**ISSN 1453 – 7303** **"HIDRAULICA" (No. 2/2018)**
**Magazine *of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics***

# Algorithm for Optimal Design of Pressurized Toroidal LPG Fuel Tanks with Constant Section Described by Imposed Algebraic Plane Curves

Assoc. Prof. PhD. Eng. **Ștefan ŢĂLU**[1], Assoc. Prof. PhD. Eng. **Mihai ŢĂLU**[2,*]

[1]Technical University of Cluj-Napoca, The Directorate of Research, Development and Innovation Management (DMCDI), Constantin Daicoviciu Street, no. 15, Cluj-Napoca, 400020, Cluj county, Romania. E-mail: stefan_ta@yahoo.com

[2] University of Craiova, Faculty of Mechanics, Department of Applied Mechanics and Civil Engineering, Calea București Street, no. 107, 200512 Craiova, Dolj county, Romania. Corresponding author* e-mail: mihai_talu@yahoo.com

***Abstract:*** *The purpose of this study is to provide a tested, validated, and documented algorithm for optimal design of pressurized toroidal LPG fuel tanks with constant section described by imposed algebraic plane curves. Computer aided investigations are carried out using three-dimensional models and can offer high benefits for the design of toroidal LPG fuel tanks used in automotive industry.*

***Keywords:*** *Automotive industry, algorithm, industrial engineering design, optimization methods, pressurized toroidal LPG fuel tank*

## 1. Introduction

During the past few decades the global auto industry has experienced some major structural changes in research and development, macro-economic structural conditions, global production networks, global climate change and global financial crisis [1-7].

The storage fuel tanks used in the automotive industry are made from aluminum alloys or various types of steel for safely storing fuel: compressed natural gas (CNG) or liquefied petroleum gas (LPG) [8-14].

The computer-aided design, construction, installation, testing and monitoring requirements of the storage fuel tanks are bounded and regulated by a comprehensive list of requirements documented in various codes and national and international standards [15-19].

The multi-objective optimization techniques of the fuel tanks are based on effective strategies and flexible tools of integrated design processes and efficient data management for decision based multidisciplinary design [1, 15-19].

Computer-aided design (both standardized and modular) of the fuel tanks involves a deeper insight of geometrical elements considering the supershapes design variables [20, 21], specific structural parameters [8-14], geometrical conditions [15], design constraints [2-7], computer tools [22-27], numerical computational methods [28-30], visualization techniques [31-37], and measurement methods [38, 39].

In order to improve the construction requirements, performance tests, comfort, safety and vehicle durability the pressurized toroidal LPG fuel tanks are located in different vehicle places especially designed by the vehicle's manufacturer (as shown in fig. 1).

**Fig. 1.** Different locations of the pressurized toroidal LPG fuel tanks

In this research, a simple and efficient algorithm for optimal design of pressurized toroidal LPG fuel tanks with constant section described by imposed algebraic plane curves is proposed.

## 2. Design methodology

In our study, an optimization algorithm of the pressurized toroidal LPG fuel tank model that can reduce final product mass, while improving storage efficiencies is proposed.
The algorithm has two parts:
A) in the first part is proposed a class of toroidal surfaces with cross-section optimized in terms of shape (without knowing their thickness);
B) in the second part is determined the optimized dimensions of the toroidal cover resulting from the mechanical resistance conditions according to the combinations of stresses encountered in exploitation or mechanical requirements imposed by homologation tests.

### 2.1 The generation of the optimized class of geometric shapes for the cross-section

The steps in this stage are as follows:
**A1**. The determination of the maximum dimensions of the cylinder (in which the tor is inserted), based on design constraints allocated to the fuel tank on the vehicle. It is determined: the radius R and the height H of the cylinder (as shown in fig. 2).

