Modal Analysis of Railroad Tank Car Using FEM

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Abstract— **In this paper, a modal analysis is performed using The Finite Element Method (FEM) to a railroad tank car used to transport fuels and chemical products. Many of these substances are dangerous, so it is essential ensure the structural integrity of the units. The first 12 natural frequencies with their respective vibration modes of the structure were obtained. These results are used to determine safe conditions at different excitation frequencies and to avoid resonance problems during operation.**

Keywords— **FEM, Modal Analysis, Natural Frequency, Tank Car, Vibration Mode**

I. Introduction

The evolution of the Finite Element Method (FEM), revolutionized the way of performing calculations and design of continuous structures, becoming a powerful analysis tool. It is possible to consider Argyris and Kelsey [1] as precursor authors of FEM, along with Turner et al. [2] whom in 1956 demonstrated the application of the method to study the mechanical behaviour of aircraft structures. Thereafter came an exponential growth of works and publications relating to the method and its applications, a situation that has increased even more now [3].

Most mechanical structures operate under dynamic conditions, so it is important to determine their vibrational behaviour. When a structure is excited by a dynamic load at a frequency that coincides with one of its natural frequencies, the structure undergoes large deformations and stresses. This is known as resonance and can be damaging and dangerous.

Modal analysis is a technique used to derive the modal model of a linear time-invariant vibratory system. The theoretical basis of the technique is secured upon establishing the relationship between the vibration response at one location and excitation at the same or another location as a function of excitation frequency. This relationship, which is often a complex mathematical function, is known as frequency response function. In the last two decades, there have been numerous applications of modal analysis that covering wide areas of engineering, science and technology. The application scope of modal analysis is expected to undergo significant expansion in the coming years [4].

With a modal analysis it is possible to determine the natural frequencies of a tank car design that will be exposed to various dynamic loads during their operation, caused by situations such as the movement of the contained liquid, irregularities or disturbances in the rail track. This makes possible to avoid resonance problems that compromise the structural integrity of the railway vehicle and spills of hazardous materials that can damage the environment, properties and humans.

II. Free Vibration of Cylindrical Shell

Shell structures, especially cylindrical shells, are widely used in many structural designs, such as offshore structures, liquid storage tanks, submarine hulls, railroad tank cars and airplane hulls. Basically a shell structure is a three-dimensional structure which is thin in one direction and long in the other two directions. Because of this geometric aspect, they are thin, light and they span over large areas. Although they are thin, they can support applied loads effectively by means of their curvatures. Most of these structures are required to operate in a dynamic environment [5].

A vibration mode is characterized by a frequency and a pattern of movement of the waves or vibration mode shapes. Each vibration mode is completely independent of other modes. Therefore all modes have different frequencies and mode shapes. In thin-walled cylinders, the mode shapes are classified longitudinal and circumferentially as illustrated in Fig.1. Where m is the number of half-waves of displacement in the length of shell, n is the number of half-waves of displacement in the circumference of the shell [6].
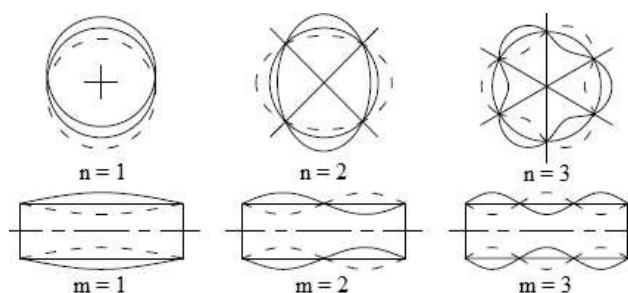

Fig. 1 Nodal patterns for circular cylindrical shells

The equation of motion for thin circular cylindrical shells can be written in matrix form as

$$[\mathcal{L}]\{u_i\} = \{0\} \tag{1}$$

Where $\{u_i\}$ is the displacement vector

$$\{u_i\} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{2}$$

The orthogonal components of the displacement vector are *u*, *v*, and *w,* in the longitudinal direction, circumferential and radial, respectively as shown in Fig. 2.
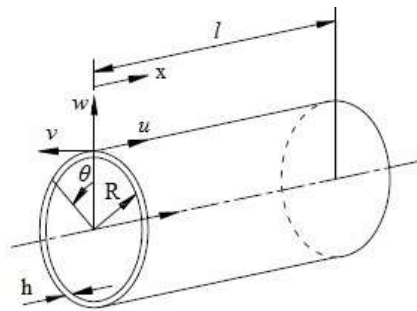
Fig. 2 Closed circular cylindrical shell and coordinate system [7]

III. MODAL ANALYSIS

In 1976 Pattabiraman and Ramamurti [8], they used the FEM to predict the dynamic behaviour of thin plate cylindrical structures, they obtained the corresponding free vibration frequencies with different boundary conditions and corroborated the efficiency of the method by comparing the results with an experimental analysis. In 2005 Alzahabi and Natarajan [9] determined the frequencies and modes of free vibration analysis using finite thin-walled cylinders with fixed supports in the end supports. The results correlated successfully with those obtained experimentally by Wang and Mechefske [10].

