DOI: https://doi.org/10.15407/pmach2019.01.060

UDC 517.95+518.517+629.735.33-519

SCREW-TYPE SYMMETRY IN MACHINE COMPONENTS AND DESIGN AT IMPLEMENTATION ON A 3D PRINTER

[1] **Tatyana I. Sheyko**,
sheyko@ipmach.kharkov.ua
ORCID: 0000-0003-3295-5998

[1, 2] **Kyrylo V. Maksymenko-Sheiko**,
m-sh@ipmach.kharkov.ua
ORCID: 0000-0002-7064-2442

[3] **Anna I. Morozova**
ORCID: 0000-0002-7082-4115

[1] A. Podgorny Institute of Mechanical Engineering Problems of NASU,
2/10, Pozharsky St., Kharkiv, 61046, Ukraine

[2] V. N. Karazin Kharkiv National University,
4, Svobody Sq., Kharkiv, 61022, Ukraine

[3] Kharkiv National University of Radio Electronics,
14, Nauky Ave., Kharkiv, 61166, Ukraine

The creation of mathematical models for the implementation of 3D printing is of considerable interest, which is associated with the active introduction of 3D printing in various industries. The advantages of using 3D printing are the following: the possibility of making non-standard models, reducing the time to create new prototypes, making simple and low cost products, and using modern super-strength materials. The manufacture of machine components with a screw-type symmetry occurs in various, often very complicated ways to include casting with the subsequent rotary machining, methods of hot deformation, electrophysical and electrochemical methods, etc. Their manufacture on a 3D printer can be very promising. In this paper, the R-functions theory is used for the mathematical and computer modeling of geometric objects with a screw-type symmetry for the case when 3D printing technology is to be implemented. An analytical recording of the objects being designed makes it possible to use alphabetic geometric parameters, complex superposition of functions, which, in turn, allows us to quickly change their structural elements. The working part of many mechanisms for moving a material along a helical rotating surface is a screw. Screws are used instead of wheels in some types of cross-country vehicles or combines. They are an indispensable part in extruders and boring stations. At large enterprises, they are used as a means of transporting bulk materials. Screws are indispensable in the food industry. Among other things, they are used in small arms, where they play the role magazines for cartridges. In this work, we build mathematical and computer models of the variable and constant pitch screws to be implemented on a 3D printer. In order to organize and intensify various processes in power plants and other technical devices, swirling is widely used. Swirling is an effective means of stabilizing the flame in the combustion chambers of gas turbine engines. It is also used to intensify heat and mass transfer in channels; in chemical, petroleum, gas and other industries. This paper considers mathematical and computer models of a screw swirler, locally twisted tube, and complex cross-section twisted tube intended for the implementation on a 3D printer. The process of building a desk lamp with a design in the form of elliptic twisted tori is shown as well.

Keywords*: R-functions theory, 3D printing, screw-type symmetry, screw.*

Introduction

Currently, the creation of volumetric models of any items is accompanied by the growth in the popularity of using 3D printers. The technology of 3D printing is based on the principle of creating a layerwise solid model. The advantages of such devices over those using the conventional methods of creating models are high speed, simplicity, and low cost.

There are different approaches to creating 3D models: 3D scanning of an existing object, obtaining a 3D model using a fairly wide range of software products whose libraries contain primitive forms of various types, and creating a 3D model using the mathematical apparatus of analytical geometry. In cases where the object to be simulated exists physically, the most convenient way to obtain a 3D model is to use a 3D scanner. However, when the object to be simulated has large dimensions or does not exist at all, such an approach is impossible. In such cases, the creation of 3D-models can be implemented using software products. But this method has a number of disadvantages too, for example, a limited set of primitives in the library modules of the programs. Here we should especially note the geometric objects with a screw-type symmetry in whose cross-sections there are no classical regions, but those composed of the known primitives [1]. In these cases, the creation of a mathematical model of the geometric object with the help of the apparatus of analytical geometry is very promising in the field of 3D modeling. For the construction of the equations of geometric objects in an analytical form, the R-functions theory can prove to be very useful. It gives the possibility of creating complex superpositions and introducing literal parameters into the logical formula. These parameters allow us to quickly change the shape of the object being designed [2–4]. Also convenient is the fact that the process of creating a model occurs in stages and there is an opportunity to introduce changes to the structure being designed.