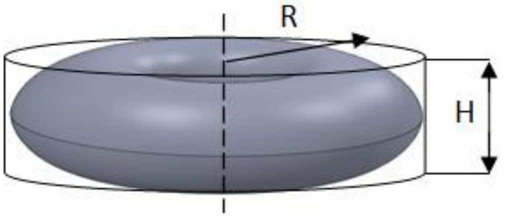
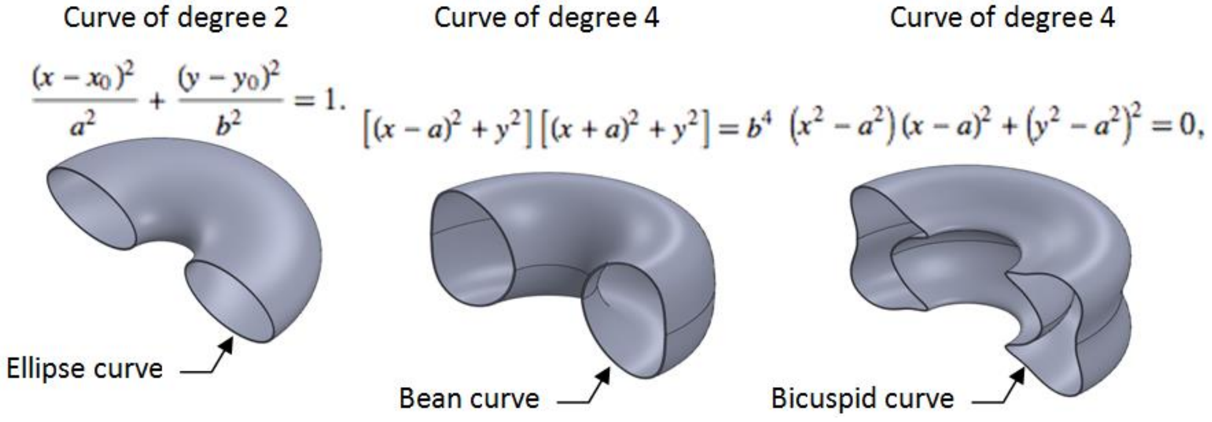


**Fig. 2.** The geometrical model of cylinder in which the tor is inserted

**A2**. The specification of the required algebraic plane curve and the mathematical equations used to generate the cross-section, and in the cases of families of curves one of the particular forms is indicated.
As an example for a series of polynomial algebraic curves closed by degrees: 2, 4, 5, 6, 8 and 12, the parametric spatial modeling of the toroidal surface is shown together with the corresponding mathematical equation used to generate the cross-section (as shown in fig. 3).



a) b) c)

