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Simulation, analysis and optimal design of fuel tank of a locomotive

A. Karkhaneh Yousefi[*1], H. Nahvi[1] and M. Shariat Panahi[2]

[1]*Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran*
[2]*School of Mechanical Engineering, Faculty of Engineering, University of Tehran, Tehran, Iran*

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Abstract. In this paper, fuel tank of the locomotive ER 24 has been studied. Firstly the behavior of fuel and air during the braking time has been investigated by using a two-phase model. Then, the distribution of pressure on the surface of baffles caused by sloshing has been extracted. Also, the fuel tank has been modeled and analyzed using Finite Element Method (FEM) considering loading conditions suggested by the DIN EN 12663 standard and real boundary conditions. In each loading condition, high stressed areas have been identified. By comparing the distribution of pressure caused by sloshing phenomena and suggested loading conditions, optimization of the tank has been taken into consideration. Moreover, internal baffles have been investigated and by modifying their geometric properties, search of the design space has been done to reach the optimal tank. Then, in order to reduce the mass and manufacturing cost of the fuel tank, Non-dominated Sorting Genetic Algorithm (NSGA-II) and Artificial Neural Networks (ANNs) have been employed. It is shown that compared to the primary design, the optimized fuel tank not only provides the safety conditions, but also reduces mass and manufacturing cost by %39 and %73, respectively.

Keywords: multi-objective optimization; fuel tanks; baffles; sloshing; Artificial Neural Networks

1. Introduction

Fluid storage tank structures have been of interest for a long time, because of their unique characteristics due to the interaction between fluid and structure. This interaction which causes sloshing can be a severe problem in vehicle stability and control (Eswaran *et al*. 2009, Schotte and Ohayon 2009). Also, prediction of the motion of liquids in tanks has many usages in numerous engineering fields (Mitra and Sinhamahapatra 2007) such as airspace vehicles (Veldman *et al*. 2007, Wei *et al*. 2008, Cheng *et al*. 2008), automobile industry and racing (Aliabadi *et al*. 2003, Popov *et al*. 1992, Lloyd *et al*. 2002) and elevated tanks with drinking water (especially subject to earthquakes) (Mitra and Sinhamahapatra 2008, Shekari *et al*. 2009, Livaoglu and Dogangun 2007).

Variation of the acceleration of vehicles and external excitation applied to the partially filled tanks lead to sloshing. The sloshing phenomenon can be described as the highly non-linear movement of the free-surface of liquids inside tanks (Souto-Iglesias *et al*. 2006). Sloshing generates dynamic loads on the tank structure and thus, becomes a problem in the design of

*Corresponding author, Ph.D. Student, E-mail: a.karkhanehyousefi@me.iut.ac.ir

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structures and particularly vehicles (Souto-Iglesias *et al*. 2006). Therefore, in the design of tanks, sloshing phenomena and associated structural behavior must be taken into consideration.

Regarding design methods and stress analysis, tanks are divided into some groups like thin and thick wall vessels, silos, partially filled tanks and so on. The tanks of liquid fuels are a branch of partially filled tanks and in order to reduce the maximum stress and sloshing phenomena, the most important part of their design is baffles layout. One of the most popular ways that is widely used for sloshing wave damping is the use of internal baffles (Eswaran *et al*. 2009, Lloyd *et al*. 2002, Akyildiz and Unal 2006, Liu and Lin 2009, Panigrahy *et al*. 2009). Furthermore, there exist some design variables such as size, installation position, the number of baffles, and so on which affect the sloshing.

In the majority of publications, the geometries of the tanks are simplified to completely rigid rectangular shapes. However, in several studies more complex or realistic geometries (Veldman *et al*. 2007, Aliabadi *et al*. 2003) or elastic behaviors (Eswaran *et al*. 2009, Mitra and Sinhamahapatra 2008) are taken into account. Baffles are also taken into account in several studies; they are assumed elastic in some (Eswaran *et al*. 2009) and rigid in most other studies.

Recent studies approach the problem of sloshing by direct numerical modeling techniques such as the finite-element method. A large variety of 2D and 3D models have been developed by different researchers (Rebouillat and Liksonov 2010). The liquid is usually modeled using Navier-Stokes equations or Euler equations. It has been shown that taking into account fluid viscosity and compressibility has no significant effect on the pressure under normal gravity (Lee *et al*. 2007). On the contrary, considerable differences have been found between the results of one-phase and multiphase models. This indicates that considering the effect of gas in the container provides more accurate results in comparison with one-fluid models (Rebouillat and Liksonov 2010).

