Computational morphogenesis and experimental measurement of 3D leaf vein structure

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Abstract. Hierarchical patterns of leaf veins have attracted extensive attention in recent years. However, it remains unclear how biological and mechanical factors influence the topology of leaf veins. Here we investigate the optimization mechanisms of leaf veins through a combination of experimental measurements and numerical simulations. The topological details of three types of representative plant leaves are measured. The experimental results show that the vein patterns are insensitive to the shape and curvature of the leaves. The numbers of secondary veins are independent of the length of the main vein, and the total length of veins increases linearly with the leaf perimeter. By integrating biomechanical mechanisms into the structural form-finding process, a transdisciplinary computational method is developed to optimize the leaf veins. The numerical results show that improving the efficiency of nutrient transport plays a critical role in the morphogenesis of leaf veins. Contrary to the popular belief in the literature, this study shows that the structural performance is not a key factor in determining the venation patterns. This work provides an in-depth understanding of the optimization mechanism of leaf veins, which is applicable to the design of high-performance shell structures.

Keywords: *Leaf veins; Topology; Computational morphogenesis; Nutrient transport; Structural stiffness; Curved shell*

Introduction

The biomechanical mechanisms underlying the patterns of leaf veins have attracted extensive attention of scientists, engineers, and designers [1-3]. Several numerical approaches have been established to investigate the branch-like vein structures. The L-system method has been used to analyze the growth process of plants [4]. However, this method only models a vein system morphologically, without considering the biomechanical requirements such as nutrient transport and shape maintaining.

Topology optimization has now become a powerful tool to explore the morphogenesis of natural materials. In the past three decades, several optimization techniques have been successfully established, including the solid isotropic material with penalization (SIMP) method [5,6], the level-set method [7,8], the evolutionary structural optimization (ESO) method [9,10] and the bi-directional evolutionary structural optimization (BESO) method [11,12]. Most recently, imposing complicated constraints during the form-finding process has been realized [13-16]. By establishing transdisciplinary computational methods for biomechanical morphogenesis, Zhao et al. [17-19] have revealed the optimization mechanisms of, e.g., plant leaves and animal stingers. Using topology optimization, a golden ratio distribution rule is found in venation systems (Sun et al., 2018). A multi-objective optimization approach is developed to explore the vein patterns on a planar plate [20]. However, there is still a lack of quantitative study on the biomechanical mechanisms of vein distributions on the shell-like mesophyll.

In this work, we investigate, both experimentally and numerically, the topology of leaf veins. The vein patterns of three representative plant leaves are measured, including the *Syringa vulgaris* L., *Rosa chinensis* Jacq., and *Cotoneaster submultiflorus* Popov. Biomechanical mechanisms of veins such as nutrient transport and loadbearing are integrated into the computational morphogenesis. The influence of the curved shape of mesophyll on the vein distribution is examined. This study reveals the optimization mechanisms underlying the intriguing layout of venation systems. The presented methodology can be applied in the design of high-performance shell structures such as aircraft skin ribs [21].

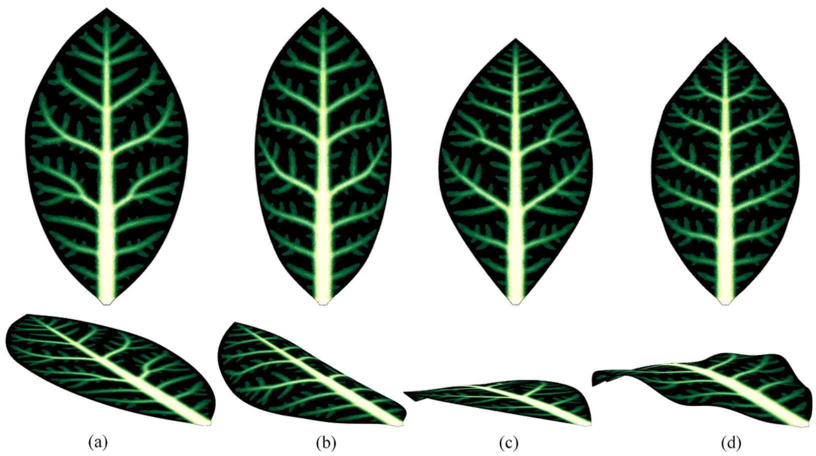

Fig. 1 Optimized topologies for nutrient transport maximization: (a) a flat leaf, (b) a leaf folded along the middle axis, (c) a leaf folded perpendicular to the middle axis, and (d) a leaf folded perpendicular to the middle axis and with wrinkled edges.

Summary

In this study, the unique topologies of leaf veins have been investigated through experimental observation and computational morphogenesis. It is found that nutrient transport plays a predominant role in determining the form of venation patterns. Contrary to popular belief in the literature, this research reveals that the structural performance is not the key factor of leaf vein patterns. Furthermore, the experimental measurements show that the numbers of secondary veins are independent of the length of main veins, and the total length of veins has a linear relationship with the leaf perimeter. The numerical results show that the vein patterns are insensitive to the variation of leaf shapes. This research deepens the understanding of the biomechanical mechanisms underlying the intriguing layout of leaf veins. The presented computational method can be used for designing efficient and innovative free-form shell structures. More details about this research can be found in [22].