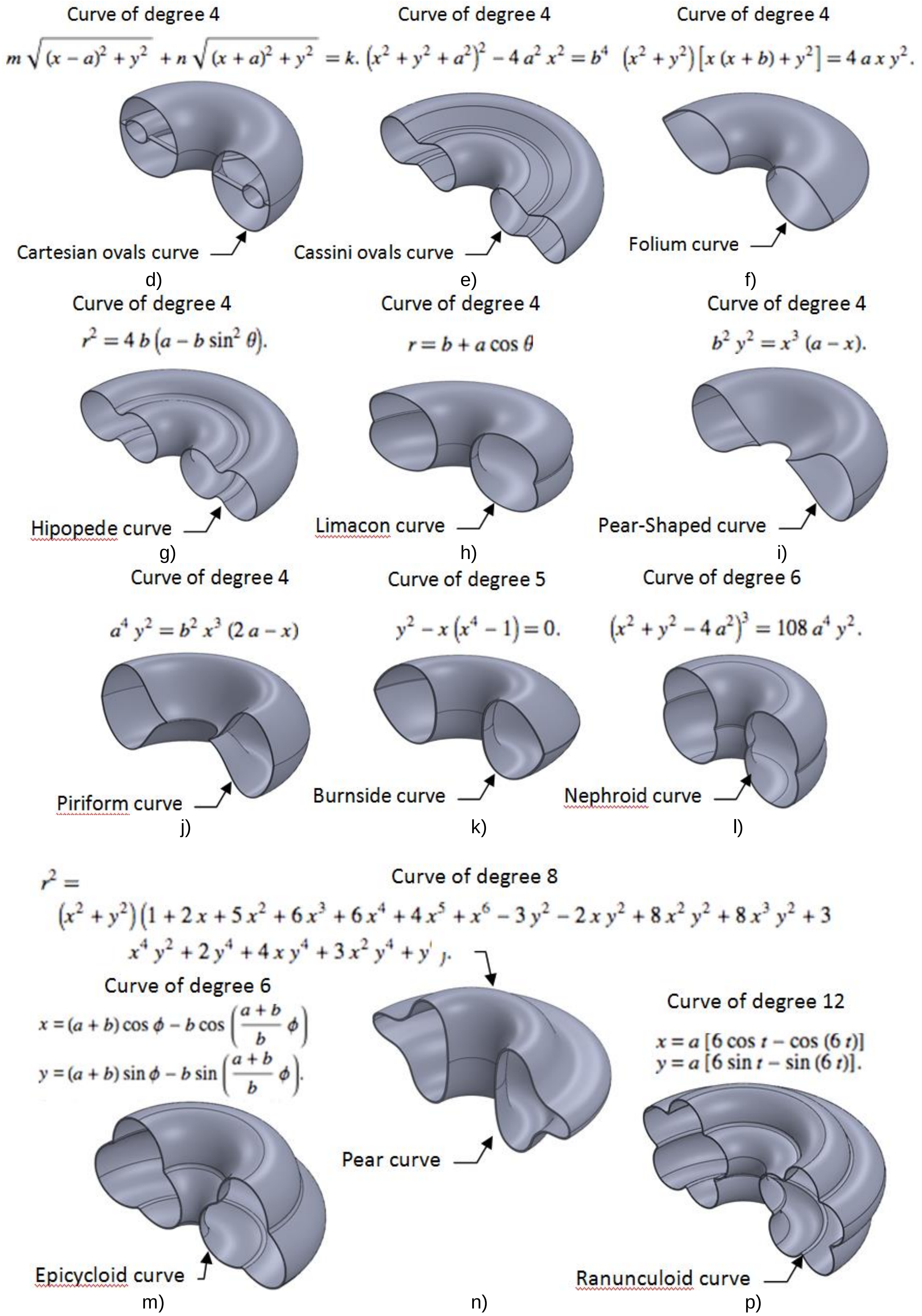


**Fig. 3.** Generation of the toroidal surface from a series of polynomial algebraic curves closed by degrees: 2, 4, 5, 6, 8 and 12

**A3**. The determination of: a) the cross-sectional symmetry axis of the toroidal surface; b) the maximum rectangular field in which the apparatus is mounted; c) the maximum rectangular range in which the closed mathematical curve describe the cross-section.
It is determined: a) the maximum dimensions of the $D_{i\ max}$ range occupied by the inner cylinder ($R_i$ and $H_{i\ max}$); b) the maximum dimensions of the $D_{e\ max}$ outer range, characterized by the external radius $R_e$ and the height $H_{e\ max}$, in which the cross-section of the torus must be enclosed, described by the mathematical equation of the imposed algebraic curve (as shown in fig. 4).

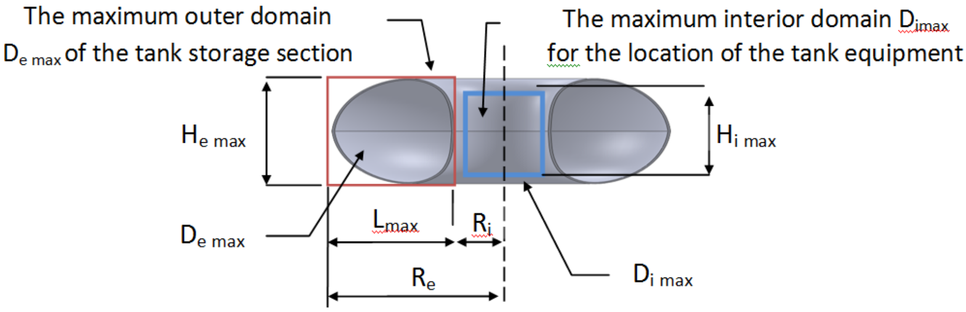


**Fig. 4.** The geometrical model of toroidal surface with the maximum dimensions of the $D_{i\ max}$ and $D_{e\ max}$

**A4**. The setting of a range of angular values of the section orientation generated by the mathematical curve, relative to the rectangular outer domain, $D_{e\ max}$. As a result, by rotation of the cross-section around the center of mass with the angular values: $\varphi_1$, $\varphi_2$, .., $\varphi_k$, which may be arbitrarily chosen, there are obtained a series of constructive variants of the toroidal surface, based on the same mathematical equation which describes the cross-section (as shown in fig. 5).

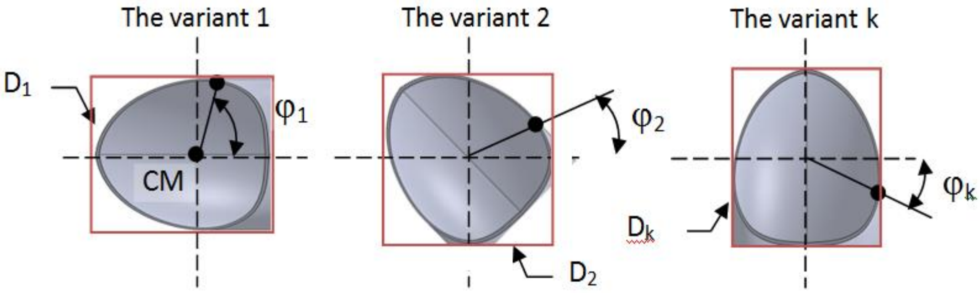


**Fig. 5.** Constructive variants of the section with the angular values: $\varphi_1$, $\varphi_2$, .., $\varphi_k$, arbitrarily chosen

**A5**. The determination of the new size dimensions: $H_k$, $L_k$, of the section rotated with the angle $\varphi_k$ (as shown in fig. 6).

