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Modal analysis of a large-scale antenna under shock base excitation

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Abstract

The shock response of a large-scale antenna is investigated in this study. The antenna height is about 12 m and its material is mainly aluminium 6061. The analysis is conducted by two approaches i.e. shock response spectrum (SRS) and modal analysis. The ratio of the maximum response of the antenna under the shock excitation to its steady-state counterpart is obtained by SRS based on the pulse duration and the system's natural characteristics. Moreover, the analysis is also performed by modal analysis in ABAQUS finite element software extracting the stress and displacement contour of the antenna structure. The results from SRS and modal analysis are in acceptable agreement. Based on the MIL-STD-810H standard, the shock distribution is considered as half-sine with 25g peak acceleration and 11 ms pulse duration. Moreover, the system's overall critical damping is considered as 5%. Regarding the maximum stress, the antenna cannot tolerate a half-sine shock pulse with 25g peak base acceleration which is a standard value for launching systems. However, applying a lower standard value i.e. 16g, is in the safe region with a safety factor of 2.3.

Keywords: Shock response spectrum; Modal analysis; Large-scale antenna; ABAQUS.

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1. Introduction

Antenna structures used in military and civil systems can encounter many mechanical shocks from various sources. Pyroshocks due to launching and separation phases in aerospace vehicles [1], near-miss underwater explosions close to ships and boats [2], pyrotechnic shocks, explosions in mining explorations, dropping and shocks/impact due to the system transportation [3] are the significant sources of shock loadings experienced by antennas. Mechanical shocks can induce highly dynamic loads on antennas causing large deflection and partial damage which lead to mechanical and/or electrical failures. Moreover, the top point of slender and long structures such as antennas are generally sensitive to base excitations [4]. Commonly, experimental methods are recommended for the shock resistance evaluation; however, if there are experimental restrictions such as huge sizes, excessively heavy weights and high costs, the numerical approaches can be utilized [5]. Therefore, large-scale antennas under dynamic loading can be investigated by numerical methods.

Shock response spectrum (SRS) is a simple and common method for shock severity estimation. In this method, based on the shock duration and the system's natural frequency, the maximum system response is obtained with respect to the steady-state response of the system. Thus, a system shock analysis can be studied by its steady-state response and natural characteristics.

The dynamic response of systems to shock excitation can be also obtained directly by numerical approaches such as finite element method. To this end, ABAQUS finite element software is used herein. ABAQUS base excitation solver uses the modal analysis approach. So, the antenna's natural frequencies and mode shapes are essential input parameters for the SRS study and modal analysis. Comparison of results obtained from SRS and ABAQUS have to be in agreement with each other.

Antenna analysis under dynamic loadings has been conducted by limited investigations [2], [4], [6], [7]. Shock analysis of a small-scale antenna (less than 1 m in length) structure subjected to underwater explosions was studied by Demir and Caliskan [2]. They utilized the SRS method for evaluating the shock severity level. Moreover, a drop test was also done for verification. Capilla et al. [4] studied vibration analysis of a monopole antenna structure by operational modal analysis for the sake of structural health monitoring. They obtained the acceleration and displacement response in the frequency domain. Shock analysis of a large-scale antenna (about 4 m in length) was investigated by Shin and Hur [6] by SRS method. The shock condition was specified based on the MIL-STD-810H standard and a transportation shock study dealing with a sawtooth function with a maximum 15g peak acceleration and minimum 5 ms pulse duration, was conducted. Furthermore, the maximum stress in the antenna was determined in order to specify the safety margin of the structure. The shock resistance of an antenna base was investigated by modal analysis and acceleration spectrum approaches by Li et al. [7]. Using ANSYS finite element software, they obtained the stress state in several sections of the structure and calculated the safety factor of every section.

