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# On the Simulation of Ballistic Shock Loads

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Blast or penetrator-impact induced shocks are presented by high acceleration levels particularly in the higher frequency range and for a short time duration. These shocks are dangerous for the equipment of combat vehicles, airplanes, ships or space-structures. As ballistic shock loads are insufficient simulated by laboratory test machines a ballistic shock simulator has been designed.
The impact induced shocks are simulated by an explosive and the vehicle to be bombarded is replaced by a simplified structure. This structure is suitable to accomodate any equipment which can be tested up to their loads limits.

## INTRODUCTION

Ballistic shock loads are mostly produced by non-penetrating projectiles. Near the impact point the shock is presented by an one-side directed impulse excitation of very short time duration, shown in figure 1. In general the velocity jump of such a shock is small. At a distance from the impact point the shock response has an oscillatory character, figure 2. Usually the hard fixed optical sightings of armored vehicles are exposed to these very high dynamic strains which can produce shock related equipment failures as disadjustments of the line of sight, damages of prisms and even mechanical destruction of components. The dynamic reliability of fire control systems are described in the technical regulations, MIL-STD-810D, ISO/DIS 8568, DEF STAN 07-55, TL 1240, for instance. Usually the test shocks are produced by impact shock machines, multi-shaker systems, electrodynamic exciters and acoustic excitations. The ballistic shock loads generated by an impact projectile or an explosive exceed considerably the acceleration amplitudes which are produced by laboratory simulation test machines. A comparison between the shock spectra determined from half-sine pulses, produced by an impact machine, with the acceleration time data, caused by an non-penetrating projectile, shows that a considerably higher dynamic strain is generated by the shot, figure 3.
Using half-sine pulses for shock testing, the low frequency range of the equipment is overstressed while the higher frequency range is underloaded. From realistic bombardments against armored vehicles it is known that the shocks can lead to defects in such equipment which had previously been tested by conventional test facilities.

## REQUIREMENTS TO A SUITABLE SHOCK SIMULATION TECHNIQUE

In order to qualify any equipment of combat vehicles a realistic method, for the simulation of ballistic shock loads is needed. For that purpose high standards are demanded of a suitable simulation technique. The shock loads to be simulated should :

- provide high acceleration levels in a wide frequency range
- have a short time duration
- be reproducible
- be easily tunable to a given spectrum
- be nearly non-destructive
- be economical.

In addition to a realistic shock excitation, the environment of the equipment must be considered. There is an interaction between the equipment and the dynamic behavior of the carrier structure.
An important point is the check of the individual built-in unit after the shock test is finished. Usually function tests are carried out and the disadjustments of the line of sight are detected if the object was an optical device.
Therefore in addition to the requirements for a realistic shock excitation the used carrier structure should :

- have enough space to accomodate the built-in units and their electronic components. The performance of operational tests must be possible
- have an easily changeable dynamic behavior
- be resistant to blast-induced shocks.

Concerning these requirements the straightforward way for shock testing built-in units would be: the bombardment of a fully equipped tank, for example, with different types of ammunition.
Bombarding tests performed on realistic vehicles for the purpose of analysing the vulnerability of actually equipments include, in addition to the economic reasons, a series of disadvantages.

Therefore suitable techniques for the simulation of ballistc shock loads have to be developed with the aim of proving the equipment of armored vehicles, ships or spacecraft structures and give design proposals for the improvement of their shock resistance.

