Vibration Condition Monitoring of the Vertical Steel Tanks

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Abstract

This paper presents the results of numerical analysis and physical simulation of the vertical steel tank for usage in the vibration condition monitoring system. For purposes of the numerical analysis the tank is considered as the double steel cylinder consisting of the inner and outside shells. The discrete model of a tank is developed. The estimations of stress and deformation are obtained when the following vertical loads are exerting: weight of the fuel, weight of the tank roof and other structural elements or equipment. The physical model of a tank is used for physical simulation. The impulse responses of this model are measured and analyzed for different levels of tank filling. The methods of Prony and Steiglitz-McBride are used for estimation of the vibration damping factor which depends on the level of tank filling.

Keywords: vertical steel tank, numerical analysis, stress, deformation, vibration analysis, damping factor

1. Introduction

Ensuring safe operation is a very important problem for many complex objects located in hard-to-reach regions and influenced by the dynamic excitation.

As a complex object we will consider a vertical weld-fabricated steel tank with environmentally hazardous substances, whose operation is associated with various internal and external influences. For example, such tank was installed at the Ukrainian Antarctic Station Vernadsky. Modal (natural modes and shapes) and dynamic (vibration) characteristics of the tank are caused by the structural and technological conditions of its assembling. In addition, these characteristics also depend on the external dynamic excitations (wind load, earthquake load), temperature variations, and the changes of the fuel level in the tank.

The following factors make such tanks extremely dangerous for people and the environment: (a) defects caused by fabrication, transportation, or installation, (b) changes of mechanical characteristics of the used materials under the influence of dynamic excitation, (c) damages in the tank structure, which can lead to the fuel leakage.

The condition monitoring system is developed for prevention of the tank failure and environmental pollution [1]. The bases of such system are: vibration measuring subsystem, control subsystem, signal processing and decision making subsystem, subsystem for simulation, determination and prediction of parameters and characteristics of the mode of deformation.

The purposes of this work are: a) numerical analysis of the vertical steel tank when the vertical loads are exerting, b) physical simulation of the tank, analysis of the impulse response and determination of features of changes in the tank model condition.

2. Development and analysis of tank model

We consider the testing object (tank) as the double steel cylinder which consists of the inner shell and the outside shell. The shells consist of welded walls, besides there are steel tubes for fuel dispensing and tank unloading.

We use Finite Element (FE) Analysis to design the discrete model of the tank, which can be representative of an actual object. For this purpose we consider the walls of shells made from steel with the following properties: density 7850 kg/m^3; modulus of elasticity 2,05 10^5 N/m^2; Poison’s ratio 0,3; shear modulus 0,79·10^5 N/m^2. Each wall is modeled by the set of the quadrilateral plane FE with six degrees of freedom. Mechanical data of weld seams are accepted the same as of the material of walls. Therefore, additional finite elements for simulation of weld seams are not used. The NASTRAN is used for design of discrete model of the tank, the presence of weld seams is ensured by the simulation of walls in the form of surfaces (bodies). Two mentioned tubes connect the inner and outside shells are modeled by two rod FE “tube”, two quadrilateral FE are replaced by eight triangle FE at the attaching point. Thus, the developed discrete model of tank consists of 3548 FE and 3393 nodes. The discrete model of tank is presented in Figure 1.

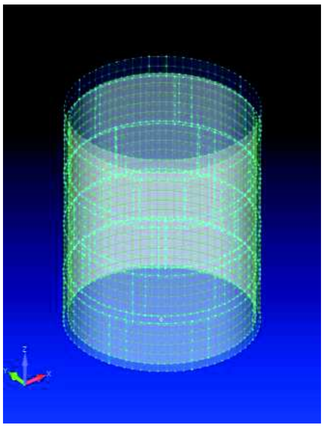

Figure 1. Discrete model of vertical steel tank as a double cylinder

The aim of analysis of the developed model is to estimate the mode of deformation when the vertical loads are exerting. We consider the following loads: weight of the fuel, weight of the tank roof and other structural elements or equipment.

Results of analysis of the stress and deformation of inner tank caused by weight of the fuel are presented in Table 1, values of the stress and deformation do not exceed the allowable values.

Table 1. Dependencies of stress and deformation on weight of the fuel

Characteristic of tank condition	Cases of fuel filling as part of tank volume			
	1/4	1/2	3/4	1
Stress, MPa	12	27	41	56
Deformation, mm	0,207	0,476	0,728	0,978

Maxima of stress and deformation of the inner tank are obtained at the bottom of walls for the four cases of fuel filling. Fig 2 shows the result of estimation of the mode of deformation for full filling.