Based on the presented literature review, no study has focused on the shock analysis of large-scale antennas by SRS and modal analyses. So, the main novelty of this investigation is dealing with shock analysis of a large height antenna, i.e., about 12 m, by SRS and modal analysis approaches. The rest of the paper is as follows. Section 2 presents the shock response spectrum method for evaluating the shock severity estimation. Next, the shock modeling in ABAQUS based on the modal analysis is explained in Section 3. Afterwards, Section 4 focuses on the results verification and antenna response subjected to shock base excitation. Finally, the concluding remarks are listed in Section 5.

2. Shock response spectrum

SRS is a trusted method for the structures response under shock loadings [8]–[11]. The idea of SRS is determination of the maximum reaction of a Single-Degree-of-Freedom (SDOF) system to a specific base pulse excitation for various values of the system natural frequencies. As shown in Fig. 1, the maximum value of the SDOF system acceleration or displacement is recorded for various systems with a specific natural frequency. By changing the natural characteristics, the maximum responses constituent a curve which is known as the SRS of the SDOF. There are several standard functions for the base excitation including half-sine, sawtooth, rectangular and triangular pulses.

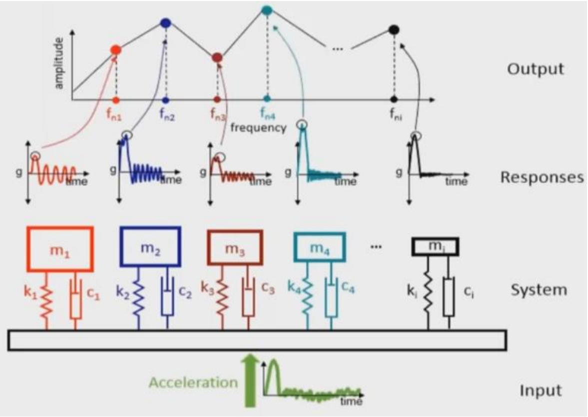
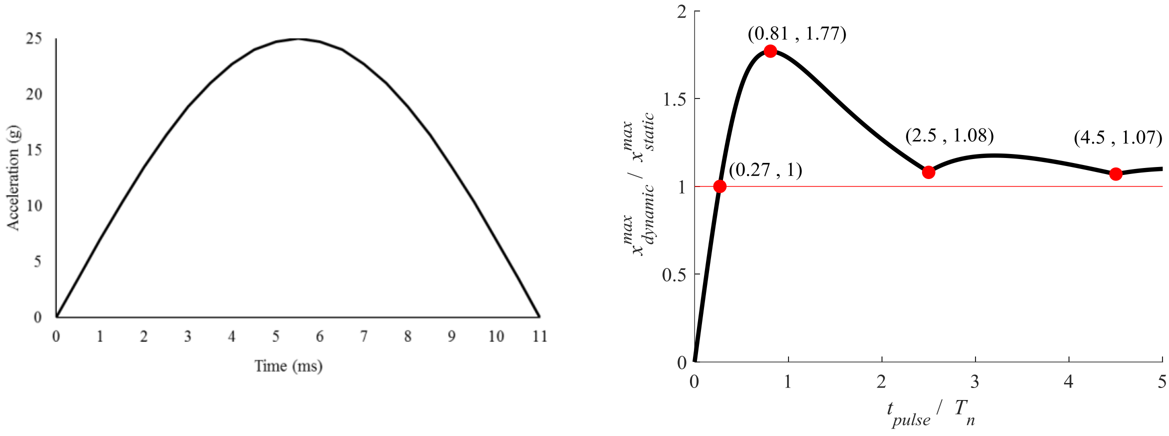


Figure 1. SRS extraction procedure.

Due to the complex nature of shock loading and its testing procedure, the shock study technique is presented in MIL-STD-810H standard [12] under different working conditions. Based on the standard, for the “Functional Shock Procedure” without measured data availability, SRS with classical pulses can be used in order to estimate the damage and severity of a shock loading. Moreover, as it is more convenient to be generated by shakers [12], the half-sine pulse is chosen for the pulse function in lieu of other pulses such as sawtooth distribution. The shock duration and its amplitude are specified in MIL-STD-810H regarding the working conditions. For launching and captive carry applications, the standard recommends a sawtooth pulse with 30g peak acceleration and 11 ms shock duration if measured data are not available. As noted before, the half-sine function is alternatively used. So, keeping the area under the curve constant [12], a half-sine pulse with 25g peak acceleration and 11 ms duration is equivalent to the sawtooth pulse. It is noteworthy to state that, while the SRS of sawtooth and half-sine pulses are different, they result in similar results since the amplitude was altered based on the identical area under the curve. Therefore, the half-sine pulse shown in Fig. 2a is used in the SRS approach for the antenna shock analysis.



