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A novel heavy-weight shock test machine for simulating underwater explosive shock environment: Mathematical modeling and mechanism analysis

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ABSTRACT

A novel heavy-duty shock test machine is developed to satisfy the newly-built shock resistance standard and simulate accurately the actual underwater explosive environments with increased testing capability. The mathematical model for the shock test machine is created to predict its dynamic performance and analyze its mechanism. Then numerical simulation is carried out to evaluate the prospective capability of the shock test machine under different shock velocity inputs. The double protection system incorporating the stroke limit of the accumulator piston and the unloading circuit can effectively prevent the secondary collision in the testing process. The simulation results have demonstrated that the shock test machine proposed in this paper can produce nearly the same shock acceleration waveform as the new shock resistance standard BV043/85 and MIL-S-901D. Moreover, this shock test machine can be regulated conveniently to adjust to a different type of equipment and be extended easily to suit more severe shock environments and heavier equipment. The proposed system configuration and associated mathematical model provide theoretical basis and useful design techniques for practical applications.

1. Introduction

Warships and shipboard equipment are often damaged by intense shock waves of the near-field non-contact underwater explosion (UNDEX) during their military service. Therefore the ability to withstand the UNDEX effects has been regarded as an important aspect of the survivability of the new and existing warships, and receives full attention from the navy of all countries. The naval powers have conducted extensive and in-depth research on the methods to examine the shock resistant capability of the key shipboard equipment. For instance, the USA formulated the military specification MIL-S-901D in 1989, and Germany proposed a new military specification defined in BV043/85, specifying the requirements for the high impact test for the shipboard equipment. Although MIL-S-901D is prepared specifically for military applications, the standard is often used for commercial products as well. For marine equipment, in general, shock test machine is a prevailing way to examine the ability to survive an underwater explosion.

However, both the light-and medium-weight shock test machines, which have maximum testing capacities of 125 kg and 2700 kg respectively and maximum impact velocity less than 3.4 m/s, can merely meet the traditional MIL-S-901 specification. Moreover, these test machines can only generate shock wave in one direction by either dropping or pendulum rotating the impacting mass. Therefore, these types of shock test machines can only meet the MIL-S-901C specification. Challengingly, there is little room to extend the shock level and capability of test payload of these two types of machines due to their nature of energy storage or impact generating patterns as well as their giant sizes. Hence equipment beyond this weight range has to be tested in underwater explosive environment in order to assess its shock resistant capability. However, this is undesirable because of associated high cost, damage to the environment and long test cycle.

Nowadays, the trend of continuous improvement of the underwater weapons to enhance accuracy and power has led to an even higher demand for the shock resistant ability of warship equipment. The latest specifications of shock-resistant ability in the world are MIL-S-901D and BV043/85, which have increased the velocity requirement to 5 m/s and even higher in special circumstances such as testing newly developed shipboard equipment. Moreover, the maximum testing capacity of the current shock machines has exceeded the limits of the traditional medium-weight ones (2700 Kg) and it still keeps increasing. Thus, various shock test equipments are developed. The U.S. Team Corporation

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developed a new type of shock test system called Subsidiary Component Shock Test System (SSTS), which contains a long stroke hydraulic actuator that can be configured to operate in either a vertical or horizontal position [1,2]. Weidlinger Associates Inc. constructed a system for Non-Explosive Shock Testing of Naval Vessels and Equipment whereby shock test with explosion can be replaced with non-explosive sources based on the very rapid release of high-pressured air from reservoirs very close to the vessel under test [3]. Germany WTD71 of Kiel developed and built a laboratory shock test machine for simulating UNDEX testing which can produce half-sine shock wave according to BV043/85 specification. MTS systems Corporation was contracted by Westinghouse Bettis to design and build a laboratory shock and vibration-testing machine for simulating UNDEX testing of naval vessel components with high load and high fidelity. This test machine can test components up to 10 t [4]. Shanghai Jiaotong University designed and built a laboratory shock testing machine named Heavyweight Dual-wave Shock Test Machine which is being debugged [5,6].

Comparing the current shock test facilities and some new concepts of shock test machines such as MTS Firing Impulse Simulators (FIS) and Full Scale Shock Simulator, it is clearly seen that the development trends of shock test machines towards three major directions. The first trend is that shock test machines are capable to generate both positive and negative shock pulses to simulate real UNDEX environment which is made up of shock wave followed by bubble pulse and structural whipping [7]. The second is that shock test machines can test heavy-weight equipment, and the last is that shock pulses can be controlled and customized conveniently [8].

