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Stiffness design of machine tool structures by a biologically inspired topology optimization method

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ABSTRACT

This paper introduces a novel approach for designing the stiffener layout inside large machine tools by applying the self-optimal growth principle of plant ramifications in nature. Firstly, numerical studies are carried out in order to 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 is 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. The suggested approach is finally applied to the re-design of an actual grinding machine column, on which the numerical analyses and experimental tests conducted exemplify the performance enhancement, and therefore is a good choice for the stiffener layout design of machine tool structures.

1. State of the art

The increasing demand for machine tools to be more productive, ecological and cost efficient poses new challenges for machine developers. Design activities of modern machine tools not only strive for excellent mechanical performances but also seek economic advantages for machine users [1–3]. On machine tool structures, only a small fraction of the material applied is critical to the kinematical functionality. This is because a majority of the material is there to connect the functional interfaces between individual components and therefore provides sufficient stiffness to carry forces so that such kinematical functionality could be fulfilled. For this reason, stiffness is no doubt a design priority, and is likely to become more important for high speed and high precision machine tools [4,5]. At this background, the primary focus for the design of machine tool structures is to increase stiffness whilst wherever possible keeping the component weights constant or reducing them.

Since the arrangement of stiffener plates inside machine tool structures could affect the overall stiffness greatly, how to determine the stiffener layout pattern is becoming a key issue. However, in traditional machine tool design, stiffener layout is usually selected based on manufacturing convenience, such as "X" shape, "#" shape or other simple shape, which may not be the best way to satisfy the criteria for required stiffness and material savings. In addition, most of the past studies on stiffener optimization have been limited to sizing optimization, where the shape and topology of stiffener plates are held constant while only a set of thickness parameters or spacing parameters is obtained [6–9]. Although sizing optimization is very easy to implement and can guide selection of reliable designs, it may also obscure new and better choices. For instance, if a completely new stiffener arrangement needs to be developed, this type of approach may not yield the true optimal solution because of its inability to modify the topology of stiffened structures.

To overcome the above shortcomings, it would be a wise way for designers to seek guidance and inspiration from the natural world [10,11]. A large number of successful biomimetic examples applied in different branches of technology, such as robotic systems [12], tribological products [13] and machining processes [14], are based on the clever and elaborate morphology of biological structures. Actually, optimization problems of stiffener layout are not confined to engineering design, natural morphogenesis of living organisms also provides similar scenarios. Specially, the ramified configurations in various biological structures, such as the leaf venation, root and axis system of plants are candidates that may immediately come to mind. Through the process of evolution, plants have been experimented with various

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load-bearing topologies for at least billions of years before the first human attempts in topology optimization. Although we are unable to confirm the extent to which plant models inspired our early ancestors, more recent examples of bionic applications for mechanical design are well documented. In the last few decades, the research in the Biomechanics Group Forschungszentrum Karlsruhe concentrated upon developing a method that mimics the growth principles of buttress roots in trees for shape optimization [15,16]. Milwich et al. developed a "technical plant stem", a biomimetic product inspired by mechanical properties found in hierarchically structured plant ramifications [17]. Ding and Yamazaki proposed a growth technique for innovative design of heat transfer systems by employing the optimality of biotic branch net in the plant world [18].

Although the morphologies and growth environments are different among various plant ramifications, they have one thing in common, that is their topologies are formed by a continuous growth process [19,20]. Compared with the conventional methods in topology optimization, the growth-based approach is more applicable to the layout design problem, because it can produce a distinct stiffener distribution rather than a vague material distribution, which leads to a considerable increase in design efficiency. Based on this understanding, the author and his colleagues performed an intensive study on adaptive growth simulation, which employs an evolutionary algorithm for supporting the generation of stiffener layout [21]. However, such algorithm is usable for structures with only one specified growth region, like the simply supported plate structure, it is not very helpful when dealing with large scale structural systems composed of several substructures. For example, the stiffener layout inside a machine tool column usually involves two parts, one is for the front/rear panels and the other is for the side panels. If the existing algorithm is utilized, these substructures will be treated individually, which cannot guarantee the global optimality of the growth results obtained. A comprehensive coordinative optimization model is therefore, essential to correct this situation.