(a) (b)

Figure 2. a) Half-sine acceleration pulse with 25g peak acceleration and 11 ms duration and b) SRS of a SDOF system with half-sine pulse excitation

A SDOF system including mass m and spring with stiffness constant k is subjected to half-sine force with peak amplitude F_0 and duration t_{pulse} as

$$F(t) = \begin{cases} F_0 \sin\left(\dfrac{\pi t}{t_{pulse}}\right) & \text{for } t < t_{pulse} \\ 0 & \text{for } t > t_{pulse} \end{cases} \tag{1}$$

By solving the equations of motion, the system SRS can be easily obtained as [13]

$$
\begin{aligned}
&x_d^{\max} = \frac{F_0}{k}\frac{1}{1-\dfrac{1}{2\alpha}}\sin\left(\frac{\dfrac{2\pi n}{2\alpha}}{1+\dfrac{1}{2\alpha}}\right),\ \alpha = \frac{t_{pulse}}{T_n},\ t < t_{pulse},\ n = 1,2,3,\ldots \\
&x_d^{\max} = \frac{F_0}{k}\frac{2}{\dfrac{1}{2\alpha}-2\alpha}\cos\left(\pi\alpha\right),\ \alpha = \frac{t_{pulse}}{T_n},\ t > t_{pulse}
\end{aligned}
\qquad (2)
$$

where T_n is the natural period of the system and is $2\pi(m/k)^{0.5}$. SRS can be graphically shown in Fig. 2b. x_{static} is the steady-state response of the system and is equal to F_0/k. Based on the SRS, provided that the ratio of the t_{pulse}/T_n is less than 0.27, the maximum dynamic or shock response of the system is less than its maximum static response; so, the static analysis is sufficient for the shock analysis. On the other hand, if the value of t_{pulse}/T_n approaches 0.81 the maximum dynamic response is about 1.77 times the maximum static response. Therefore, SRS facilitates the maximum dynamic system acceleration or displacement extraction based on the maximum static response. In other words, performing a static analysis is sufficient for estimating the maximum response of the system under various shock loadings, provided that the SRS of the shock function is known.

As noted before, shock response can be directly obtained by finite element method as well. Shock modeling procedure in ABAQUS software is presented in the following section.

3. Shock modeling in ABAQUS

Among the finite element packages, ABAQUS is a well-known software for solid mechanics analysis. So, ABAQUS is utilized to obtain the antenna structure response to shock base excitation. ABAQUS uses a modal analysis approach for obtaining a response to base excitation conditions. So, a “Frequency” step subset of “Linear Perturbation” analyses is chosen as the study step in order to extract the natural frequencies and mode shapes. Next, the “Modal Dynamics” step is considered for transient analysis. Due to the various sources of friction in structures, an overall damping coefficient is considered as well. Based on the MIL-STD-810H standard the critical damping ratio is generally taken as 5% for the shock analyses. So, “Modal Damping” for all modes is taken into account in the “Frequency” step. In order to enable a base excitation loading, an “Acceleration base motion” boundary condition is taken into account. In this type of boundary condition, the excitation is applied on the nodes with suppressed displacements.

