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Review

Lightweight Research in Engineering: A Review

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Received: 14 October 2019; Accepted: 3 December 2019; Published: 6 December 2019

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Abstract: In the field of mechanical equipment manufacturing, the focus of research and development is not on weight reduction, but on how to choose between the rigidity and performance of components (such as strength or flexibility). For this contradiction, lightweight is one of the best solutions. The problems associated with lightweight were initially considered and systematically studied in aircraft manufacturing in engineering. Therefore, lightweight has been greatly developed in aviation research and has played an increasingly important role in construction machinery. This paper presents a brief description of the current status of lightweight in machinery by reviewing some significant progress made in the last decades. Potential research topics are also discussed from the four aspects of material, structure, bionics, and manufacturing, and they forecast the development trend of lightweight in the future construction machinery. The entire body of literature about the field is not covered due to the limitation of the length of paper. The scope of this review is limited and closely related to the development of lightweight technology in engineering applications.

Keywords: lightweight; topology; structure optimization; bionics; manufacturing; engineering

1. Introduction

Lightweight is a multidisciplinary engineering science that consists of knowledge bases in the fields of materials mechanics, computational technology, materials science, and manufacturing technology. The goal of lightweight is to minimize the structural weight under certain boundary conditions while meeting certain life and reliability requirements. Lightweight is one of the most important laws for the growth of nature. In nature, the essence of lightweight is to achieve maximum efficiency with minimal consumption. In the field of science and engineering, lightweight is a discipline that is both traditional and new. In modern society, the requirements for lightweight are not only technically achievable and affordable, but also sustainable.

This paper presents a brief description of the current status of structural optimization by reviewing some significant progress made in the last decades. Since the length of this paper is limited, it does not cover the entire body of literature for the field. The scope of this review is limited and closely related to the authors' own research interests.

The paper is organized as follows: lightweight research background and significance are introduced in Section 2. Section 3 offers a survey of the lightweight mathematical model and solution. Lightweight pathways and research progress are briefly discussed in Section 4 and mainly includes four aspects: material, structure, bionics and manufacturing technology, and 3D printing. Section 5 concludes the paper with some personal perspectives on the future development of lightweight.

2. Lightweight Research Background and Significance

In the field of mechanical equipment manufacturing, the focus of research and development is not on weight reduction, but on how to choose between the rigidity and performance of moving components. For this contradiction, lightweight technology is the most one of the good solutions [1]. For example, lightweight components enable faster machining speeds, higher precision and longer life for mechanical equipment, while lightweight robots move faster, more agilely and with higher precision. Under the requirements of lightweight, mechanical equipment can also use smaller and more economical drive systems, to enhance the market competitiveness of products.

The problems associated with lightweight first appeared in aircraft manufacturing and the aerospace industry [2]. While mastering theoretical knowledge, rich design experience is also indispensable. Increasingly high demands have prompted lightweight engineers to continually learn and apply all new technologies and knowledge in a targeted manner, to address the lightweight system issues they face. The iconic breakthrough in this field is to make full use of the carrying capacity of the skin and replace the truss structure with an unstructured structure. The principle of solid wall and shell generated from the aerospace manufacturing field has spread to high-performance locomotives and ships and the field of shipbuilding, large wind-power plants, automobile body manufacturing, and machine tool manufacturing.

It is estimated that by 2020, the market value of lightweight in the German electronics industry and machinery manufacturing industry will reach 40 billion euros. The new concept of material and structure optimization design technology has been applied to an unprecedented scale in the European and American aviation and aerospace industries. For example, the optimization design of the leading-edge rib of the Airbus A380 wing, through the application of topology, size, and shape optimization technology, the overall weight reduction of the aircraft reaches 500 kg. Similar major technologies have been used by other major aircraft manufacturers in Europe and the United States. Experience has shown that typical optimization designs for individual structural components can achieve at least 20% weight loss on a classic design basis. The lightweight design of aerospace vehicles has great economic performance, which can reduce the manufacturing cost and improve the resource utilization, while ensuring the design requirements [3,4].

The structural cost (materials for steel, concrete, masonry, etc.) accounts for more than 50% of the main construction cost, and structural optimization can reduce the total construction cost by 10% to 35%. This invisible total profit is very large, has basically no risk, and can be easily obtained through small optimization investment, which is helpful for reducing corporate investment, increasing corporate profits, and improving capital turnover, and has great economic value design optimization.

According to calculations, when a car loses 10 kg, and the fuel consumption per 100 km decreases by an average of 0.51 L, the carbon dioxide emissions are reduced by 12 g/km. The current car still has about 35% weight-loss potential. If lightweight material substitution is used to do this, it is equivalent to about 1 kg of aluminum instead of 2 kg of steel, and the load-carrying capacity is unchanged. In the field of machinery manufacturing alone, the German industry's annual reduction in carbon dioxide emissions through lightweight measures is equivalent to a year's total carbon dioxide emissions in a large German city. Lightweight design helps reduce aircraft fuel consumption. The energy efficiency of the fuel depends mainly on the power of the engine and the total mass of the fuselage. Therefore, reducing the weight of the fuselage can significantly improve the power density, carrying capacity, reliability, and running speed of the aircraft, while maintaining the same performance and cost. Reducing fuel consumption can also reduce greenhouse gas emissions effectively and make aircrafts more environmentally friendly.

3. Lightweight Mathematical Model and Solution

The problem of lightweight ultimately comes down to the maximum and minimum problem of solving the objective function under certain constraints. The difficulty is that the constraints are not easy to establish in different engineering problems, or different working conditions, different backgrounds, and different hard requirements. The current solution steps can be roughly simplified, as shown in Figure 1.

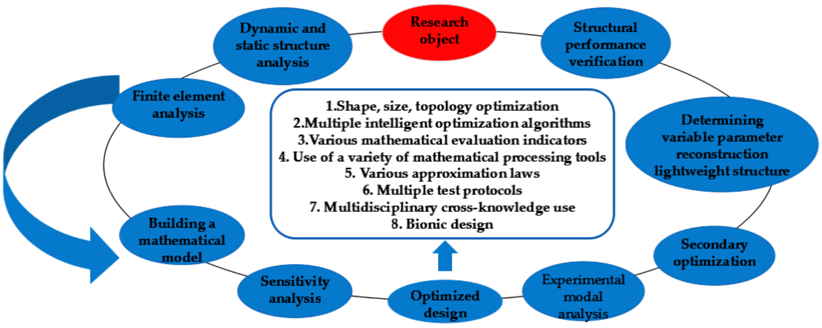

Figure 1. The current solution steps.

There are generally two modeling ideas of structural optimization methods [1,5]: One is to seek structural stiffness maximization (minimum compliance) under volume or mass constraints, and the other is to seek structural minimum volume or mass under stiffness constraints. Mathematical modeling is the first step in lightweight. Regardless of whether the optimization is a static problem, a dynamic problem, or a shape, size, and topology problem, it can generally be expressed in the form of nonlinear programming. The standard nonlinear programming model is as follows:

$$Min f(X) \tag{1}$$

$$\begin{gathered} S.t. \quad \mathrm{g_j}(X) = 0, j = 1, 2, \cdots, p \\ \mathrm{g_j}(X) \leq 0, j = p+1, p+2, \cdots, m \\ X^L \leq X \leq X^U \end{gathered} \tag{2}$$

where, $f(X)$ is the objective function, generally taking the structural weight; $g_j(X)$ is the constraint function, which may include the physical equation and the coordination equations, static or dynamic strength, stiffness limit, etc.; $X = \left(X^1, X^2, \cdots, X^N\right)^T$ is the design variable; and X^U and X^L are the upper and lower limits of X, respectively. It is necessary to make the following explanation about the model:

- Design variables can be either continuous or discrete. For engineering structure design, the variables are usually a lot.
- The objective function and the constraint function are continuously differentiable in most cases and may also be noncontinuous and nondifferentiable.
- The constraint function is usually implicit and has a nonlinear nature. The degree of nonlinearity is different for different problems or different design points of the same problem. Because the constraint conditions in complex engineering may be very diverse, the degree of nonlinearity and linearity are also different for the structure's design. At the same time, our solution was obtained through iterative optimization. For the optimization result, different variables are grouped with different requirements. Due to the fact that each set of variables must be fully analyzed, one by one, the amount of calculations is usually very large. Therefore, the number of times structural analysis is usually an important indicator of the efficiency of an optimization method [1].