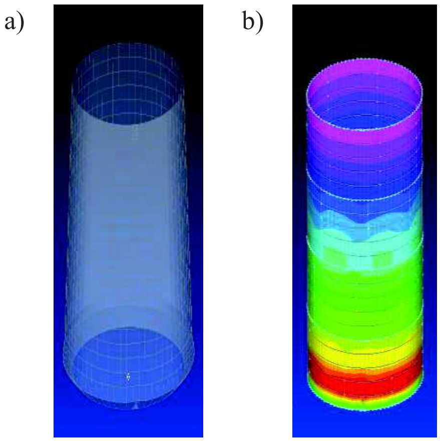

Figure 2. Mode of deformation of inner tank full filling: a) deformation; b) stress

The results of analysis of the stress and deformation of the tank as a double cylinder caused by weight of the tank roof and other structural elements or equipments are presented in Fig. 3. Maxima of stress (0,6MPa) and deformation (0,016 mm) are observed in elements of the bottom of walls and in elements of the top of the tank ring (in part in weld seams). The obtained value of load caused by weight of the tank roof and other equipments is considerably less than the bound of calculated stress. Received results show that the surface pressure caused by weight of the fuel on the tank's wall stresses the model elements much more than the axial load weight of the tank roof and other equipment.

Thus, for the purposes of further research, different levels of tank filling can be considered as a cause of changes in the tank condition.

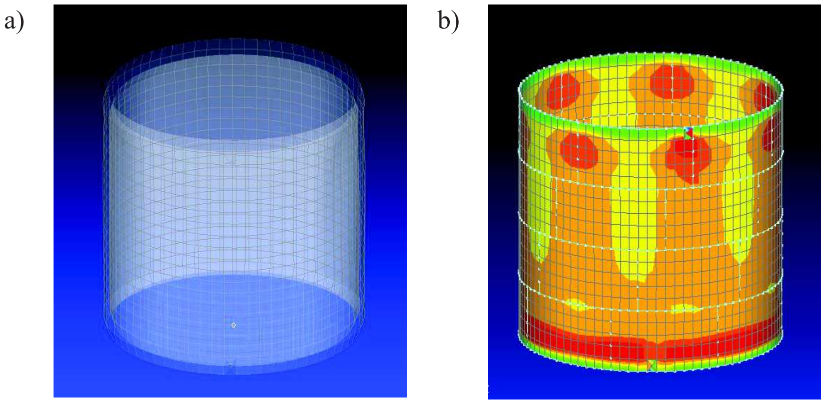

Figure 3. Mode of deformation of tank as a double cylinder caused by weight of the tank roof and equipments: a) deformation; b) stress

3. Physical simulation of tank and analysis of impulse responses

A small-size vertical steel container, with capacity of 0,04m^3, is considered as a physical model of a tank. We use the vibration method of free oscillations, which consists in the impact excitation of the testing object and further analysis of object's impulse response. The unit of two MEMS MS8002.D accelerometers are used to measure the impulse responses in two directions: in horizontal plane and vertical plane [2]. Figure 4a shows the physical model of the tank with mounted unit of accelerometers, and Figure 4b illustrates the object's simulation model, on the surface of which the spots of impact excitation are indicated as "x" and the spots of impulse responses measurement are indicated as "o".

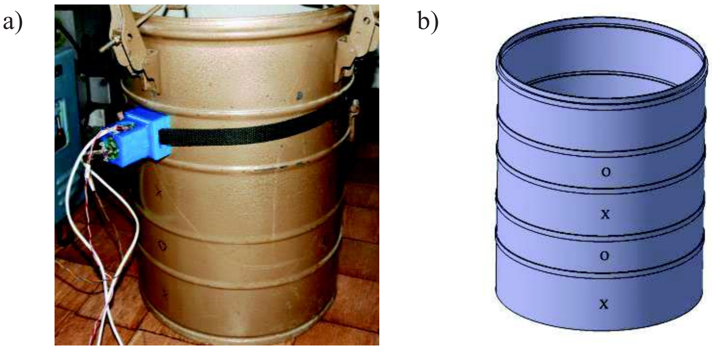

Figure 4. Models of tank: a) physical model of tank with mounted unit of accelerometers; b) three-dimensional simulation model

Measurements of the object's impulse responses are carried out for the mentioned above cases of liquid filling. The example of Welch periodogram of impulse response is presented in Fig. 5 (impact is in the orthogonal direction to axes of sensitivity of both accelerometers, container is empty). Figure 5 shows the presence of two spectral components in the frequency band (300 Hz, …, 500 Hz), whose amplitudes exceed the others.

