The Netherlands requirement of 1.5 times STANAG 4142 and will be tested to STANAG 4141. The lower part of the enclosure is the IMU enclosure, which houses the IMU platform assembly containing the motion sensors (gyros and accelerometers) used for navigation. The upper part of the enclosure contains the system electronics, power conditioning components, interface panel and display. The enclosure is attached to the deck by eight bolts inside the IMU and to the bulkhead by two flexible brackets located near the top rear of the upper enclosure.

Shock loads imposed on the single enclosure system must be born by the IMU housing and the interface to the upper housing. Therefore, a finite element model of the single enclosure system was developed to provide design guidance and insight into the shock survivability of the enclosure. The model was comprised of two-dimensional quadrilateral and triangular elements representing the enclosure exterior and beam elements representing internal ribs and stiffeners. Lumped masses are used to represent various internal components (IMU platform, power supplies, card racks, etc.). The enclosure is rigidly connected to a large seismic mass at the eight bolt hole locations in the deck plate of the lower enclosure and is flexibly connected at the two upper support brackets.

The modal transient method of analysis was used because it is a more efficient method of obtaining the response of a structure to time dependent loading than the direct transient method. The shock excitation was obtained by applying a forcing function to the seismic mass with the proper time history and amplitude to develop a shock spectrum equal to or greater than 1.5 times STANAG 4142. Three separate shock response computations are required to determine the response to vertical, athwartships and fore-aft shock stimuli. With the mode shapes, natural frequencies and shock input, the time history response of enclosure deformations and stresses were computed.

The pass-fail criterion was based on the yield strength of the enclosure material. The upper enclosure is constructed of 6061-T6 wrought aluminum plates and bars. This material has a minimum yield strength of 40,000 psi. The lower enclosure is an aluminum casting alloy per MIL-A-21180, A356-T6, class 1 and has a minimum yield strength of 28,000 psi.

The maximum response occurred when the model was excited in the athwartship's direction. Even though the shock level is half of the vertical shock, the enclosure is much more responsive, resulting in a stress level of approximately 15,500 psi. This is far below the lower enclosure's yield strength of 28,000 psi.

The dual enclosure system is intended for those customers requiring a shock capability meeting the requirements of BR3021, Grade Curve G and/or having limited vertical space. For customers requiring BR3021, Grade Curve G, the electronics enclosure is shock isolated with standard NATO "X - mounts" to provide additional protection for the interface display. The display is supported by its own internal shock isolation system to protect the unit when it is subjected to shock levels 1.5 times those of STANAG 4142.

For those customers who desire a dual system yet do not require the greater shock levels of BR3021, the electronics cabinet can be hard mounted along with the IMU cabinet. A finite element model of the electronics cabinet hard mounted to the deck was developed to verify this design concept. This model, which is similar to the single enclosure model, was constructed of two-dimensional quadrilateral and triangular plate elements to represent the enclosure exterior, and beam elements to represent the

various internal ribs and stiffeners. Lumped masses were used to represent various internal components (power supplies, card racks, etc.) The enclosure was rigidly connected to a large seismic mass at six bolt hole locations in the deck plate of the enclosure. There were no upper support brackets in this configuration. The methods, procedures and pass-fail criteria were similar to those used in the single enclosure analysis.

The maximum response occurred in the fore-aft direction with the maximum stress reaching approximately 14,311 psi. This is well below the yield strength of 40,000 psi.

IMU SHOCK DESIGN AND ANALYSIS

The most shock sensitive components in the IMU assembly are the three ring laser gyros. Therefore, a shock isolation system was developed internal to the enclosure to attenuate the variety of shock stimuli to less than the gyro performance level of 56 g's. In order to permit a reasonable safety factor, a design goal of 40 g's was chosen as the maximum allowable level to be experienced by the gyros.

Another requirement of this IMU shock system is the ability to maintain precise attitude alignment to the ship's deck. This is a difficult goal to achieve in a shock isolation system because the nature of such a system is to allow the isolated mass to "float" independently of the deck motion and thus prevent the high shock from being transmitted to the sensitive components.

Since the MK 49 system must fit through a 24 inch diameter submarine hatch, the overall size of the shock isolation system, which is located inside the IMU enclosure, and the sway space or the amount of relative motion between the isolated mass and the deck is limited.

The IMU platform, which contains the shock isolation system, is shown in Figures 3 and 4. The IMU consists of a sensor block assembly (SBA), rotator, outer frame, shock isolators and base plate.

