EXPERIMENTAL MODAL ANALYSIS OF BOLTED ENVIRONMENTAL STORAGE TANK WITH NEW WIND GIRDER

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ABSTRACT

This paper deals with experimental modal analysis of bolted storage tank, commonly used in many applications such as sewage treatment. Experimental modal analysis is crucial for the evaluation of dynamic properties, which helps with the assessment of wind-induced loads. Vortex shedding at specific wind speeds can excite natural frequencies, potentially causing damaging vibrations. Although the tanks have a simple cylindrical shape, their construction from overlapping steel sheets, stiffening girders, and bolted joints complicates numerical modelling. This makes it difficult to accurately define stiffness, mass distribution, damping, and boundary conditions. To minimize these differences, a prototype of a small, bolted tank is designed and built including all above-mentioned parts. Experimental modal analysis is performed on the prototype using three configurations of upper girders. The first case is without girders, the second one uses standard L-shaped beams, and the third one uses a new designed wind girder. It was found that the lowest first natural frequency f = 42.3 Hz was for the case with new designed wind girder. The first natural frequency of the tank without girders was f = 50.1 Hz. The most suitable case was a tank equipped with L-shaped girder with the first natural frequency equal to f = 86.7 Hz.

KEYWORDS

Modal Analysis, Experiment, Storage Tank, New Wind Girder

1 INTRODUCTION

Modal analysis is a pivotal tool in designing bolted tanks due to their impact on dynamic behaviour and therefore their stiffness against outer loads such as wind or seismic waves. The analysis identifies natural frequencies (f), damping ratios (ξ) and mode shapes which play key roles in suppressing resonance. Modal analysis of bolted tanks is usually performed via numerical modelling. However, numerical simulations require some simplification and prerequisites. Experimental modal analysis is necessary for the evaluation of built bolted tanks and for the validation of numerical models. One of the examples of modal analysis of a horizontally suspended cylindrical tank (which was welded together) was studied by Amabili et al. [Amabili 2001]. Mazuch et al. [Mazuch 1996] published work comparing natural frequencies and modes of vertical partially filled storage tank using finite element analysis and experiment. Their tank can be considered small because it was made of a thick wall tube with a diameter of 77.3 mm and a height of 231 mm. Explicit dynamic analysis for various wind loads and natural frequencies was performed by Chiang and Guzey [Chiang 2019]. They also compared buckling capacity for various tank slenderness.

The bolted tanks are assembled by individual sheets connected by bolts which means simple installation and variability. This manufacturing process is suitable, but it requires a thorough assessment of dynamic properties. Overall stiffness and damping are influenced by sheet thicknesses and individual connections. Damping of bolted connections was studied by Gaul and Lenz [Gaul 1997], also by Chatterjee in their degree project [Chatterjee 2023]. Aerodynamic forces act on structure during wind pressure loads and cause vibration. One of the main phenomena is vortex shedding where vortices form and shed behind the tank with a certain frequency. The vortex shedding frequency is dependent on Strouhal number (*St*), which is defined by the ratio of vortex shedding frequency and characteristic dimension to wind speed. For cylinder, *St* is around 0.2 depending on Reynolds number (*Re*). For large *Re* (approximately above 10^5), *St* for smooth surfaces is greater; more can be found for example in [Dalton 2013]. The influence of 3D parameters on vortex shedding, like spanwise correlation or mode shapes, was studied by Zhou et al. [Zhou 2020]. The critical wind speed is determined by vortex shedding frequency that is close to the natural frequency of construction. Due to this speed, resonance can occur which leads to possible structural damage. Therefore, it is necessary to design tanks with specific modal properties. Author Peter Irwin studied the vortex shedding and resonance of tall buildings in his paper [Irwin 2010].

Important design features of bolted tanks are so-called wind girders. These girders are usually mounted in horizontal connections; therefore, some call them ring stiffeners. Their function is to increase buckling capacity, which is one of the key properties for tanks [Chiang 2019]. Appropriate design of wind girders is for that reason important due to safety maintenance, especially in high wind speed regions. The design of wind girders concerning their stiffness was evaluated by Zeybek et al. [Zeybek 2019]. Bu and Qian [Bu 2015, Bu 2016] compared applicability of individual approaches for the design of top girders (also intermediate wind girders).