After the lightweight approach and the mathematical model are determined, we need to solve the model. In recent years, there have been many methods for solving lightweight optimization problems, such as mathematical programming, optimization criterion method, emerging meta-heuristic bionic optimization algorithm, etc., which have attracted many experts and scholars, and have been widely used in engineering field.

From the point of view of engineering and mechanics, the criterion method [6] offers some criteria that should be met when the structure reaches the optimal design (such as synchronous failure criterion, full stress criterion, energy criterion, etc.). Then the solution satisfying these criteria is obtained by the iterative method. The method is characterized by fast convergence, no direct relation between the number of times of reanalysis and the number of design variables, and a small amount of calculation. However, it is limited in its application, which is mainly applicable to the case where the structural layout and geometric shape have been determined. Although the standard method has its shortcomings, from the perspective of engineering application, it is more convenient. The simplest criterion method is the synchronous failure criterion method and the full stress criterion method.

The structural optimization [7] problem is summarized into a mathematical programming problem, and then solved by mathematical programming. The mathematical programming methods commonly used in structural optimization are nonlinear programming, and sometimes linear programming. In special cases, dynamic programming, geometric programming, integer programming, or random programming may be used.

Heuristic algorithms have been a solution trend in recent years. These algorithms include genetic algorithm (GA), neural network algorithm, simulated annealing algorithm, fruit fly algorithm [8], artificial bee colony algorithm [9], particle swarm algorithm [10] (PSO), ant colony optimization algorithm [11], Cuckoo search algorithm [12], multi-island genetic algorithm [13], and the new raindrop algorithm [14]. The algorithm is simple and easy to implement, and it has few parameters. It has great advantages in dealing with many engineering problems and has also been applied in the field of structural optimization.

The development of lightweight software systems is as important as basic method research, and software is a tool for lightweight and the actual structure. The aviation industry first stimulated the development of structural optimization, and it is also the main industry for developing and applying structural optimization software. After the zero-sensitivity analysis and finite element modeling ideas are taken into consideration, there are many existing software programs, such as ANSYS Workbench, SolidWorks, Optistruct, Adams, Abaqus, Hyperworks, UG, ISIGHT, TOSCA, CATIA, and ADINA.

4. Lightweight Pathways and Research Progress

Increasing the payload and lightweight design of the aircraft structure, the integration of materials, structure, and manufacturing process is the eternal driving force to lead the optimization design theory and technology development. Therefore, according to lightweight design objects, such as automobiles, airplanes, folding electric vehicles, various beams, etc., under the condition of ensuring the basic performance of various lightweight objects, the quality can be reduced via the following ways (see the Figure 2).

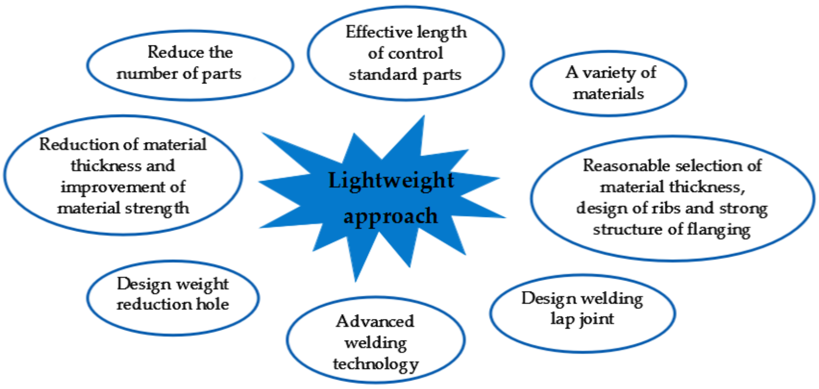

Figure 2. Lightweight approaches.

Lightweight is divided into lightweight materials, lightweight manufacturing, and lightweight structure. The lightweight material is lightened by the use of lightweight materials, to ensure structural performance. Typical applications are in the medical, automotive, and aerospace industries. Lightweight construction is designed to meet the requirements by improving structural design. The application of structural optimization technology to achieve lighter weight is superior to the former two in terms of low cost, short cycle, easy implementation, and light-weighting effect. In recent years, it has been widely used in the field of engineering machinery lightweight.

A detailed classification of lightweight technologies is shown in Figure 3.

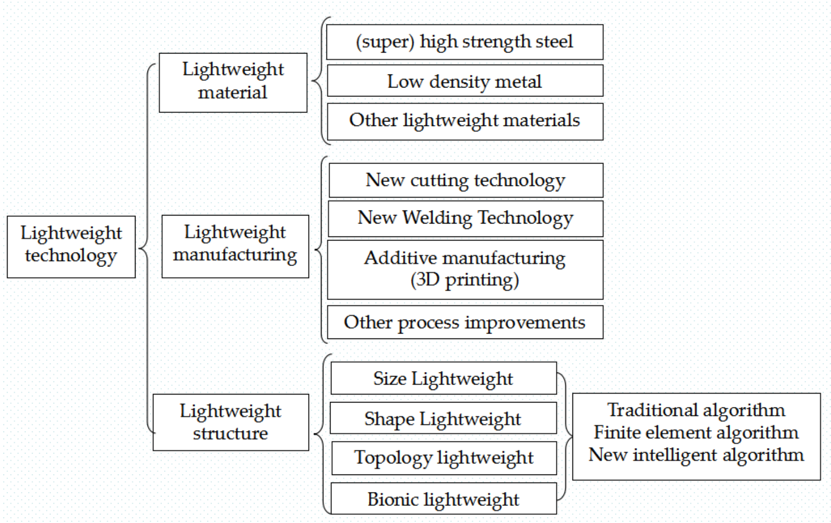

Figure 3. Lightweight technologies.

4.1. Material Lightweight

The key to lightweight materials is to find new materials with superior mechanical properties that can replace raw materials. Generally, the density of new materials is lower than the raw materials, and the strength is higher than the raw materials. Since it is related to important factors such as product performance and price, the choice of materials for the product is critical. High-strength steels, aluminum alloys, magnesium alloys, plastics, and composite materials are all lightweight materials [15–18]. Lai et al. [19] focus on the recent experience achieved by Fiat in introducing HSS up to reach a share higher than 60% in weight applying and developing new methodologies to solve in the design phase any criticality arising from the use of this material. It is possible to create a lightweight material made with gypsum and EPS [20] waste with enhanced mechanical properties, low density, and outstanding thermal behavior. However, the use of coarse EPS waste has a negative effect on the Shore C surface hardness, especially with latex and fibers. Liu et al. [10] proposed a structural optimization method for commercial front bumper system made of carbon fiber composite materials, which combined Kriging modeling technology with improved PSO algorithm to find the optimal strength and crash-worthiness requirements, to achieve weight reduction in 2016. In 2017, Zaiß et al. proposed new concepts for quality assurance of lightweight material. This provided a way of thinking for lightweight technology [21]. A lightweight, injectable, high-rigidity plastic composite to replace the aluminum in the chassis of the chassis was developed [22]. In 2018, Ma et al. [23] used HC70E and DOMEX700W to replace the traditional Q235E, which reduced the container quality by 19.2%. The carbon fiber composite materials, aramid fiber materials, and Balsa wood were used by Zhong et al. [24] in order to light the four-rotor UAV fuselage. The lightweight material was selected, and the weight analysis of the trailer chassis and trailer structure was carried out. It was found that the weight of the trailer structure was significantly reduced by 73.61%, thereby reducing the fuel consumption and preventing carbon dioxide emissions from environmental pollution [25]. Lightweight concrete has recently been introduced into structural engineering applications in Thailand in order to study the performance of porous lightweight concrete [26].

