Aeolian Liquid Vibrations in Conical Tanks with Baffles under Wind Loading with Fuzzy Parameters

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Abstract: - The Aeolian liquid vibrations in conical reservoirs caused by low-velocity, steady winds have been under consideration. Both amplitudes and dominant frequencies of wind loadings have been constantly changed, so to adequately describe the vibration process, fuzzy logic methods have been applied. At the first stage, the crisp initial value problem for conical shells with and without baffles has been considered. The liquid inside the reservoirs has been supposed to be an incompressible and ideal one, and its flow induced by the forced harmonic excitation, has been considered as potential. So, there exists a potential to satisfy the Laplace equation. The impermeable condition has been used at wetted surface boundaries of the shell, whereas the dynamic and kinematic boundary conditions have been set on the free liquid surface. A system of singular integral equations has been obtained for values of the velocity potential and the function describing the free surface rise. Its solution has been gained by boundary element methods. The crisp boundary value problem has been reduced to the second-order system of differential equations. After receiving the crisp solution of this system, the initial data have been fuzzified, involving triangular fuzzy numbers, and the fuzzy initial value problem has been formulated. The numerical solution to this problem with uncertain intervals involved has been obtained and analyzed.

Key-Words: - sloshing damping, baffles, environmental safety, wind loads, storage tanks, fuzzy logic, Aeolian fluid vibrations.

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1 Introduction

Many research schools for several decades have been focused on problems of fluid-structure interaction (FSI). Nowadays, this interest is growing even more due to the rapid development of new industries, such as nuclear turbine construction [1], wind energy [2], aerospace [3] and petrochemicals. The creation of new industrial designs requires a thorough analysis of the strength and reliability of equipment. Although only a full-scale experiment could provide the most objective data, its implementation is associated with significant material difficulties and could lead to the spilling of hazardous contents, breakage of expensive samples, and also cause harm to personnel. So, methods of computer modeling the dynamic processes are coming to the forefront. Among them, finite element and finite volume methods, boundary element methods (BEM), [4], [5], integral equation, and transformations approach, [6], should be mentioned.

2 Problem Formulation

The very important and interesting application of FSI concerns with vibrations of fluid-filled structures with the free liquid surfaces, [7]. A lot of research has been devoted to analytical and numerical solutions for sloshing in cylindrical shells. The shells with porous baffles have been considered in [8], [9], non-linearity and compressibility effects have been estimated in [10], and the parametric resonance has been studied in [11]. For sloshing damping and improving the reservoir quality, different devices have been used, such as floating roofs, [12], vertical and horizontal baffles, [13], as well as innovative materials [14], [15], [16], [17]. Tank materials properties have been treated also in [18], [19]. Different reservoir forms have been considered in [20].

Much less attention has been paid to conical shells in interaction with liquid in the scientific literature, despite the wide use of thin-walled conical shells in various fields of technology, [21]. In aerospace engineering, such shells have been applied as fuel tanks in airplanes and satellites. It has been known to use shells in submarines, torpedoes, water-based ballistic missiles, and offshore drilling rigs of the ocean engineering field. As for civil engineering, the conical shells have been applied in protective containers in elevated water tanks.

It should be noted that elevated water tanks are usually subject to variable wind load. Both amplitudes and frequencies of this load are uncertain parameters that usually are in a certain interval. To adequately describe a process with such parameters, the concepts of fuzzy logic have been applied, [22].

The main objective of this paper has been to develop new effective methods for the analysis of fluid vibrations in conical shells with and without baffles under aeolian loads with fuzzy parameters, [23], [24]. The paper has been organized as follows. At first, the liquid vibrations in conical shells have been studied in crisp formulations. Then the loading parameters have been fuzzified using triangular fuzzy numbers.

A system of second-order ordinary differential equations with fuzzy parameters and initial data has been obtained.

3 Problem Solution

Crisp formulation

The V-shape conical shell with a horizontal circle baffle, partially filled with a liquid has been considered. Figure 1. Let R_1 and R_2 be the upper and lower radii of the shell, and $H=H_1+H_2$ is the filling level. It has been assumed the baffle is located at height H_1.