Two approaches exist for designing partially filled tanks. The first approach is based on the dynamic loads caused by external excitation of tanks and the second one is based on safety conditions suggested by the transportation standards of safety such as DIN and UIC. It is obvious that the loading conditions of the second approach are more critical.

Based on the first approach of designing partially filled tanks, some studies have been done on the simplified tanks. Sloshing damping in baffled rectangular tanks and pressure distributions have been investigated (Eswaran *et al*. 2009, Akyildiz and Unal 2006, Goudarzi *et al*. 2010, Biswal *et al*. 2006) and the effect of baffle shapes, excitation frequencies and volume of fluid on the sloshing has been studied numerically and experimentally. Besides, some researchers have studied the optimization problem of tanks. They have reduced the maximum pressure and the free surface deviation of liquid by modifying baffles position and tank dimensions (Craig and Kingsley 2007, Kim and Lee 2008).

In the second approach, the transformation standards suggest the most critical loading conditions (such as crash, instability) that may be experienced. In such conditions, vehicles and their attachments undergo the maximum loads. Thus, compared with the first approach, tanks are assumed to be elastic and can be modeled in details due to the convenience of analysis. Some projects have been done by PEBA engineering company and American Strategic Alliance for Steel Fuel Tanks (SASFT) on the vehicles tanks by the use of standard loading conditions.

In this paper, the fuel tank of a locomotive, under the DIN EN 12663 standard load conditions, has been analyzed considering sloshing phenomenon. In order to reduce the mass and manufacturing cost of the baffles, the fuel tank has been optimized using modified Niched-Pareto Genetic Algorithm and Neural Networks.

Table 1 Mechanical properties used in modeling of fuel tank

Material	Mechanical Property	Unit	Value
S355MC	Young's modulus	GPa	200
	Poisson's ratio	-	0.3
	Density	Kg/m^3	7800
	Yield Strength	MPa	355
	Ultimate Strength	MPa	470

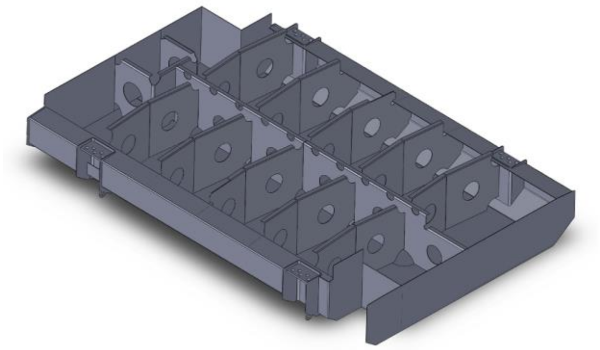

Fig. 1 Geometry of the primary design of tank and baffles installation positions

2. Tank modeling and FE analysis

The fuel tank of the locomotive ER 24 is considered as an analysis model. The length, width and height of the primary design are 4324 mm, 2850 mm and 626 mm, respectively, and it is made of steel plates (S355MC) with a thickness of 4mm. Table 1 shows the mechanical properties of the S355MC. Weight of the tank is 1410 Kg when it is empty and it can store up to 6550 liters of fuel. It has 5 transversal and 2 longitudinal baffles. Not only each of the baffles has some horizontal and vertical bents, but also consists of some semicircular and circular holes, so the geometry of baffles is more complicated than ones studied by others. Fig. 1 shows the geometry of the tank and baffles installation positions. Also the tank is fastened to the chassis of the locomotive with 20 bolts located on the 4 support plates so, in the modeling, it is logical to suppose that the upper faces of these support plates are fixed.

3. CFD modeling

In order to study the sloshing phenomena, it is assumed that the tank is filled with water up to a height of 500 mm and filled with air from 500 to the top. In order to mesh the fluid regions 2235147 tetrahedral elements are used. Due to the large number of elements in the fluid regions and to reduce the running time, the tank is assumed to be rigid.

To excite the fuel, it is assumed that the locomotive is moving at a certain speed opposite to the *z*-direction, and then suddenly stops with the constant breaking acceleration of 1.4 m/s^2. Fig. 2 shows the velocity vs. time plot of the locomotive ER 24 that is applied to the tank for modeling the sloshing.

