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RESERVE OF ANALYTICAL SURFACES FOR ARCHITECTURE AND CONSTRUCTION

Abstract. *After a period of relative calm in the construction and design of thin-walled large-span shells and network multilayer shell structures, which, according to the world's leading architects, began in the 1980 s, the time has come for the expanded use of spatial structures in the architecture of public and industrial buildings. Less commonly, shells are used in small-sized housing construction: ecological villages, noospheric and bionic architecture. The entire 20th century did not stop research on the development of analytical and numerical methods for analyzing shells for strength and stability, for the creation of new building materials. Geometers have created and studied more than 600 analytical surfaces that can be mistaken for the mid-surfaces of civil and mechanical engineering shells. As a result, by the beginning of the 21st century, architects and engineers had all the necessary tools to continue the traditions of the "golden age of shells". The analysis of problems with the use of new forms in parametric architecture, carried out in the article, showed that more than ten classes of surfaces from their classification have not yet found application in architecture and mechanical engineering. It is assumed that the number of applied classes of surfaces will not expand, and new ideas for the shaping of shells will be based on the use of already well-known surfaces, namely, surfaces of revolution, transfer, umbrella, minimal, ruled and wavy surfaces. Mainly, shell structures will be designed taking into account environmental, energy-saving requirements and transforming structures.*

Keywords: *analytical surfaces, surface classification, thin shells, shell architecture, shells in mechanical engineering, parametric architecture.*

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РЕЗЕРВ АНАЛИТИЧЕСКИХ ПОВЕРХНОСТЕЙ ДЛЯ АРХИТЕКТУРЫ И СТРОИТЕЛЬСТВА

Аннотация. *После периода относительного затишья в строительстве и проектировании тонкостенных большепролетных оболочек и стержневых многослойных оболочечных структур, который по мнению ведущих архитекторов мира начался в 1980-е годы, наступило время расширенного применения пространственных структур в архитектуре общественных и промышленных зданий. Реже оболочки применяются в малогабаритном жилищном строительстве: экологические деревни, ноосферная и бионическая архитектура. Весь 20-й век не прекращались исследования по развитию аналитических и численных методов расчета оболочек на прочность и устойчивость, по созданию новых строительных материалов. Геометры создали и изучили более 600 аналитических поверхностей, которые могут быть приняты за срединные поверхности оболочек строительного и машиностроительного назначения. В итоге к началу 21-го века архитекторы и инженеры имели весь набор необходимых средств для продолжения традиций «золотого века оболочек». Анализ проблем с применением новых форм в параметрической архитектуре, проведенный в статье, показал, что более десяти классов поверхностей из их классификации не нашел еще применения в архитектуре и машиностроении. Сделано предположение, что число применяемых классов поверхностей не будет расширяться, а новые идеи формообразования оболочек будут базироваться на использовании уже хорошо известных поверхностей, а именно, поверхностей вращения, переноса, зонтичных, минимальных, линейчатых и волнообразных поверхностей. В* *основном будут проектироваться оболочечные структуры с учетом экологических, энергосберегающих требований и трансформирующиеся структуры.*

Ключевые слова: *аналитические поверхности, классификация поверхностей, тонкие оболочки, архитектура оболочек, оболочки в машиностроении, параметрическая архитектура, перспективы применения оболочек.*

Introduction

Spatial structures covering large areas without intermediate supports have been known to human kind for a long time [1, 2]. In the old days, shells were widely used in various technological structures: vertical shafts, horizontal and inclined tunnels, pipelines, furnaces and defensive structures. In most cases, shells of revolution were used, in particular domes.

Then, in connection with the development of analytical and experimental methods for investigating shells and shell structures, the shapes of the structures used became more complicated. They began to satisfy the ever-growing demands of architects and engineers and found application where structures with a frequent grid of columns, walls and composite low-span buildings were previously used.

The greatest enthusiasm for thin-walled shells continued until the 1980s [3], then interest in them began to decrease, but in connection with the demands of society at the beginning of the 21st century, their wider rational use in small-sized housing, in industrial and public buildings began [4]. This was caused by the emergence of refined numerical methods for calculating strength, stability and seismicity, the creation of new building materials [5] and a large offer from geometers of new forms of the median analytical surfaces of thin-walled shells [6] and rod shell structures.