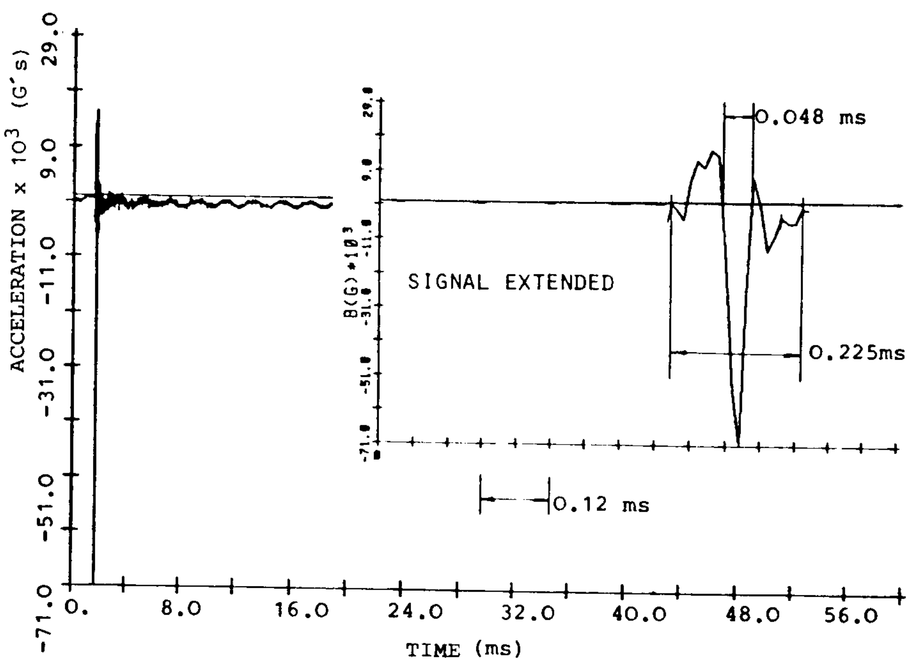


Fig. 1- Shock excitation near the impact point

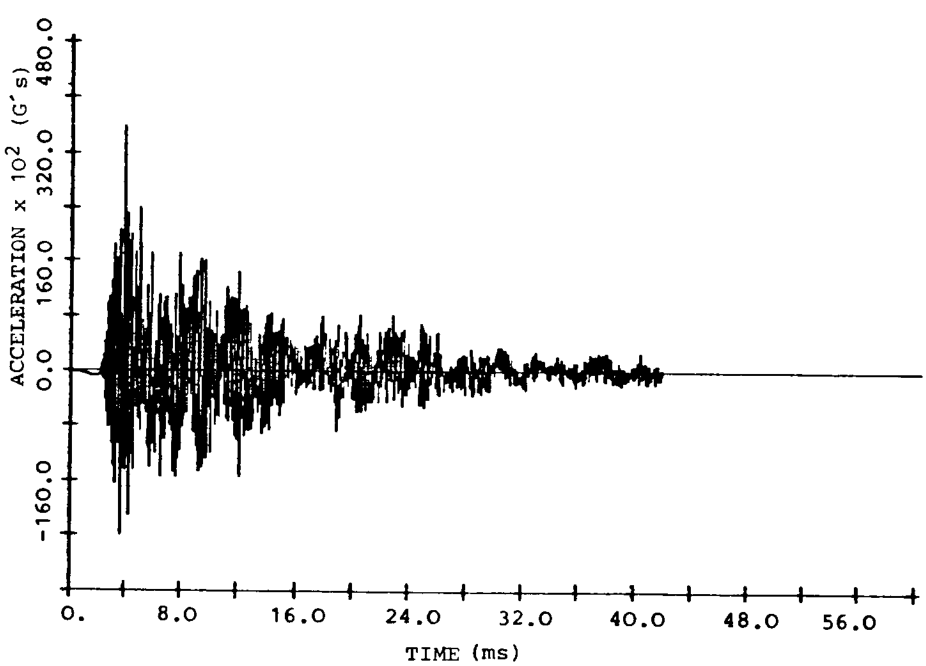


Fig. 2- Shock response

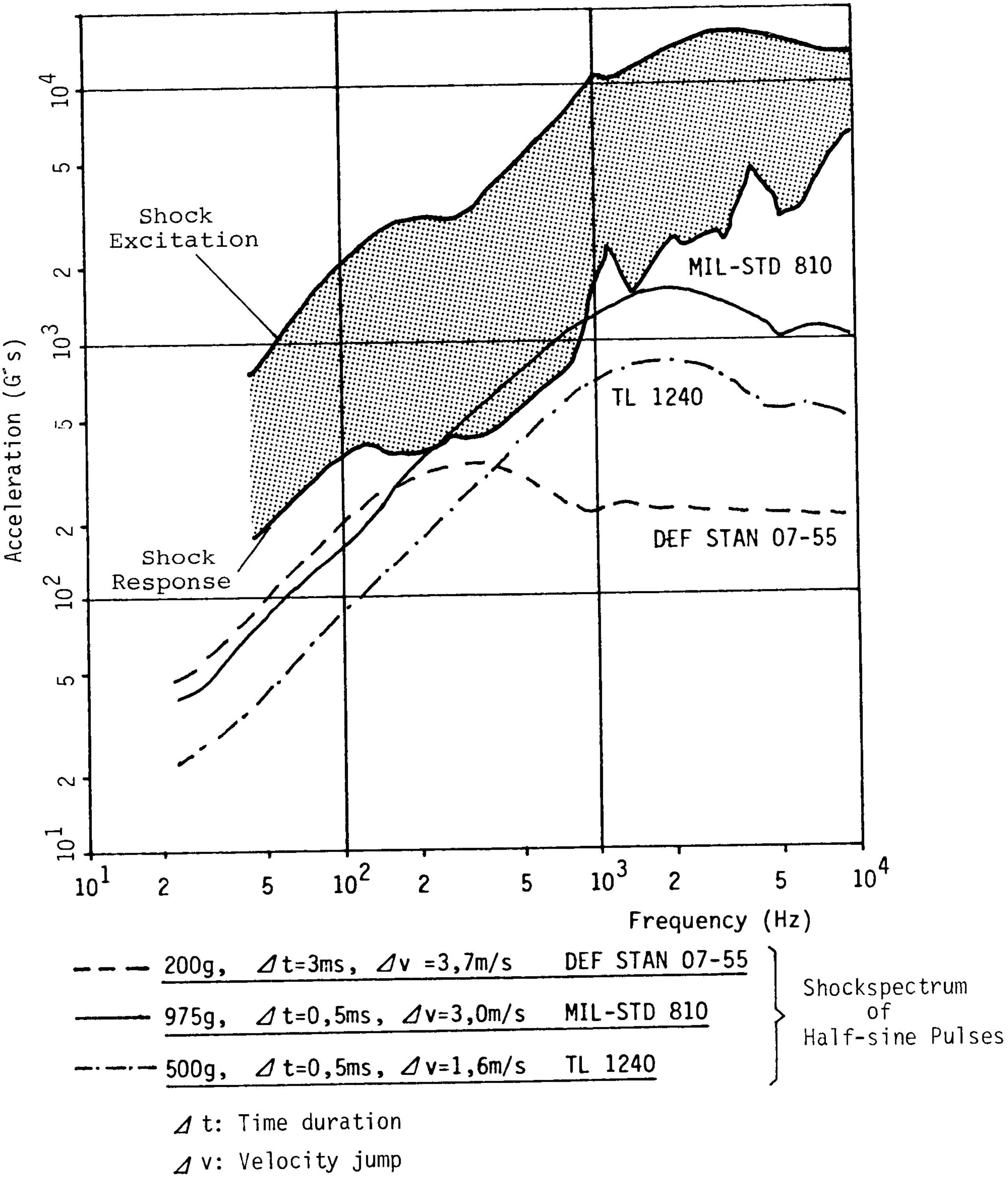


Fig. 3- Comparision of penetrator-impact induced shocks with half-sine pulses produced by impact shock machines

## SIMULATION OF BALLISTIC SHOCK LOADS

The shock tests described in the technical regulations are mainly based on one directed shocks like half-sine pulses, rectangular pulses, initial- or terminal-peak sawtooth pulses.
They are good reproducible and suitable to simulate rough handling and travelling loads.
Shock loads produced by non-penetrating hits are not simulatable by conventional laboratory tests.

In order to simulate ballistic shock loads related to the requirements a simple structure based on plates was selected. As the shock propagation depends on mass and stiffnes a carrier structure should have similar dynamic properties like the real vehicle. For that purpose a finite element model, based on the STARDYNE-computer code, of a simplified plate structure, as shown in figures 4 and 6, was created to calculate frequencies and modes up to 2 kHz.
In order to change the dynamic parameters several configurations were considered :

* equal wall-thickness, free installed
* equal wall-thickness, with baffle, free installed
* different wall-thickness, free installed
* different wall-thickness, one side fixed
* equal wall-thickness, with baffle, one side and bottom fixed
* different wall-thickness, with two baffles, one side and bottom fixed
* different wall-thicknes with three baffles one side and bottom fixed
* different wall-thicknes with three baffles one side and bottom fixed and partly closed cover.

To evaluate the particular design alternatives for each variant the modal density was calculated up to 2 kHz.
In figure 5 the modal densities for each variant are represented versus the first eigenfrequency, figure 5.