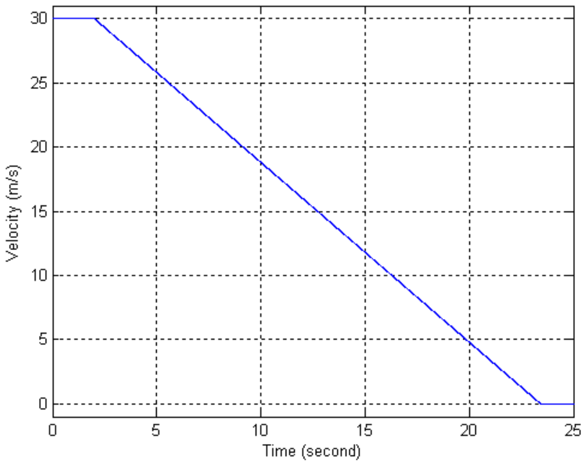

Fig. 2 Velocity vs. time plot of the locomotive ER 24

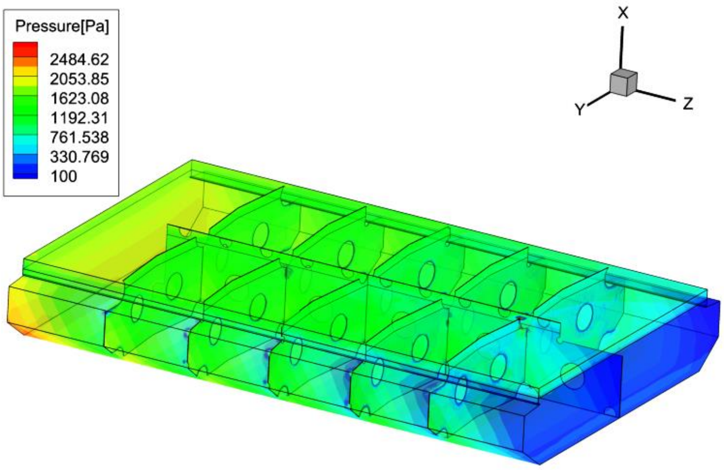

Fig. 3 Pressure distribution on the tank 4 seconds after the braking

The pressure distribution on the baffles and tank walls 4 seconds after the braking is shown in Fig. 3. It has been seen that the maximum pressure on the walls of the tank in the braking time was less than 5.5 KPa.

4. Structural modeling

As mentioned before, structural analysis of the tanks has been simplified by the suggested standard load conditions. For this purpose, in railway applications, the DIN EN 12663 standard, defines the minimum structural requirements for railway vehicle bodies. This European standard provides a uniform basis for the structural design of the vehicle body. The loading requirements for the vehicle body structural design are based on proven experience and the aim of this European

Table 2 Defined acceleration by DIN EN 12663 standard

Direction of acceleration	Static load cases	Fatigue load cases
Longitudinal (*z*)	$\pm 5\times g^{*}$	$\pm 0.2\times g$
Transversal (*y*)	$\pm 1\times g$	$\pm 0.2\times g$
Vertical (*x*)	$(1\pm 2)\times g$	$(1\pm 0.25)\times g$

*minimum ±3×g for locomotives

Table 3 Load conditions details

Load Condition	a_z	a_y	a_x	Safety Factor (SF)	Minimum Allowable SF
1 (static)	+3×g	0	-1×g	S_y/σ_{max}	1.15
2 (static)	0	+1×g	-1×g	S_y/σ_{max}	1.15
3 (static)	0	0	-3×g	S_y/σ_{max}	1.15
4 (static)	0	0	+1×g	S_y/σ_{max}	1.15
5 (fracture)	+5×g	0	-1×g	S_{ut}/σ_{max}	1.5
6 (fatigue)	±0.2×g	±0.2×g	(1±0.25)×g	---	Infinite Life

Table 4 Results of FEA

Load Condition	σ_e (MPa)	Safety Factor (SF)
1	104	3.41
2	73	4.86
3	67	5.30
4	30	11.83
5	170	2.76
6	37	>1 (infinite life)

Standard is to allow the designer to maintain requisite levels of safety (DIN EN 12663).