At the Faculty of Engineering (now the Engineering Academy) of the RUDN University since 1962, under the leadership of prof. V.G. Rekach, systematic work has been carried out on the investigation of shells of non-canonical form. These investigations continue to this day. They are conducted by both students [7], postgraduates [8], and the teaching staff of the RUDN Engineering Academy [9, 10, 11].

The most complete analytical surfaces are presented and mathematically described in the monograph [6]. There are more than 600 surfaces distributed in 38 classes, which in turn consist of subclasses, groups and subgroups. Analytical surfaces are well represented in electronic libraries [12, 13].

Many works are devoted to the use of analytical surfaces in architecture [1] and mechanical engineering [14, 15]. I.A. Mamieva [16, 17] and E.A. Grinko [18], apparently, was the first to try to find out the analytic surfaces most frequently used by architects and to establish cases of single use in practice of some analytic surfaces well known to geometers.

Most commonly used analytical surfaces

Here, the leaders, of course, are *cylindrical, conical* [19] *surfaces*, *linear surfaces of negative Gaussian curvature* ($K < 0$), as well as *surfaces of revolution* [20, 21].

Ruled surfaces, including *torso surfaces* ($K = 0$), *cylindroids* ($K < 0$), *cylindrical helical strips* and *cylindrical surfaces with aerodynamic profiles*, *rotative* and *spiroid surfaces* with straight generatrices are often used in mechanical engineering, shipbuilding and aircraft construction.

Translation surfaces, especially direct transfer surfaces, are taken as the basis for the formation of the median surfaces of hundreds of thin shells on rectangular plans [11]. They can be seen in any city in developed countries.

Umbrella shells and *umbrella-type shells* are actively used to cover markets, shopping centers, circuses, religious buildings and to protect radar stations [22]. Radar umbrella shells are operated at Domodedovo, Vnukovo, Sheremetyevo and other airports in Russia.

The next class of surfaces in terms of the frequency of their use in the national economy can be considered the class of *cyclic surfac*es [23]. They are used in the shaping of civil, industrial, and agricultural structures. They have found the same wide application in mechanical engineering.

Seventeen *algebraic surfaces of the second order* are usually assigned to a separate class, but almost all of these surfaces can be classified into other classes [6, 24]. All surfaces of the 2nd order, except for imaginary ones, can be seen in the outlines of many architectural structures and engineering products.

Of the class of *helical surfaces*, the most often used are the group of ruled [25] and circular [26] helical surfaces. In mechanical engineering, there are examples of the use of helical surfaces of variable pitch [27]. *The surface of the screw pillar* ***and*** *the surface of St. Elijah* can often be seen in the outlines of the supporting columns of old buildings. *The tubular helical surface* is well known and widely used in both architecture and mechanical engineering (coils). It can be found on almost any playground (children's slides) [26] and on attractions.

More and more architects support the idea of using *minimal surfaces* in architecture. There was even an architectural trend "Minimal Surface Architecture". However, most of the ideas are implemented only in projects. There are 15 known minimal surfaces that have a parametric form of the task. The article [28] gives examples of constructed thin-walled shell structures built in the form of a minimal surface of revolution (*catenoid*), minimal ruled surface (*right helicoid*) and minimal transfer surface (*the first Sherk s*urface). The Olympic Stadium in Munich was erected in 1972 using minimal surfaces close to that of *Schwarz surface*.

Rarely used analytical surfaces

It is very rare to use objects in the form of one-sided surfaces. There are about a dozen installations and sculptures in the form of a *Mobius strip*. There are several wire art objects imitating *the Klein surface*. A mathematical model of a 2×2 m *Boy surface* is available at Smith College, McConnel Hall.

Figure 1 - Hotel Marques de Riscal, Spain, architect Frank Gerhy

Figure 2 - Shallow reinforced concrete covering of the Nekrasovsky (Maltsevsky) market in St. Petersburg, 1960

Torso coverings of public buildings, obtained by parabolic bending of a steel sheet, have already been used in several cases (figure 1). Their shape is not an analytical surface, since they are plotted on two edge curves experimentally. However, G. Monge proved the possibility of obtaining an equation for a torso surface containing two predetermined curves.

