3D solid modelling and optimal design of a particular toroidal LPG storage tank

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Abstract. Current work presents an approach in CAD modeling of a particular toroidal LPG fuel tank with variable square cross-section used in automotive industry, followed by a state of stress and linear deformation analysis. The CAD modeling can be used for a better understanding of design requirements of toroidal LPG fuel tanks and improving designs.

1. Introduction

Parametric modeling technologies of the fuel storage tanks in automotive industry are an important topic which has been explored over the last few decades [1-6].

3D CAD solid models can be used as virtual prototypes to increase product competitiveness and safety in exploitation through innovative ideas in product design, testing, and quality process [7-11].

Storage fuel tanks used in automotive industry contain technologically advanced components that involve exacting requirements and manufacturing and their design takes into account the supershapes design variables, specific structural parameters, precise geometrical conditions of linkage structural parameters, computer tools, numerical computational algorithms and methods, visualization techniques, generative design and verification conditions [12-17].

2. Design methodology

Let’s consider the surface generated by revolving of a closed generating curve \(C_G\) along a guiding curve \(C_{D1}\), square form with connected round corners, being tangent in the movement on a second internal curve \(C_{D2}\), as shown in figures 1 and 2.

![Figure 1. The parametric 3D solid model.](image)
Figure 2. The axonometric representation of the geometric 3D solid model.

The offset between the curve $C_{D1}$ and the curve $C_{D2}$ determines the dimensional variation of the square cross-section by continuously modifying of the square's side with this value. The plane of the generating curve $C_G$ is orthogonal to the plane of the coplanar reference curves $C_{D1}$ and $C_{D2}$ (circles).

These toroidal solids have two symmetry planes: one horizontal and one vertical, as shown in figure 3. The existence of the symmetry planes gives the advantage of product manufacturing using two parts and their subsequent assembly by welding.

Figure 3. The symmetry planes of the 3D toroidal solid: a) the horizontal plane; a) the vertical plane.

The following parameters were applied as input parameters to the 3D parametric model (figure 1): a) a square generating curve with a value $L = 110, \ldots, 210$ mm, rounded to corners with $R = 30$ mm, and b) the guiding curves: the curve $C_{D1}$ and the curve $C_{D2}$, circles with the following diameters: $\phi_{C_{D1}} = 300$ mm and $\phi_{C_{D2}} = 140$ mm. The eccentricity between the curve $C_{D1}$ and the curve $C_{D2}$ has the value of $e = 25$ mm. Different isometric views of the parametric 3D model are shown in figure 4.

Figure 4. Different isometric views of the parametric 3D solid model.
Optimized CAD design of these fuel storage tanks was imported to SolidWorks 2018 software for analysis with the: Static, Thermal and Design Study modules.

The parameterized model used in the numerical simulation is shown in figure 3a, and the notations are specified in figure 3b which specify the surfaces where are applied the loads and restrictions.

The design data used are:
- the lateral cover has a diameter of $D = 250$ mm and length $L = 700$ mm;
- the tank material is AISI 4340 steel;
- the maximum hydraulic test pressure: $p_{\text{max}} = 30$ bar, applied on surface $S_1$;
- the working temperature between the limits: $t = -30$ °C up to $t = 60$ °C;
- the duration of the tank exploitation: $n_a = 15$ years;
- the fastening to the supporting surface $S_3$;
- the corrosion rate of the material: $v_c = 0.07$ mm/years.

The applied optimization function is intended to achieve a minimum mass.

The calculation had the following parameterized: - Mesh: mesh standard type, solid mesh with high quality, automatic transition, Jacobian in 29 points, element size 15 mm, tolerance 0.75 mm, degrees of freedom 437622; number of nodes 147948, number of elements 82637.

The applied restriction of constraint is that the value of Von Mises effort $\sigma_{\text{rez}} \leq \sigma_a = 710$ N/mm$^2$ ($\sigma_a$ - the admissible value of the traction stress of the material). Applying the optimization procedure, the obtained values are: the thickness $s = 7.7$ mm for $t = -30$ °C with the stress value of the $\sigma_{\text{rez, max}} = 706.35$ N/mm$^2$ and linear deformation value $u_{\text{max}} = 2.389$ mm.

Distributions of the state of stress and of linear deformations are shown in figs. 5 and 6.

As we can see the highest values of efforts in the 3D model appear in the inner connection zones: A, B and E, at the upper part C and at the connections of the supporting legs with the cover in zones: D and F. But the most important values of efforts appear is zone A (figure 4).

The resultant linear deformation state is maximum in zone C due to the fact that in the lower part F this deformation is limited by the presence of the tank support legs at $u_{\text{max}} = 0.756$ mm (figure 6).

![Figure 5. Distributions of the state of stress of the parametric 3D model.](image-url)
The formula for calculating the thickness is the following:

\[ s_{\text{real}} = s_{\text{opt}} + v_c \cdot n_a + \text{abs}(A_i) + \Delta s_a, \tag{1} \]

where:
- \( v_c \), corrosion rate of the cover, \( v_c = 0.07 \) mm/year;
- \( n_a \), number of years of exploitation, \( n_a = 15 \) years;
- \( A_i \), the lower deviation of the laminate sheet, \( A_i = -0.6 \) mm, for \( s = 3...5 \) mm;
- \( \Delta s_a = 0.1 \) s = 0.5 mm, thinning of the sheet caused by the head cover embossing.

Finally, the minimum thickness of the sheet laminate is determined as:

\[ s_{\text{real min}} = 7.7 + 0.07 \cdot 15 + \text{abs}(-0.6) + 0.1 \cdot 7.7 = 10.12 \text{ mm}. \tag{2} \]

A laminate sheet of AISI 4340 steel with a thickness of \( s = 10.5 +0.25 -0.6 \) mm is chosen for analysis. The numerical simulation was made for \( n_a = 15 \) years which corresponds to the end of exploitation time when the cover thickness is minimal \( s = 8 \) mm.

The variation of stress and of linear deformations with temperature is shown in table 1.

| \( t \), °C | -30 | -20 | -10 | 0 | 10 | 20 | 30 | 40 | 50 | 60 |
|------------|-----|-----|-----|---|----|----|----|----|----|----|
| \( \sigma \), N/mm² | 639.4 | 644.5 | 654.2 | 663.1 | 661.4 | 650.5 | 638.4 | 635.9 | 648.9 | 664.5 |
| \( u \), mm | 2.109 | 2.087 | 2.114 | 2.119 | 2.137 | 2.158 | 2.161 | 2.183 | 2.186 | 2.192 |

The graph and law of variation as a function of temperature are given for: a) the Von Mises stress variation (figure 7a) and b) the resulting linear deformations (figure 7b).

Distributions of the state of stress and of linear deformations for different temperatures: a1 & b1) \( t = -30 \) °C, a2 & b2) \( t = 0 \) °C, a3 & b3) \( t = 30 \) °C and a4 & b4) \( t = 60 \) °C) are shown in figure 8.
Figure 8. Distributions of the state of stress and of the linear deformations for different temperatures: (a1 & b1) $t = -30^\circ$C, (a2 & b2) $t = 0^\circ$C, (a3 & b3) $t = 30^\circ$C and (a4 & b4) $t = 60^\circ$C.

3. Conclusions
The proposed parametric modeling technologies of the toroidal LPG fuel tanks in automotive industry CAD allows the determination of optimal geometric dimensions that satisfy the requirements imposed by optimization functions. The confidence level of using this toroidal LPG fuel tank in commercial market could be improved by subjecting this product to suitable tests based on automotive safety norms.
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