Starting from the parameters

$M_{jk}$ : Mass matrix of the structure

$K_{jk}$ : Stiffness matrix of the structure

$C_{jk}$ : Damping matrix

$x_k$ : Displacement vector

$q_k$ : Generalized parameters

$F_j$ : Force vector

$\psi_{jk}$ : Eigenvectors, summarized in a modal matrix

$\omega_j$ : Undamped natural frequencies

$m_j$ : Generalized masses

$\alpha_j$ : Estimated modal damping values

$\Omega$ : Frequency of excitation

a complex transfer function model of the simplified structure was calculated.

Equation of motion:

$$M_{jk} \cdot \ddot{x}_k + C_{jk} \cdot \dot{x}_k + K_{jk} \cdot x_k = F_j(t) \cdot e^{i\Omega t} \tag{1}$$

modal transformation:

$$x_k = \psi_{kl} \cdot q_l \tag{2}$$

transformed equation of motion:

$$m_j \cdot \ddot{q}_j + m_j \cdot \alpha_j \cdot \omega_j \cdot \dot{q}_j + m_j \cdot \omega_j^2 \cdot q_j = \psi_{kj} \cdot F_k(t) \cdot e^{i\Omega t} \tag{3}$$

using:

$$q_j = \hat{q}_j e^{i\Omega t} \tag{4}$$

$$\eta_j = \Omega / \omega_j$$

response acceleration:

$$\ddot{x}_l = \frac{-\eta_j^2}{m_j (1 - \eta_j^2 + i \cdot \alpha_j \cdot \eta_j)} \psi_{lj} \cdot \psi_{kj} \cdot F_k(t) e^{i\Omega t} \tag{5}$$

transfer function:

$$H_{lk}(\Omega) = \frac{\eta_j^2}{m_j(1-\eta_j^2 + i\cdot\alpha_j\cdot\eta_j)}\,\psi_{lj}\cdot\psi_{kj} \tag{6}$$

Then the response acceleration $\ddot{x}_l$ to a fourier transformed impact force $f_k(\Omega)$ is given by:

$$\ddot{x}_l = H_{lk}(\Omega)\cdot f_k(\Omega)\,. \tag{7}$$

The next step is the estimation of a loading function which represents the impact of a projectile. To get realistic loading functions the penetration process must be calculated in detail.
For a simple estimation of the force time history it is sufficient to consider the ballistic parameter of the projectile, mass, final velocity and angle of impact.
Due to experience in the field of bombardment of armored vehicles it is possible to make assumptions concerning the time duration and the deceleration of the penetrator.
In addition to that the shape of the loading function is of interest. For a rough estimation it is sufficient to use triangular or saw-tooth shapes. In general the compression phase is characterized by a steep gradient.

Example:

Mass of the projectile: $m = 0{,}85$ kg

Final velocity : $v = 800$ m/s

Deceleration law : $a(t) = -\hat{a}(1 - t/T)$

Depth of penetration : $s = 160$ mm

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Acceleration : $\hat{a} = 0{,}67\cdot v^2/s = 2{,}67\cdot 10^6$ m/s²

Time duration : $T = 3\cdot s/v = 0{,}6$ ms

Force amplitude : $F = m\cdot\hat{a} = 2{,}27\cdot 10^6$ N.

In addition it is assumed that the impact force is represented by a saw-tooth shape, figure 7.

From equation (7) the response spectrum of the analytical model was calculated. These responses were compared with actual shock data from bombarding tests.
The result of such preliminary investigations is the simplified structure as shown in figure 4.

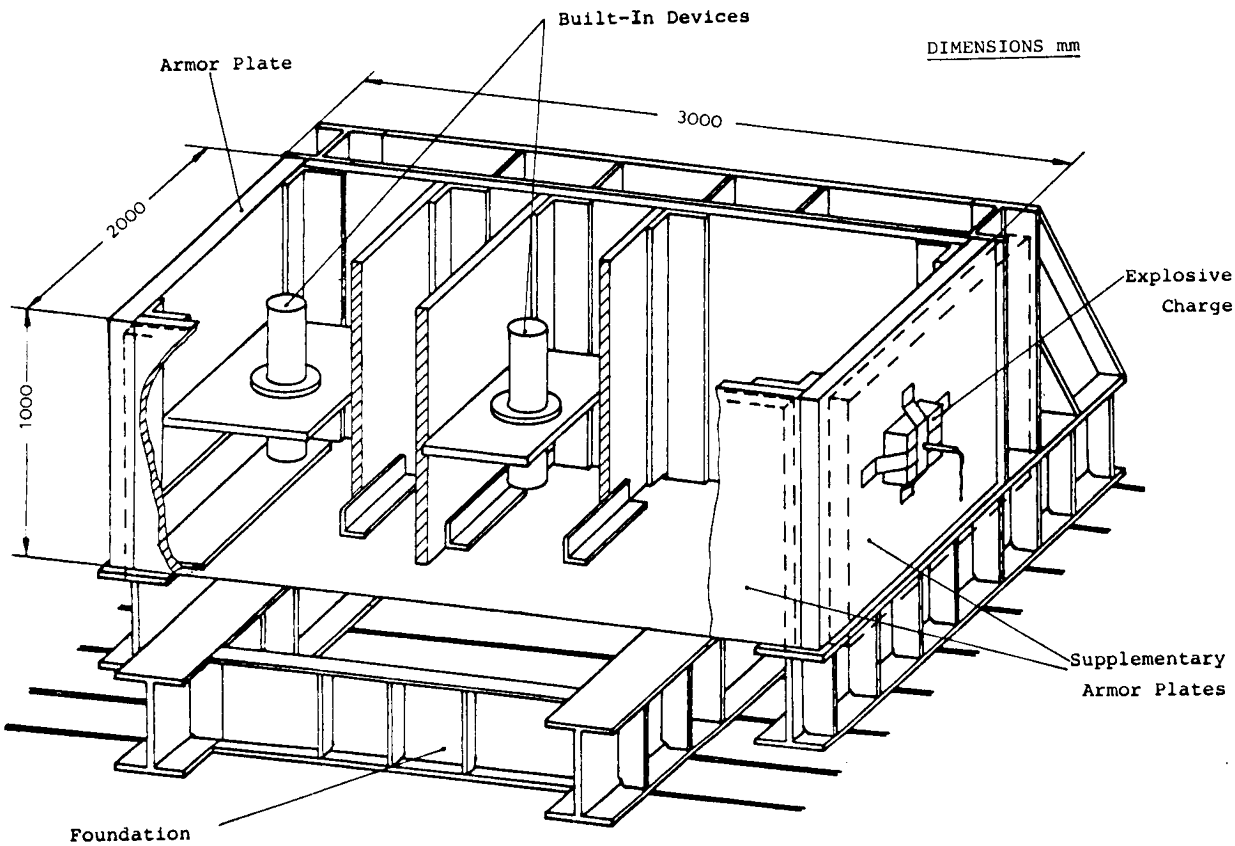



Fig. 4- Ballistic shock simulator (SBS)