The SBA is part of the inner axis of a two-axis indexing scheme [1] and contains three gyros, three accelerometers, and a high voltage power supply. Also attached to the SBA is a magnetic shield assembly. The SBA is supported at opposite ends by noise isolators [2] and a torque motor/synchro pair which is supported by the rotator forming the inner indexing axis. The rotator is also supported by noise isolators and a torque motor/synchro pair which is connected to the outer frame forming the outer indexing axis. The outer frame is supported by six shock isolators and a base plate arranged in a hexapod configuration.

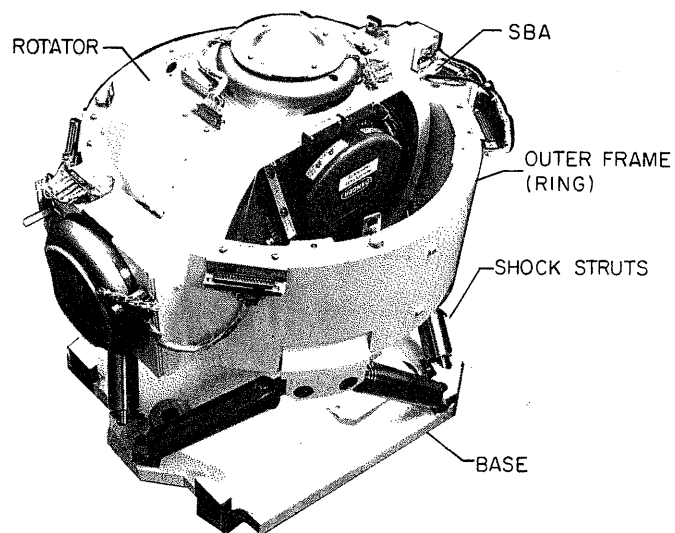


Figure 3. IMU Platform

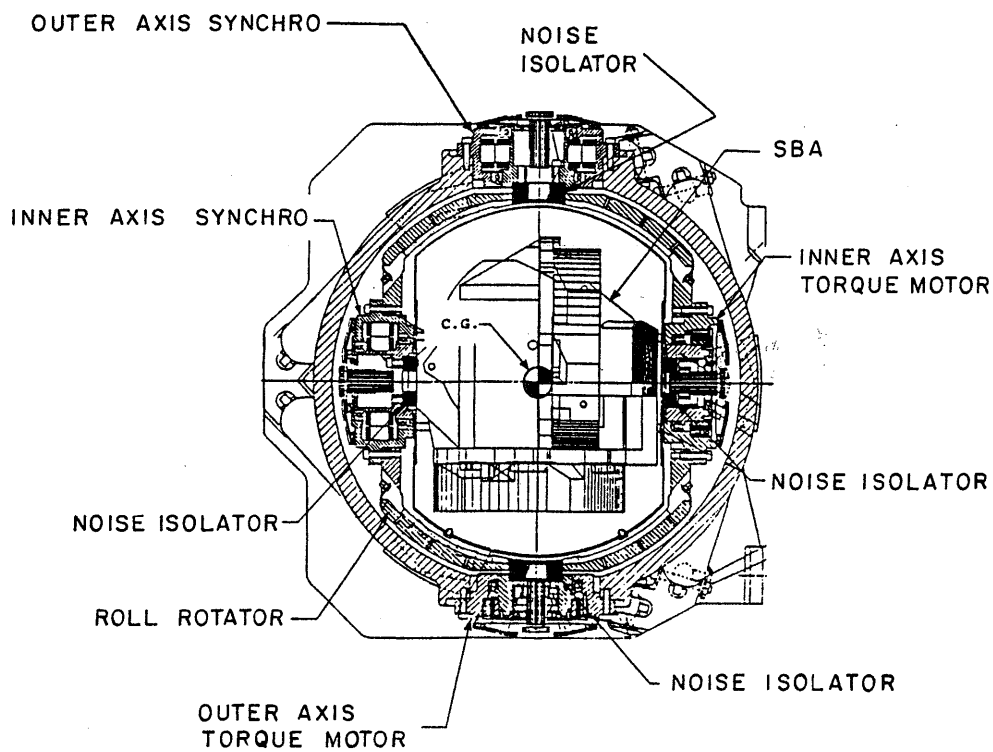


Figure 4. IMU Platform

The shock isolators are custom designed, tension-compression liquid spring/dampers. Silicone oil is compressed to provide preload, spring and damping forces, all in one compact unit. An internal mechanical linkage allows full isolator motion in tension or compression and automatically recenters the shock to its neutral position to within .0005 inches.

A number of parameters, such as shock strut preload, spring and damping characteristics, total stroke required, and strut geometry can be varied to control the performance of the shock isolation system.