Using this approach, fluid does not enter in the tank design calculations and its effects on the tank are considered as some static loads. Now, only the walls and baffles will be meshed with tetrahedral elements. According to DIN EN 12663, in order to calculate the forces on the fastenings during the vehicle operation, the masses of the components must be multiplied by the specified accelerations presented in Table 2 (DIN EN 12663).

Here, g=9.81 m/s^2 is the gravity acceleration and its effect must be considered in each six load cases listed in Table 3, where S_y and S_{ut} are yield strength and ultimate strength, respectively. In this table, the minimum allowable safety factors that have been defined by DIN EN 12663 are presented.

Moreover, it is assumed that the tank is fully filled with the fuel, because in such conditions, the greatest force values will be generated. Besides hydrostatic pressure, two other kinds of forces are applied to fixed supports and baffles i.e., the forces caused by solid and fluid. To calculate these forces, the mass of the solids (the tank components) and fuel must be multiplied by the suggested accelerations. Then, in each part of the tank that is surrounded by baffles, the resultant force should be inserted as a uniform pressure on the surface of walls and baffles. Now FE analysis can be done. Table 4 shows the maximum Von-Mises equivalent stress (σ_e) in the components of the tank resulted from FEA.

Table 5 Range of the optimization variables

variable	Unit	Primary Value	Min. of Variable	Max. of Variable
x_1	mm	4	2	5
x_2	degree	5	0	10
x_3	mm	100	0	100
x_4	-	5	3	5

It is seen that even under the critical loads (load condition 5), the minimum safety factor is larger than the values suggested by DIN EN 12663. So, the primary design of the tank can be improved in order to reduce the mass and manufacturing cost. Also, by comparing the CFD and structural analysis results, it is seemed that the load conditions of the structural analysis create lager stresses. Thus, in the processes of design and optimization of the tank, this load condition must be taken into account.

5. Optimization variables and objectives

Like most researches that have been done in the field of partially filled tanks and in order to reduce the computations, in this survey, the geometry parameters of baffles are taken as optimization variables. These variables include the thickness (x_1), angle of bent (x_2), radius of circular holes (x_3) and number of the transversal baffles (x_4). The weight of the variable parts of the tank (baffles) is calculated as 333 Kg (%24 of the total weight). Table 5 lists the variable values in the primary design and the range of the variable values in the optimization process.

Reduction of the mass and manufacturing cost have been considered as the optimization objectives. The manufacturing cost has been defined as a function of the cost of welding, cutting and bending in the processes of manufacturing the baffles. The manufacturing cost is expressed as

$$f_2(\vec{X}) = \left(\frac{x_4}{5} + 0.1 \times \frac{x_2}{10}\right) + \left(\frac{x_4}{5} \times \frac{x_1}{5} \times \frac{x_3}{100}\right) + \left(\frac{x_4}{5} \times \frac{x_1}{5} \times \frac{x_2}{10}\right) \tag{1}$$

where the three terms in the right hand side of Eq. (1) are the cost of welding, cutting and bending processes, respectively. In order to normalize, these terms have been divided by their maximum values.

5.1 Neural networks

Acknowledging the discouraging computational cost associated with Optimization methods, especially using population-based optimization scheme like Genetic Algorithms wherein function/constraint evaluations are required in the order of up to several thousands, a simulation-assisted approach was employed in the problem. This approach combines the speed and low computational cost of a neural approximator with the versatility of a multi-objective evolutionary search algorithm to come up with multiple non-dominated solution schemes. Overall, this method expedites the Design/Optimization process; thus makes it applicable to the complicated engineering problems such as design and optimization of mechanical components with complex geometries and intricate loading conditions.

Generally, simulation-assisted methods such as Artificial Neural Networks (*ANNs*), are of great use in solving practical optimization problems such as *FE* problems (Hornik *et al*. 1989, Jin *et al*. 2002). Neural Networks are powerful function approximators capable of capturing and representing complex input/output relationships. As reported by many researchers (Ray *et al*. 1996, Liew *et al*. 2002), the integration of Design/Optimization problems with neural networks suggests substantially low computational cost while maintaining acceptable levels of accuracy. In other words, instead of applying *FEM* in every iteration of the process, *NN*s could be employed to predict the component's performance.

