Final Report of Spider Web Simulation

Changrui Cai, and Jiahua He

***Abstract*—This study explores the deformation of elastic materials from a bionics perspective, with a focus on the deformation of spider silk upon impact by a flying insect. Through simulation of the stress response of an octagonal spider web structure under central loading, we want to replicate and analyze the deformation characteristics of spider silk threads under impact conditions. By understanding these interactions, we hope to learn the mechanical properties of spider silk and contribute to the design of elastic materials.**

I. Introduction

With the rapid development of technology, the application of elastic materials in various fields is becoming increasingly widespread and has become one of the hot directions in science research due to their unique advantages including high dynamic bending elasticity, stretchability and high mechanical strength [1]. Elastic materials, with their excellent features have shown great potential for applications in multiple different fields, such as aerospace, medical devices and bionic robots.

With the rapid development of technology, the application of elastic materials in various fields is becoming increasingly widespread and has become one of the hot directions in science research due to their unique advantages including high dynamic bending elasticity, stretchability and high mechanical strength [1]. Elastic materials, with their excellent features have shown great potential for applications in multiple different fields, such as aerospace, medical devices and bionic robots.

In recent years, the development of bionics has further inspired the innovation of elastic materials. By drawing inspiration from the unique structure and function of biomimetic material, scientists continuously design high-performance elastic materials. These materials not only enable complex deformation, but also maintain excellent mechanical properties under impact and extreme conditions, providing a new approach for engineering applications [2]. Therefore, research on the performance of elastic materials in biomimetic scenarios has become an important topic in the field of materials science and engineering.

In this project, the goal is to study the deformation of spider silk. Due to the unique mechanical properties and excellent energy absorption ability of spider silk. Spider silk not only has high strength and ductility, but also exhibits excellent impact resistance in complex dynamic environments, providing an ideal model for the design of high-performance elastic materials.[3]

This study focuses on the deformation behavior of spider silk when flying insects collide with it from a biomimetic perspective. We simplify the spider web model into an octagonal structure. Through computer simulation, we want to study the deformation characteristics of the spider web structure under impact conditions. By simulating and analyzing the deformation characteristics of spider silk under impact conditions, we hope to learn the mechanical properties of spider silk and contribute to the design of elastic materials.

II. Simplify

Spider Web Structure: The spider web is simplified into a regular octagonal structure, where each point is connected to the central point by a single rod.

Fixed Points: The eight points of the octagon are fixed in space and do not move.

Simplified Impact Force: The insect's impact is simplified as a continuously decreasing force applied to the central point of the web.

III. Numerical value

To obtain the maximum force generated by insects colliding with spider webs, we can use the following formula to obtain:

$$F = \Delta p/\Delta t = m \cdot v/\Delta t$$

Where, F is the force, $\Delta p = m \cdot v$ is the change in momentum, Δt is the duration of the collision. And from the reference, we can have the m = 0.012 kg, v=1.5 m/s and t = 0.05 s [7]. So the maximum force generated by insects colliding with spider webs is 0.36N. The Young's modulus of spider silk varies between 1.5 and 12 GPa [8]. For the purpose of our analysis, a representative modulus value of 5 GPa was selected. The typical diameter of spider silk ranges from 0.2 mm to 1 mm; in this study, a diameter of 0.5 mm was adopted as a representative value [8]. Furthermore, based on reference data, the damping coefficient of spider silk is assumed to be 0.3 [9]. From the reference, the numerical value we have can be shown below:

Young's modulus	Diameter of Spider web	Maximum impact force	Damping coefficient	Blue Line	Red Line
5GPa	0.5mm	0.36N	0.3	L=1cm	L=1.7cm

IV. Result

The time interval is 0.05 seconds in this simulation, and delta_t = 0.0001s. Our team decided to use the gradient and Hessian of elastic energy to compute the displacement of the rods. In the simulation, the gradient is calculated using the following formula, which represents the residual force in the system under the current state:

$$\text{gradient} = (\text{elastic\_modulus*area/length})\text{*displacement} - \text{force} \tag{1}$$

The Hessian is calculated by using the formula below:

$$\text{Hessian} = (\text{elastic\_modulus*area/length}) \tag{2}$$

The Hessian represents the system's second derivative, which describes the rate of change in elastic energy [10]. With the calculation of these parameters, our group applied the Newton-Raphson approach here: Gradient generates the system's displacement from equilibrium, and the Hessian changes the step size to determine the location of the equilibrium state, or minimum elastic energy [11].