A model of the IMU platform as subjected to BR3021, Grade Curve G was developed using the commercially available systems simulation program, TUTSIM™. The IMU was modeled as a lumped parameter system (masses, springs, dampers, etc.) similar to that shown in Figure 5. The SBA is connected to the rotator by three non-linear springs (one for each coordinate, although only one spring is shown for simplicity). Since the noise isolators are a combination of linear steel springs and elastomeric snubbers, they are modeled as bi-elastic (non-linear) springs. The rotator is connected to the outer frame in a similar fashion. The outer frame is supported by six spring-dampers which are connected to the base. The shock struts are modeled as preloaded linear springs with a non-linear damper. The model also accommodates the various angles at which the struts are oriented in the IMU (see Figure 3).

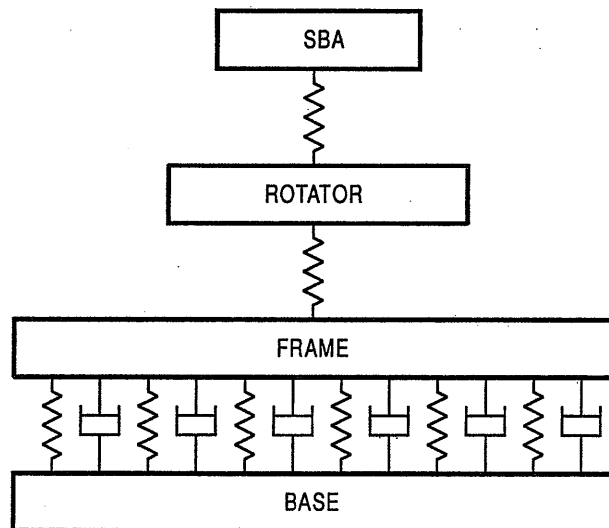


Figure 5. IMU TUTSIM Model

With TUTSIM™, the characteristics of the problem are modeled using block diagrams similar to those used in control system theory. TUTSIM assembles the system equations from the block diagram structure and solves them numerically to yield the time response of the system.

Virtually any of the model variables such as SBA acceleration, rotator displacement, spring forces, damping forces, or relative displacement between the SBA and the rotator, can be plotted against time. Shown in Figure 6 is a plot of frame acceleration versus time, which provides some insight as to the attenuation performance of the shock struts. This plot shows that the design goal of reducing the transmitted accelerations from greater than 200 g's to approximately 30 g's is achieved with this design.

EXPERIMENTAL RESULTS

In order to further increase confidence in the shock design of the MK 49 cabinet and IMU, a test was performed to STANAG 4141 using the MIL-S-901C medium weight shock machine. A production version of a single enclosure system, using steel weights to simulate electronics racks and power supplies, and a production version of an IMU with dummy components were installed on the machine and subjected to increasing hammer height blows until the shock spectrum levels of STANAG 4141 were achieved.