Velaroidal shells on a flat rectangular plan are rarely found. Their middle surfaces are outlined along the surface of direct transfer with a generating curve, which changes its curvature during motion [29] and becomes a straight line on the contour. It is known the velaroidal shell for covering an industrial workshop, designed by M. Mihailescu [30], a shallow reinforced concrete velaroidal shell, erected over the Nekrasov market in St. Petersburg in 1960 (figure 2) and a fragment of the coating of the Cultural Center in Muscat (Oman) [31]. The "*Velaroidal Surface*" group is often included in the class of translation surfaces.

Figure 3 - Art-object in the form of a surface with the spherical directing curve

Surfaces with a spherical directing curve have a curved line lying on a sphere as a directing curve [4]. Of the many surfaces proposed by geometers, only one surface with the spherical directing curve was found on the playground (figure 3).

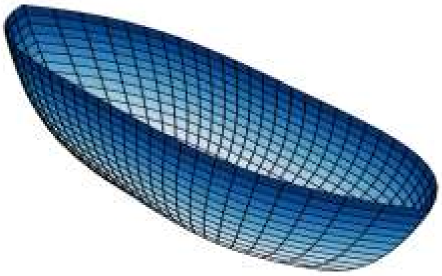

***Figure 4 - The surface of the ship's hull generated by a family of lines parallel to the waterline* [32]**

***Figure 5 - The second building of the German Historical Museum, Berlin, architect Bei Yuming,* 2003**

The class of *continuous topographic surfaces* is given by the continuous frame of their contours (level lines) specifies [6]. Surfaces of revolution are also included in this class, but it is generally accepted to separate them into a separate class. Continuous topographic surfaces can also include explicitly defined algebraic surfaces, *Catalan surfaces* ($K < 0$), *surfaces of the same slope* ($K = 0$). Continuous topographic surfaces are mainly used in topography, mining, landscape architecture, and shipbuilding. In shipbuilding, they are called *hydrodynamic surfaces* [32] or algebraic surfaces for ship hulls (figure 4). They are used very rarely in the construction business, and they are not intended for use in the construction industry.

Spiral surfaces on circular cones are usually used to generate spiral chambers [33]. The architects have found applications for *a cylindrical-conical helical strip* (figure 5), *a spiral conical strip* [18] and *a tubular helical surface*.

Helically-formed surfaces are often confused with spiral surfaces, but Helically-formed surfaces can have any spiral on any surface as a directing curve, and the generating curve can change its shape during movement. As an example, we can cite a cylindro-spherical Helically-formed strip and architectural structures in the form of shells. One of the structures with a ruled spiral roof is given in the article [18].

Surfaces from the "*Carved surfaces*" class are fully included in the "*Surfaces of congruent sections*" class. Carved surfaces include circular helical surfaces and helical surfaces with arbitrary flat generatrix curves. If we take into account all groups of surfaces with rigid plane generatrices of curves included in the class of surfaces of congruent sections, then it must be assumed that these surfaces are popular with architects, especially since all geometric problems for them have already been solved. In [34] some forms of carved surfaces for architectural structures are considered, and in article [35] an example of a real structure with congruent curves is given.

Analytical surfaces that have not found practical application

Wave-shaped, wavy and *corrugated surfaces* are represented in architecture very widely; however, they are all made in the style of digital architecture, i.e. the surfaces were constructed according to the given reference points and are not analytical surfaces (figure 6).

Figure 6 - I. Viner-Usmanova Sports Palace in Luzhniki, Moscow

Figure 7 - Sports facility in the shape of several identical velaroid surfaces on a flat circular plan with a singular point in the center

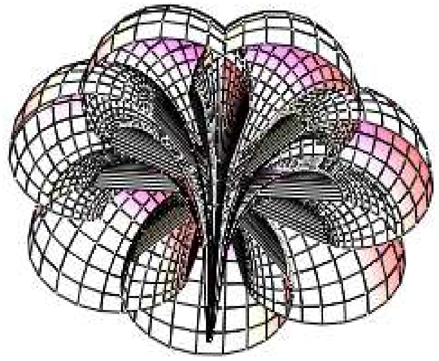

Figure 8 - One of the shapes of the Sievert surface

Velaroid surfaces in a ring plan cannot be included in the translation surface class. In a paper [18], they are called *velaroidal type surfaces*. There are several projects of sports facilities (figure 7), the geometry of these surfaces is well developed [36], but no real structures of this form have been found.