The authors of this work also designed new wind girders intended for high-capacity bolted tanks and performed a parametric numerical study [Drahorad 2023]. The publication contains also numerical modal analysis which does not reflect the construction details of girders due to simplification. Because of the numerical nature of the results, the aim of this work is to evaluate the manufacturability of girders, their installation and their properties on the tank prototype. Therefore, this work presents an experimental modal analysis of proposed new wind girder (NWG) and conventional L-shape girder for comparison.

Although the modal properties of the structures are important, no literature were found dealing with the experimental modal analysis of bolted storage tank equipped with wind girders. This paper presents an experimental modal analysis of an empty bolted tank, and the same tank equipped with two different types of wind girders, with a comparison of the results.

2 MATERIALS AND METHODS

The first part of this section deals with the designing process and manufacturing of bolted tank. The smaller prototype is built compared to common storage tanks due to limited space. However, all components and used technologies remained exact with larger configurations. Size reduction was achieved by shortening metal sheets and reducing the number of plates for construction. In the following parts, experimental modal analysis is discussed including describing measuring tools, analysis settings and the experiment itself.

2.1 Design of Tank Prototype

For purposes of experimental modal analysis, steel bolted tanks prototype was manufacture. Fundamental geometry parameters are described in Tab. 1 and its total weight was 119.7 kg. The tank assembly was built with four curved metal sheets with holes near the edge. The final cylindrical shape of the tank was achieved using these holes for bolt connection. The tank has a steel bottom with a welded flange collar with holes which allowed us to connect of tank wall to the bottom. The bottom is also extended for fixation of the tank to the ground. For a studied tank, two types of wind girder are manufactured, mentioned in publication [Drahorad 2023]: NWG and L60x60x6 (L60). Assembled prototype with both wind girders is shown in Fig. 1. NWG mounted at the top of the tank wall on the left side, while the standard L60 girder is displayed on the right side.

The material of the tank wall was KOSMALT S300E. It is hot rolled steel suitable for enamelling with yield stress 300 MPa. More mechanical properties of this material can be found in [Steel 2025]. The material of the rest (bottom and girders) was made of structural steel S235. Shell sheets and girders were additionally powder-coated for anticorrosion protection. It is a surface finishing that consists of applying an electrostatically charged powder to a metal surface and then the powder is hardened [Coating 2025]. The bottom of the tank also had surface finishing with protection paint. After installation, all connections were sealed by silicon sealant to simulate the standard operating conditions of the tank.

FIGURE 1 ASSEMBLED PROTOTYPE, LEFT WITH NWG AND RIGHT WITH STANDARD GIRDER L60

Diameter of tank D	980 mm
Height of tank H	785 mm
Thickness of tank wall t_w	3 mm
Thickness of bottom t_b	5 mm

TABLE 1 FUNDAMENTAL DIMENSIONS OF PROTOTYPE

The fundamental geometry of NWG was obtained from publication [Drahorad 2023]. The girder is composed of two segments, V-segment and P-segment, folded together. However, original geometry was designed for large-capacity tanks, whose construction parameters are slightly different, especially the dimensions of basic metal sheets used for tanks. Therefore, it was necessary to modify slightly the shape of the girders so that they could be mounted on the prototype and the main geometry requirements were met. A key feature was keeping overlapping segments which forms girder with varying thickness. These overlapping segments result in variable stiffness. The final girder was formed by eight V-segments and two P-segments. P-segments were connected by short plates to prevent weakened places with possible plastic joints.

The case with conventional girder was constructed by four curved L-shaped beams L60 which were connected by shorter L-shaped connection members. The connection members were bolted to girders and to tank wall to reach higher stiffness. The main difference between NWG and L60 is the distinct area moment of inertia in the circumferential direction. While the moment of inertia along the circumference of conventional girders (L-shape, U-shape profiles) can be considered uniform, NWG provides a non-uniform moment of inertia due to its advanced geometry, see Fig. 2. However, this difference causes difficulties in designing and it requires detailed evaluation. The proposed dimensions of girders are mentioned in Tab. 2.