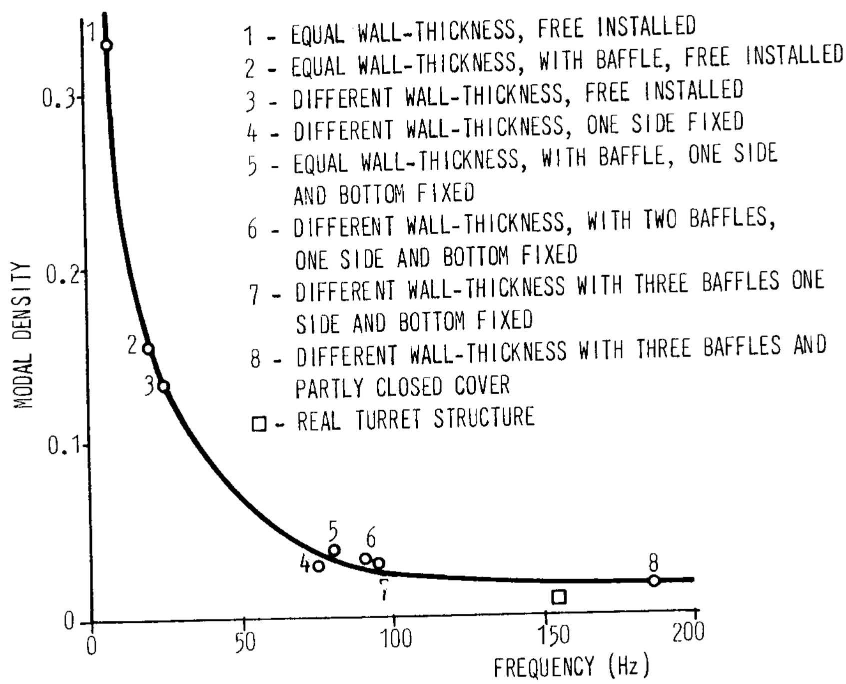



Fig. 5- Design alternatives of the SBS

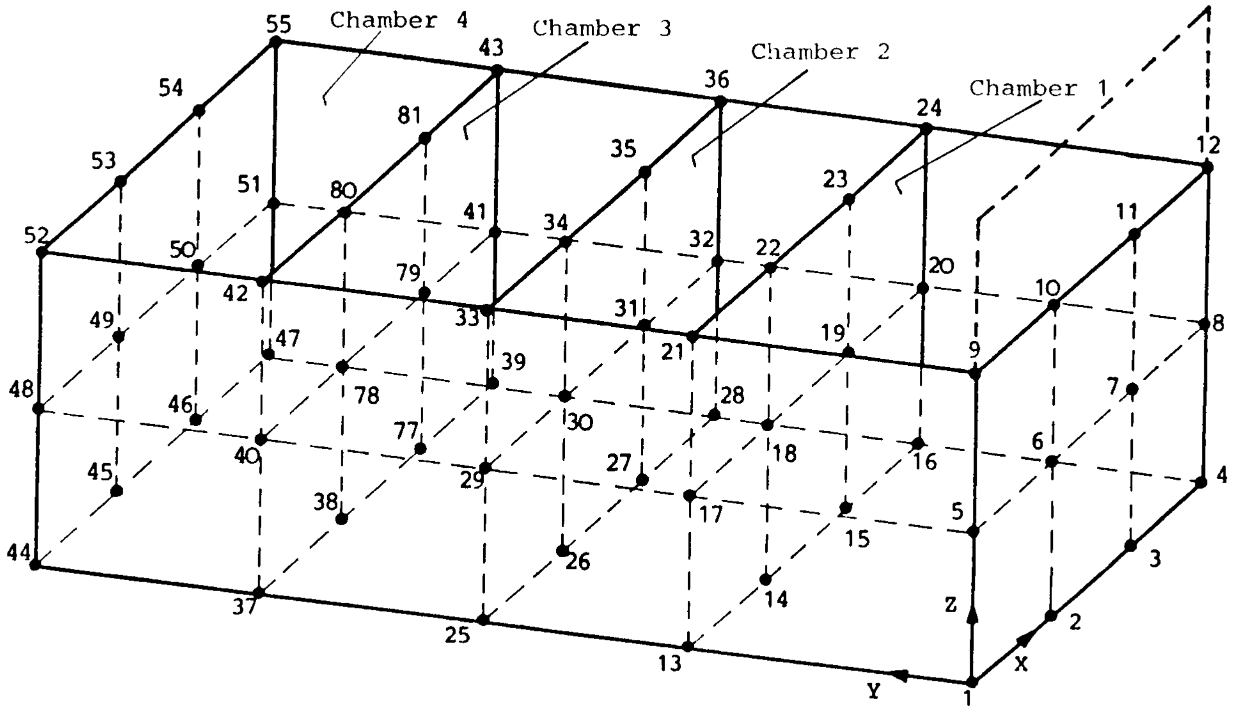



Fig. 6- Nodal points of the SBS

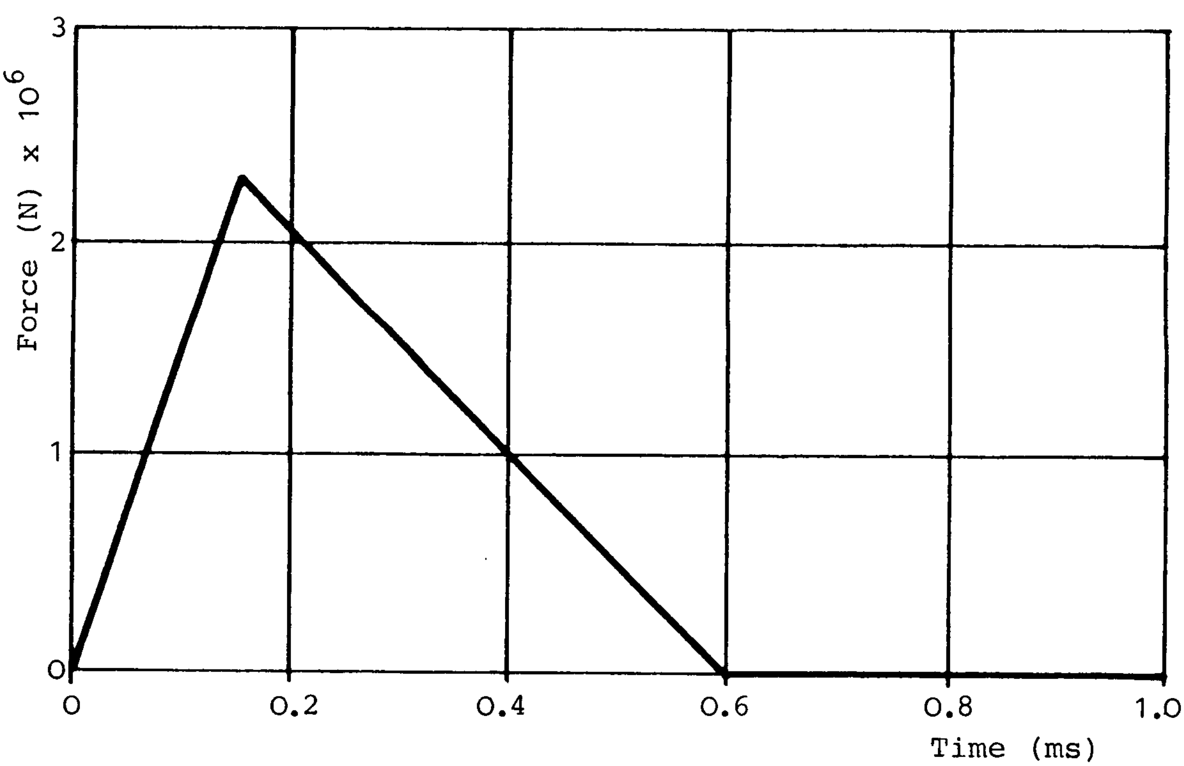



Fig. 7- Estimated force time history of an impact

The structure consists of armored plates of a thickness of 120 mm and has the dimensions 1000 * 2000 * 3000 mm. The plates are bolted and partly welded. The simulator is bolted to an elastic foundation.
The interior is divided into seperate chambers in which the equipment to be tested is installed. The dynamic properties of the structure are variable based on changing mass and stiffness. In addition to the analytical assessment of the modal parameter, experimental modal analysis had been carried out using GENRAD 2515 for data acquisition and SDRC software for evaluation.
The mass of the simulator is changeable from 6500 kg to 12 000 kg the lowest eigenfrequency from 9 Hz to 186 Hz.
In order to simulate ballistic shock loads the knowledge of the stiffness of the carrier structure is important as the stiffer the equiment is mounted the higher are the shocks.

The shocks to be simulated are produced by an explosive formed to a cube and free deplaced to the structure.

The responses due to blasting the shock simulator are measured by piezoelectric and piezoresistive accelerometers which are bolted or glued to the structure and to the test object.