Architects and mechanical engineers were not interested in *surfaces of constant Gaussian curvature* ($K = const$). If we do not take into account the sphere with $K = R^2 = const$, then the remaining *surfaces of constant positive Gaussian curvature* have not found application in various branches of human activity. Only *the Sievert surface* (figure 8), with certain geometric parameters, becomes similar to a self-intersecting surface of the umbrella type, which can attract architects. Among the surfaces of the subclass "*Surfaces of constant negative Gaussian curvature*", only *the pseudo-sphere* has found application in landscape architecture and as large-scale mathematical models made of steel wire, plywood and aluminum [31, 37].

There is a good architectural future for *algebraic surfaces of the higher order* [6]. The shape of some existing curved structures in the world can be easily approximated by these surfaces. Such surfaces as the *parabolic surface of Schroda, Goursat, Euler, the tooth surface*, *surfaces with two and three* (figure 9) *double straight lines*, all of the 4th order; *an 8th order surface* with a 4th order Lamé curve, a 4th order Lamé curve and an ellipse in the third principal coordinate sections [6], etc. It is easy to find application in architecture, or to use them to solve various technical problems in mechanical engineering.

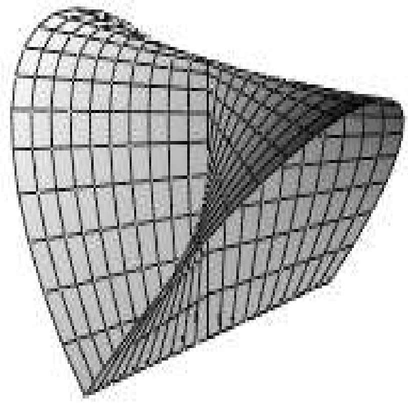

Figure 9 - Conical Wallis edge of the 4th order

Among *the surfaces of constant mean curvature*, the most famous are the sphere ($H = R$), the cylindrical surface of revolution ($H = R / 2$) and the minimal surfaces ($H = 0$). These surfaces are used in architecture and mechanical engineering. Less known surfaces are *nodoid* and *unduloid surfaces of revolution*, which attract close attention from mathematicians who develop the problems of conjugation of two surfaces of revolution [38].

The study of scientific, popular science and reference literature, materials contained on the Internet, showed that some classes of surfaces have not yet found application in the construction and engineering industries. These are *helix-shaped* and *pseudo-minimal* [39] *surfaces*, most of the surfaces from the classes "*Affine-minimal surfaces*", "*Peterson surfaces*", except for translation surfaces of curves of the second order, "*Bonnet surfaces*", "*Blutel surfaces",* except for surfaces of the second order*, "Hoshimoto surfaces"* [40], *"Weingarten surfaces*", except surfaces of revolution. These surfaces are used to study some physical processes, to solve purely mathematical problems and to define surfaces isometric to surfaces of revolution.

Possibilities of using new analytical surfaces in engineering structures

The analysis carried out in works [17, 41] showed that architects and engineers used only about 5% of more than 600 analytical surfaces proposed by mathematicians-geometers. Architects working in the styles “Parametric architecture”, “Geometric high-tech” and “Industrial architecture” mainly use them.

In the 21st century, free-form architecture and parametric architecture began to dominate the design of shell structures. Some architects support this trend [42], others doubt its usefulness [43]. E.V. Ermolenko [43] from Moscow Architectural Institute (Moscow) notes: «…. postmodernism, deconstructivism, parametric architecture oversaturated the space of human life, a style crisis arose».

Apparently, architects have already exhausted the set of existing surface classes. Taking into account the public demand for large-span structures and public buildings of unusual shape, surfaces from well-studied classes of surfaces of revolution, transfer, umbrella, minimal, ruled and wavy (figure 6) surfaces will be used. Shell structures will be designed taking into account environmental [44], energy-saving requirements and transforming structures.

Conclusion

Passion for shell structures should not grow into an end in itself. I.A. Bondarenko [45] warns that “at the same time, one should not slide into populism. It is necessary to observe a sense of proportion in everything. Unfortunately, today all the successes and failures of architects are based mainly on their personal business and human qualities. Individualism and hypertrophied - "breakthrough" - creative creativity are too encouraged. ... This leads to the fact that something insubstantial can be passed off as a professional achievement, as an architectural innovation - senseless design originality. "

Young architects enthusiastically embraced new trends and reviving traditions in the design of thin-walled shells that existed in the 1920-1960s, and modern shell core systems [46].

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