A. Establishement of FEM Model

The model selected of study is a DOT-111 tank car as illustrated in Figure 3, it is standardized by the Association of American Railroads (AAR) and the Department of Transportation of the United States. It is the common unpressurized tank car used in North America. Tanks to be built with this specification must be circular in cross section, with elliptical formed heads set convex outward. They have a minimum plate thickness of 11.1 mm and a capacity ranging between 30,000 and 125.000 liters.
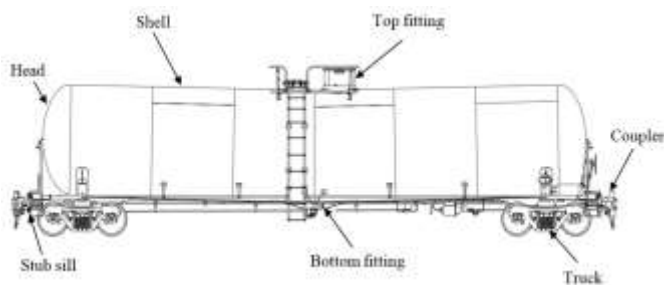

Fig. 3 Principal components of a Tank Car

Tank Car is a complex assembly structure, and it cannot be directly modelled. Thus, the model must be discrete and simplified. In the modelling, trucks and couplers were removed also other accessories were ignored which are of not great influence on the performance vibration of the whole car.

The modelled tank car was generated by CAD and is presented in Figure 4 and 5.
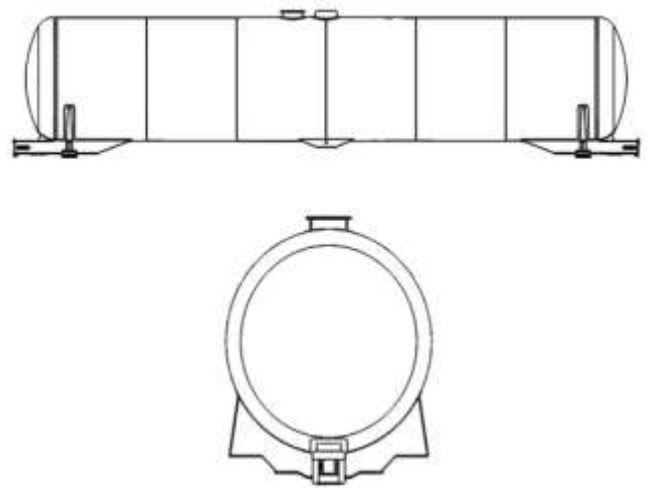

Fig. 4. Front and longitudinal view of the tank car

Fig. 5 Isometric view of the tank car

The dimensions and capacities of the tank car model proposed are presented in Table I.

TABLE I

DIMENSIONS AND CHARACTERISTICS OF TANK CAR

Characteristics	Magnitude
Full Length	17 m
Length	16.36 m
Diameter	3.04 m
Shell Thickness	12.7 mm
Maximum Capacity	115,000 l
Weight	20,453 Kg
Material	TC-128 B Steel

The material selected for the model is the TC-128 B steel carbon, which is special for the construction of railroad tank car normalized by the AAR. Some properties are listed below in Table II.

TABLE III

TC-128 B PROPERTIES [11]

Characteristics	Magnitude
Density	7916.5 kg/m^3
Young´s Modulus	206.85 GPa
Poisson´s Ratio	0.3
Tensile Yield Strength	344.74 MPa
Tensile Ultimate Strength	558.48 MPa

IV. DISCRETIZATION OF MODEL

The discretization and the analysis were performed using ANSYS Workbench. The meshing model presented in Figure 6, and 7 is solid with the exception of the tank which was generated as a surface.

Fig. 6 Longitudinal view of tank car

Fig. 7 Detail of the mesh in the stub sill

Some important characteristics of the generated mesh is presented in Table III, which are crucial for the evaluation and qualification of the mesh.