From the oscillatory acceleration, time histories are calculated shock spectra which are a useful tool for evaluating shock loads.

## PARAMETER IDENTIFICATION

In order to simulate penetrator-impact induced shock loads the essential parameters must be known. For that purpose accelerometers had been attached at those points as shown in figure 6. Then the SBS had been blasted at different locations. These experimental investigations give information about the influence of the:

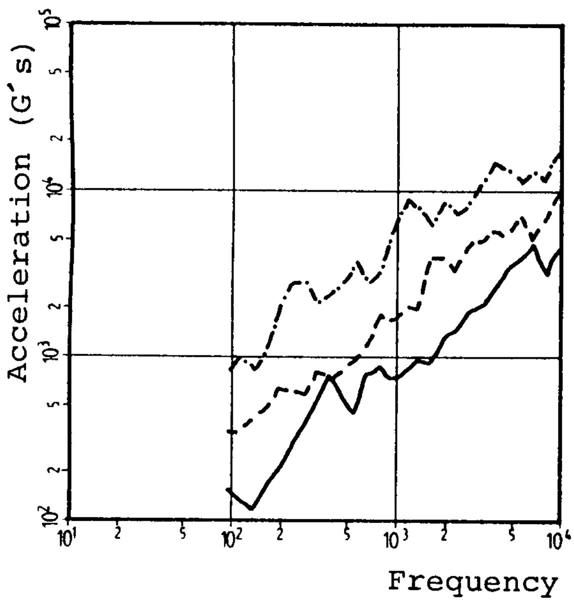
- explosive charge
- kind of explosive
- point of excitation
- dynamic properties of the SBS.

Finally these investigations are required to get knowledge about the reproducibility of the shock tests carried out with the SBS and their stability and resistance against blasting.

The results ot these preparatory investigations are:

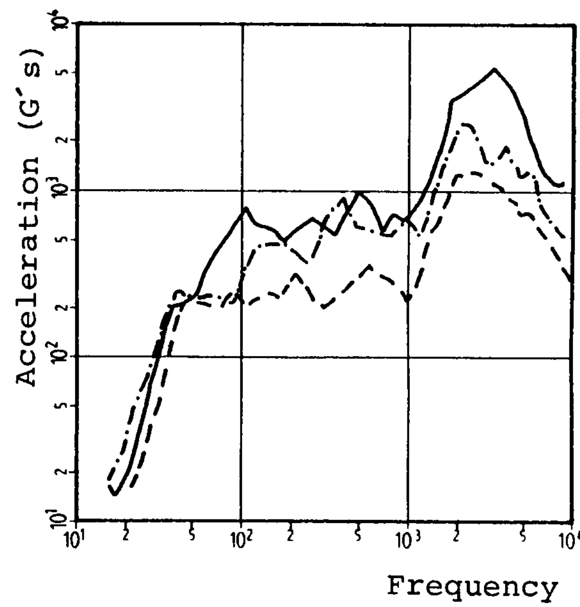
* <u>The influence of the amount of the explosive to the induced shocks</u>

The shock level in the entire frequency range depends on the explosive charge. An increase of the quantity of the explosive results in a rising gradient of the shock spectrum, figure 8.
The relationship between the quantity and the induced shocks is non-linear and can approximately be described by a cubic function in a particular frequency range.