In this study, two Multi-Layer Perceptron (MLP) networks were used to approximate mass and maximum Von-Mises equivalent stress that later will be used in the optimization process. In each case, the input vector consists of 4 parameters that are the geometric properties of the baffles. Each network has one hidden layer with 6 neurons and a single neuron in its output layer. The networks were trained using 44 data sets generated using a normally distributed set of input vectors across the design space. Also the networks were trained using the Bayesian algorithm (train *BR*) and %15 of data sets were used for testing and %10 for validating the results. The training resulted in the sum of squares of errors less than %1, implying a fairly accurate approximation of the objectives and constraints.

These networks are then used to approximate the properties of other tanks with different shapes that would be produced during the optimization process.

5.2 Multi-Objective Optimization

The two distinct objectives of the problem were to minimize the mass and manufacturing cost. The first objective, tank's mass and maximum Von-Mises equivalent stress (constraint), approximated by the neural networks and the second objective could be easily evaluated by the Eq. (1). Thus, the multi-objective optimization problem could be stated as:

Minimize (*Mass, Manufacturing Cost*)

Subject to: Max (Von-Mises Stress) ≤ Allowable Stress (2)

Due to multiple, often conflicting requirements in the design of mechanical components, the traditional practice of seeking a single, globally optimum solution is no longer justifiable and the use of a search strategy capable of finding Pareto-optimal solutions becomes inevitable. Multi-Objective Optimization (*MOO*) gives the designer the opportunity to evaluate a set of viable solutions that satisfy more than one performance criterion, but to different extents. The definitions of these solutions rely on the notions of *Pareto Dominance* and *Pareto Optimality*. A design vector ***b**** is Pareto optimal if no feasible vector ***b*** exists, which would decrease some criteria without causing a simultaneous increase in at least one other criterion. The vector ***b**** corresponding to the solutions included in the Pareto optimal set is called non-dominated. Essentially, defining the generic *efficiency* index as $OF_1(\vec{b})$, a typical minimization-based *MOO* problem is defined as

$$min\{OF_1(\vec{b}), OF_2(\vec{b}), \dots, OF_M(\vec{b})\} \tag{3}$$

Consider two candidate solutions $\{\vec{b}_j, \vec{b}_k\} \in \Omega_{\vec{b}}$, if for any two objective vectors

$$v(\vec{b}_j) = \{OF_1(\vec{b}_j), \dots, OF_M(\vec{b}_j)\}$$
$$v(\vec{b}_k) = \{OF_1(\vec{b}_k), \dots, OF_M(\vec{b}_k)\} \tag{4}$$

The following condition holds

$$\forall i \in \{1,2,\dots,M\}: OF_i(\vec{b}_j) \le OF_i(\vec{b}_k) \ \& \ \exists i \in \{1,2,\dots,M\}: OF_i(\vec{b}_j) < OF_i(\vec{b}_k) \quad (5)$$

Then vector $v(\vec{b}_j)$ is said to dominate vector $v(\vec{b}_k)$. Moreover, if no feasible solution $v(\vec{b}_k)$ exists that dominates solution $v(\vec{b}_j)$, $v(\vec{b}_j)$ is classified as a non-dominated or Pareto optimal solution. More simply, $\vec{b}_j \in \Omega_{\vec{b}}$ is a Pareto optimal solution if a feasible vector $\vec{b}_k \in \Omega_{\vec{b}}$ does not exist which would decrease some criteria without causing a simultaneous increase in at least one other criterion (Coello 1999).

The implementation of the Pareto-based optimal design of components requires an efficient *MOO* tool. Several such tools have been developed over the past two decades, including Srinivas and Deb's (1994) Non-dominated Sorting Genetic Algorithm, *NSGA*, Knowles and Corne's (1999) Pareto Archived Evolution Strategy, *PAES*, Horn *et al*'s (1994) Niched–Pareto Genetic Algorithm and *NPGA*. The optimization algorithm used in this study is the modified *NSGA*, namely *NSGA-II* due to its flexibility and its adaptability to nearly all engineering problems. It is a powerful tool to efficiently search the design domain and is also capable of dealing with nearly all types of explicit and implicit constraints.

The *NSGA-II* algorithm used a population of 100 chromosomes along with an adaptive parameter setting strategy in which mutation and crossover rates changed according to the improvement rate of the average population fitness in five consecutive generations. Mutation and crossover rates were allowed to change within the spans of [0.02-0.15] and [0.8-0.95], respectively. The search was terminated when the change in the sum of normalized objective values from two consecutive generations fell below 0.005. The average results from 5 typical runs are presented in the following section.