TABLE IIIII

CHARACTERISTICS OF THE MESH

Elements	112,447
Nodes	437,472
Skewness	0.38
Orthogonal Quality	0.71

The requirement for clustering is that the mesh must be fine enough to solve the primary features of the flow being analysed. The resolution depends on the boundary mesh that was decided to start from, and also the parameters controlling the generation of the interior meshing. Skewness is one of the primary quality measures for a mesh. Skewness determines how close to ideal (i.e., equilateral or equiangular) a face or cell is. According to the definition of skewness, a value of 0 indicates an equilateral cell (best) and a value of 1 indicates a completely degenerate cell. Degenerate cells (slivers) are characterized by nodes that are nearly coplanar. Cells with a skewness value above 1 are invalid. One important indicator of mesh quality is a quantity referred to as the orthogonal quality. Where range for orthogonal quality is 0-1, where a value of 0 is worst and a value of 1 is best [12].

According to the quality parameters of ANSYS Workbench, the values of skewness and orthogonality, the mesh qualifies as very good.

V. RESULTS

The first 12 Natural frequencies were determined, With their respective modes of vibration and are presented in the table IV.

TABLE IVV

FREQUENCIES, VIBRATION MODES AND DEFORMATIONS OBTAINED

	Frequency [Hz]	Vibration Mode		Maximum Vector Deformation
		n	m	
1	10.379	2	0	13.365
2	11.853	2	1	19.442
3	12.001	3	1	20.972
4	15.216	3	1	18.463
5	18.015	3	1	17.264
6	20.862	4	1	22.560
7	21.756	4	2	20.508
8	23.736	5	2	22.013
9	24.098	6	2	22.772
10	27.915	6	3	18.817
11	28.133	6	2	20.207
12	32.263	5	1	19.503

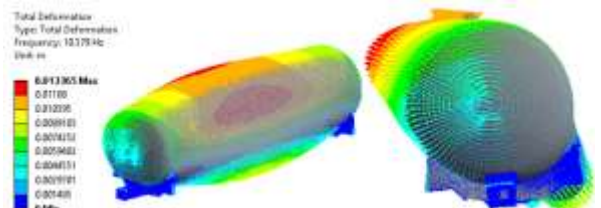The corresponding vector plots for each mode are presented in figures 7 to18.

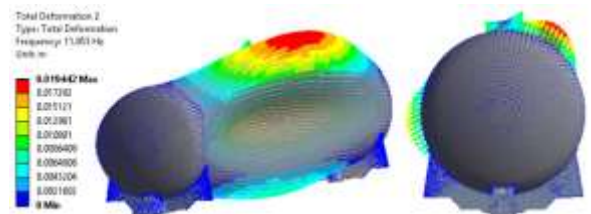Fig. 8 Isometric and front view corresponding to mode 1

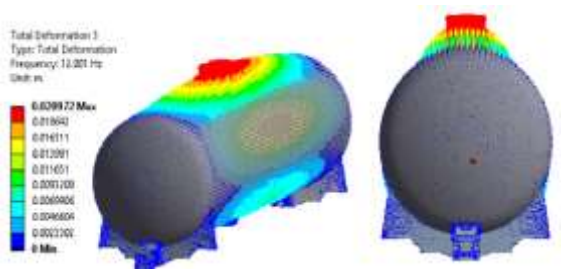Fig. 9 Isometric and front view corresponding to vibration mode 2

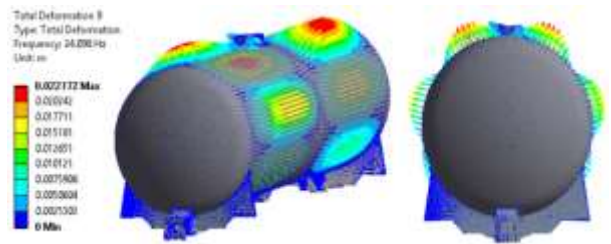Fig. 10 Isometric and front view corresponding to vibration mode 3