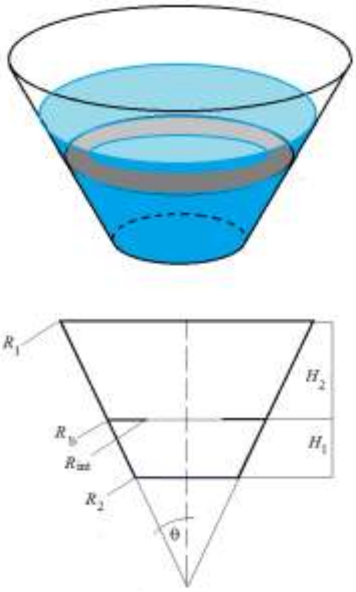


Fig. 1: Baffled conical shell and its draft

The liquid inside the shell has been supposed to be an ideal and incompressible one, and the liquid flow due shell vibrations is irrotational. In these suppositions the velocity potential φ could be introduced, so that **V**=gradφ, and due to incompressibility condition of continuum media $\mathrm{div}\mathbf{V} = \frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} = 0$ the Laplace equation for φ determining has been obtained as follows:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0. \qquad (1)$$

Then a system of governing equations of elastic shell motion with the liquid, in the operator form has been gained in the form, [11].

$$\mathbf{LU} + \mathbf{M\ddot{U}} = \mathbf{P}_l + \mathbf{Q}, \qquad (2)$$

where **L**, **M** are elastic and mass forces operators, $\mathbf{U} = (u_1, u_2, u_3)$ is the shell displacement vector, $\mathbf{Q}(t)$ is the external surface load, $\mathbf{P}_l = (p - p_0)\mathbf{n}$ is the liquid pressure, and **n** is an external unit normal to the surface. The pressure value, according to the Bernoulli integral, could be represented as follows:

$$p - p_0 = -\rho_l \left[\frac{\partial \varphi}{\partial t} + a_x(t)x + a_z(t)z + gz\right]. \qquad (3)$$

Here ρ_l is the fluid density, x and z are horizontal and vertical coordinates of a point in the liquid, g is gravitational acceleration, $a_x(t), a_z(t)$ are accelerations of the exciting force in horizontal and vertical directions, p_0 is the atmospheric pressure. According to [13], the following boundary value problem has been formulated:

$$\mathbf{LU} + \mathbf{M\ddot{U}} = \mathbf{P}_l + \mathbf{Q}, \nabla^2\varphi = 0, \frac{\partial\varphi}{\partial n} = \frac{\partial w}{\partial t}\Big|_{S_1}, w = (\mathbf{U}, \mathbf{n}), \frac{\partial\varphi}{\partial n} = \dot{\zeta}\Big|_{S_0}, p - p_0]_{S_0} = 0. \quad (4)$$

to define unknown functions $\mathbf{U}$, φ, and $\zeta = \zeta(x, y, t)$ which describes a level and position of the liquid free surface. Here S_1 is the wetted shell surface, and S_0 is the free liquid surface. Next, the unknown functions ζ and Φ can be expressed in cylindrical coordinates (r, θ, z) as follows:

$$\zeta(r, \theta, t) = \sum_{k=1}^{\infty}\sum_{j=0}^{\infty} d_{kj}(t)\cos(j\theta)\zeta_{kj}(r), \quad (5)$$

$$\varphi(r, \theta, z, t) = \sum_{k=1}^{\infty}\sum_{j=0}^{\infty} \dot{d}_{kj}(t)\cos(j\theta)\,\varphi_{kj}(r, z). \quad (6)$$

Here $d_{kj}(t)$ are unknown time-dependent coefficients for each wave number j, the basic functions $\zeta_{kj}(r)$ and $\varphi_{kj}(r, z)$ are solutions of the spectral linear boundary value problem, [12], [13].

$$\nabla^2\varphi_{kj} = 0, \frac{\partial\varphi_{jk}}{\partial \boldsymbol{n}} = 0\Big|_{S_1}, \frac{\partial\varphi_{kj}}{\partial \mathrm{n}} = \frac{\partial\zeta}{\partial t}\Big|_{S_0}, \zeta_{kJ}(r) = \frac{\partial\varphi_{kJ}(r,z)}{\partial z}\Big|_{S_0} = \frac{\chi_{kj}^2}{g}\varphi_{kj}(r, H), \quad (7)$$

where χ_{kj}^2 are fundamental sloshing frequencies. So, for the function $\zeta(r, \theta, t)$ one could obtain:

$$\zeta(r, \theta, \mathrm{t}) = \frac{1}{g}\sum_{k=1}^{n}\sum_{j=1}^{m} \cos(j\theta)\,\chi_{kj}^2\varphi_{kj}(r, H)d_{kj}(t). \quad (8)$$