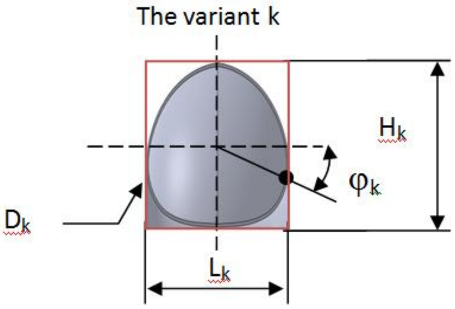


**Fig. 6.** Constructive variant of the section with the angular value $\varphi_k$

**A6**. The determination of the optimal dimensions of the geometric section rotated with the $\varphi_k$ angle (obtained from the condition of a maximum enclosed area in the curve by a centroid scaling so that the curve is included in the rectangular domain $D_{e\ max}$) checking the conditions:

$$L_{k\ scaled} = L_{max} \text{ and /or } H_{k\ scaled} = H_{max}. \qquad (1)$$

It is obtained the mathematical equation describing the curve that shapes the cross-section of the toroidal surface which has a maximum volume for a required angle $\varphi_k$.

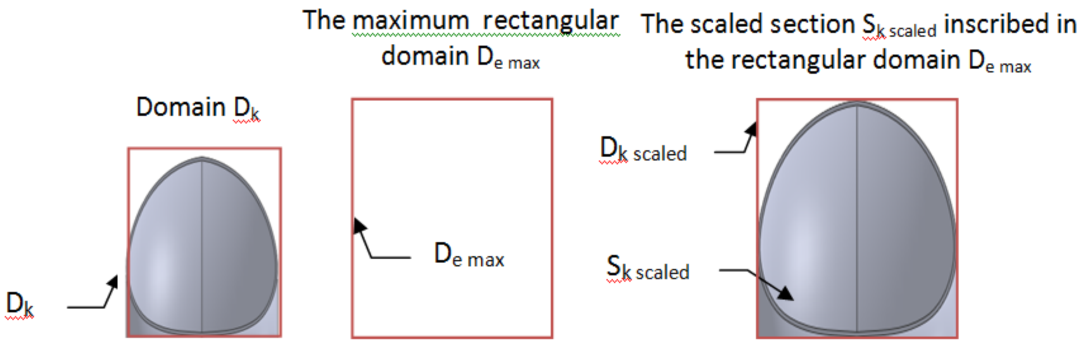


**Fig. 7.** Constructive variant of the optimal section with the angular value $\varphi_k$

It is noted that the curve may be simultaneously or not tangent to all sides of the rectangular domain $D_{e\ max}$, but it has the maximum area inscribed in this rectangle.

In practice, there are also situations in which the families of curves have several parameters: a, b, c, .., as in the equations of the Cassini ovals, where the values of the parameters: a, b, c, ... are determined so that the curve which results to have a maximum area inscribed in the rectangle of the outer domain $D_{max}$ (as shown in fig. 8).