Three parameters must be specified in the analysis i.e. minimum number of modes, maximum time increment and minimum analysis duration. The number of modes is defined based on the total mass participation factor of modes and the effective mass concept. Referring to Ref. [15], for obtaining acceptable results in modal analysis, the effective mass in each direction has to be at least 90% of the total mass in the same direction. In other words, the minimum effective mass in X, Y and Z directions has to be 90%\ of the total mass of the structure. Moreover, the effective masses relating to rotations around X, Y and Z axes have to be 90% of the moments of inertia around each axes denoted by IXX, IYY and IZZ in ABAQUS data file. Another important remark in the transient analyses is the time marching increment. In this study, the maximum time increment is set to 10% of the minimum natural period of the system [16]. Thus, after specifying the modes number, the minimum natural period which is obtained from the maximum natural frequency to set the maximum time increment. Finally, the third parameter is the minimum total analysis duration which is equal to the minimum natural period of the system [16].

In summary, two shock evaluation approaches including the SRS concept and shock base excitation modeling in ABAQUS were presented in Sections 2 and 3, respectively. The response of the antenna to the shock excitation and the comparison of the two approaches are dealt in the following.

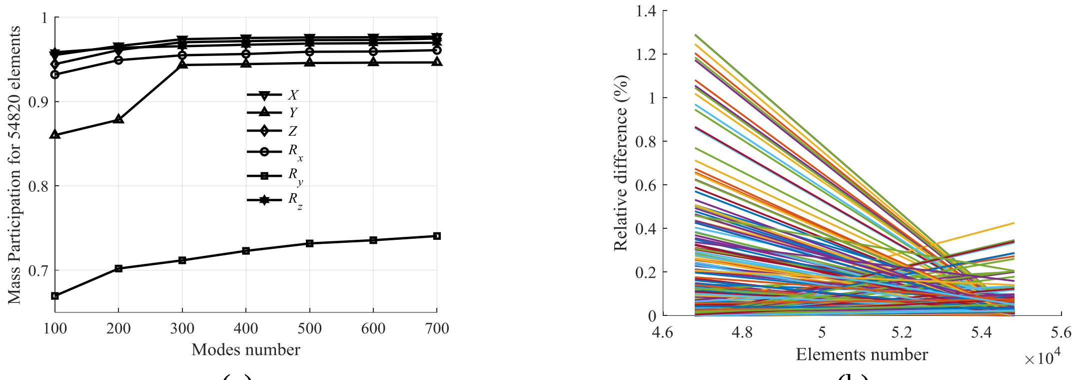
4. Results and discussion

The response of the antenna structure to the shock base excitation is presented in this section. As noted earlier, SRS and modal analysis methods necessitate natural frequencies and mode shapes extraction. Thus, frequency analysis of the antenna has to be performed at first. Fig. 3a and b show the antenna and its finite element model in ABAQUS, respectively. The antenna structure sections shown by number 1, are rigid enough to be eliminated from the model. So, the boundaries shown by number 2 are considered as clamped conditions (Encastre condition in ABAQUS software). Moreover, for simplicity, the bolts and nuts are removed as well. Furthermore, the antenna structure is made of aluminum 6061 T6 material with Young's modulus, Poisson's ratio and density as 69 GPa, 0.3 and 2700 kg/m3, respectively. In the lower section of the structure a polyamide base (denoted by number 3 in Fig.3b) is considered to enhance the vibration damping capability. The mentioned properties for polyamide are 2.4 GPa, 0.3 and 1150 kg/m3, respectively.

(a) (b)