Thus, the expansion of the field of application of the apparatus of the R-functions theory for creating the mathematical models of the engineering objects to be built on a 3D printer is an urgent scientific and technical problem.

The aim of this work is to create mathematical and computer models of geometric objects with a screw-type symmetry on the basis of the R-functions theory in order to implement 3D printing technology.

Main Part

R-operations [2] $fk \wedge_0 fl = fk + fl - \sqrt{fk^2 + fl^2}$; $fk \vee_0 fl = fk + fl + \sqrt{fk^2 + fl^2}$ and a helical non-orthogonal coordinate system [4] $\begin{cases} x1 = x\cos\alpha + y\sin\alpha \\ y1 = -x\sin\alpha + y\cos\alpha \end{cases}$ are used in this work. When constructing the equations corresponding to geometric objects with cyclic-type point symmetry, to reduce the number of R-operations, we will use the results of the following theorem [4].

Theorem. Let the translational region $\Sigma_0 = [\sigma_0(x, y, z) \ge 0]$ be symmetric about the abscissa axis, and the region $\Sigma_1 = [\sigma_0(x - r_0, y, z) \ge 0]$ can be located inside the sector $-\alpha \le \theta \le \alpha,\ 0 < \alpha < \frac{\pi}{n}$. The regions $\Sigma_k = \left[\sigma_0\left(r\cos(\theta - 2\pi k/n) - r_0, r\sin(\theta - 2\pi k/n, z)\right) \ge 0\right]$ have been obtained by rotating the region $\Sigma_1 = [\sigma_0(x - r_0, y, z) \ge 0]$ in the xOy plane around the origin of the coordinates to the angles $2\pi k/n$. Then the equation of the boundary $\partial\Omega$ of the region $\Omega = \bigcup_{k=0}^{n-1} \Sigma_k$ has the form

$$\omega(x, y) \equiv \sigma_0(r\cos\mu(\theta, n) - r_0, r\sin\mu(\theta, n), z) = 0,$$

where $r = \sqrt{x^2 + y^2}$, $\theta = \mathrm{arctg}\frac{y}{x}$,

$$\mu(n\theta) = \frac{8}{n\pi}\sum_k (-1)^{k+1} \frac{\sin\left[(2k-1)\frac{n\theta}{2}\right]}{(2k-1)^2}.$$

Then the equation of the boundary $\partial\Omega$ of the region $\Omega = \bigcup_{k=0}^{n-1} \Sigma_k$ has the form

$$\omega(x, y) \equiv \sigma_0(r\cos\mu(\theta, n) - r_0, r\sin\mu(\theta, n), z) = 0,$$

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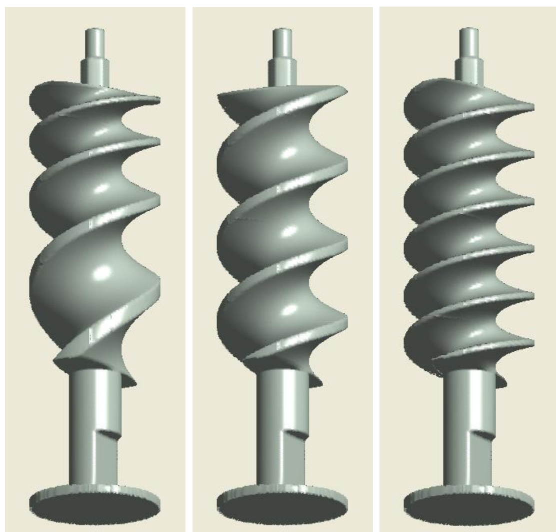


a b c

Fig. 1. Screw:
a – *N* – variable pitch; b – *N*=5; c – *N* = 3

In the process of numerical implementation, for the construction of the equation of the boundary $\partial\Omega$ with the rational accuracy, the number of the series members $k = 5$ is sufficient.

In addition, to construct an object of a given thickness δ, its normalized equation $\omega(x, y, z) \ge 0, \left.\frac{\partial\omega}{\partial n}\right|_{\partial\Omega} = 1$ was used. It is well known that the function $\omega(x, y, z)$ in the neighborhood of the boundary $\partial\Omega$ behaves like the distance to $\partial\Omega$. Then the function $\omega1(x,y,z)=\frac{\delta}{2}-|\omega(x,y,z)|\geq 0$ will be positive only in the belt width δ. In some cases, the use of this approach can significantly reduce the number of R-operations, and consequently, the computational process.

