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1 Introduction

Equipment mounted on warship vessels is subjected to a strong regulation in order to guarantee its performance under extreme situations such as underwater explosions (UNDEX) without contact with the hull. These explosions impart high accelerations to critical instruments and machines mounted on the ship, thus they must be designed to withstand these accelerations while keeping uninterrupted operation. The specification MIL-DTL-901E [1] establishes that the endurance of critical equipment must be validated in a shock testing machine. Depending on the size, weight, location on the vessel and type of vessel, the equipment must be tested in a different shock machine.

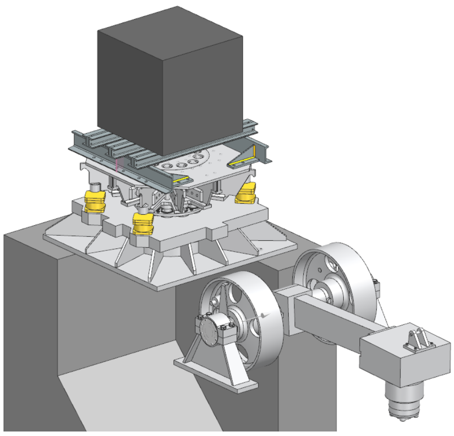

Figure 1: Medium Weight Shock Machine loaded with an equipment (cube) mounted on a set of channels.

The Medium Weight Shock Machine (MWSM) was designed for the validation of onboard equipment from 250 up to 6000 lb. The MWSM, displayed in figure 1, consists on a hammer installed as a pendulum which is released from a specific height (stipulated by [1])) which impacts an anvil table from below, transmitting an impact force to it. The anvil table travel after the impact is limited by top and bottom stops. The equipment being tested is fixed to the anvil table with a set of channels which provides a certain degree of flexibility to the assemblage load-anvil table.
The simulation of a shock test in a MWSM has been traditionally studied by means of simplified models that do not incorporate contact forces and approximate the flexibility of the channels by means of linear spring-damper forces [2, 3]. In this work, the simulation of shock tests in the MWSM is attained using analytical continuous contact-impact force models in the framework of a flexible multibody formulation based on the floating frame of reference method (FFR) combined with a modal reduction technique.

2 Multibody model

The MWSM consists of two rigid bodies, the anvil table and the hammer; a variable number of flexible bodies, which are the intermediate channels mounted between the anvil table and the load or equipment;

and the device being tested, which can be regarded as rigid or flexible. Elasticity in flexible bodies is parameterized by means of a set of deformation modes computed before the dynamic simulation.
The impact of the anvil table with the hammer and with the top and bottom stops is modeled by the Hunt-Crossley contact model described in [4], in which the contact force is a function of the local deformation and the relative normal velocity of the bodies colliding. The restitution coefficient has been estimated from physical experiments on the real machine.

3 Flexible multibody dynamic formulation

The rigid body motion of the MWSM is parameterized with natural coordinates, while deformation modes are selected as elastic coordinates. According to FFR, the dynamics of a flexible body can be described as a superposition of an elastic deformation over a rigid body motion assuming the hypothesis of small deformations. Upon that base, the FFR-Augmented Lagrangian index-1 formulation with position and velocity projections (FFR ALI1-P) [5] is built. The formulation requires 3 steps: first, accelerations are computed by means of an Augmented Lagrangian Index-1 scheme:

$$\left[\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q}^* + \mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\left(\boldsymbol{\lambda}^* + \boldsymbol{\alpha}\ddot{\mathbf{\Phi}}\right)\right]^{\{i\}} = \left[\mathbf{Q}_e - \dot{\mathbf{M}}\dot{\mathbf{q}}^* + \frac{1}{2}\left(\dot{\mathbf{q}}^{*\mathrm{T}}\mathbf{M}_{\mathbf{q}}\dot{\mathbf{q}}^*\right)^{\mathrm{T}}\right]^{\{i\}} \tag{1a}$$

$$\boldsymbol{\lambda}^{*\{i+1\}} = \boldsymbol{\lambda}^{*\{i\}} + \boldsymbol{\alpha}\ddot{\mathbf{\Phi}}^{\{i\}}; \quad i = 0,1,2,... \tag{1b}$$

with $(\dot{\cdot})$ and $(\ddot{\cdot})$ representing first and second temporal derivatives, $(\cdot)^*$ denoting unprojected magnitudes, $\mathbf{q}^{\mathrm{T}} = \left[\mathbf{q}_r^{\mathrm{T}} \quad \mathbf{q}_f^{\mathrm{T}}\right]^{\mathrm{T}}$ gathering the set of generalized coordinates conformed by rigid ($\mathbf{q}_r$) and flexible ($\mathbf{q}_f$) coordinates, $\mathbf{\Phi}$ identifying the vector of kinematic constraints, $\mathbf{M}$ representing the mass matrix, $\mathbf{Q}_e$ the vector of external forces, $\mathbf{K}$ the elastic stiffness matrix, $\boldsymbol{\lambda}$ the approximate Lagrange multipliers, $\boldsymbol{\alpha}$ a diagonal penalty matrix and with the superscript i indicating the iteration index.
The second stage involves an iterative projection of $\mathbf{q}^*$ onto the position constraints manifold:

$$\left(\bar{\mathbf{P}} + \varsigma\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\alpha}\mathbf{\Phi}_{\mathbf{q}}\right)\Delta\mathbf{q}^{\{i+1\}} = \bar{\mathbf{P}}\left(\mathbf{q}^{\{i\}} - \mathbf{q}^*\right) - \mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\varsigma\boldsymbol{\alpha}\mathbf{\Phi}, \quad \mathbf{q}^{\{i+1\}} = \mathbf{q}^{\{i\}} + \Delta\mathbf{q}^{\{i+1\}} \tag{2a}$$

wherein $\bar{\mathbf{P}}$ is the projection matrix, $\boldsymbol{\lambda}$ the Lagrange multipliers and ς a penalty factor.
Finally, velocities $\dot{\mathbf{q}}^*$ are projected onto $\dot{\mathbf{\Phi}} = \mathbf{0}$:

$$\left(\bar{\mathbf{P}} + \varsigma\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\alpha}\mathbf{\Phi}_{\mathbf{q}}\right)\dot{\mathbf{q}} = \bar{\mathbf{P}}\dot{\mathbf{q}}^* - \mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\varsigma\boldsymbol{\alpha}\mathbf{\Phi}_t. \tag{3}$$

4 Results

The MWSM model has been evaluated in a set of shock tests with a rigid load and results show a great level of convergence with the measurements of the corresponding shock tests in the real machine.

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