4.2. Structure Lightweight

Lightweight structure is a comprehensive analysis of the overall physical layout of each structural parameter of the product under the premise of satisfying the functional requirements and safety performance of the product, achieving the effect of quality reduction and stable performance. Lightweight structure is the best distribution of materials in the structure. It mainly includes structural topology optimization, shape optimization, size optimization, topography optimization, free shape optimization, etc. In recent years, combining them for lightweight design has become a mainstream practice.

4.2.1. Size Lightweight

Size lightweight refers to the optimization of the basic dimension structure by means of mechanical analysis. It means that the basic shape and size of the components have been determined, and the functions of the products have also been realized in order to improve performance and reduce costs. Many different types of sizes can be selected for optimization, and we can optimize the critical size (dimensions) of the product. Generally, the optimal size selection is based on the required functional and mechanical properties constraints to select the optimal combination from a certain limited range.

A lightweight design method for automobile body structure based on sensitivity analysis and side collision was proposed [27]. The thickness of the body structure parts is taken as the design variable, the modality and rigidity of the body-in-white are the constraints, and the body-in-white mass is the minimum. The sensitivity of the part thickness to the modality and stiffness of the body is analyzed. The thickness of the body parts that are insensitive to the modality and stiffness of the vehicle body and the crashworthiness are selected to optimize the calculation with the minimum body mass. The result of the optimization reduced the body by 14.8 kg. The simulation calculation of the side collision is carried out on the lightweight vehicle and occupant restraint system, and compared with the results before the lightweight, the vehicle crashworthiness and the safety of the occupant are compared and checked, according to the collision result. The thickness of the body parts was readjusted. The results show that the lightweight body meets the requirements of collision safety, and the dummy's C-NCAP score is acceptable. In 2014, Shi et al. [28] established the multidisciplinary design optimization model of the vehicle door, analyzed the sensitivity of the design variables, removed the design variables that had less influence on the structure, constructed the approximate response surface of each performance, and applied the genetic algorithm based on the response surface for multidisciplinary optimization. Zhang et al. [29] used the three-dimensional SolidWorks drawing software to establish a three-dimensional model of the gantry machining center. The key dimension sensitivity analysis of the V-shaped rib beam structure was carried out, and the beam size design was carried out by the extreme dimension adjustment method. During 2015, the shape and size of the ship's bottom slab and the upper building slab were optimized, to seek the optimal distribution of materials. Based on the above mentioned data, the volume fraction is set as the restriction condition of the model, and the structural natural frequency is set as the objective function [30]. Wang et al. [31] took the wall thickness length and transition angle of each section of hollow half-axle of automobile steering drive axle as design variables, the minimized quality of half-axle as optimization objective, and the second-order constrained mode frequency and equivalent stress at the end corner transition of half-axle spline as constraints, established a lightweight optimization model of half-axle. A combination of 10 design variables and three levels of numerical simulation tests was obtained by using an orthogonal experimental design. The response surface approximation model was established by the least-squares method, and the model was optimized by the sequence quadratic programming algorithm. Liu et al. [32] carried out a study on the optimization of the machine tool column topology. According to the results of the material distribution, the basic shape of the machine tool column was designed. Five different types of stiffened plate structures were compared. It was found that the material consumption of the W-type stiffened plate structure was less and the comprehensive mechanical properties were better. The W-type stiffeners were selected to optimize the layout and size of the column, and the lightweight design of the column structure was realized. Chen et al. [33] used the correlation analysis method to analyze the influence of design variables such as 90 position shapes and thicknesses on the structural rigidity of the SUV body-in-white, and selected the design variables with lightweight potential. Then, the multiperformance optimization design of the 30 design variables was carried out and finally achieved a good lightweight effect in 2016. In 2017, Wang et al. [34] established the optimization mathematical model for the cross-section size of the frame longitudinal beam, and the finite element analysis software programs were used to carry out modal analysis of the optimized frame solid model in order to verify its dynamic characteristics meet the dynamic requirements, which indicated that the lightweight optimization design is reasonable and effective. For the lightweight design of satellite structures, Li et al. [35] considered the manufacturing process constraints of augmented materials comprehensively, applied the topological optimization method to find the optimal path of force transmission in the feasible design space of structures, abstracted the corresponding truss structure on the basis of this method, and then applied the dimension optimization method to design the optimal truss member cross-section size. Finally, considering the optimal rod size and structural processing constraints, geometric reconstruction is carried out in order to obtain a structural design scheme for additive manufacturing. In 2018, Ma et al. [36] studied the lightweight design of the Chinese University Student Formula Race Car frame through size optimization under the premise of satisfying the frequency, strength, and stiffness constraints. Finally, the nonlinear optimization model was approximated by sequential linear programming, and a good lightweight effect was achieved. Jiang et al. [37] established a mathematical model with the minimum span beam as the objective function, the allowable stress of the beam as the constraint, and the unit thickness as the variables in the optimization of the spar size. By taking the volume of spar as objective function, the allowable stress of the spar as constraint, and web thickness as design variable, size optimization is conducted for the main spar and the rear spar. Subsequently, Xu et al. [6] took a midsize off-road vehicle frame as the optimization object, used the experimental design method to carry out the sensitivity analysis of design variables, and established the structural optimization model based on the necessary trade-offs of design variables. Simultaneously, the multi-island genetic optimization algorithm was used to calculate the natural frequencies of the frame under the three conditions of maximum stress, displacement and free mode, so as to optimize the discrete sizes of the frame plates under the constraints of natural frequencies, geometric sizes, and strength. Deng et al. [38] took the folding electric vehicle and main folding frame for the object and used SolidWorks to establish a simplified three-dimensional model of the main folding frame, which was imported into the ANSYS Workbench for static analysis. Lightweight design of the main folding frame connecting rod by topology optimization and size optimization under the static-load, sudden-braking, sharp-turn conditions. Zhang et al. [39] used a horizontal machining center bed as the research object, and used the wall thickness of the bed and the longitudinal thickness, the lateral thickness of the rib as the design parameters, and carried out an orthogonal test on the test data by least-squares method. The response surface model of the bed mass, maximum deformation, maximum stress, and the first four natural frequencies are obtained. Taking the minimum bed mass as the optimization goal, the maximum deformation amount, the maximum stress, and the first four natural frequencies remain unchanged, and the objective function is solved by the stepwise quadratic programming method, to complete the size optimization. The optimization results show that the bed quality is reduced by 5.01% when the static and dynamic characteristics of the bed are basically unchanged.

4.2.2. Shape Lightweight

Shape optimization structure can further improve the product's superiority and the performance of the product by further improving the topography and shape characteristics of parts under the condition of the overall topological relationship being roughly determined. For example, in the same part of the hole, whether the rectangle is suitable, or the circular is more superior, that is shape optimization. The different sections of the boom were analyzed, from the quadrilateral section to the nine-sided section and the large rounded corner section, and obtained the influence of the section shape on the function, stability, and expansion of the boom, which has a certain reference value for other scholars to study the shape optimization structure [40].