The working part of many mechanisms for moving a material along a helical rotating surface is a screw. The screw is a metal rod with a helical surface. The field of their application is rather wide. They are used instead of wheels in some types of cross-country vehicles or combines. They are indispensable components in extruders and at boring stations. At large enterprises, screws are used as a means of transporting bulk materials. These components are indispensable in the food industry, where they are parts of presses for food processing and integral parts of meat grinders. Among other things, screws are used in small arms, where they play the role of magazines for cartridges. Screw production occurs in various, often very complex ways, to include casting with the subsequent rotary machining, hot deformation and cold bending, welding, etc. The 3D printing of screws can prove to be very promising. To make the latter possible, we construct a mathematical and computer model for both a variable and constant pitch screw (Fig. 1).

$\alpha=\frac{2\pi}{N}z;\begin{cases} xx=x\cos\alpha+y\sin\alpha \\ yy=-x\sin\alpha+y\cos\alpha \end{cases}$ at $N=\frac{10/z+4/(10-z)}{1/z+1/(10-z)}$ (Fig.1, a); $N=5$ (Fig. 1, b); and $N=3$ (Fig. 1, c);

$$f1=\left(1-\frac{xx^2}{0.8^2}-\frac{yy^2}{2.3^2}\right)\wedge_0 z(9-z)\geq 0;\ fn11=\left(\left(0.8^2-x^2-y^2\right)\wedge_0 -z(z+4)\right)\vee_0 f1\geq 0;$$

$$fn1=\left(\left(\left(2.3^2-x^2-y^2\right)\wedge_0 (4.3+z)(-z-4)\right)\vee_0 fn11\right)\wedge_0 \left(4-x^2-y^2\right)\geq 0;$$

$$fs=(x-0.4)\wedge_0 (-z-2)(z+4)\geq 0;\ fn=fn1\wedge_0 -fs\geq 0;\ fv=\left(0.3^2-x^2-y^2\right)\wedge_0 (11-z)(z-8)\geq 0;$$

$$f=fn\vee_0 fv\geq 0;$$

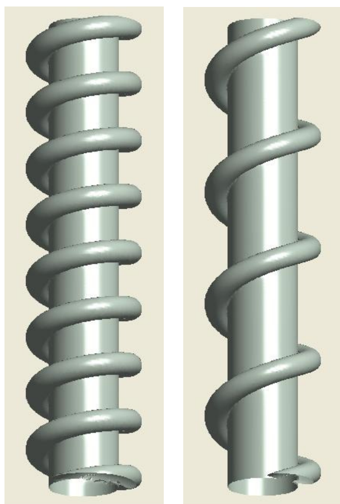
$$\rho=\sqrt{x^2+y^2};\ \theta=arctg\frac{y}{x};\ no=6;\ ff=\theta\frac{no}{2};\ \mu=\frac{8}{no\pi}\sum_k(-1)^{k+1}\frac{\sin[(2k-1)ff]}{(2k-1)^2};$$

$$x1=\rho\cos\mu;\ f22=(0.4-x1)\wedge_0 (10-z)(z-8)\geq 0;\ W=f\vee_0 f22\geq 0.$$

In this case, of particular interest is the construction of a variable twist pitch in the form of a continuous function $N=f(z)$.

In power plants and other technical devices, to organize and intensify various processes, flow swirling is widely used.

Flow swirling is an effective means of stabilizing the flame in the combustion chambers of gas turbine engines; it is used to intensify heat and mass transfer in channels in the chemical, oil, gas and other industries [1]. The swirlers used in practice differ in the method and nature of swirl and in the length of the swirling device. Consider the screw swirler (Fig. 2), locally twisted tube (Fig. 3), and complex cross-section twisted tube (Fig. 4) that were proposed in [1].



a b

Fig. 2. Screw swirler:
a – h=1; b – h=2

Screw Swirler

$$\rho=\sqrt{x^2+y^2};\theta=arctg\frac{y}{x};zz=z-\frac{\theta h}{2\pi};ff=\frac{\pi}{h}zz;$$

$$\mu=\frac{4h}{\pi^2}\sum_k(-1)^{k+1}\frac{\sin[(2k-1)ff]}{(2k-1)^2};$$

$$fp1=\left(0.04-(\rho-0.8)^2-\mu^2\right)/0.4\geq 0;$$

$$fp2=\left(1-x^2-y^2\right)/2\geq 0;\ fp3=\left(0.36-x^2-y^2\right)/1.2\geq 0;$$

$$W=\overline{fp1\vee_0 fp3}\geq 0.$$

At $h=1$ (Fig. 2, a); at $h=2$ (Fig. 2, b).