Using the integral representation, [21], for the unknown potentials, the system of singular integral equations has been obtained, for each basic function $\varphi_{kj}(r, z)$ for the conical shell without baffles. If baffles have been installed, then the multi-domain boundary element method has been involved, as in [12], [13]. After receiving the basic functions $\zeta_{kj}(r)$ and $\varphi_{kj}(r, z)$ with corresponding fundamental frequencies χ_{kj}^2, the next system of the ordinary differential equations has been built:

$$\ddot{d}_{0k}(t) + \chi_{0k}^2(1 + a_z(t)/g)d_{0k}(t) = 0,$$
$$\ddot{d}_{1k}(t) + \chi_{1k}^2\left(1 + \frac{a_z(t)}{g}\right)d_{1k}(t) + a_x(t)F_{1k} = 0, \quad (9)$$

where $F_k = (r, \varphi_{1k})/(\varphi_{1k}, \varphi_{1k})$, $k = \overline{1, M}$. The initial data for simulating system (9) are following:

$$d_{0k}(t) = 0, \dot{d}_{0k}(t) = 0,\ d_{1k}(t) = 0, \dot{d}_{1l}(t) = q_1 \quad (10)$$

with nonzero initial velocities for some l. The accelerations $a_x(t)$ and $a_z(t)$ have been presented as follows $a_x(t) = a_0\cos(f_0 t)$, $a_z(t) = a_1\cos(f_0 t)$. Here f_0 is an approximate wind loading frequency. So, the crisp problem of determining the free surface elevation has been reduced to system (10) of differential equations with boundary conditions (11) depending the parameters: f_0, q_1, a_0, $\overline{a_1}$, $\overline{a_1} = a_1/g$. However, the deterministic analysis did not provide adequate information when studying such uncertainties as the frequencies and amplitudes of wind loads oscillations, and the possibility of initial non-zero speed of the free surface.

Fuzzification of parameters

Crisp parameters $f_0, q_1, a_0, \overline{a_1}$ have been fuzzified as triangular fuzzy numbers $B = (b_1, b_2, b_3)$ using non-axisymmetric membership functions $\mu_B(x)$ presented in Figure 2.

The membership functions $\mu_B(x)$ has been defined as:

$$\mu_B(x) = \begin{cases} (x - b_1)/(b_2 - b_1), & b_1 \le x \le b_2 \\ (b_3 - x)/(b_3 - b_2), & b_2 \le x \le b_3 \\ 0, \quad x < b_1, & x > b_3 \end{cases}$$

Crisp intervals B_α, defined by α-cut operation, [22], have been obtained accordingly:

$$B_\alpha = \left[b_1^{(\alpha)}, b_3^{(\alpha)}\right], \qquad b_1^{(\alpha)} = (b_2 - b_1)\alpha + b_1,$$
$$b_3^{(\alpha)} = (b_2 - b_3)\alpha + b_3 \quad (11)$$

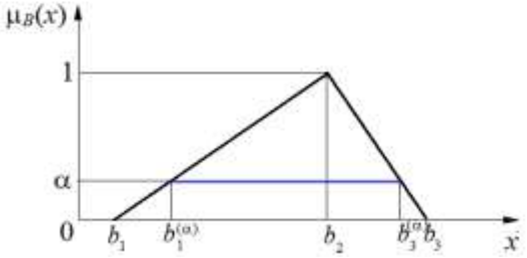


Fig. 2: Membership function $\mu_B(x)$ and α-cut intervals

Then all crisp parameters have been fuzzified as: $f_0 \leftrightarrow F_0 = (f_{01}, f_{02}, f_{03})$,
$q_1 \leftrightarrow Q_1 = (q_{11}, q_{12}, q_{13})$,
$a_0 \leftrightarrow A_0 = (a_{01}, a_{02}, a_{03})$,
$\overline{a_1} \leftrightarrow A_1 = (a_{11}, a_{12}, a_{13})$.

After fuzzification, the numerical solution of system (9) has been gained using methods elaborated in [23], [24]. The α-cuts intervals for the function ζ have been obtained for different α. This allows us to analyze the uncertainties introduced by the wind load at estimating the level of free surface elevation.

Numerical results and discussion

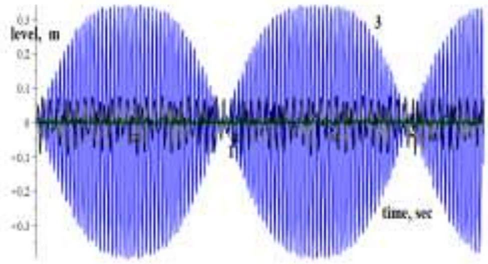
The crisp analysis has been carried out first. In numerical simulation, the V – shape conical tank has been considered to have R_1 = 1.m, R_2 = 0.4m, and θ=π/6. The corresponding value of H could be easily found as $H=(R_1-R_2)\cot\theta$. There have been exposed numerical simulation outcomes for wave numbers j =0, 1 and different baffle positions, declared by the height H_1 in Table 1. Four eigenvalues for each j have been involved. The radius of the conical shell at the baffle position has been designated as R_b, and the free surface radius as R_{int} (Figure 1). First, the natural frequencies have been obtained for the unbaffled conical tanks. It corresponds to values H_1= H_2 =0.5m, R_{int}/R_b=1. The values of H_1 and H_2 have been chosen arbitrary, but H_1+H_2=1.0m. Furthermore, the baffles have been considered at different positions, namely H_1=0.5m and H_1=0.8m assuming different baffles sizes, R_{int}/R_b=0.5 and R_{int}/R_b=0.2. It would be noted also that the first harmonic frequencies are lower than axisymmetric ones for considered conical tanks.