Based on the curve-surface equation, geometric design variable parametric mapping definition of the new method, and shape optimization design problem design variables less and more constraints, experts took the shape optimization design of two squirrel cage elastic support slots as an research object, the optimization design of squirrel cage elastic support slots with single symmetry, double symmetry, and ellipse periodic distribution was obtained. The slots were found to be excellent, and the shape is narrow at both ends [41]. Zhang et al. [42] proposed a new method of hole-shape optimization on general composite surface. The method of parameter mapping was used to optimize the hole shape on the surface structure, and the failure function value on the hole circumference curve was selected as the optimization design objective. The effects of Mises, Tsai-Hill, and Tsai-Wu failure criteria and three different material systems on the optimization results are compared when elliptic function is used to describe the hole shape. Finally, an example of spline function to describe the hole shape was given in 2011. Developing new methodologies for shape optimization of openings on three-dimensional curved panels that are used widely in aeronautical and aerospace engineering. To circumvent the difficulties associated with the hole boundary shape parameterization, a virtual punching method that exploits Boolean operations of the CAD modeler was proposed [43] for the definition of shape design variables. Compared with the parametric mapping method developed previously, the virtual punching method was shown to be an implicit boundary representation for this specific kind of structure. Instead, the parametric mapping method was based on the explicit boundary representation. A zero-order genetic algorithm (GA) was correspondingly implemented into the design procedure of the virtual punching method in order to execute the optimization process for two reasons. First, it makes it possible to avoid sensitivity analysis that is relatively difficult due to the implicit boundary representation formulation and the use of an unstructured mesh. Second, the computing cost of the GA is practically affordable in shape optimization because often only a small number of design variables are involved. Numerical tests are carried out for typical examples of the stress concentration minimization around openings on the curved panels in 2012. Zhang et al. [29] used the three-dimensional SolidWorks drawing software to establish a three-dimensional model of the Longmen Machining Center. Based on the original beam structure, the well-shaped ribbed plate (original beam structure), ten-shaped ribbed plate, X-shaped ribbed plate, and V-shaped of beam structure schemes were designed. The ANSYS software is used to compare and determine the V-shaped rib beam structure as the optimal solution. Isogeometric Analysis uses NURBS to achieve seamless connection of computer-aided geometric design (CAD), finite element analysis (FEA), and structural optimization [44]. This method uses the NURBS control point of the geometric model boundary as a design variable, which greatly simplifies the optimization process. However, due to the large changes in the design variables during the optimization process, the adjacent control points are too close or too far apart, resulting in grid overlap and malformation, reduced computational accuracy, and even interruption of the iterative process in 2013. Taking the rotating shell structure as the object, Sun et al. [45] derived the parameterized expression of the opening boundary of the rotating shell based on hyperelliptic equation and coordinate mapping transformation, and carried out the study on the dynamic optimization of the opening shape in 2015. In order to improve the precision, efficiency, and convergence of structural optimization calculation, the quasi-equal-arc length method and the sequence response surface approximation modeling method (SRSM) based on uniform design are proposed to achieve the precise approximation of spatial hyperelliptic curves respectively, which have certain application value for the design of structural shape optimization in time-consuming engineering. Simultaneously, Zhang et al. [46] discussed the extended shape optimization problem of support structures, namely Dirichlet boundary and free boundary simultaneous optimization. Different from traditional FEM, weighted B-spline finite element method and the level set function were applied as structural analysis tools to consider Dirichlet boundary conditions automatically compensates for displacement field shape optimization. In 2018, aiming at the lightweight design of the steering wheel of a certain model [47], the hybrid analysis model of the steering wheel skeleton beam body was established. The skeleton section was parameterized, and the non-sensitive parameters identified by the sensitivity analysis of different section shape parameters were used as design variables, and the performance evaluation index was used as the constraint condition to carry out the lightweight design of the steering wheel skeleton. Zhang [48] studied the excellent properties of honeycomb structure with high strength, light weight, energy absorption, shock absorption, sound insulation and heat insulation. Shape optimization was performed from three angles of the thickened joint, nonregular hexagon and gradient edge thickness honeycomb structure. From the theoretical analysis and experiment, the compressive and flexural properties of three honeycomb structures were explored. It is one of the most widely used structures in lightweight design. Ma et al. [23] optimized the structural design of the side plate assembly by changing the reinforced steel shape and the shape of cross section, and optimized the structural design of the automobile cargo box guard plate assembly by reducing the number of reinforcing steel bars and changing the position of reinforcing steel bars.

4.2.3. Topology Lightweight

Topology optimization is used to determine the distribution of materials by analyzing the distribution of structural forces. Reducing or simply removing material in places with small forces, retaining or adding materials to areas with large forces or complex forces. In the case of meeting the mechanical constraints of the material, the material is distributed as much as possible to reduce the structural quality reasonably. Actually, the structural topology design [49] seeks the optimal distribution of materials within the design area, i.e., it should be determined which points of the space are material points and which points remain as holes. Structural topology optimization includes topology optimization of discrete structures and topology optimization of continuous variable structures [50]. In recent years, some progress has been made in structural topology optimization design, and topology optimization of truss structures in engineering is the most studied. Back to the truss theory proposed by Michell et al. in 1904, this theory can only be used for single-case conditions and relies on the selection of appropriate strain fields, which cannot be applied to engineering practice. In 1964, the ground structure approach was proposed, and numerical methods were introduced. Since then, the study of topology optimization has revived, and some analytical and numerical theories have been proposed. At present, the numerical methods for continuous structure topology optimization include: level set method, branch and bound, steepest descent method, homogenization method, variable thickness method, variable density method, progressive structure optimization method, and so on.