Local Twist Tube

$$a=1; b=5; l=1; fi1=2\pi\frac{z}{h}; fi2=2\pi\frac{l}{h}; fi3=2\pi\frac{z-b+a}{h};$$

$$fi12=\left(fi1+fi2-abs\left(fi1-fi2\right)\right)/2;$$

$$\alpha=\left(fi12+fi3+abs\left(fi12-fi3\right)\right)/2;$$

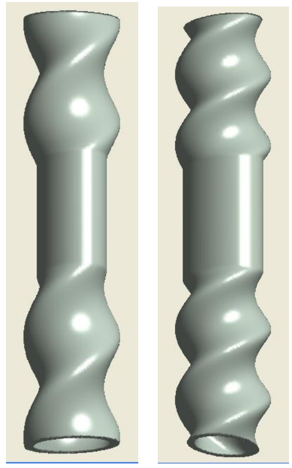
$$\begin{cases} xx=x\cos\alpha+y\sin\alpha \\ yy=-x\sin\alpha+y\cos\alpha \end{cases};$$

$$\omega s1=1-xx^2-\frac{yy^2}{1.5^2}\ge 0; \omega s=0.2-\left|\omega s1\right|\ge 0;$$

$$W=\omega s\wedge_0\left(10-z\right)\left(z+5\right)\ge 0.$$

At $h=7$ (Fig. 3, a); at $h=5$ (Fig. 3, b).

It should be noted that specifying information in an analytical form with the use of literal parameters allows us to quickly introduce changes to the form of the object under study.



a b

Fig. 3. Local twist tube:
a – h=7; b – h=5

Complex Cross-Section Tube

$$\alpha=0; (\alpha=\frac{\pi z}{40}; \alpha=\frac{\pi z}{30}; \alpha=\frac{\pi z}{20});$$

$$\begin{cases} xx=x\cos\alpha+y\sin\alpha; \\ yy=-x\sin\alpha+y\cos\alpha; \end{cases}$$

$$fkv=\frac{10^2-xx^2}{20}\wedge_0\frac{10^2-yy^2}{20}\ge 0;$$

$$f91=\frac{16-xx^2}{8}\ge 0; f92=\frac{16-yy^2}{8}\ge 0;$$

$$fr=ro^2-f91^2-f92^2\ge 0;$$

$$f9=f91+f92+\sqrt{f91^2+f92^2+\frac{fr}{8ro^2}\left(\left|fr\right|+fr\right)}\ge 0;$$

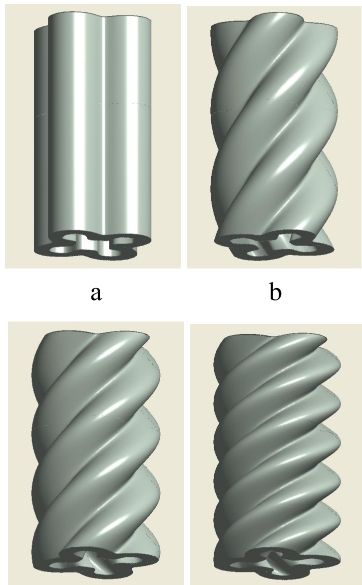
$$f11=f9\wedge_0 fkv\ge 0;$$

$$f11o=\left(\frac{4^2-\left(xx-10\right)^2-yy^2}{8}\right)\vee_0\left(\frac{4^2-\left(xx+10\right)^2-yy^2}{8}\right)\ge 0;$$

$$f12o=\left(\frac{4^2-\left(yy-10\right)^2-xx^2}{8}\right)\vee_0\left(\frac{4^2-\left(yy+10\right)^2-xx^2}{8}\right)\ge 0;$$

$$f1o=f11o\vee_0 f12o\ge 0; f1k=f11\vee_0 f1o\ge 0; f1=ht-\left|f1k\right|\ge 0;$$

$$W=f1\wedge_0\left(L^2-z^2\right)\ge 0$$ (Fig. 4).