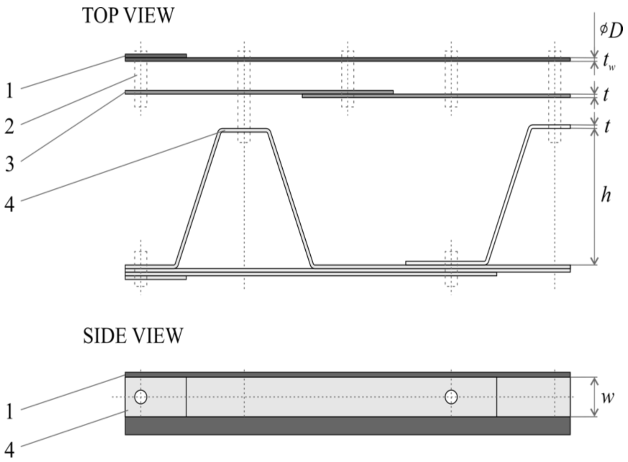


FIGURE 2 SHAPE OF SEGMENTS FORMING NWG: ITEM 1: TANK WALL, ITEM 2: BOLTED CONNECTION, ITEM 3: P-SEGMENT, ITEM 4: V-SEGMENT

	Thickness of segments	Height of V segment	Width of segments	Number of V / P segments
NWG	t = 4 mm	h = 150 mm	w = 50 mm	8/2
	Thickness	Height	Width	Number of connection members
L60	t_1 = 6 mm	h_1 = 60 mm	w_1 = 60 mm	4

TABLE 2 FUNDAMENTAL DIMENSIONS OF GIRDERS

2.2 Experimental Modal Analysis

For experimental measurements of tank modal properties, hardware of company Brüel & Kjær (B&K) was used. Impact hammer B&K type 8202 was used for the excitation of the structure. It has an integrated sensor for acting force B&K type 8200. The hammer was equipped with a plastic tip. Due to the construction of a force sensor, charge amplifier B&K type 2647 A had to be used. Excitation was applied in the normal direction to the tank wall surface at each point of interest.

Response of construction was measured by triaxial accelerometer B&K type 4524 B. During the selection of the accelerometer, its weight was considered due to minimization of result distortion. Correct orientation of the accelerometer was guaranteed by alignment of its coordinate system with the coordinate system of the measured structure. The accelerometer was attached to the surface by a special substance of bee wax supplied by the manufacturer. The substance provided a mechanically stable connection and was thermally stable (the temperature during measurement was 23 °C), which helped with the measured frequency range. The data collection was realized by measuring module B&K LAN-Xi type 3050-A-040; afterwards, data were analysed in the software BK Connect.

The geometry of the tank wall was defined by a grid containing 192 measuring nodes, as shown in Fig. 1. The girder geometry was defined using an additional 48 or 24 nodes (NWG or L60), and 25 further nodes were used to define the tank bottom. The measuring nodes were evenly distributed across the tank wall, considering its symmetry and ensuring sufficient resolution for mode shape interpolation. The reference point for response sensing was selected based on preliminary testing conducted along the tank circumference (except for the evaluation of the tank bottom). The aim of preliminary testing was to find the optimal position to reflect the dominant mode with high sensitivity. The tank was fixed to the ground by M16 bolts using chemical anchors. This way of anchoring was consulted by the manufacturer of the prototype and was based on practices commonly used in the industry.

In BK Connect, the geometry was defined using nodes corresponding to the grid on the tank prototype. Subsequently, the previously mentioned impact hammer with charge amplifier and accelerometers was configured. The frequency response function in each measuring node was averaged from five measurements, which means the structure was excited by hammer five times in every node. Each measurement was evaluated individually for data consistency. For expected frequency values, the analysis upper limit was set to 200 Hz with a resolution of 0.5 Hz. The sampling rate was high enough to cover the measured range without aliasing.

3 RESULTS

In this section, results of experimental modal analysis for three configurations of tanks are presented. Firstly, the presented results describe a tank without girder. The next section presents the result of the tank with NWG. The last section shows natural frequencies and modes of the tank with standard girder L60. Each case has six evaluated mode shapes while equivalent modes with very close frequencies are excluded.

3.1 Storage Tank without Girder

Mode shapes of the storage tank wall without girder, shown in Fig. 3, highlight that number of circumferential waves (4,5,6) rises with increasing natural frequency. Except for mode shape four and five, which are more complex, and their shape can by caused by overlapping of the sheets and the bolted joints.

The measured damping ratios are significantly higher than damping ratio corresponding to the modal shape of the welded tank [Amabili 2001]. Sealing of overlapping steel sheets in bolted tanks increases the damping ratio. The modal analysis of the storage tank bottom was evaluated separately. The first three mode shapes of the tank bottom are presented in Fig. 4. The vibration of the bottom is not of interest, as it is not excited by wind flow.