Before 2010, topology optimization developed rapidly, and many experts studied and expanded it from different angles. Kim et al. [51] applied topology optimization in thin-walled beam section design for the first time successfully. The cross section of the different thin-walled beams is very useful for identifying the orientation and position of the reinforcement. In proposing topological optimization problems, a simple power law is applied to the relationship between the density of elements with holes and the mechanical properties of the elements. Wang et al. [52] proposed a new method for topological optimization of level set models with structural boundaries embedded in scalar functions of higher dimensions. Allaire et al. [5] proposed a new numerical method based on the combination of classical shape derivatives and forward propagation level set methods. This level set model can flexibly handle complex topological changes and succinctly describe the boundary shape of the structure. Topological changes, fidelity, and automation of boundary representations can be handled and compared to other methods based on boundary changes or homogenization. In this paper, only direct and linear velocities are achieved, and nonlinear speed functions may greatly increase computational efficiency and efficiency of fast fusion. Based on previous research, Wang et al. [53] combined the Radial Basis Function (RBF) with the traditional level set method to construct a more effective structural topology optimization method. RBF implicit modeling with multiquadric (MQ) splines was developed to define the implicit level set function with a high level of accuracy and smoothness. An RBF-level set optimization method was proposed to transform the Hamilton–Jacobi partial differential equation (PDE) into a system of ordinary differential equations (ODEs) over the entire design domain of the method of lines. Subsequently, Guo et al. [54] reviewed the development history and research status of structural topology optimization from two aspects, discrete structure topology optimization and continuum structure topology optimization, and put forward the research direction of topology optimization in theory, practical application, expansion, and software research. At the same time, Chen et al. [55] proposed a level set method for structural stiffness topology optimization by implicitly embedding the boundary of the structure into a zero-level set model of a high one-dimensional scalar function. The dynamic motion of the level set function is controlled by a Hamiltonian–Jacobi-type partial differential equation, which indirectly realizes the dynamic evolution of the structure boundary topology and shape. The normal motion velocity in the partial differential equation is established based on the shape sensitivity analysis result of the optimized objective function, combining finite element method and finite difference method, to realize numerical calculation of the elastic equilibrium equation and the Hamilton–Jacobi equation. The method can optimize the topology and shape of the structural design boundary and obtain the smooth boundary form simultaneously. There is no intermediate density material phenomenon like the homogenization method or the density function penalty method and the chessboard format numerical calculation singularity problem. Luo et al. [56] proposed a new semi-implicit level set method for structural shape and topology optimization. The structure boundary is implicitly expressed as the zero-level set of high-dimensional scalar functions, including appropriate time-marching schemes, to achieve discrete level set processing. The main feature of the present method is it does not suffer from any time-step size restriction, as all terms relevant to stability are discretized in an implicit manner. The semi-implicit scheme with additive operator splitting treats all coordinate axes equally in arbitrary dimensions with good rotational invariance. Hence, the present scheme for the level set equations is stable for any practical time steps and numerically easy to implement with high efficiency. Liu et al. [57] took the engine hood of a certain type of vehicle as the research object, and took the topology optimization method as the guidance, designed three different schemes (original structural optimization, small hole reconstruction, and overall reconstruction) to optimize the structure of the hood, and analyzed its mechanical properties. Based on the original structure, the topology optimization of the uniformly distributed holes in the part with less load on the structure is relatively conservative, and the lightweight margin is small, but the feasibility is large. In the original structural scheme, some holes have been dug in the cover plate in order to reduce the weight, and the holes in the original structure cannot be rearranged, so that fewer parts can be lightened, which limits the topology optimization design. Therefore, the small holes in the original structure of the cover plate are filled, leaving only three large pairs of holes in the cover plate structure, and then topology optimization is performed, and the holes on the inner plate are rearranged according to the optimization result. All the holes in the original hood structure are filled, and then analyzed by topology optimization software to re-divide and design the overall structure. The topography of the outer ring of the cover plate is unlikely, and the outer ring of the cover plate may have an assembly relationship with other parts of the body. Therefore, in the optimization scheme, the outer-ring structure of the cover plate is separated, and as an untreated structure, only the internal structure is optimized. Many scholars [58–60] optimized the stiffened layout of thermoelastic structures and thin-walled structures under inertial load successively. Qiu et al. [61,62] carried out topological optimization of size-dependent sandwich structure and functionally graded material structure respectively.

Kang et al. [63] proposed a topology optimization based on node nonlocal density interpolation structure, which avoided the checkerboard pattern and the "island" phenomenon successfully. In this method, design variable points can be positioned at any locations in the design domain and may not necessarily coincide with elemental nodes in 2011. By using the Shepard family of interpolants, the density value of any given computational point is interpolated by design variable values within a certain circular influence domain of the point. Liu et al. [64] studied the structural topology optimization design problem under the condition of simple harmonic load, with the specified displacement response amplitude of the structure as the design target and the structural volume as the constraint. The variable density method and the sensitivity filtering method are used to optimize the topology of the dynamic displacement response. In order to eliminate the local modal phenomena that are prone to appear in the dynamic topology optimization problem, a polynomial interpolation model of material properties is introduced, and the sensitivity redistribution method is adopted to avoid the checkerboard phenomenon in the topology optimization process in 2012. The SIMP mode was established [65] according to the variable density method in order to meet the requirements of high modality and high lightweight of the workpiece square mirror in 2013. The maximum stiffness or strain energy is often used as the objective function of optimization, and the volume constraint of the whole structure is the optimal constraint. It can be transformed into the objective function with the minimum volume under the given structural stiffness constraint. Assume that the material density is constant within the cell and is used as a design variable, while the material properties are used. The exponential function of density is simulated. The exponential function relationship of relative density has greatly improved the elimination of checkerboard phenomenon and numerical stability. Yang et al. [66] conducted a finite element analysis on the bonnet of a car under four common conditions (the forward bending conditions, lateral bending conditions, torsional bending conditions, and constrained mode conditions). The topology optimization method was adopted to optimize the central area of the inner hood of the hood with the minimum weighted strain energy as the optimization target. Optimize the area of the hood ribs, and export the STL file with OSS mooth, regenerate the surface, import it into CATIA, modify the model according to the topology-optimized shape and material distribution path, and obtain the topology-optimized hood. The hood plate with optimized topology is obtained, and high-strength steel, aluminum alloy, and magnesium alloy are selected as replacement materials, respectively. In 2014, the optimized aluminum alloy solution with topological structure was the optimal lightweight solution. Zhang et al. [67] researched on various simultaneous topology optimization methods extended from standard formulas discussed the scalability and accessibility of topology optimization. Zhu et al. [68] introduced the AWE method to maintain the topology optimization formula for the extended shape retention of the specific local domain configuration. Compared with the standard topology optimization design maximizing structural stiffness, this formulation has evidently shown that the coordination of multipoint displacements and the effect of shape-preserving can be successfully achieved. Cai et al. [69] proposed an efficient and flexible design method, which integrates B-spline finite element method and level set function to solve stress-constrained shape and topology-optimization problems. Any structure of complex geometry is embedded within an extended, regular, and fixed Eulerian mesh, no matter how the structure is optimized. High-order B-spline shape functions are further implemented to ensure precisions of stress analysis and sensitivity analysis. The parameters involved, rather than the conventional discrete form of LSF, are used directly as design variables, to simplify the numerical calculation process. Specifically, LSF is constructed by an R function that combines cubic splines into implicit functions, providing flexibility for shape optimization within a fixed grid frame, while compactly supported radial basis functions (CS-RBF). It is used as an implicit function stress-constrained topology optimization function to calculate stress and stress sensitivity with high precision. Zhang and Yang [30] took the ship floor frame and superstructure frame as the research object. In order to improve the space layout of the top of the cabin, the topology of the superstructure frame was optimized, and the optimal distribution of materials was sought. The structure type and structure of the topology optimization were obtained. The type makes the material distribution more reasonable. In 2016, Zhu et al. [70] explored the latest advances about topology optimization techniques for aircraft and aerospace structural design. Lee et al. [71] proposed a novel P-norm correction method and a maximum stress-constrained topology optimization lightweight design. The modified P-norm correction method to overcome the limitation of conventional P-norm methods by employing the lower bound P-norm stress curve. Zheng et al. [72] used the method of topology optimization and size optimization to optimize the frame structure of FSAE racing car, and verified the lightweight design of L-shaped and cantilever beams with yield strength constraints. In order to avoid gray areas, Zhou et al. [73] proposed an approximate symbolic distance function to regulate LSF and KS functions. The bounded normalized attribute of KS functions is a symbolic distance function or a normalized first order approximation. The novelty lies in the fact that many arbitrarily shaped engineering features are considered basic design primitives. The Kreisselmeier–Steinhauser (KS) function of Boolean operations is used as LSF, which uses implicit functions to ensure smooth description and topological changes of basic features and the entire structure. Second, using the modified Heaviside function to smooth the transition of the air-solid material at a fixed point. To calculate the mesh, a narrow-band integration scheme was developed for effective sensitivity analysis. Level Set Method (LSM) to describe design geometry and Extended Finite Element Method (XFEM) were used to solve control equations and measure design performance [74]. Chen et al. [75] introduced the application of topology in bridge design. The basic principles of structural topology optimization are systematically illustrated from three aspects: physical model, mathematical model, and optimization algorithm. This paper introduces the application of topology optimization technology, to find the structure of bridge structure, and shows the structure derivation process and optimization results in topology optimization. In view of the difficulties faced by the current structural topology optimization technology in the bridge type finding, the direction of future research is discussed. Zhu et al. [76] proposed a conformation-preserving topological optimization design method to suppress the warping deformation of local structural domains. The optimization results showed that the constraint of local strain energy on the shape-holding domain could suppress the warping deformation in complex projects effectively. In 2017, Zhang et al. [77] introduced the free curve of closed B-spline as the structural topology optimization of basic design elements in order to realize topology optimization with a small number of design variables. Complex shape of design domain is rigorously modeled by means of level-set description and Boolean operation. Topology optimization is carried out conveniently within the framework of fixed grid. Computing accuracy is ensured effectively with the use of finite cell method. Xie et al. [78] established a simplified vehicle model for the front longitudinal beam of electric vehicles and used the Kriging method, genetic algorithm, and fruit fly optimization algorithm to lightly design the front longitudinal beam. Teng et al. [79] proposed a progressive structural topology optimization model with the objective of maximizing the natural frequencies of specific modes and minimizing the weighting function of dynamic compliance in order to achieve multi-objective dynamic structural topology optimization design. Gao et al. [80] studied the topological optimization of a given fixed boundary continuum under uniform force. The variance of the reaction forces at the boundary between the elastic solid and its foundation is firstly introduced as the evaluation criterion of the uniformity of the reaction forces. Then, the standard formulation of optimal topology design is improved by introducing the variance constraint of the reaction forces. Sensitivity analysis of the latter is carried out based on the adjoint method. In 2018, Picelli et al. [81] proposed a horizontal set method to solve the problem of minimum stress and stress-constrained shape and topology optimization. This method solved the sub-optimization problem in each iteration in order to obtain the best boundary velocity. Zhu et al. [82] focused on the dynamic response structure topology optimization method under harmonic fundamental acceleration excitation. In the dynamic response analysis, we propose using the large mass method (LMM) in which artificial large mass values are attributed to each driven nodal degree of freedom (DOF), which can thus transform the base acceleration excitations into force excitations. Mode displacement method (MDM) and mode acceleration method (MAM) are then used to calculate the harmonic responses and the design sensitivities due to their balances between computing efficiency and accuracy especially when frequency bands are taken into account. Wang et al. [83] took the support frame of photovoltaic panel cleaning robot as an example and proposed a lightweight design method based on the combination of topological optimization and response surface method. A numerical simulation experiment combination of seven design variables is obtained by using the Box–Behnken experimental design. Furthermore, a response surface approximation model for the bearer frame is established based on quadratic polynomial regression equations. An iteration optimization is conducted on the model with multi-objective genetic algorithm, the multi-objective genetic algorithm to carry out iterative optimization calculation on the approximate model. Hou et al. [84] used Sines standard to deal with fatigue constraints based on the background of pressure topology optimization in order to avoid the failure of connection area in multi-fastener connection design. Q-P relaxation was used to solve the singularity problem related to stress constraints in order to achieve the purpose of topology optimization. Subsequently, Wang and Ruan [85] carried out lightweight design of the steering vertical arm about commercial vehicle based on the topology optimization technology of HyperWorks. On the basis of the results of the topology optimization of the vertical arm, the second design of the vertical arm was carried out. By comparing the structure of the vertical arm before and after optimization, it was found that the weight of the new structure was reduced by 13.02%, while the original strength and stiffness remained basically unchanged. Huang et al. [86] established a mathematical model for topological optimization of a naval gun bracket by homogenization method theory, which takes the cell density of a microstructure as the design variable, the minimum compliance as the objective function, and the volume function as the constraint function. It implements the topology optimization process with ANSYS finite element software. In addition, it is an important step to make the optimization result manufacturable. This also provides a design idea for general mechanical structure problems. Bai et al. [87] carried out the topological optimization design of the rack and obtained the optimum material distribution of the rack structure. Referring to the optimized structure, the frame model is rebuilt, and the finite element analysis is carried out to verify the reliability of the results, which improves the utilization rate of materials under the condition of meeting the requirements. Shen et al. [88] took the smallest flexibility of a harvester gearbox shell as the objective function, combined with the variable density method and Lagrange multiplier method in order to optimize the gearbox topology, removed some redundant materials, and designed reinforcing ribs. In order to realize the lightweight design of the cold-end fan blade in the case of bird impact, Wu et al. [89] started from the point of structural topology optimization calculation, met the strength requirements of airworthiness regulations, while reducing the mass by 37.9%. It has certain practical reference value and broad application prospects in dynamic optimization of engineering structures. Level set-based optimization for two-dimensional structural configurations with thin members is presented. A structural domain with thin thickness is defined as a narrow band region on the zero-level contour [90] of the level set function. No additional constraints or penalty functional is required to enforce semi-uniformity in member thickness. An improved topology optimization approach named adaptive bubble method (ABM) was proposed to overcome the shortcomings of the traditional bubble method, such as the frequent remeshing operation and the tedious merge process of holes [91]. Recently, an algorithm [92] combining solid isotropic material with penalty (SIMP) and bidirectional evolutionary structure optimization (BESO) was proposed, while topological optimization of lightweight cellular materials and structures. An example of a simple support beam and a cantilever beam demonstrates the effectiveness of the method, but the method assumes the uniqueness of the microstructure of the lightweight porous material, which is somewhat idealized and is not conducive to actual demand.