a b c d

Fig. 4. Complex cross-section twisted tube:
a – α=0; b – α=πz/40; c – α=πz/30; d – α=πz/20

It should be noted that the tube of the cross-section shown is very difficult to manufacture, especially if we need to change the twist parameter. Therefore, it is advisable to do it on a 3D printer. Since, by changing the parameter α, we obtain a required twist pitch tube, ready to be 3D printed, then by changing the parameters ht and L, we obtain a pipe of the desired thickness and length.

Consider the process of building a designer desk lamp (Fig. 5, 6). The lamp consists of a stand with holes for electrical wiring and a lampshade.

Stand

$$p=10; xp=x/p; yp=y/p; zp=z/p; f1=\frac{p}{19}\left(9.5^2-xp^2-yp^2-\left(zp+8\right)^2\right)\ge 0;$$

$$R = 4; N = 10; \alpha = \operatorname{arctg}\frac{yp}{xp}; X1 = \sqrt{xp^2 + yp^2} - R; f2 = zp; zn = f2 - 1;$$

$$\begin{cases} XX = X1\cos\alpha + zn\sin\alpha \\ ZZ = -X1\sin\alpha + zn\cos\alpha \end{cases} \quad \begin{cases} XX2 = X1\cos\alpha - zn\sin\alpha \\ ZZ2 = X1\sin\alpha + zn\cos\alpha \end{cases}$$

$$t1 = 1 - \frac{XX^2}{0.04} - \frac{ZZ^2}{0.25} \ge 0; t2 = 1 - \frac{XX2^2}{0.04} - \frac{ZZ2^2}{0.25} \ge 0; tor = t1 \vee_0 t2 \ge 0;$$

$$\omega podn = (f1 \wedge_0 f2) \vee_0 tor \ge 0; \text{(Fig. 5, a)};$$

$$\begin{cases} xx = xp\cos\alpha 1 + yp\sin\alpha 1 \\ yy = -xp\sin\alpha 1 + yp\cos\alpha 1 \end{cases} \quad \begin{cases} xx1 = xp\cos\alpha 1 - yp\sin\alpha 1 \\ yy1 = xp\sin\alpha 1 + yp\cos\alpha 1 \end{cases} \quad \alpha 1 = \frac{\pi}{2}zp;$$

$$f31 = 1 - xx^2 - \frac{yy^2}{0.25} \ge 0; f32 = 1 - xx1^2 - \frac{yy1^2}{0.25} \ge 0;$$

$$f3 = f31 \vee_0 f32 \ge 0; f4 = f2(7 - zp) \ge 0;$$

$$\omega n = f3 \wedge_0 f4 \ge 0; \quad \omega pod = \omega podn \vee_0 \omega n \ge 0; \text{ (Fig. 5, b)};$$

$$stt = (0.4^2 - xp^2 - yp^2) \wedge_0 (8 - zp)(zp - 6) \ge 0;$$

$$\omega shnur1 = (0.2^2 - xp_2 - zp^2) \wedge_0 (yp + 0.2) \ge 0;$$

$$\omega shnur = (xp^2 + yp^2 - 0.2^2) \wedge_0 -\omega shnur1 \ge 0;$$

$$\omega podst = (\omega pod \vee_0 stt) \vee_0 \omega shnur \ge 0; \text{ (Fig. 5, c)}.$$

Shade

$$f5 = 2 - \left| \frac{p}{9}(4.5^2) - xp^2 - yp^2 - (zp - 6.5)^2 \right| \ge 0;$$

$$f6 = zp - 6.5 \ge 0; \omega aa = f5 \wedge_0 f6 \ge 0;$$

$$Ra = 4.8; Na = 10; \alpha a = \operatorname{arctg}\frac{yp}{xp}; X1a = \sqrt{xp^2 + yp^2} - Ra; za = zp - 7.3;$$

$$\begin{cases} XXa = X1a\cos\alpha a + za\sin\alpha a \\ ZZa = -X1a\sin\alpha a + za\cos\alpha a \end{cases} \quad \begin{cases} XX2a = X1a\cos\alpha a - za\sin\alpha a \\ ZZ2a = X1a\sin\alpha a + za\cos\alpha a \end{cases}$$