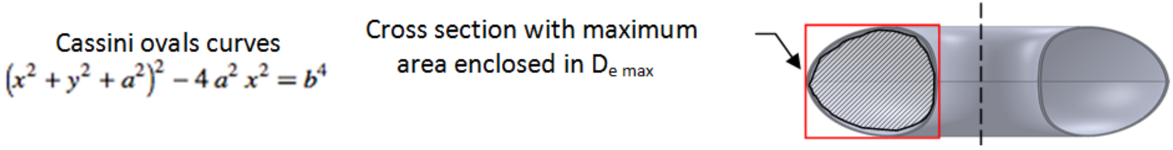
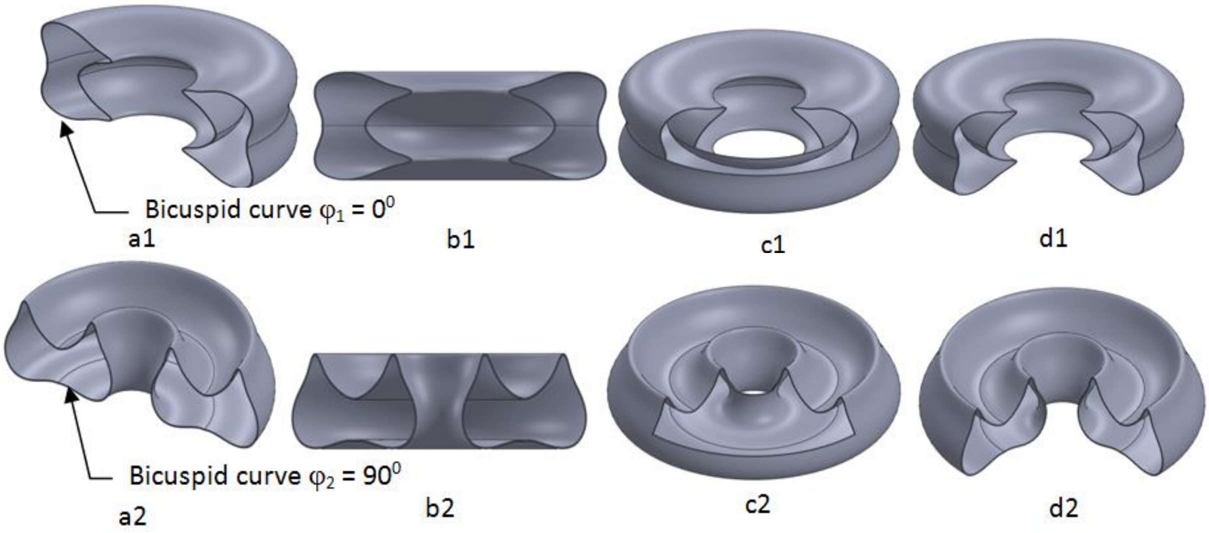


**Fig. 8.** Constructive variant of the optimal section with the angular value $\varphi_k$ considering Cassini ovals curves

**A7**. The generation of a family of toroidal surfaces with cross-sections described by closed algebraic curves obtained with the same type of mathematical equations.

In fig. 9, is shown the generation of a toroidal surface family based on the Bicuspid algebraic curve for the following angles of rotation: $\varphi_1 = 0^0$, $\varphi_2 = 90^0$, $\varphi_3 = 135^0$ and $\varphi_4 = 180^0$.

For each angle of rotation, graphical representations were made on the parameterized model as follows: half section in axonometric view (fig. 9a1 to 9a4); half section in front view (fig. 9b1 to 9b4); $^1/_8$ superior section in axonometric view (fig. 9c1 to 9c4); and three-quarter section in axonometric view (fig. 9d1 to 9d4).



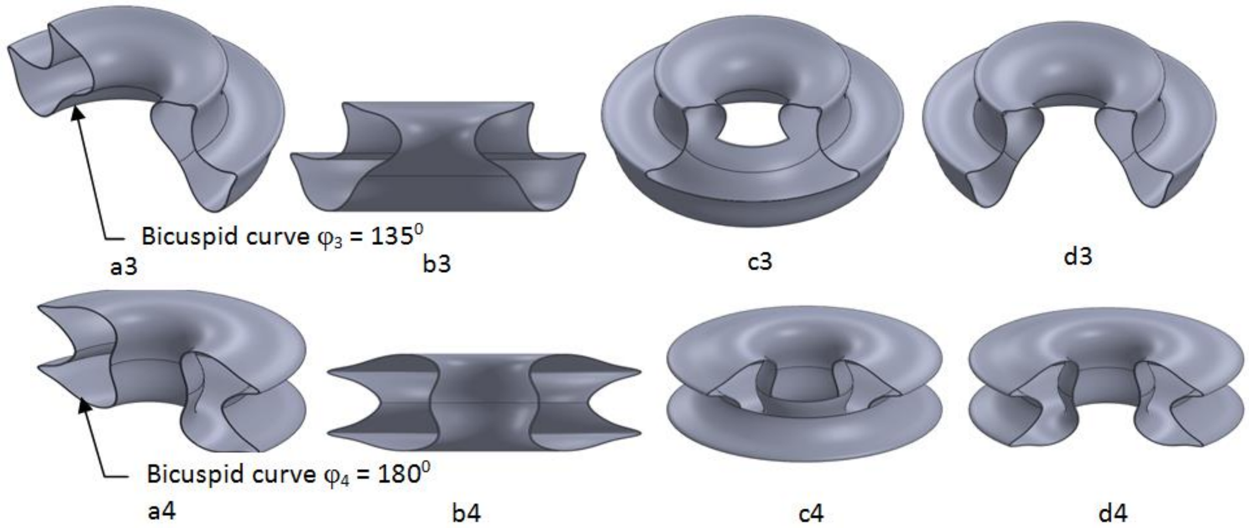


**Fig. 9.** The generation of a toroidal surface family based on the Bicuspid algebraic curve (for the following angles of rotation: $\varphi_1 = 0^0$, $\varphi_2 = 90^0$, $\varphi_3 = 135^0$ and $\varphi_4 = 180^0$) in different graphical representations

**A8**. The selection form of the generated family of toroidal surfaces from the variants whose section shows the maximum enclosed area in the curve.