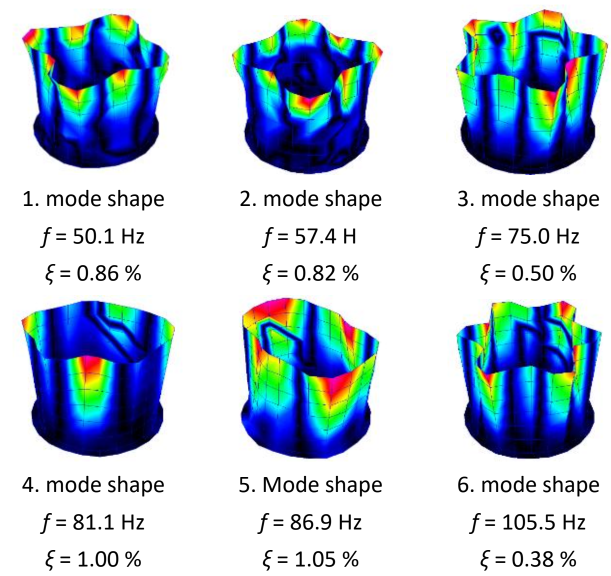


FIGURE 3 MODE SHAPES OF STORAGE TANK WALL WITHOUT GIRDER

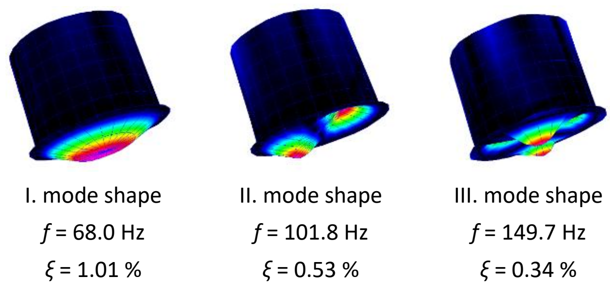


FIGURE 4 MODE SHAPES OF STORAGE TANK BOTTOM

3.2 Storage Tank with NWG

Mode shapes of the storage tank wall with NWG are displayed in Fig. 5. From the figures, it is apparent that the first mode has a lower number of waves compared to the tank without girders. The corresponding natural frequency is significantly lower which means girder has negative influence on the modal properties of the tank. Adding the girder has an impact on the stiffness and mass distribution of the tank which leads to changes in natural frequencies and mode shapes.

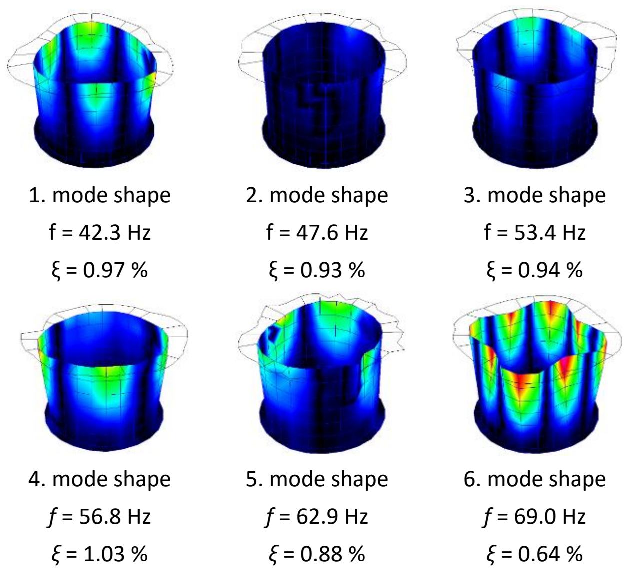
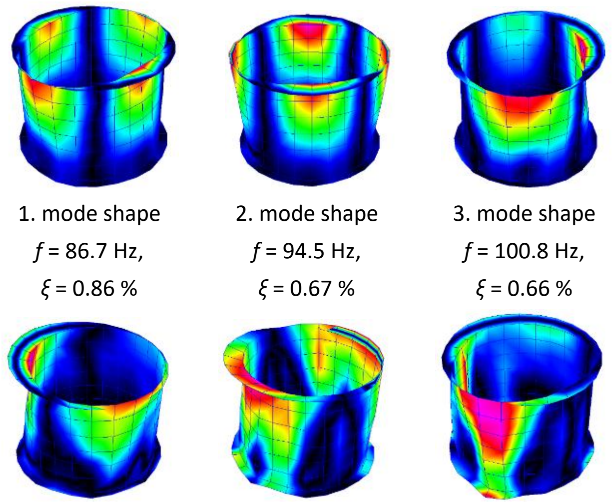


FIGURE 5 MODE SHAPES OF STORAGE TANK WALL WITH NWG

3.3 Storage Tank with L60

Fig. 6 displays mode shapes of the storage tank wall with girder L60. While comparing shapes with tank without girders or with NWG, presented mode shapes are different. The first mode shape contains only two circumferential waves, and the first natural frequency is significantly higher. Next mode shapes have higher frequencies and represent the swaying of the whole tank. This concludes that standard girders L60 sufficiently increase the stiffness and modal properties of the tank prototype.