Figure 3. a) Antenna and b) its finite element model in ABAQUS

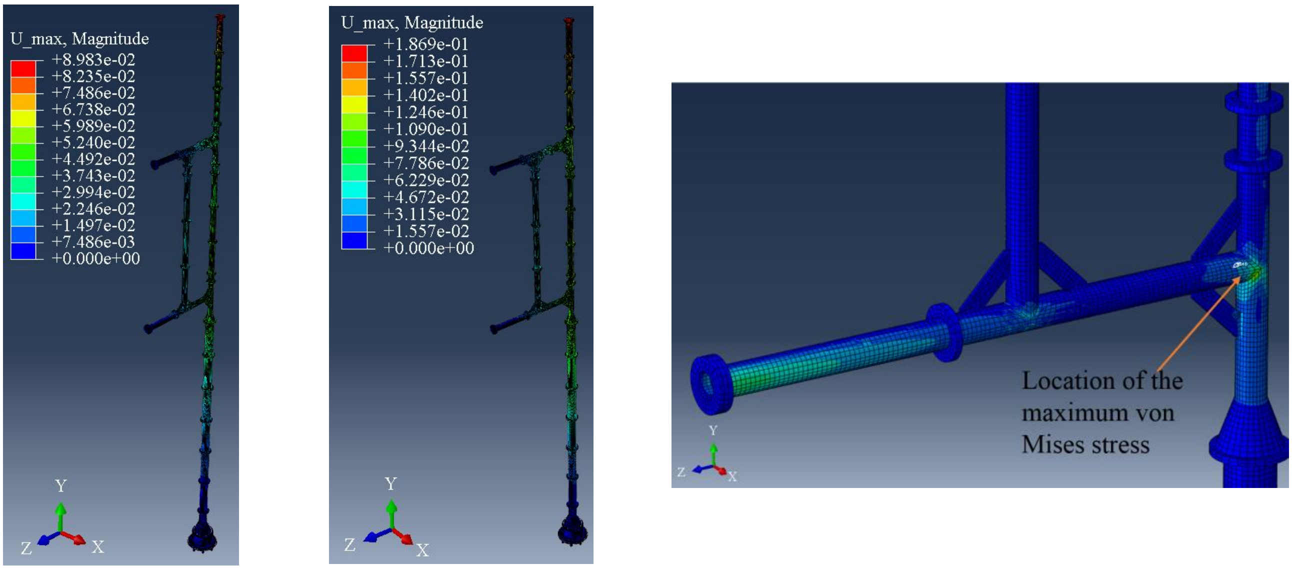
As stated before, frequency analysis has to be conducted at first. Fig. 4a and b show the mass participation factor in all directions and the relative difference of the first 300 natural frequencies with respect to finer mesh, respectively. One can see that after the 300 modes, except direction Y, all the effective masses in all directions are greater than 90% of the actual mass and moments of inertia. The effective mass increase rate in the Y direction is very slow which needs a very large number of modes for reaching the 90% threshold. As the deformation in the Y direction is insignificant (shown in the following) the number of modes is kept at 300. Furthermore, the system is discretized by about 46000, 55000 and 68000 hexahedral quadratic elements (C3D20R code) and the relative difference of every frequency (shown by a specific color) for every mesh number is shown with respect to finer mesh. As observed in Fig. 4b, the relative difference of the first 300 natural frequencies between 55000 and 68000 elements mesh are less than 0.5%. Thus, 300 modes are considered for the modal analysis and the model is discretized by about 55000 quadratic elements. The 300th natural frequency is about 2161 Hz which leads to 5e-5 s for the time increment. Moreover, as the first frequency is about 7 Hz, the total simulation time has to be at least 0.14 s which is considered as 0.15 s in this study.



(a) (b)

Figure 4. a) Mass participation in all directions for 54000 elements and b) relative difference of the first 300 natural frequencies with respect to finer mesh

As stated before, the shock pulse duration is 11 ms. Moreover, the first natural period of the antenna is about 0.14 s. So, the ratio of t_{pulse}/T_n is about 0.08. Referring back to Fig. 2b, it is observed that in this ratio, the maximum dynamic response with respect to the maximum steady-state response is about 0.4. In other words, without performing the shock analysis, it is estimated that the maximum displacement due to the shock analysis is 40% of the maximum displacement in the steady state or static analysis without damping consideration. In order to verify this ratio, both shock and static analyses are shown in Fig. 5a and b, respectively which are conducted by ABAQUS using the modal analysis method. The maximum displacement magnitude occurs at the top point of the antenna and is about 9 cm and 19 cm for the shock and static loadings, respectively and their ratio is about 0.47. Thus, the two ratios obtained from SRS and ABAQUS simulation are in acceptable agreement. Moreover, the maximum von Mises stress is about 316 MPa in the dynamic analysis and its position is in the lower joint of the structure (shown in Fig. 5c). By enabling the modal damping with 5% critical damping the maximum displacement magnitude and stress reduce to 6.5cm and 280 MPa, respectively. As the maximum stress is greater than the Al6061 yield stress, which is about 240 MPa, the antenna cannot tolerate the 25g peak acceleration for the half-sine shock loading. Based on the SRS, if the antenna structure stiffness is decreased, the natural period increases and consequently the t_{pulse}/T_n ratio declines. So, the peak shock response can be suppressed to lower values.