## 2.2 The determination of the optimized dimensions of the toroidal cover

The steps in this stage are as follows:
**B1**. The calculation of the toroidal cover optimized dimensions from the condition of resistance to simple or combined mechanical stresses, based on the following design process:
- The initial design data are: the maximum static hydraulic pressure; the working temperature between the limits $T_{min}$ to $T_{max}$; the exploitation time of tank; the corrosion velocity of material.
- The toroidal surface is parametrically computed according § 2.1 subchapter.
- To reduce the computational time, the 3D parametric model is chosen based on the constructive symmetry of the toroidal surface (½, ¼ or $^1/_8$ of the initial model), taking into account some constructive features of the fuel tank which are related to the fixation elements, piping, filling or drain connections, etc.
- The selection of the execution material for all the tank elements.
- The loads are applied to the parameterized model structure such as: tank's own weight, fuel weight, inertia forces (resulting from the acceleration or deceleration processes of the vehicle), force given by compression or decompression of the fuel, the temperature variation of the environment or fuel, unequal pressure distributions exerted on the interior walls of the tank as a result of the flowing or emptying process, symmetrical loading/unloading cycles used for fatigue calculation, the equipment and devices weight supported by the tank, impact forces at crash tests or ballistic tests, non-linear variation laws of temperature for the fire resistance test, increasing variation laws of burst test pressures, laws for periodic or random vibration generation sources, concentration forces and moments, mass distributions, various tank forces on the surface structure of multilayer membranes, etc.
- The geometrical constraints are specified accordingly and it is generated the 3D mesh that approximates the geometric domain of the 3D model.
- For structure optimal dimensioning, the following variables are computed: element thicknesses, connection rays, linear and angular dimensions (considered as discrete, within a specified range or continuous values).
- The structure constraints are considered as: a) constraints of geometrical parameters and mechanical properties resulting from the simulation calculation such as stresses, linear or angular displacements, vibration frequencies, temperatures, safety factors, etc., relative to the admissible values; b) constraints of mass properties related to: volume, mass, area, coordinates of the mass center, etc.; c) dimensional constraints; d) economic constraints as: materials costs, total cost of manufacturing. All these computed constraints may be smaller or equal than a specified value or into prescribed limits.

- The objective optimization function is written and the aim is to find a solution which optimizes the objective function value subject. There are generated various computational scenarios that combine multiple solicitation variants and after determination of the optimal values is chosen the fuel tank geometry.

**B2**. The choice of the technological variant based on the low-cost option.

## 3. Conclusions

In this study, a simple and efficient algorithm for optimal design of pressurized toroidal LPG fuel tanks with constant section described by imposed algebraic plane curves was proposed.

The high benefits of using this algorithm are: facilitating and simplifying the design process; reducing time to create optimal structures and reducing risk, offering predictable performance and improving reliability of the data.

This algorithm can also be extended for the generation of cross-sectional toroidal surfaces described by other types of closed non-linear plane curves that would be considered as design objectives in the future studies.

**Conflict of Interest:** The authors declare that they have no conflict of interest.

## References

[1] Hirz, Mario, Wilhelm Dietrich, Anton Gfrerrer and Johan Lang, *Integrated Computer-Aided Design in Automotive Development*, Springer-Verlag Berlin Heidelberg, 2013. DOI: 10.1007/978-3-642-11940-8.

[2] Ghiţă, C. Mirela, Anton C. Micu, Mihai Ţălu and Ştefan Ţălu. "3D modelling of a gas tank with reversed end up covers for automotive industry.", *Annals of Faculty of Engineering Hunedoara - International Journal of Engineering, Hunedoara*, *Romania*, Tome XI, Fascicule 3 (2013): 195-200.