6. Results and discussion

The Pareto set of solutions is presented in Fig. 4 and the details of the selected point and the primary design are presented in Table 6. However, due to some practical limitations in welding of plates with a thickness less than 3 mm, finally, the red point shown in Fig. 4 is selected as the optimal solution. In the Table 6, the details of the primary design have been listed again.

Focusing on the distribution of non-dominated solutions in Fig. 4, it can be observed that

Table 6 Comparison of primary and optimal design

Property	Primary Design	Optimal Design
x_1	4	3.18
x_2	5	0
x_3	100	0
x_4	5	3
Mass (Kg)	1409.25	1278.5
Manufacturing Cost	2.25	0.6
Max. Von-Mises stress (MPa)	170	291
Safety Factor	2.76	1.56

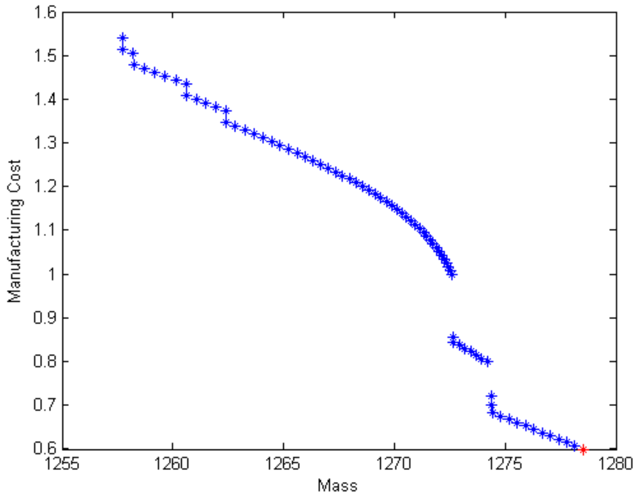

Fig. 4 Pareto front obtained by application of the proposed multi-objective optimization approach

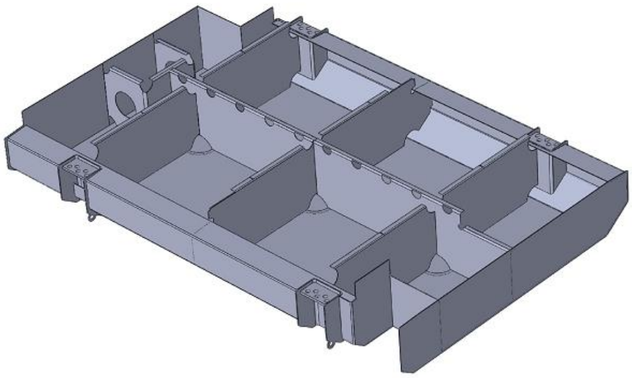

Fig. 5 The geometry of the optimal design of tank and baffles installation positions

Table 7 Comparison of the *FEA* results and the predictions of the neural networks

Property	Prediction of Network	FEA Answer	Error (%)
Mass (Kg)	1278.5	1279.25	0.06
Max. Von-Mises stress (MPa)	291	280	3.78

compared to the original design, the two endpoints along the axes represent %10.7 reduction in the total mass (%45.3 reduction in the variable mass) and %73.3 reduction in the manufacturing cost. Also, the optimal design reduces the total mass by %9.28 (%39.3 reduction in the variable mass). The schematics of the optimal tank design and the baffles installation positions are shown in Fig. 5.

In order to verify the mass and maximum Von-Mises equivalent stress approximated by the neural networks, the optimal tank under the presented load conditions in Table 3 is analyzed by the *FEA* and the results are listed in the Table 7. It can be seen that the neural networks have been trained well and the obtained solution is reliable.

7. Conclusions

The behavior of the fuel tank of the locomotive ER 24 has been investigated under the sloshing phenomena by using the velocity vs. time plot. Also, the tank has been analysed under the standard load conditions of DIN EN 12663. Comparison of the pressure distributions obtained in the *CFD* and structural modeling shows that the structural modeling creates larger stresses in the tank walls.

Then, the fuel tank has been optimized in order to reduce the mass and manufacturing cost. Using the *NSGA-II* algorithm and *ANNs*, the modification of the baffles layout has been done. It has been shown that in the optimized tank compared with the primary design, mass has been reduced by %39 and manufacturing cost has reduced by %73, considering the proposed cost function (Eq. (1)).

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