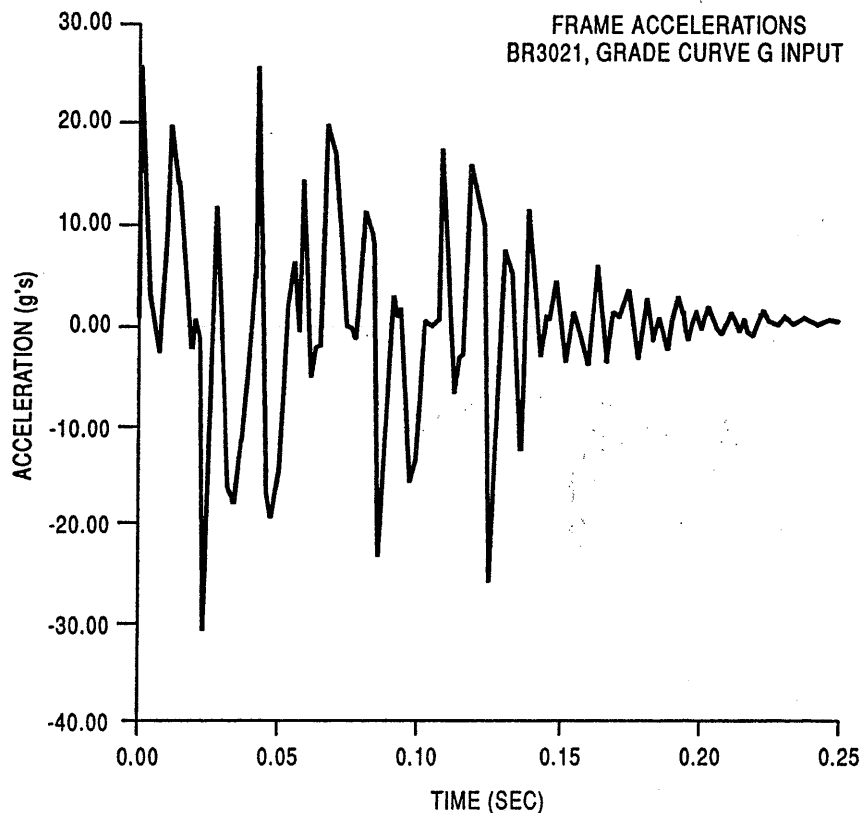


Figure 6. IMU Frame Accelerations BR3012-G Vertical Shock Analysis Results

Figure 7 shows the vertical acceleration (g's) versus time (sec) of the frame on the IMU resulting from a 3 foot hammer height blow with the anvil table set for 1.5 inch travel. This hammer height exceeds what is required by MIL-S-901C. The data, which was filtered at 300 Hz, shows that the maximum acceleration is approximately 32 g's, well below the design goal of 40 g's.

Previous tests on a prototype IMU shock isolation system verified that the returnability accuracy of the system was ± 26.5 arc seconds. Accuracy of the production version is expected to be better since the production shock struts use more precise rod end bearings and have consistently measured individual returnability of .0001 inches during factory acceptance testing.

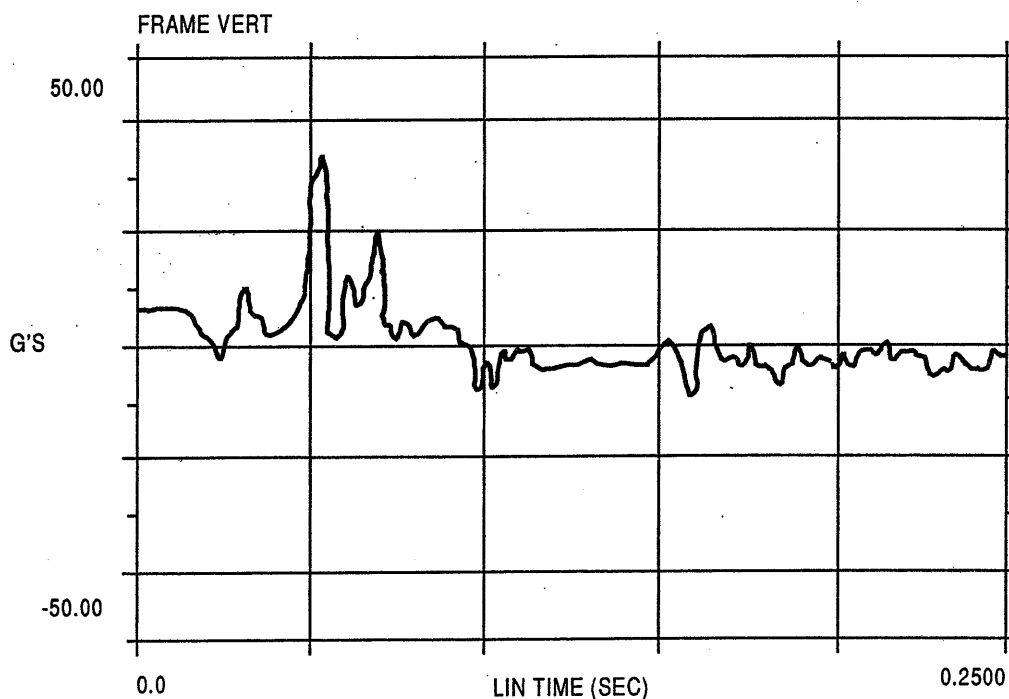


Figure 7. IMU Frame Accelerations Vertical Shock Input Experimental Results

SUMMARY

The Sperry Marine MK 49 Ship's Inertial Navigation System (SINS) was developed to meet a variety of shock stimuli, such as MIL-S-901C, BR3021, STANAG 4141 and STANAG 4142, and to serve the navigation needs of a broad spectrum of military customers. During development, various dynamic analyses and experimental tests were performed as aids to designing the cabinet and IMU shock isolation system. The cabinet design was analytically verified to 1.5 times STANAG 4142 and tested to STANAG 4141. The IMU shock isolation design was analyzed to shock inputs of BR3021, Grade Curve G and tested

to STANAG 4141. The tests to STANAG 4141, which were performed on the MIL-S-901C medium weight shock machine, were successful in verifying the MK 49 shock design concept.

ACKNOWLEDGMENT

The development of the MK 49 shock design is a result of contributions made by many individuals at Sperry Marine. Acknowledgment and appreciation are hereby given to all of those people.

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