[3] Ghiţă, C. Mirela, Anton C. Micu, Mihai Ţălu, Ştefan Ţălu and Ema I. Adam. "Computer-Aided Design of a classical cylinder gas tank for the automotive industry." *Annals of Faculty of Engineering Hunedoara - International Journal of Engineering, Hunedoara*, *Romania*, Tome XI, Fascicule 4 (2013): 59-64.

[4] Ghiţă, C. Mirela, Anton C. Micu, Mihai Ţălu and Ştefan Ţălu. "3D modelling of a shrink fitted concave ended cylindrical tank for automotive industry." *Acta Technica Corviniensis – Bulletin of Engineering, Hunedoara, Romania*, Tome VI, Fascicule 4 (2013): 87-92.

[5] Ghiţă, C. Mirela, Anton C. Micu, Mihai Ţălu and Ştefan Ţălu. "Shape optimization of vehicle's methane gas tank." *Annals of Faculty of Engineering Hunedoara - International Journal of Engineering, Hunedoara, Romania*, Tome X, Fascicule 3 (2012): 259-266.

[6] Ghiţă, C. Mirela, Anton C. Micu, Mihai Ţălu and Ştefan Ţălu. "Shape optimization of a thoroidal methane gas tank for automotive industry." *Annals of Faculty of Engineering Hunedoara - International Journal of Engineering, Hunedoara, Romania*, Tome X, Fascicule 3 (2012): 295-297.

[7] Ghiţă, C. Mirela, Ştefan C. Ghiță, Ştefan Ţălu and Simona Rotaru, "Optimal design of cylindrical rings used for the shrinkage of vehicle tanks for compressed natural gas." *Annals of Faculty of Engineering Hunedoara - International Journal of Engineering, Hunedoara*, Tome XII, Fascicule 3 (2014): 243-250.

[8] Bică, Marin, Mihai Ţălu and Ştefan Ţălu. "Optimal shapes of the cylindrical pressurized fuel tanks." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics (HIDRAULICA)*, no. 4 (December 2017): 6-17.

[9] Ţălu, Ştefan and Mihai Ţălu. "The influence of deviation from circularity on the stress of a pressurized fuel cylindrical tank." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics (HIDRAULICA)*, no. 4 (December 2017): 34-45.

[10 Vintilă, Daniela, Mihai Ţălu and Ştefan Ţălu. "The CAD analyses of a torospheric head cover of a pressurized cylindrical fuel tank after the crash test." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics (HIDRAULICA)*, no. 4 (December 2017): 57-66.

[11] Ţălu, Mihai. "The influence of the corrosion and temperature on the Von Mises stress in the lateral cover of a pressurized fuel tank." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics (HIDRAULICA)*, no. 4 (December 2017): 89-97.

[12] Ţălu, Mihai and Ştefan Ţălu. "Analysis of temperature resistance of pressurized cylindrical fuel tanks." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics (HIDRAULICA)*, no. 1 (March 2018): 6-15.

[13] Ţălu, Mihai and Ştefan Ţălu. "Design and optimization of pressurized toroidal LPG fuel tanks with variable section." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics (HIDRAULICA)*, no. 1 (March 2018): 32-41.

[14] Ţălu, Mihai and Ştefan Ţălu. "The optimal CAD design of a 3D hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics (HIDRAULICA)*, no. 2 (June 2018): 49-56.

[15] *** Certification tests of LPG and CNG. Accessed January 10, 2018. http://vzlutest.cz/en/certification-tests-of-lpg-and-cng-c3.html.

[16] Kișioglu, Yasin. "Burst tests and volume expansions of vehicle toroidal LPG fuel tanks." *Turkish J. Eng. Env.*, vol. 33 (2009): 117-125. DOI: 10.3906/muh-0905-2.

[17] Kartal, Fuat and Yasin Kișioglu. "Fatigue performance evaluations of vehicle toroidal liquefied petroleum gas fuel tanks." *J. Pressure Vessel Technol*, vol. 139, issue 4 (2017): 041402. DOI: 10.1115/1.4035976.

[18] Ziółkowska, Monika and Dorota Wardzińska. "Corrosiveness of fuels during storage processes", published by IntechOpen. Accessed January 10, 2018. http://dx.doi.org/10.5772/59803.

[19] Khobragade, Rashmi and Vinod Hiwase. "Design, and analysis of pressure vessel with hemispherical and flat circular end." *International Journal of Engineering Science and Computing*, vol. 7, no. 5 (2017): 12458-12469.

[20] Ţălu, Ştefan and Mihai Ţălu. "Constructive CAD variants of toroidal LPG fuel tanks used in automotive Industry." *Advances in Intelligent Systems Research,* vol. 159 (2018): 27-30. DOI: 10.2991/mmsa-18.2018.7.