However, one of the key technologies for developing new shock test machines is how to supply enough energy and dissipate it in a short time, which can be controlled and also user-friendly with good vibration isolation design [9–11]. In this paper, we propose a novel heavy-duty shock test machine and establish its mathematical model for the integrated dynamic system, and also analyze its mechanism and dynamic performance. The key features of this new shock test machine are (i) high energy storage capacity; (ii) instantaneous release of tremendous energy; (iii) rapid dynamic response; (iv) high automaticity; (v) hydraulic damper energy dissipation; (vi) enhanced testing capacity of 5000 kg; and (vii) meets both the latest shock resistance standard of MIL-S-901D and BV043/85.

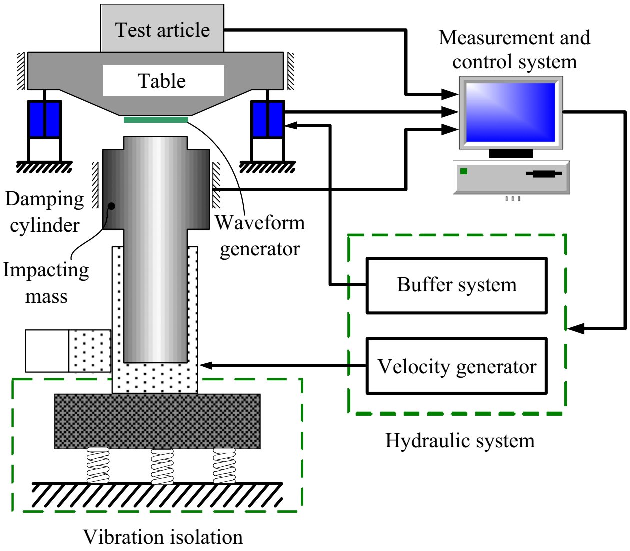

Fig. 1. Schematic of the system of the Heavy-weight Shock Test Machine.

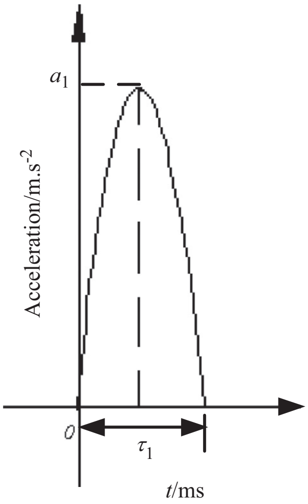

Fig. 2. The semi-sinusoidal acceleration pulse.

2. System description of the heavy-weight shock test machine

Fig. 1 shows a schematic of the system of the proposed heavy-weight shock test machine, which produces semi-sinusoidal acceleration pulses vertically as shown in Fig. 2. The shock test machine consists of a hydraulic system made up of a velocity generator and a buffer system, a measurement and control system, and a vibration isolation system. With the test item mounted on the table, the impacting mass, driven by the velocity generator, applies impact load to the waveform generator located at the bottom of the table and produces a semi-sinusoidal acceleration wave required in the specification. Meanwhile, the buffer system, comprised of hydraulic damping cylinders, limits the stroke of the table and prevents it from bouncing off after the impact. The measurement and control system can collect and process data, and monitor important parameters such as pressure of the whole system, velocity of the impacting mass, and acceleration of the table as well as the test item.

3. Mathematical model of the integrated dynamic system

The generation of the wave of the shock testing machine is based on the principle of collision, whose working mechanism can be simplified to three degrees of freedom vibrating system as shown in Fig. 3. The system is composed of springs, dampers and masses, in which k_s represents the coefficient of elasticity of the waveform generator while $C(t)$ the damping coefficient of the hydraulic damping cylinder. Since the damping cylinder merely serves to prevent the table from flying off too high when hitting the impacting mass, this paper will not study the damping property of the cylinder.

Without loss of any important features, the mathematical model of the shock test machine is established based on the following hypotheses: (1) the impacting mass, the table and the foundation mass are rigid bodies, while the waveform generator is regarded as a linear elastic body; (2) on the instant of impact, the compressed gas in the air bag of the accumulator is in heat insulation, i.e. without energy exchange with the outside; (3) only local pressure loss is taken into account due to the shortness of the pipeline of the hydraulic system; (4) the mechanical friction loss and leakage in the motions of piston and spools are ignored; (5) the liquid pressure in each chamber is regarded as evenly distributed; (6) the velocity distribution of each cross-section flow