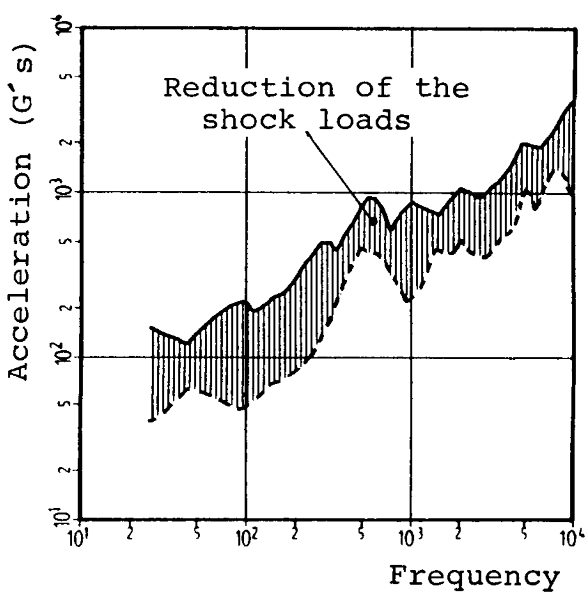

—— 0.05 kg PETN
– – – 0.25 kg PETN
–·–·– 0.50 kg PETN

Fig. 8 - Influence of the explosive charge



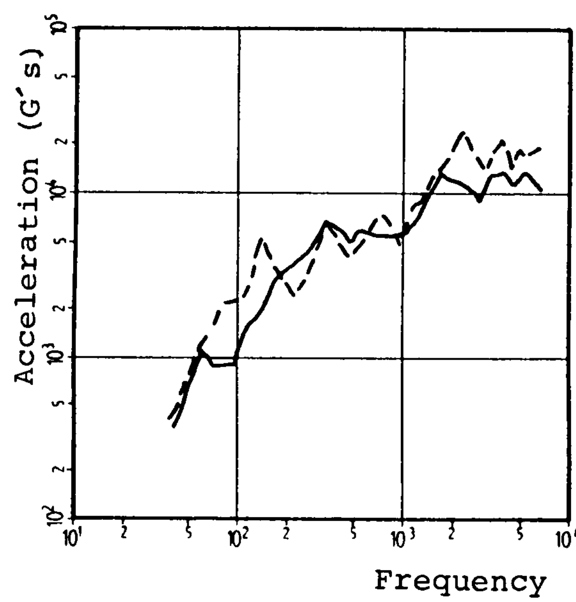

—— Front plate left
– – – Side plate
–·–·– Front plate right

Fig. 9 - Influence of the point of excitation




—— direct contact
- - - - distance: 30 mm
Explosive charge: 0.25 kg PETN

Fig. 10 - Influence of the distance between front plate and explosive




—— Original test
– – – Retest 3 months later

Fig. 11 - Reproducibility of blast test

## * The influence of the kind of explosive to the induced shocks

In general the shock loads depend on the detonation velocity of the explosive used. A mining explosive like AMMONGELIT with a detonation velocity of about 2,4 km/s results in a sufficient excitation of the lower frequency range but is unable to produce high shock loads in the higher frequency range.
High explosives like NITROPENTA, HEXOGEN,both have a detonation velocity of 8,4 km/s, or OCTOGEN with 9 km/s produce shock loads which are comparable with penetrator-impact induced shocks in the entire frequency range.

## * The influence of the point of excitation to the induced shocks

The changing of the point of excitation influences the shock loads, figure 9. In this case the SBS had been blasted by an explosive charge of 0,25 kg PETN at the locations 50, 29 and 7, figure 6. The travelled shocks were measured at a built-in unit installed at chamber 3. The g-loads are different as the shock propagation depends on the dynamic properties of the SBS. The structure in the x-direction is more elastic than in the y-direction. To get very high dynamic strains the equipment to be tested must be mounted in chamber 1 or chamber 4 and blasted at the locations 6/7 or 49/50.

In many chases it is desirable to reduce the shock loads to be simulated. In general the equipment is protected against the blast. The excitation is mainly caused by the stress wave. In order to damp the stress wave amplitude the distance between the armor plate of the SBS and the explosive was changed. The influence of the change of the distance is presented in figure 10.

## * The reproducibility of shock tests using the SBS

The reproducibility of the simulated shock loads at the equipment is of importance and depends mainly on the state of the used explosive. A long time of storage can result in a change of the density and the detonation velocity respectively.
The dynamic properties of the SBS are unimpared against the blast-tests as door plates are used.
From a multitude of shock tests carried out with the SBS the reproducibility lies in a band width of about 15 to 20%. An example of the reproducibility is given in figure 11.

## * The influence of the dynamic properties to the induced shocks

The shock propagation and the g-loads depend on the stiffness of the structure. In order to raise shock loads the test object must

be hard fixed.
Figure 12 shows the mounting of a base plate carrying a test object. The base plate is bolted by an angle shape to the front plate. In addition the base plate contacts the front plate by a groove. After blasting by an explosive charge of 1 kg PETN the elastic restraint was distorted.
In order to maintain the closing shape a stretching device was installed as shown in figure 13. After blasting with the same explosive charge the mounting was unchanged.
The comparison of the shock propagation in y- and z-direction of the mountings is presented in the figures 14 and 15. In the entire frequency range a considerable higher dynamic strain is transferred using the mounting b).

## RESULTS

The method introduced is applied to produce penetrator-impact induced shock loads. By use of the described parameters it is possible to increase the simulated shock level up to the individual load limit of the test object. In order to evaluate the shock resistance of the equipment shock measurements are necessary at the suspension points where the shocks are initiated, at the equipment itself and into the device. This knowledge is required to find out critical areas and to provide design proposals for improvements.

The comparisons of shocks produced by a non-penetrating projectile with simulation results are shown in the figures 16 and 17. At the suspension points the shocks differ in a wide frequency range. In general it is difficult to simulate initiation shocks because the dynamic properties of the bombarded structure differs from the simulator. The shock responses at the equipment itself are sufficiently simulated in the entire frequency range.
Usually the initiation shocks are higher than the shock response outside or inside the built-in units, figure 18. The difference between the shocks is absorbed by the suspension.
For the improvement of the shock resistance the shock distribution inside the equipment is of main interest, figure 19. Critical shocks are detectable if the shock distribution is different.
An important point is the check of the individual built-in unit. In addition to an operational test the change of the position of the line of sight is measured. This shows a relationship between shock loads and possible equipment failures and enables a finale valuation of the test object.