1. mode shape	2. mode shape	3. mode shape
f = 86.7 Hz,	f = 94.5 Hz,	f = 100.8 Hz,
ξ = 0.86 %	ξ = 0.67 %	ξ = 0.66 %
4. mode shape	5. mode shape	6. mode shape
f = 108.3 Hz,	f = 142.4 Hz,	f = 149.2 Hz,
ξ = 0.62 %	ξ = 1.31 %	ξ = 0.52 %

FIGURE 6 MODE SHAPES OF STORAGE TANK WALL WITH STANDARD GIRDER L60

Using NWG led to a decrease in first natural frequency (by 15 %) compared to results without girder. On the other hand, using standard girder L60 caused an increase in the first natural frequency by over 70 %.

4 DISCUSSION

In this paper, three configurations of bolted tanks were experimentally tested. Configuration was based on the usage of girders. Measurement and evaluation were difficult due to the complex geometry of NWG made by overlapping plates which might have not been adjacent to each other properly. That led to bouncing and distortion of response from the impact hammer causing difficulty evaluation. For a proper understanding of vibration of NWG, a new finer grid would be necessary (like the grid of a cylinder wall). Based on the results, it can be concluded that standard girder L60 performed superiorly in the case of the prototype. Usage of this type of girder led to a significant increase in natural frequencies. Distinct mode shapes were caused by different stiffness and mass and are not considered negative. Modal analysis of the tank with NWG suggested that usage of these girders was not ideal for this dimension of the tank. Natural frequencies were lower than in the case of tanks without girders and significant vibration were present on NWG. This phenomenon is due to the disproportional size and mass of the girder compared to the overall prototype and girder's distance from the axis of the tank. The original geometry of NWG was designed for large storage tanks which have larger mass and size compared to girders. Based on the performed experiments, NWG is not suitable for small-capacity tanks.

Next research could be focused on performing numerical modelling of the prepared prototype including two types of girders. Modal analysis of numerical models can be validated by experimental data and help understand the dynamic behaviour of tanks. Another research topic could deal with the effects of bolts, sealant and other construction features. These features could influence the distribution of stiffness and mass which could lead to distortion compared to expected modal properties. Since these tanks are meant to keep water, the influence of water level should be also researched in the case of modal properties. A validated numerical model could help understand this phenomenon.

5 CONCLUSIONS

Based on the performed measurements, it was observed that using various girders has a significant influence on mode shapes and natural frequencies of the tank prototype. The main difference between tested girders is a difference in circumferential stiffness and various concentrations of mass. The L60 girder exhibits a uniform distribution of area moment of inertia, with a maximum radial distance of 60 mm from the tank axis. In contrast, the NWG features a variable area moment of inertia and reaches a maximum distance of 150 mm from the tank axis. Given the small dimensions of the tank prototype, this distance is considered excessive. Comparing natural frequencies and the mode shapes of both girders led to the conclusion that modal properties are vastly distinct. Substantial differences in mode shapes are observed across all configurations. Using NWG led to lower natural frequencies compared to a tank without a girder and using standard girder L60 led to an increase in natural frequency. From the mentioned findings, it is apparent that NWG cannot universally replace standard girders for every tank size. Wind girders are an important component of large-capacity tanks used in various technical industries, as their cost can represent a significant portion of the total tank price. Therefore, selecting an appropriate type of girder with sufficient stiffness is essential. Based on the obtained results, it can be summarized:

- The behaviour of NWG and L60 are vastly different, due to the different distance of the centre of gravity of the girder from the tank axis and distribution of area moment of inertia according to circumference.
- Natural frequencies are significantly distinct. The highest natural frequencies were achieved by the model with L60 and the lowest by model with NWG.
- L60 cannot be universally replaced by NWG, because mode shapes of the tank and natural frequencies are significantly different when using these two types of girders.
- Usage of NWG for very small capacity tanks is not suitable due to a decrease of the tank's natural frequencies.

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