$$t1a = 1 - \frac{XXa^2}{0.04} - \frac{ZZa^2}{0.25} \ge 0; t2a = 1 - \frac{XX2a^2}{0.04} - \frac{ZZ2a^2}{0.25} \ge 0;$$

$$tora = t1a \vee_0 t2a \ge 0;$$

$$\omega a = \omega aa \vee_0 tora \ge 0; \text{ (Fig. 6, a)};$$

$$fd = (0.5^2 - xp^2) \vee_0 (0.5^2 - yp^2) \ge 0;$$

$$fbl = (0.1 - |7 - zp|) \wedge_0 \left(\frac{p}{9}(4.5^2 - xp^2 - yp^2 - (zp - 6.5)^2) \right) \ge 0;$$

$$\omega per = (fd \wedge_0 fbl) \wedge_0 (xp^2 + yp^2 - 0.5^2) \ge 0;$$

$$\omega abaj = \omega a \vee_0 \omega per \ge 0; \text{ (Fig. 6, b)};$$

$$\omega lampa = \omega abaj \vee_0 \omega podst \ge 0 \text{ (Fig. 6, c)}.$$

By changing the values of the letter parameters R, Ra, zn, za and setting $t2 = 0, t2a = 0,\ f32 = 0$, we obtain the lamp design with the pattern shown in Fig. 7.

Thus, any sizes characterizing this object can be changed.

The visualization of all the constructed models was carried out using the RFPreview program [5, 6].

Fig. 8 shows all the 3D printed models.

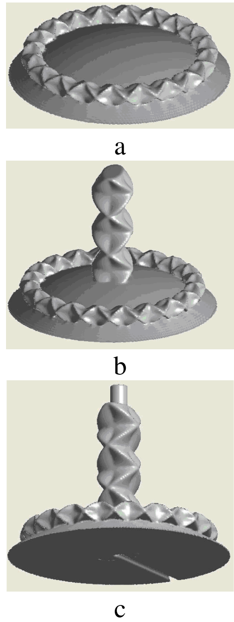


Fig. 5. Step-by-step lamp base construction:
a – lower part;
b – column added;
c – holes and wire grooves added

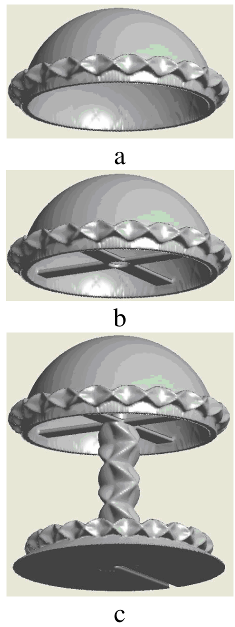


Fig. 6. Step-by-step construction of the lampshade and whole lamp:
a – lampshade;
b – cross-shaped mount added;
c – lamp assembly

The constructed mathematical models have been implemented on an Anet A8 3D printer using the most inexpensive and affordable Fused Deposition Modeling (FDM) technology. Its main disadvantages are the capability of using only plastic, the sensitivity to temperature drops, plastic spreading and need to organize supporting structures. The use of other more advanced 3D printing technologies (for example, Selective Laser Sintering (SLS), in which nylon, glass, plastic, ceramics, and various powdered metals can be used as raw materials) will improve the appearance of the printed products and their strength characteristics.

Fig. 7. Visualization of the lamp model with modified letter parameters:
a – stand; b – lamp shade; c – lamp assembly