## SUMMARY

Shocks produced by non-penetrating projectiles are very dangerous for the equipment of combat vehicles, airplanes, ships or space structures. Usually these shock loads are not simulatable by laboratory test machines. As the hard fixed optical sightings of armored vehicles are exposed to very high dynamic strains shock related failures like disadjustments, damage of prisms and even mechanical destructions

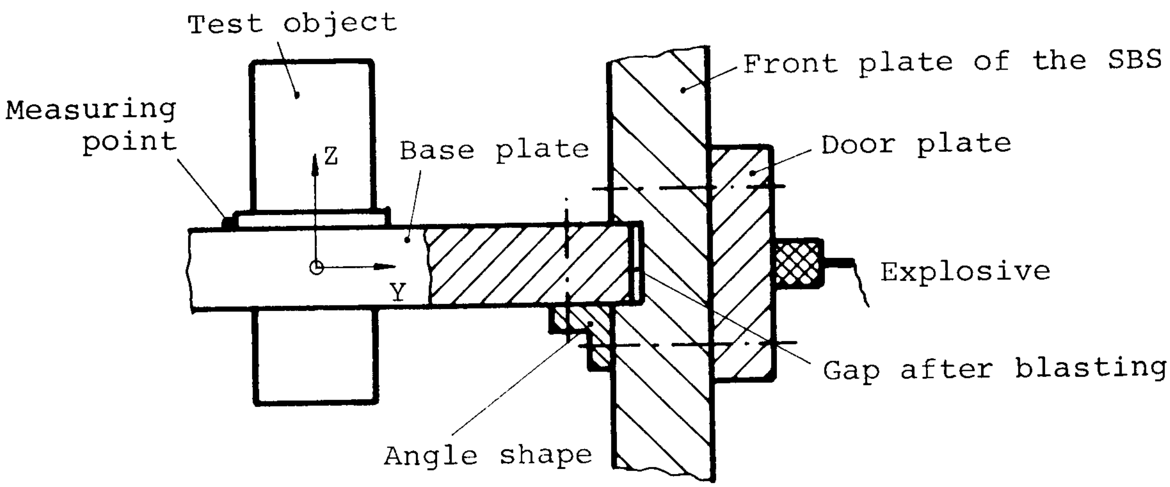



Fig. 12 - Mounting a): Elastic fixed base plate

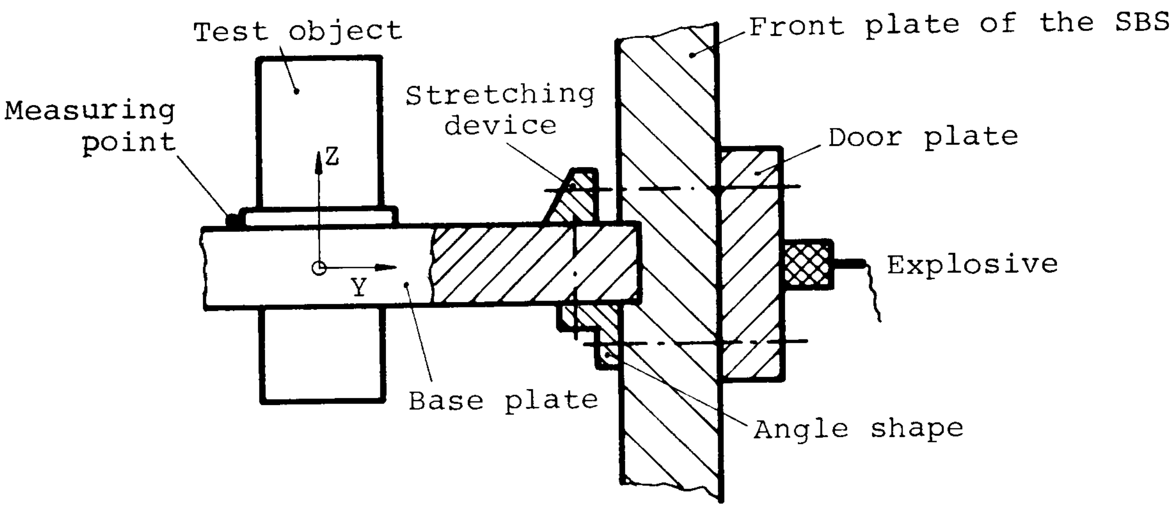
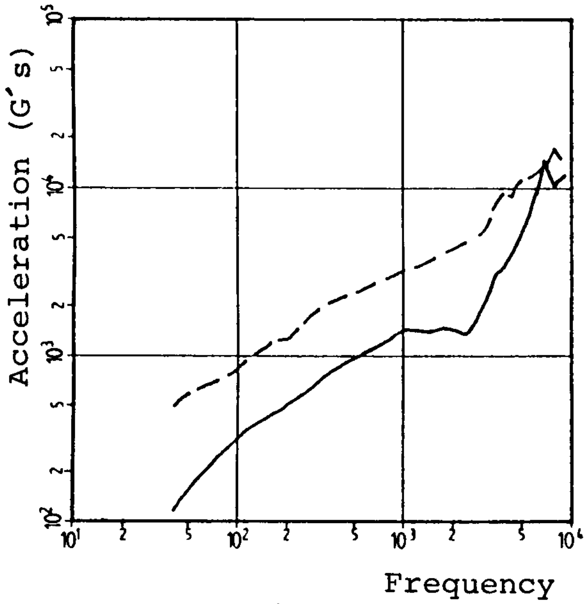
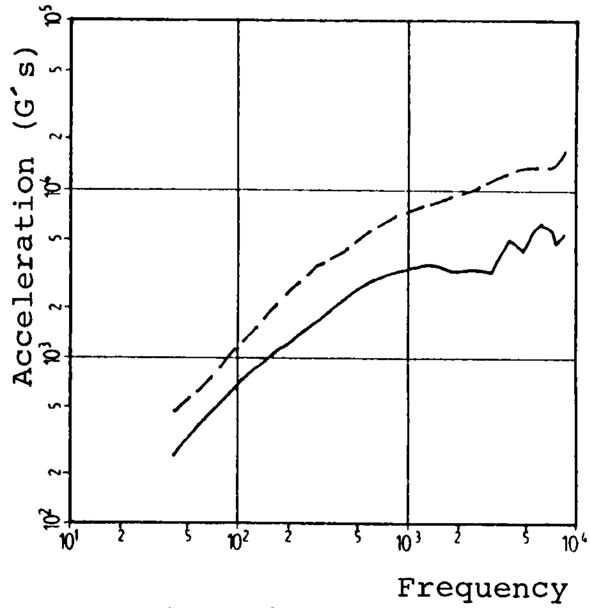