Acknowledgements

This contribution is the result of the research supported by the Australian Research Council (FL190100014 and DE200100887).

References

[1] B. Blonder, C. Violle, L.P. Bentley, and B.J. Enquist, Venation networks and the origin of the leaf economics spectrum, Ecol. Lett. 14 (2011) 91-100.

[2] I. Md Rian, M. Sassone, Tree-inspired dendriforms and fractal-like branching structures in architecture: A brief historical overview, Front. Archit. Res. 3 (2014) 298-323.

[3] A. Runions, M. Fuhrer, B. Lane, P. Federl, A.G. Rolland-Lagan, P. Prusinkiewicz, Modeling and visualization of leaf venation patterns, Acm. T. Graphic. 24 (2005) 702-711.

[4] P. Prusinkiewicz, A. Lindenmayer, The Algorithmic Beauty of Plants, Springer-Verlag, New York, 1990.

[5] M.P. Bendsøe, Optimization of Structural Topology, Shape, and Material, Springer-Verlag Berlin Heidelberg, Berlin, 1995.

[6] O. Sigmund, K. Maute, Topology optimization approaches: A comparative review, Struct. Multidiscip. Optim. 48 (2013), 1031-1055.

[7] G. Allaire, F. Jouve, A.M. Toader, A level-set method for shape optimization, Comptes rendus. Mathématique 334 (2002), 1125-1130.

[8] M.Y. Wang, X.M. Wang, D.M. Guo, A level set method for structural topology optimization, Comput. Methods in Appl. Mech. Eng. 192 (2003), 227-246.

[9] Y.M. Xie, G.P. Steven, A simple evolutionary procedure for structural optimization, Comput. Struct. 49 (1993), 885-896.

[10] Y.M. Xie, G.P. Steven, Evolutionary Structural Optimization, Springer, London, 1997.

[11] X. Huang, Y.M. Xie, Convergent and mesh-independent solutions for the bi-directional evolutionary structural optimization method, Finite Elem. Anal. Des. 43 (2007), 1039-1049.

[12] X. Huang, Y.M. Xie, Bi-directional evolutionary topology optimization of continuum structures with one or multiple materials, Comput. Mech. 43 (2009), 393-401.

[13] A.B. Chen, K. Cai, Z.L. Zhao, Y.Y. Zhou, L. Xia, Y.M. Xie, Controlling the maximum first principal stress in topology optimization, Struct. Multidiscip. Optim. 63 (2021), 327-339

[14] Y.Z. He, K. Cai, Z.L. Zhao, Y.M. Xie, Stochastic approaches to generating diverse and competitive structural designs in topology optimization, Finite Elem. Anal. Des. 173 (2020), 103399.

[15] Y.L. Xiong, S. Yao, Z.L. Zhao, Y.M. Xie, A new approach to eliminating enclosed voids in topology optimization for additive manufacturing, Addit. Manuf. 32 (2020), 101006.

[16] Z.L. Zhao, S.W. Zhou, K. Cai, Y.M. Xie, A direct approach to controlling the topology in structural optimization, Comput. Struct. 227 (2020), 106141.

[17] Z.L. Zhao, S.W. Zhou, X.Q. Feng, Y.M. Xie, On the internal architecture of emergent plants, J. Mech. Phys. Solids. 119 (2018), 224-239.

[18] Z.L. Zhao, S.W. Zhou, X.Q. Feng, Y.M. Xie, Morphological optimization of scorpion telson, J. Mech. Phys. Solids. 135 (2020), 103773.

[19] Z.L. Zhao, S.W. Zhou, X.Q. Feng, Y.M. Xie, Static and dynamic properties of pre-twisted leaves and stalks with varying chiral morphologies, Extreme Mech. Lett. 34 (2020), 100612.

[20] Z. Sun, T.C. Cui, Y.C. Zhu, W.S. Zhang, S.S. Shi, S. Tang, Z.L. Du, C. Liu, R.H. Cui, H.J. Chen, X. Guo, The mechanical principles behind the golden ratio distribution of veins in plant leaves, Sci. Rep. 8 (2018), 13859.

[21] L. Song, T. Gao, L. Tang, X. Du, J. Zhu, Y. Lin, G. Shi, H. Liu, G. Zhou, W. Zhang, An all-movable rudder designed by thermo-elastic topology optimization and manufactured by additive manufacturing, Comput. Struct. 243 (2021), 106405.

[22] J. Ma, Z.L. Zhao, S. Lin, Y.M. Xie, Topology of leaf veins: Experimental observation and computational morphogenesis, J. Mech. Behav. Biomed. Mater. 123 (2021), 104788.