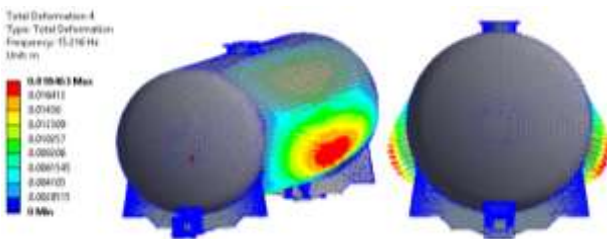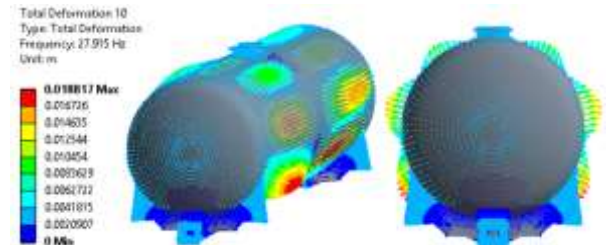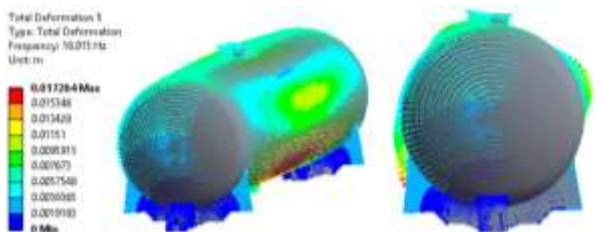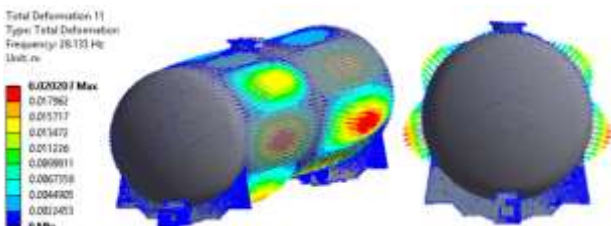Fig. 11 Isometric and front view corresponding to vibration mode 4

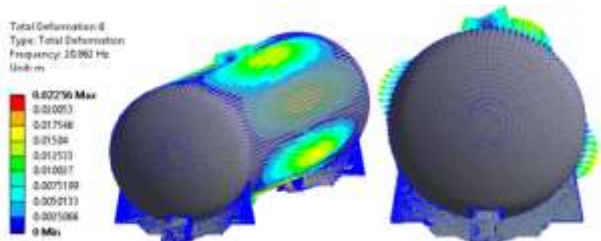Fig. 12 Isometric and front view corresponding to vibration mode 5

Fig. 13 Isometric and front view corresponding to vibration mode 6

Fig. 14 Isometric and front view corresponding to vibration mode 7

Fig. 15 Isometric and front view corresponding to vibration mode 8

Fig. 16 Isometric and front view corresponding to vibration mode 9

Fig. 17 Isometric and front view corresponding to vibration mode 10

Fig. 18 Isometric and front view corresponding to vibration mode 11

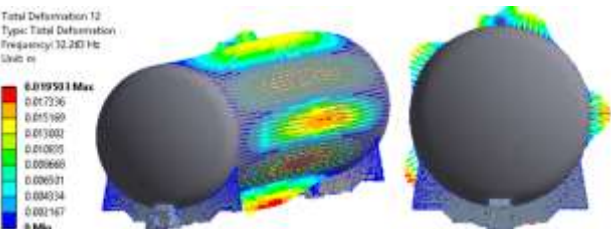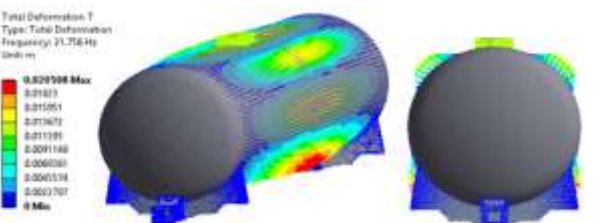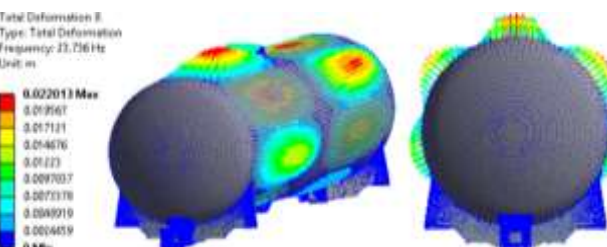Fig. 19 Isometric and front view corresponding to vibration mode 12

VI. CONCLUSIONS

The determined deformation vectors are in the range from 13 to14. The results also indicate the location of maximum deformation. The minimum natural frequency obtained is 10,379Hz indicating good rigidity in the tank car. This concludes that the tank car would have no problem of resonance due to that frequencies obtained do not match the excitation frequencies generated by irregularities in the railway. This concludes that the tank car would have no considerable problems of resonance because the frequencies obtained do not match the excitation frequencies generated by the irregularities on the rail track which are in the range from 2 to 3 Hz., or the frequency of movement of the liquid contents which are in the range of 0.16 to 0.26 Hz in the longitudinal mode and from 0.56 to 0.74Hz in the lateral mode [13].

The use of computerized FEM as a tool for structural analysis allows to determine the natural frequencies of a tank

car in a fast and accurate way. This leads to improving the design, allowing later modifications, using a faster and cheaper design cycle, due to the reduction of construction of prototypes, providing significant advantages to industry.

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