Fig. 13 - Mounting b): Hard fixed base plate



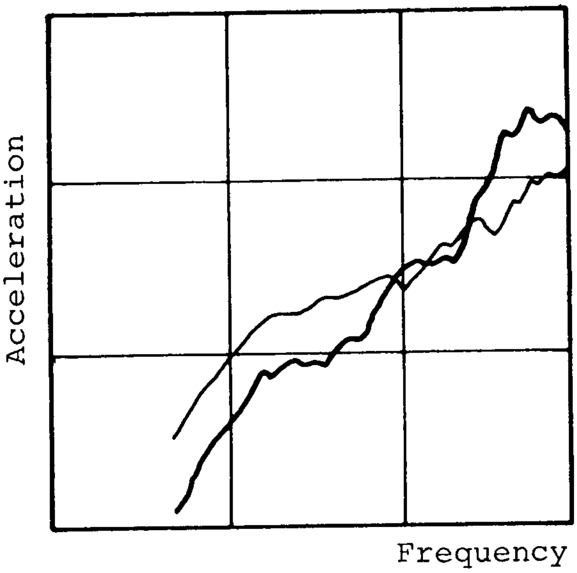

—— Mounting a)
– – – Mounting b)

Fig. 14 - Influence of the structure to the shock propagation in y-direction



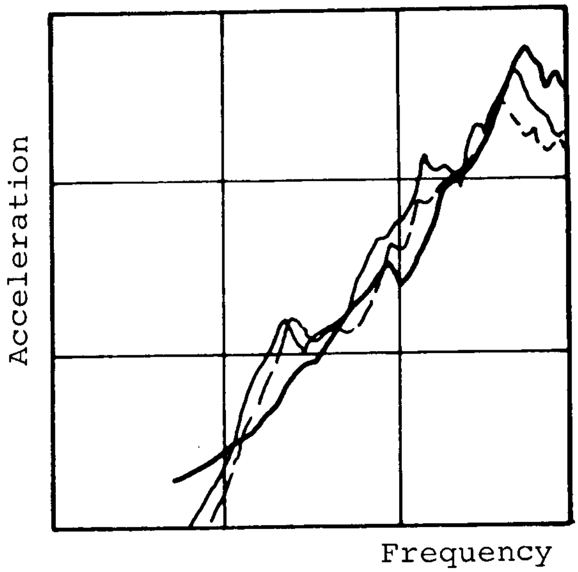

—— Mounting a)
– – – Mounting b)

Fig. 15 - Influence of the structure to the shock propagation in z-direction



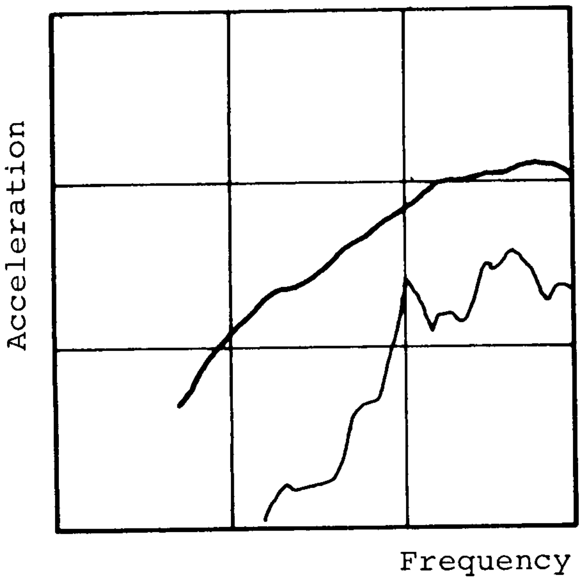

— Shot
— SBS

Fig. 16 - Comparision of initiated shocks between real bombardment and simulation



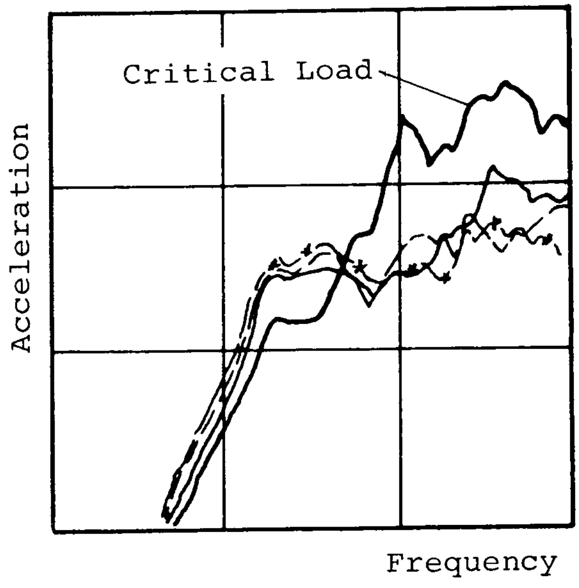

— Shot
— SBS
--- SBS

Fig.17 - Comparision of shock responses between real bombardment and simulation




— Excitation
— Response

Fig. 18 - Comparision between initiated shock and shock response at the equipment




— Measur. Point A
— -"- -"- B
--- -"- -"- C
—x—x -"- -"- D

Fig.19 - Shock distribution inside the equipment to find out critical areas

of components are possible.
From realistic bombardments against armored vehicles it is known that the shocks can lead to defects in such equipment which previously been tested by conventional test systems.
There is a need for a realistic test method for verification of equipment. For that purpose a suitable shock simulation technique is introduced. The armored vehicle is replaced by a simplified structure with similar dynamic properties. The shocks are produced by a high explosive. The shock simulator has the dimensions 1m * 2m * 3m, consists of armor plates and is bolted to an elastic foundation. The interior is divided into seperate chambers in which the equipment to be tested can be installed. Mass and stiffness can be varied to adjust the dynamic properties to real vehicles. Due to the dimensions of the simulator it is possible to accommodate complete firing control systems.
This is important for operational tests of the equipment.
The produced shocks are tuned to given shock spectra by dosing the quantity of the explosive, by changing the point of excitation and by varying the stiffness of the simulator.
The method can be used for verification of equipment which is in reaity exposed to high g-levels by short time durations.
Additionally the equipment can be tested to its load limit. The weakest points are then recognizable. The knowledge of the load limits is required to increase the protection against shock.
As the Simulator is unimpaired against the blastings a multitude of shock tests can be executed with the same test set up. The handling is easy and ballistic shock tests are carried out economically.

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