[21] Ţălu, Ştefan and Mihai Ţălu. "CAD generating of 3D supershapes in different coordinate systems." *Annals of Faculty of Engineering Hunedoara - International Journal of Engineering, Hunedoara, Romania*, Tome VIII, Fascicule 3 (2010): 215-219.

[22] Ţălu, Ştefan and Mihai Ţălu. "A CAD study on generating of 2D supershapes in different coordinate systems." *Annals of Faculty of Engineering Hunedoara - International Journal of Engineering, Hunedoara, Romania*, Tome VIII, Fascicule 3 (2010): 201-203.

[23] Ţălu, Ştefan. *Limbajul de programare AutoLISP. Teorie şi aplicaţii. (AutoLISP programming language. Theory and applications)*. Cluj-Napoca, Risoprint Publishing house, 2001.

[24] Ţălu, Ştefan. *Grafică tehnică asistată de calculator. (Computer assisted technical graphics)*. Cluj-Napoca, Victor Melenti Publishing house, 2001.

[25] Ţălu, Ştefan. *Reprezentări grafice asistate de calculator. (Computer assisted graphical representations).* Cluj-Napoca, Osama Publishing house, 2001.

[26] Ţălu, Ştefan. *AutoCAD 2005*. Cluj-Napoca, Risoprint Publishing house, 2005.

[27] Ţălu, Ştefan and Mihai Ţălu. *AutoCAD 2006. Proiectare tridimensională. (AutoCAD 2006. Three-dimensional designing)*. Cluj-Napoca, MEGA Publishing house, 2007.

[28] Ţălu, Ştefan. *AutoCAD 2017*. Cluj-Napoca, Napoca Star Publishing house, 2017.

[29] Ţălu, Mihai. *Calculul pierderilor de presiune distribuite în conducte hidraulice. (Calculation of distributed pressure loss in hydraulic pipelines).* Craiova, Universitaria Publishing house, 2016.

[30] Ţălu, Mihai. *Mecanica fluidelor. Curgeri laminare monodimensionale. (Fluid mechanics. The monodimensional laminar flow).* Craiova, Universitaria Publishing house, 2016.

[31] Țălu, Mihai. *Pierderi de presiune hidraulică în conducte tehnice cu secțiune inelară. Calcul numeric și analiză C.F.D. (Hydraulic pressure loss in technical piping with annular section. Numerical calculation and C.F.D.)*, Craiova, Universitaria Publishing house, 2016.

[32] Ţălu, Ştefan. *Geometrie descriptivă. (Descriptive geometry)*, Cluj-Napoca, Risoprint Publishing house, 2010.

[33] Florescu-Gligore, Adrian, Magdalena Orban and Ştefan Ţălu. *Cotarea în proiectarea constructivă şi tehnologică. (Dimensioning in technological and constructive engineering graphics).* Cluj-Napoca, Lithography of The Technical University of Cluj-Napoca, 1998.

[34] Florescu-Gligore, Adrian, Ştefan Ţălu and Dan Noveanu. *Reprezentarea şi vizualizarea formelor geometrice în desenul industrial. (Representation and visualization of geometric shapes in industrial drawing).* Cluj-Napoca, U. T. Pres Publishing house, 2006.

[35] Racocea, Cristina and Ştefan Ţălu. *Reprezentarea formelor geometrice tehnice în axonometrie. (The axonometric representation of technical geometric shapes).* Cluj-Napoca, Napoca Star Publishing house, 2011.

[36] Ţălu, Ştefan and Cristina Racocea. *Reprezentări axonometrice cu aplicaţii în tehnică. (Axonometric representations with applications in technique).* Cluj-Napoca, MEGA Publishing house, 2007.

[37] Bîrleanu, Corina and Ştefan Ţălu. *Organe de maşini. Proiectare şi reprezentare grafică asistată de calculator. (Machine elements. Designing and computer assisted graphical representations).* Cluj-Napoca, Victor Melenti Publishing house, 2001.

[38] Niţulescu, Theodor and Ştefan Ţălu. *Aplicaţii ale geometriei descriptive şi graficii asistate de calculator în desenul industrial. (Applications of descriptive geometry and computer aided design in engineering graphics).* Cluj-Napoca, Risoprint Publishing house, 2001.

[39] Ţălu, Ştefan. *Micro and nanoscale characterization of three dimensional surfaces. Basics and applications*. Napoca Star Publishing House, Cluj-Napoca, Romania, 2015.