(a) (b) (c)

Figure 5. Maximum displacement magnitude contour of the antenna for the a) half-sine shock with 25g peak acceleration and 11ms pulse duration and b) steady state analyzes. c) von Mises stress for the shock analysis

Another solution can be increasing the distance from the antenna to the shock source, resulting in the peak acceleration value decrease. Based on the MIL-STD-810H, in the “Functional Procedure” group, a lower standard peak acceleration is 20g sawtooth pulse which is a standard pulse for flight vehicle applications. This pulse is equivalent to 16g peak acceleration in half-sine function. Therefore, the antenna shock analysis is also conducted for the new pulse function. Fig. 6 shows the maximum displacement magnitude in the antenna which is 4.2 cm. The maximum von Mises stress location is similar to Fig. 5c and its value is about 103 MPa. Thus, the most critical section in the antenna is the lower joint with the safety factor of 2.3.

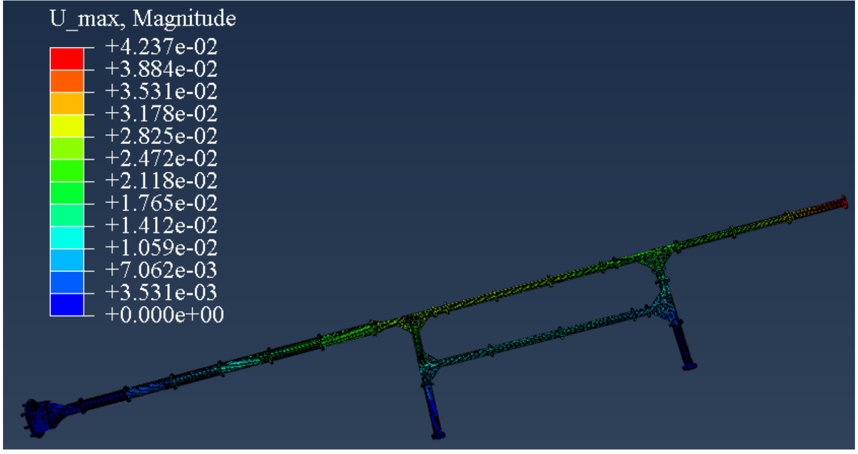


Figure 6. Maximum displacement magnitude contour of the antenna for the half-sine shock with 16g peak acceleration and 11ms pulse duration

5. Conclusions

A 12m-height antenna subjected to shock base excitation was investigated by SRS and modal analysis approaches. The maximum displacement due to the shock loading was estimated by SRS with respect to the steady state response of the system. Moreover, the antenna shock response was obtained by the modal analysis as well within ABAQUS finite element software. By comparing the ratio of the maximum displacement to the maximum static displacement between SRS and ABAQUS, an acceptable agreement was concluded. Furthermore, regarding the standard for shock testing i.e. MIL-STD-810H, a half-sine pulse function with 25g peak acceleration and 11 ms duration was taken as the base excitation. Also, the critical damping factor was taken as 5%. The maximum stress due to the shock function was more than 300 MPa which is greater than the Al6061 yield stress. Moreover, the maximum displacement magnitude at the top point was about 9cm. Based on the standard, a lower shock function possesses 16g peak acceleration. The maximum stress and displacement magnitude were reduced to about 103 MPa and 4.2 cm, respectively. Also, the maximum stress location was in the lower joint of the structure and it is the most critical section with a safety factor of 2.3.

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