4.2.4. Bionics lightweight

Biological structure is the result of hundreds of millions of years of natural selection and evolution of life. It has incomparable advantages over the structure of artificial materials [93]. Bionics is a technical imitation of the functions of animals and plants in nature, which provides a bridge between biology and technology and provides new ideas for solving technical problems. By reproducing the principles of biology, humans have found many technological solutions. Structural bionics is an important branch of bionics. It mainly studies the structure, material, and function of organisms and designs bionic structures.

Mechanical structural bionics mainly imitates the special abilities of organisms; studies the structure, function, and working principle of organisms; extracts useful configuration features and transplants these principles into engineering technology; invents superior instruments, devices, or machines; and creates new technologies to improve their structural efficiency [94], which is also the ultimate goal of lightweight design. The function of living things is far superior to any artificially manufactured machine. Bionics is a discipline that is used to achieve and effectively apply biological functions in engineering. There are many parts or mechanical designs in the industrial manufacturing field that are inspired by biology, such as applying the shape or skin structure of a dolphin to the submarine design principle: imitating the bat's function of ultrasonic positioning and ranging to produce radar equipment; imitating the shell-built large-span thin-shell building; imitating the femoral structure to build the column, which eliminates the area where the stress is particularly concentrated, and can withstand the maximum load with the least building materials. Supporting human weight-bearing and moving bones, the dense bones in the cross section are distributed around, and the soft bone marrow fills the lumen. Interestingly, this conclusion is also reflected in many animal and plant tissues in nature. For example, the stem of many plants that can withstand the strong wind is a vascular structure with hollow cross section. Therefore, it is possible to apply the idea of structural bionics to lightweight design, which is difficult to achieve by traditional methods.