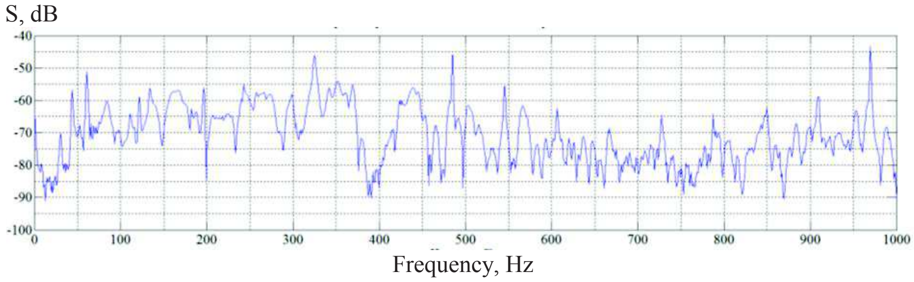

Figure 5. Welch periodogram of impulse response under impact in the orthogonal direction to axes of sensitivity of both accelerometers

The methods of Prony and Steiglitz-McBride are used for analysis of the impulse responses and estimation of vibration damping factor depending on the level of liquid filling. In conformity with Prony's method, the impulse response, consisting of the N samples, is approximated by the model of sum of q complex exponents [3]:

$$\hat{x}[n]=\sum_{k=1}^{q} A_k \exp[(\alpha_k + j2\pi f_k)(n-1)T + j\theta_k] \tag{1}$$

where T is a sampling period; n is a number of time step; $A_k, \alpha_k, f_k, \theta_k$ indicate the amplitude, damping factor, frequency, and phase angle of k component respectively.

The equation (1) can be presented in the form of z-transform:

$$\hat{x}[z]=\sum_{k=1}^{q} \frac{h_k z}{z_k(z-z_k)} \tag{2}$$

where $h_k = A_k \, exp(j\theta_k)$; $z_k = exp[(\alpha_k + j2\pi f_k)T]$ and $z = exp(j2\pi fT)$.

Estimations of the unknown parameters $A_k, \alpha_k, f_k, \theta_k$ are obtained by using the estimations of coefficients of the discrete transfer function of certain filter with the finite pulse characteristic. The N-sampling impulse response of testing object is used as the filter pulse characteristic h(k). It is necessary to assure the identical equality of the discrete transfer function of the filter to transformation (2), if Prony's method is used.

The method of Steiglitz-McBride [4] also allows synthesizing the filter if the pulse characteristic is given. But this method does not demand the identical equality (2), in this case the following condition is fulfilled:

$$\sum_{k=0}^{N} \left| h(k) - h_*(k) \right|^2 \to \min \tag{3}$$

where $h_*(k)$ is the pulse characteristic of recursive filter with given polynomials order of numerator and denominator of the discrete transfer function.

The following data are used for estimation of vibration damping factor by the method of Steiglitz-McBride: N=4096 and q=10. Results of estimation of frequency and damping factor for two low-frequency components of impulse responses are presented in Table 2 for different levels of liquid filling.

Table 2. Estimations of frequencies and damping factors (modulus) depending on the level of liquid filling

Cases of liquid filling as part of tank volume		0	1/4	1/2	3/4	1
Component 1	Frequency, Hz	340	354	327	367	337
	Damping factor	20	36	39	54	102
Component 2	Frequency, Hz	445	476	444	465	449
	Damping factor	2	11	14	34	45

It can be seen, the increase of liquid filling results in increase of damping of components of the impulse response. This fact can be used as feature of changing of the tank condition during the vibration condition monitoring of vertical steel tanks.

4. Conclusions

The numerical analysis of the vertical steel tank is carried out when vertical loads are exerting. Received results show that surface pressure caused by weight of the fuel on wall of tank stresses of elements of tank model much more than axial load weight of the tank roof and other elements and equipment.

The physical simulation of tank is done. Impulse responses of tank’s physical model are measured and analyzed for different levels of liquid filling. Estimations of vibration damping factor are obtained by the method of Steiglitz-McBride for different levels of liquid filling. Received results show that increase of liquid filling results in increase of damping of components of the impulse response.

Results of the presented work can be used for vibration condition monitoring of vertical steel tanks.

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