The work presented in this paper is undertaken to extend the capability of adaptive growth method towards global coordinative optimization problems and investigate contributions the growth simulation can make to the design of large scale machine tool structures. The reminder of this paper is organized as follows. In Section 2, the potential of leaf venation as concept generators for stiffener layout design of machine tool structures is confirmed. In Section 3, a mathematical model explaining the optimality of plant morphogenesis is presented. Then, an improved evolutionary algorithm is developed based on a global coordinative model so as to alleviate the programming and computing efforts for implementing the generation of stiffener layouts for machine tool structures. The re-design of an actual grinding machine column is conducted in Section 4. Results before and after bionic optimization are compared in terms of numerical and experimental studies. The main findings of the research work are concluded in Section 5.

2. Biomechanical significance of leaf veins in nature

After billions of years of selection, nature has evolved many ingenious topologies, providing inspiration for designers to solve engineering problems. One prominent category of such topologies is the hierarchically structured plant ramifications like leaf venation, whose mechanical stiffening role has been widely recognized by both biologists and engineers [22–24]. The leaf veins extend fully in order to get enough surface stiffness to bear the dead weight and the environmental loads. The stiffener plates inside machine tools also require high stiffness to withstand a surface load so as to guarantee the machining accuracy. While such a question – 'What can we learn for machine tool design from natural leaf venation?' – is the starting point of this research, the solution is not limited to a copy or mimicry of a particular structure, but the common configuration ideas that could be used for a large number of products and may even generate new technical applications for machine tool development.

To move between bionic ideas and their concrete implementation, a designer needs some methods to bridge the gap between biology and engineering. However, it is difficult to give a precise assessment because biological systems are more complex than engineering systems. Assume that bio-solutions to engineering problems exist everywhere in nature, we only need to determine what analogous function to search for and at what level to search for it. Basically, there are three levels at which analogical analysis could be considered, namely structure (topology or shape), loading and function similarities [25]. The prototype that can serve the engineering purpose for stiffener layout design is outlined in the flow diagram shown in Fig. 1.

(1) Structure (topology or shape) similarity is critical for analogical prototype selection, since biology is a self-optimal system for its efficient material distribution. A plant leaf can be viewed as a lightweight cantilever, which is permeated with mechanically stiffening veins. Branching strategy has been developed for leaf venation in order to guarantee the global rigidity and local isotropy. For machine tool structures, the key components such as bases, columns, carriages and tables are usually box beam structures, in which the stiffener plates are branched horizontally and vertically so as to enhance the overall stiffness. It can be found that hierarchy and reticulum

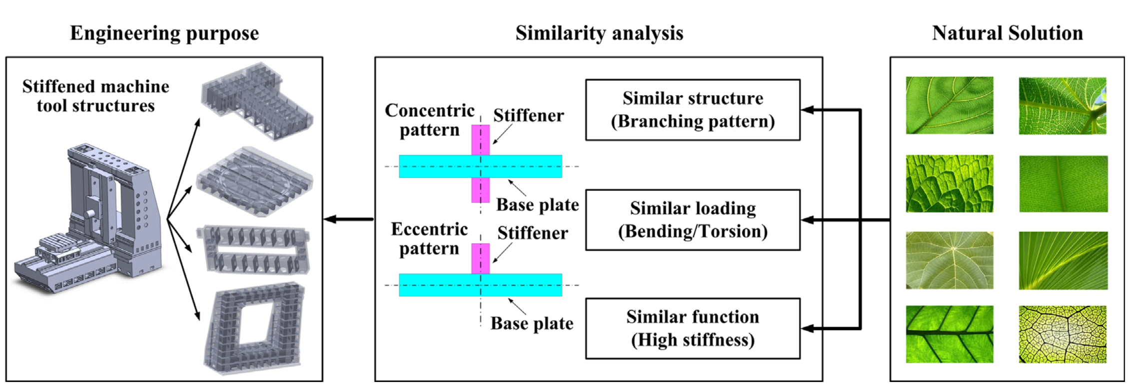

Fig. 1. Similarity between leaf venation and stiffened machine tool structures.