Before 2010, Zhang et al. [95] studied the porous structure of chicken eggshells, parrot eggshells, pork bones, mung beans, soybeans, ginkgo biloba, lotus seeds, and apple epidermis. From the point of view of the distribution of pore density, size, and geometry, the pore of natural structure can be divided into uniform pore, gradient pore, and multi-hole. The development of an optimal porous bearing based on the gradient configuration of natural materials also indicates that the biomimetic porous structure design is expected to be widely developed and applied in the field of materials and mechanical engineering in the future. Zhou et al. [96] established a driving mechanism to flap the wing angle in a motion cycle for the phenomenon of tilting to the left or to the right caused by the incomplete symmetry of the flapping wing. The mathematical model of the difference between the difference and the angular velocity, and the optimization of the objective function by the pattern search method under the constraints of mechanics and bionics. Zhao et al. [97] summarized the configuration of light and high-efficiency biological structures and applied them to the structural bionic design of high-speed machine tool work ribs. Ansys' APDL parametric language was used to establish an optimization model to determine the optimal structural parameters of the workbench ribs. The bionic annular sandwich rib structure is used in the rib layout of the workbench, and the diagonal ribs are arranged in the direction of the maximum deformation gradient to realize the weight reduction of the structure and the improvement of the static and dynamic characteristics. Subsequently, Qing et al. and Liu et al. [98,99] introduced the lowest cutting resistance and higher in the cutting process based on the geometry and excellent biomechanical functions of animal teeth, claw toes, and body surface. The service life provides the basis for bionic research for the optimization of geometrical parameters and mechanical properties of cutting tools. Helms et al. [100] learned about the biologically inspired engineering design process and gained a deep understanding of biologically inspired design. At the same year, Ma et al. [101] analyzed the structural similarity between Dragonfly membrane fin and aircraft fuselage reinforcement frame, extracted the structural characteristics that determine the excellent mechanical properties of dragonfly membrane fin structure(polygon unit and wing angle), and applied them to the design of aircraft fuselage reinforcement frame. Liu et al. [102,103] designed wind turbine blades based on the characteristics of plant leaf vein distribution and mechanical properties. According to the high similarity between human respiratory system and engine intake-and-exhaust system, the model of automobile exhaust manifold was established [104–107] by using human bronchus, and verified the mechanical performance analysis respectively. Meanwhile, Quinn et al. [108] discussed how to apply bionics to engineering. Han et al. [109,110] of Jilin university conducted dynamic and modal analysis of bionic surface shape gear.

Shu et al. [111] reviewed the research of biological heuristic design in 2011. In 2012, Cadman et al. [112] attracted much attention in mechanics and biology because of its unique chemical, mechanical, and structural properties, based on the special ultralight cell natural material of cuttlebone. Since the square ribs are stretched between each other during casting cooling, cracks are likely to occur during cooling or residual internal stress is high after casting, and rupture of the rib may occur due to impact [113]. The honeycomb structure design to improve the dynamic and static stiffness of the whole machine of the moving beam gantry machining center by using bionics principle were adopted. Based on the characteristics of plant veins and dragonfly-wing veins, structural bionic design of the aircraft bracket was carried out [114]. In the design of the end-face reinforcement ribs, the main reinforcement ribs are arranged mainly along the stress-gradient direction and the deformation-gradient direction, the secondary reinforcement ribs are arranged on both sides of the main reinforcement rib, and the distribution density of the reinforcement ribs is increased in the large stress area. In the design of the end-face reinforcement ribs, the main reinforcement ribs are arranged mainly along the stress-gradient direction and the deformation-gradient direction, the secondary reinforcement ribs are arranged on both sides of the main reinforcement rib, and the distribution density of the reinforcement ribs is increased in the large stress area. Fu et al. [115] proposed a lightweight structure design of the vein-to-rib-cage beam with reference to the biological vein structure with similar structure, force, and functional characteristics of the upper flange plate of the crane, mimicking the structural characteristics of the vein inclination and stagger. Zhao et al. [4] studied the research methods and processes of structural bionics, analyzed the typical application and progress of structural bionics in the field of mechanical engineering, summarized the role of structural bionics in the field of mechanical applications, and prospected the development prospects of structural bionics. Based on structural bionics, topology optimization and dimension optimization design methods, Wang [116] carried out optimization design research on the rotary table of key parts of 4 m NC vertical lathe, aiming at improving structural stiffness and reducing its mass, optimizing the target demand analysis of the rotary table, and finding the bionic prototype. Based on the excellent bearing performance of the water lily plant, Wang Lian, we use the fuzzy similarity analysis method to calculate the similarity between Wang Lian and the rotary table, and determine that Wang Lian works for the rotation, by extracting the configuration law of the leaf vein structure of Wang Lian, constructing two bionic optimization models of the rotary table, and performing static analysis. The combination of structural bionics and topology optimization provides a new idea for obtaining more reasonable structural form of machine-tool parts. Based on the idea of structural bionic optimization design, combined with topological optimization analysis, structural bionic optimization design research on the main metal structure of QD75T/31.5 m bridge crane-box girder were carried out in 2013 [117]. Based on the fuzzy similarity theory, the similarity calculation between the biological prototype and the box-shaped main beam was carried out, and the bamboo and Wanglian were determined as biological prototypes. The structure and configuration of two biological prototypes of bamboo and Wanglian were studied and extracted, and then they were applied to the study of structural bionic optimization design of the box-shaped main girder of bridge cranes. Two kinds of bionic main girder models were established. The static analysis and modal analysis of the bionic main beam are carried out. The design results can be used for reference by crane designers and provided a new design idea for the crane to break through the traditional experience design. Based on the similarity between the wind turbine and the king palm plant in terms of configuration and stress environment, the structural properties of the king palm plant are used to lighten the structure of large wind turbine towers and blades [118]. Meng [119] explored and studied the structural bionics design method of engineering machinery, and carried out bionics design on the structure and chassis structure of engineering machinery. The system combs the various theoretical theories on which structural bionics depends. It briefly explains the general methods and processes of structural bionics research and application. It clarifies the relationship between structural bionics theory and engineering machinery structural design, and it provides a new innovative design idea for engineering machinery. The bionic structure design and finite element static analysis of the excavator's stick were carried out based on the hollow structure of the bone dispersion, the ribbed plate structure of the Wanglian blade and the Xianren column, and the hierarchical structure of the shell and the bamboo. Liu and Chen [120] aimed at the lightweight design requirements of thin-walled parts, based on the analysis of the shape and configuration of Wang Lian's vein branching structure, took the aircraft cover prototype as the object, and applied the structural bionic design method, to carry out the structural bionic lightweight design of the rib distribution form inside the cover plate. Fu et al. [121] used bamboo as a bionic object to optimize the structural design of the transverse rib of the normal rail box girder, which made the crane box girder structure lighter. Qi et al. [122] studied the structure of bamboo based on bionics principle. Bamboo joints have the function of fixing bamboo body, increasing the mechanical strength of the stem, making the stem stronger, not easy to lodge and deform. The lightweight design of tower equipment was discussed. In 2014, Li et al. [123] designed a new method for the layout of reinforced ribs in large machine tools based on the natural growth principle of plant veins. If we confirm the potential of leaf venation as concept generators for creating the optimal load-bearing topology for stiffened machine-tool structures, then a mathematical model explaining the optimality of plant morphogenesis is presented. Based on this, an evolutionary algorithm was developed, which uses three growth strategies to determine the candidate stiffeners to grow or atrophy with respect to the loads applied. The proposed growth-based method could generate a distinct stiffener layout, which is different to those produced by the conventional topology optimization methods, and thus offers unique possibilities of improving the design efficiency and commonality for machine-tool development. Huang et al. [124] designed the tail swing structure of the underwater fish robot based on the advantages of high efficiency, low noise, high speed, and high maneuverability of underwater organisms. Chen et al. [125] discussed the biological skeleton of fish bones, leaves, and feathers and carried out a structural layout design of a large aspect-ratio wing, with the help of bionics theory. Based on structural bionics, You et al. [126] used the topological principle to optimize the design of the rib structure inside the column of nose milling machine. After the improvement, the quality of the column was reduced and the stiffness and mechanical properties were improved significantly in 2015. In 2016, a bamboo-like tower structure [127] was proposed. The application method of structural bionic design theory in bionic design of tower structure was proposed, and a bionic tower model for the bamboo-like structure was established. Bamboo was chosen as the biological prototype, and the similarity between the tower and the bamboo was calculated from the aspects of structure, function, load, and constraint, which verified the rationality of the biological selection. The knot-like feature structure of bamboo was extracted and used for tower design. A bionic tower with five reinforcement sections was proposed, and the geometric model of the tower was established. It can provide theoretical reference for tower structure design. Bao et al. [128] proposed a bionic design method of lightweight strengthened structure, which studied honeycomb according to the characteristics of leaf veins and leaves to optimize the shape and distribution of reinforcing plates. Chen et al. [129] pointed out that two biomimetic structures that appeared in recent years did not meet the requirements according to the characteristics of three-dimensional lightweight structure of beetle's front wing, which was helpful for the biomimetic application research of improving the structure of beetle's front wing. Jia et al. [130] elaborated the correlation between structural bionics and structural design of engineering machinery and also provided a new idea for the innovative design of engineering machinery in 2017. In 2018, Shan et al. [131] designed the bionic robot thigh, according to the CT of the human femur, and established an asymmetric spatial tetrahedral mesh structure along the vertical stress line inside the thigh, to achieve its weight reduction. It provides a new idea for the design and manufacture of humanoid robots. Cao et al. [132] studied the structure of lightweight and high-rigidity organisms, designed the frog plate bionic structure of SCARA manipulator arm by Pro/E three-dimensional software, and used ANSYS Workbench to analyze the statics and modal analysis to obtain the optimal stiffness and lightweight ribbed bionic II model. Wang et al. [133] carried out bionic design based on bamboo and realized lightweight design of the crane. Compared with the transverse ribs of traditional box girder, the bionic design of bamboo can correspondingly reduce the number of transverse ribs, which could meet the stability requirements, as well as the lightweight requirements, while also meeting the strength and toughness requirements. Zhao et al. [134] explored the biomechanical morphology of the leaves and stems of representative emergent plants by combining experimental and numerical methods, and they developed an interdisciplinary topological optimization method that combines mechanical properties and dual ecological constraints. In the two-way evolutionary structure optimization technique, the proposed biophysical insights are expected to be used to design efficient and advanced structures (aircraft wings and turbine blades).