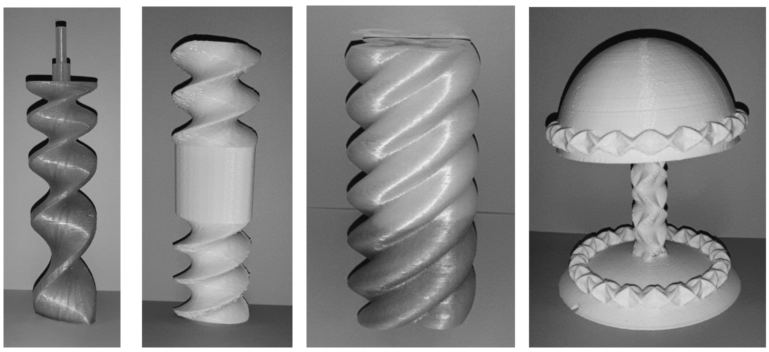


Fig. 8. Implementation of 3D printed models

Conclusions

The creation of mathematical models for the implementation of 3D printing is of considerable interest, which is associated with the active introduction of 3D printing in various industries. The advantages of using 3D printing are obvious. These are the production of non-standard models, reduction of time for the creation of new prototypes, reduction of the repair time, simplicity and considerable cheapness of production, and use of modern super-strength materials. In this paper, we developed a general approach to the construction of mathematical and computer models of geometric helical symmetry objects, with the models based on the R-functions theory. By changing the swirl law, we change only the form of the function α in the corresponding coordinate transform. The reliability of the results obtained, their adequacy to the objects being designed is confirmed by visualization, both under the operating conditions of the RFPreview program, and the implementation on a 3D printer.

An analytical recording of the objects being designed makes it possible to use alphabetic geometric parameters and a complex superposition of functions, which, in turn, allows us to quickly change their structural elements. The property of positiveness of the constructed functions in the internal points of the object is very convenient for the implementation of 3D printing.

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Received 31 January 2019

Гвинтовий тип симетрії в деталях машин та дизайні при реалізації на 3D-принтері

[1] Шейко Т. І., [1,2] Максименко-Шейко К. В., [3] Морозова А. І.

[1] Інститут проблем машинобудування ім. А.М. Підгорного НАН України,
61046, Україна, м. Харків, вул. Пожарського, 2/10

[2] Харківський національний університет імені В. Н. Каразіна,
61022, Україна, м. Харків, майдан Свободи, 4

[3] Харківський національний університет радіоелектроніки, 61166, Україна, м. Харків, пр. Науки, 14

Створення математичних моделей для реалізації 3D-друку становить значний інтерес, що пов'язаний з активним впровадженням 3D-друку в різні галузі промисловості. Переваги застосування 3D-друку: виготовлення нестандартних моделей, скорочення часу на створення нових прототипів, простота і значна дешевизна виробництва, використання сучасних надміцних матеріалів. Виготовлення деталей машин з гвинтовим типом симетрії відбувається різними, часто дуже складними способами. Це литво з подальшою токарною обробкою, способи гарячої деформації, електрофізичні та електрохімічні способи тощо. Дуже перспективним може виявитися їх виготовлення на 3D-принтері. У цій роботі застосовується теорія R-функцій для математичного та комп'ютерного моделювання геометричних об'єктів з гвинтовим типом симетрії під час реалізації технології 3D-друку. Аналітичний запис проектованих об'єктів дає можливість використовувати буквені геометричні параметри, складні суперпозиції функцій, що, в свою чергу, дозволяє оперативно змінювати їхні конструктивні елементи. Робочої деталлю багатьох механізмів для просування матеріалу уздовж гвинтової поверхні, яка обертається, є шнек. Шнеки використовуються замість коліс в деяких видах всюдиходів або комбайнів. Вони є незамінною деталлю в екструдерах і на бурових станціях. На великих підприємствах їх використовують як засіб транспортування сипучих речовин. Шнеки незамінні в харчовій промисловості. Крім іншого, вони використовуються в стрілецькій зброї, де деталь виконує роль магазина для патронів. В роботі побудовано математичні і комп'ютерні моделі шнеків зі змінним і постійним кроком закрутки, реалізовані на 3D-принтері. В енергетичних установках та інших технічних пристроях широко використовується закрутка потоку для організації та інтенсифікації різних процесів. Закручування є ефективним засобом стабілізації полум'я в камерах згоряння газотурбінних двигунів; використовується для інтенсифікації тепло- і масообміну в каналах; в хімічній, нафтовій, газовій та інших галузях промисловості. Побудовано математичні і комп'ютерні моделі шнекового завихрювача, труби з локальної закруткою, скрученої труби складного поперечного перерізу, які реалізовані на 3D-принтері. Також було здійснено процес побудови настільної лампи з дизай-нерським оформленням у вигляді скручених торів еліптичного перерізу.

Ключові слова: *теорія R-функцій, 3D-друк, гвинтовий тип симетрії, шнек.*

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