Table 1. Natural frequencies of V– shape conical tanks with baffles

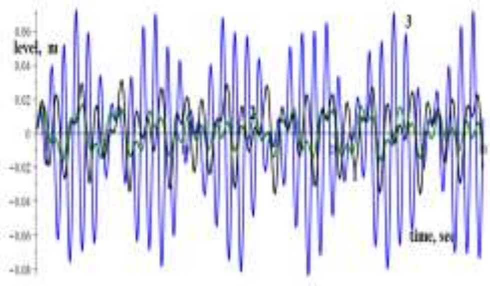
n			1	2	3	4
H_1	H_2	R_{int}/R_b	j =0			
0.5	0.5	1	3.4665	6.6819	9.8451	12.998
0.5	0.5	0.5	3.4088	6.6687	9.8433	12.998
0.5	0.5	0.2	3.4053	6.6354	9.8432	12.998
0.8	0.2	0.5	2.5271	6.3874	9.7242	12.921
0.8	0.2	0.2	2.4433	6.0590	9.5651	12.884
H_1	H_2	R_{int}/R_b	j =1			
0.5	0.5	1	1.4164	4.9977	8.2065	11.377
0.5	0.5	0.5	1.2284	4.9747	8.1974	11.376
0.5	0.5	0.2	1.1722	4.9436	8.1963	11.376
0.8	0.2	0.5	0.8155	4.7425	8.0039	11.205
0.8	0.2	0.2	0.6306	4.1916	7.8497	11.203

According to [23], [24], the most characteristic frequency of wind load is f_0=0.07Hz, and its range is f_0∈(0.025,2.5) Hz. So, the triangular fuzzy number could be introduced as follows $F_0=(0.025, 0.07, 2.5)$. Note that the frequencies, given in Table 1, are within the interval for f_0 at n=1, j=0,1 and therefore system (9) will include differential equations in which these frequencies appear. The following presentations have been implemented also for fuzzified parameters: $A_0=$ (0.01, 0.1, 0.2), $A_1=$ (0.01, 0.05, 0.2), Q_1 =(0.01, 0.05, 0.075).

Below the α-cut intervals have been considered for all fuzzified parameters, and the lower and upper bounds of α−cuts for the free liquid surface elevation have been estimated. Figures 3a)-3b) demonstrate both crisp solutions, and lower and upper α−cuts bounds for function ζ via time for different α.



a) α=0.25



b) α=0.75

Fig. 3: Lower and upper α−cuts bounds for function ζ via time

Number 2 in these figures corresponds to the crisp solutions, by numbers 1 and 3 the lower and upper bounds of α−cuts have been marked. From the results obtained, it could be seen that with a sufficiently large α, small oscillations of the free surface occur: the largest amplitude reaches 0.3 m at the upper bound of α− cuts at α=0.25.

Thus, for the available initial data from [25] and the results of this research, the following conclusion could be made. The process of the fuel tank filling under wind load is stable for α− cuts 0.75 and higher. But with a probability close to 0.25, beating modes are possible, Figure 3a). This could happen at the extreme values of fuzzy variables. So, during the fuel tank filling, constant monitoring of the wind load is required, with a temporary stop of filling when the wind load acceleration increases. Protective coatings and other dampers also need to be used.

4 Conclusion

Wind load action and resulting Aeolian fluid vibrations in fuel tanks is a process with many uncertainties. For mathematical modeling such phenomena, fuzzy logic concepts with fuzzy differential equations implementation are necessary. In this research, the effective numerical method has been proposed to describe the disturbance of the liquid-free surface in the container under wind loads with the usage of fuzzy logic concepts. Numerical simulation of $\alpha-$ cuts for the free surface elevation has been carried out. The intervals of dangerous frequencies and the wind load accelerations have been defined. This makes it possible to provide practical recommendations on the process of fuel tank filling. In the future, it is planned to study the influence of baffles and floating covers, and other damping devices on the level of elevation of the free surface under the action of wind load, using concepts of fuzzy logic, and nonlinear formulations.

Future research will be concerned with different reservoir forms and horizontal and vertical partition considerations. In addition, the optimal forms and places of baffle installation will be considered using advanced methods of non-linear programming, [26].

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Olena Sierikova: conceptualisation, data curation.
- Elena Strelnikova carried out the simulation and the optimization.
- Denys Kriutchenko: visualization, data curation.
- Kyryl Degtyarev: carried out the simulation and the optimization.
- Vasyl Gnitko: methodology
- Volodymyr Doroshenko: formal analysis.

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The authors have no conflicts of interest to declare.