4.3. Lightweight Manufacturing Technology and 3D Printing

Lightweight materials are only one aspect of research. When new materials are identified, new production processing conditions are needed to reduce weight. The organic integration of new material and new technology into product development not only improves the product performance, but also effectively shortens the production time and material consumption of the product and shortens the whole life cycle of the product. The development and research of new technology has pointed out a new way for lightweight. The optimization of lightweight manufacturing technology can be divided into cutting, welding, and improvement of other processes of Tox connection. Cutting technology is mainly considered to adopt advanced equipment or improved process method to improve the machining accuracy and efficiency. In welding technology, besides using advanced welding equipment, good welding technology can not only improve the welding strength, but also make the appearance of welding neat and beautiful.

The 3D Kagome lattice structure, 3D pyramid structure, and hexagonal diamond structure were designed. The selected material was fabricated by using an Objet 350 3D printer and a polypropylene-based photopolymer called Objet Durus White RGD430 in 2014 [135]. In 2016, Li et al. [136] proposed a density-aware internal support structure modeling scheme in order to realize the lightweight modeling of 3D-printing model which conforms to the mechanical characteristics. The Density-Controllable internal support structure was generated according to the structural analysis. Simultaneously, Jiang et al. [137] proposed a "weak balance" lightweight modeling scheme, to generate the internal filling structure of 3D printing model. The scheme can generate internal density-varying fillings based on structural analysis automatically. The lattice structure has many properties superior to solid materials and traditional structures. It can integrate many functions. Tao and Leu [138] used AM technology to make a computer-aided design model, which is more complex than the traditional program, by adding materials layer by layer. In 2017, Eichenhofer et al. [139] introduced a new type of additive manufacturing technology for fiber reinforced thermoplastic composites, namely ultra-lightweight continuous lattice manufacturing, and demonstrated its ability to characterize anisotropic materials in digital manufacturing structures. Nguyen et al. [140] used topology optimization as an innovative design tool, to facilitate additives manufacturing, by adding materials layer by layer, to achieve complex geometry. Almost any product can be manufactured, and the best product structure can be created with the least amount of materials, but can still ensure the product attributes of machinery. Li et al. [35] applied topological optimization method and size optimization to find the best path of force transmission and the optimum cross-section size of truss members for the lightweight design of satellite structures. Considering the optimum rod size of truss members and the constraints of structural processing, geometric reconstruction was carried out to obtain the structural design scheme for material-added manufacturing to achieve lightweight design. Sun et al. [141] generated honeycomb path trajectories with controllable parameters based on material and compressive stress analysis. An adaptive generation technology of lightweight honeycomb 3D-printing path was proposed, which provided a new idea for direct printing generation of lightweight structure with improved local load-carrying performance in 2018. A novel compression-resistant lattice composite material by introducing a novel optimization method and metallization method was proposed [142], which made a great contribution to lightweight in 2019. Based on the bionics principle, Shan et al. [131] designed the bionic robot thigh according to the CT scan human-femur surface. Using laser melting technology, the lower thigh of the robot was printed in 3D, without the support of its internal mesh, in order to verify the manufacturability of the solid and spatial mesh chimera structure.

5. Conclusions and Prospect

This document is only a part of the literature at home and abroad in recent years and is for reference only. By reading a large number of research literature and books, the optimization problems of lightweight structure are all generated according to the characteristics of the research objects and the rigid requirements of researchers. Currently, the modeling ideas are relatively fixed and mature, and optimization methods are needed to solve this problem, which mainly include size, shape, and topology optimization. Before 2000, due to the limited technology, the size and shape optimization were used. After 2000, the topology optimization developed and is still relatively perfect so far. In recent years, combining these three methods for lightweight research has become part of the mainstream in engineering. At the same time, the imitation organism has excellent performance, is lightweight, and has a high-efficiency structure, which embodies the optimal distribution of materials and provides prototypes and methods for the lightweight design of mechanical structures. The best innovation of the 21st century is the intersection of biology and technology, and lightweight is conducive to saving materials and protecting the environment. It conforms to the national concept of low carbon, energy saving, and environmental protection. It benefits the country and the people, and it is more conducive to enterprises. A large number of theoretical methods and engineering application practices show that structural lightweight technology not only provides an effective design tool for the development of aircraft structures, but, more importantly, brings about changes in design concepts. This has always been the goal pursued by our engineers. In the future, we will continue our research on lightweight [143]:

- The research of lightweight model is limited to engineering software modeling. From the perspective of mathematics, we can describe the modeling by borrowing mathematical tools and specific mathematical relations guided by the physical background of the research object in the future.
- Practicality and precision of construction machinery. Combine the specific dynamic and static problems of the project with lightweight design to make it closer to the actual machine.
- Optimization of reliability. The reliability of structure is increasingly becoming an important indicator of modern structural design. The comprehensive design based on reliability size, shape, and topology optimization should be a research direction in the future.
- The combination of lightweight and additive manufacturing can effectively reduce the risk of revision and optimization of design, which is a very new trend in the future.
- The new intelligent algorithm can be cited to solve the lightweight model.
- Multidisciplinary cross-bionic lightweight will also be an exploration trend in mechanical engineering in the future.

Author Contributions: Conceptualization, J.W., Y.L., G.H., and M.Y.; methodology, J.W. and Y.L.; formal analysis, J.W.; investigation, J.W. and Y.L.; resources, Y.L.; data curation, J.W.; writing—original draft preparation, J.W. and Y.L.; writing—review and editing, J.W., Y.L., G.H., and M.Y.; funding acquisition, Y.L. and G.H.

Funding: This study was funded by the National Natural Science Foundation of China (51475366, 51475146, 51875454).

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

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