Figure 1 below is the initial state of the web simulation.

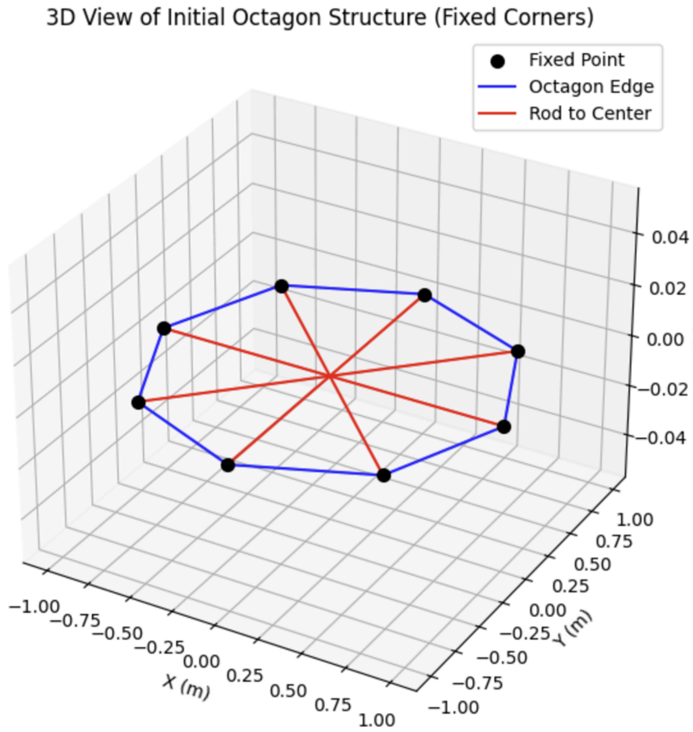

Fig. 1 Initial state of the web simulation

The simulation consists of 16 rods in total. The 8 blue rods are identical, each with a length of 1 cm and a radius of 0.3 mm. After running the simulation, the force was applied directly to the center and the force is perpendicular to the x-y plane. The picture of the 3-D view has been collected each 0.01s and are listed in the next page:

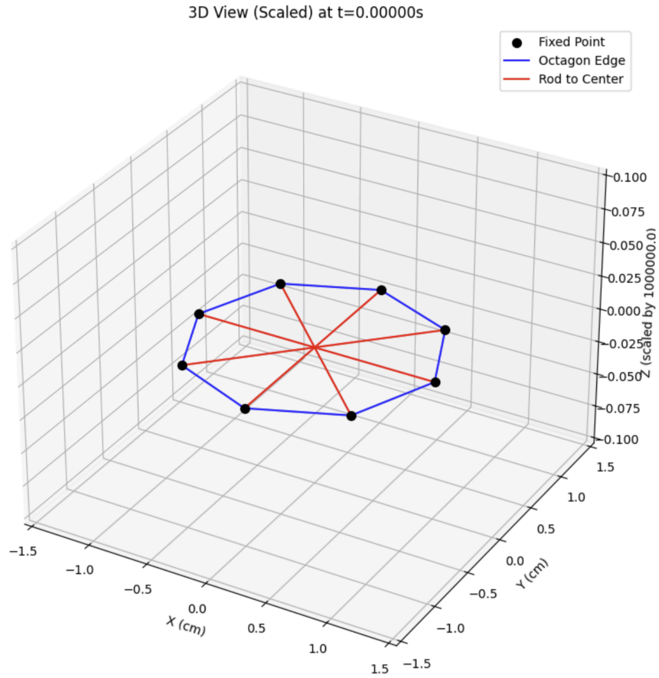

Fig. 2 3D view of web at 0s

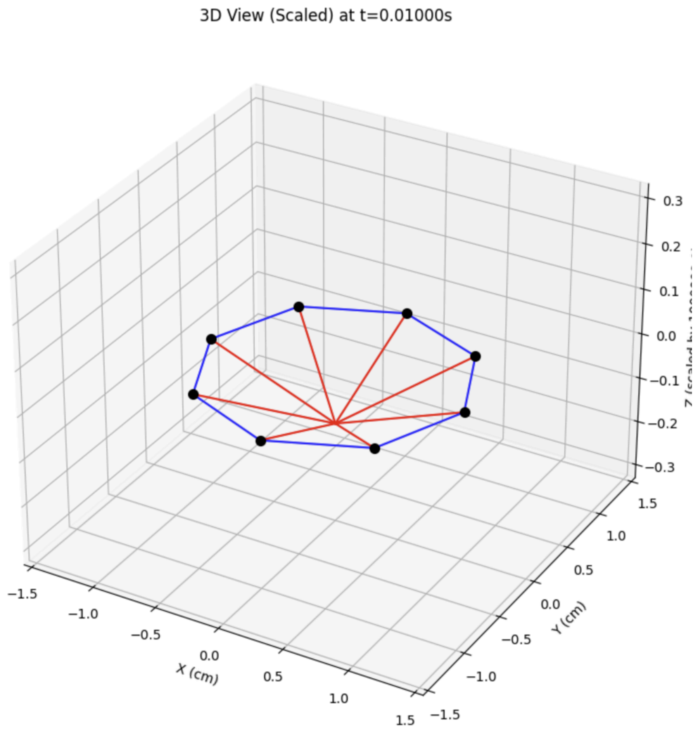

Fig. 3 3D view of web at 0.01s

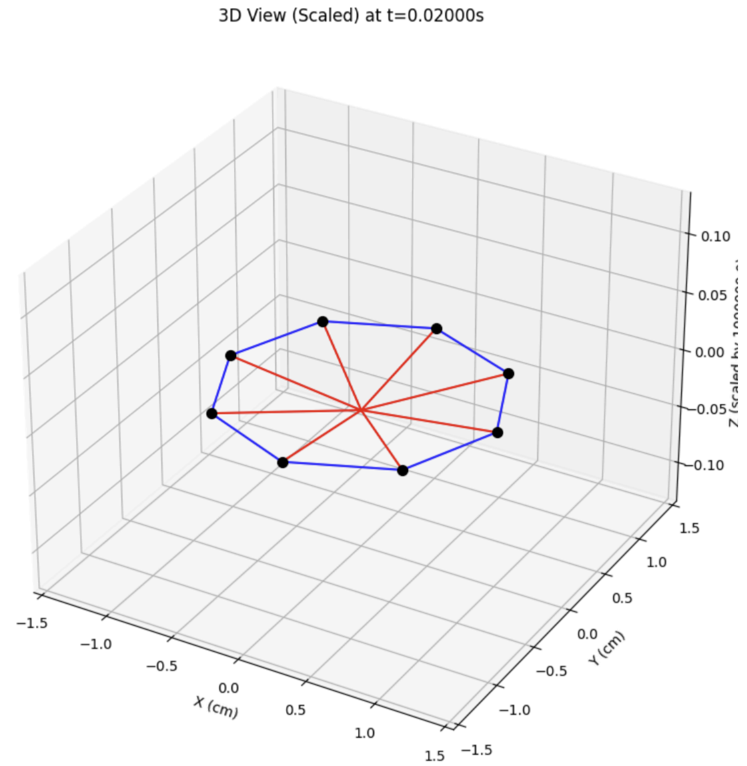

Fig. 4 3D view of web at 0.02s

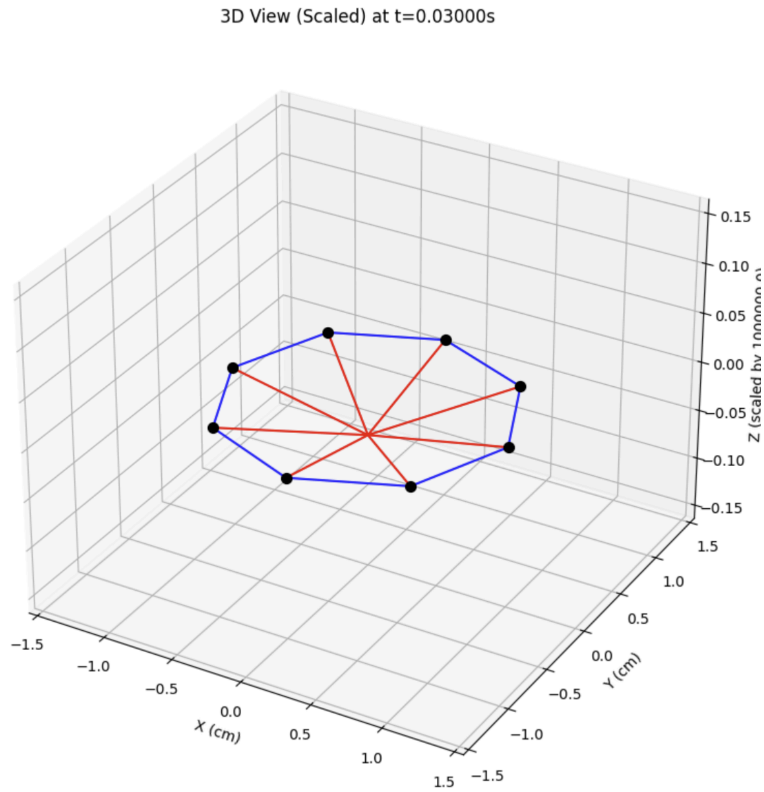

Fig. 5 3D view of web at 0.03s

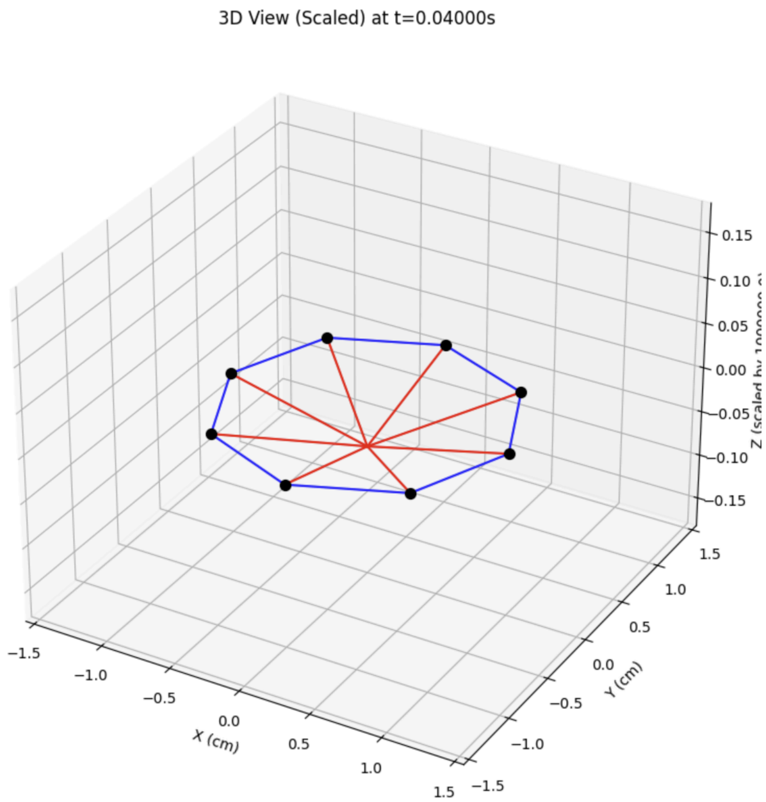

Fig. 6 3D view of web at 0.43s

The applied force is relatively small, but because the web has a high Young's modulus, its deformation is difficult to observe directly. To address this, a scaling factor of 1,000,000 has been applied to the Z-axis in the 3D view for better visualization. Considering the presence of damping, the web exhibits oscillatory behavior and oscillates frequently. At the start of the simulation, the web deforms in the negative Z-axis direction, reaching its maximum displacement of -1.436 × 10^{-7} m. After a few seconds, it rebounds in the positive Z-axis direction, surpassing the zero point and reaching a higher position. The displacement of the web of 0.05s and 20s are listed:

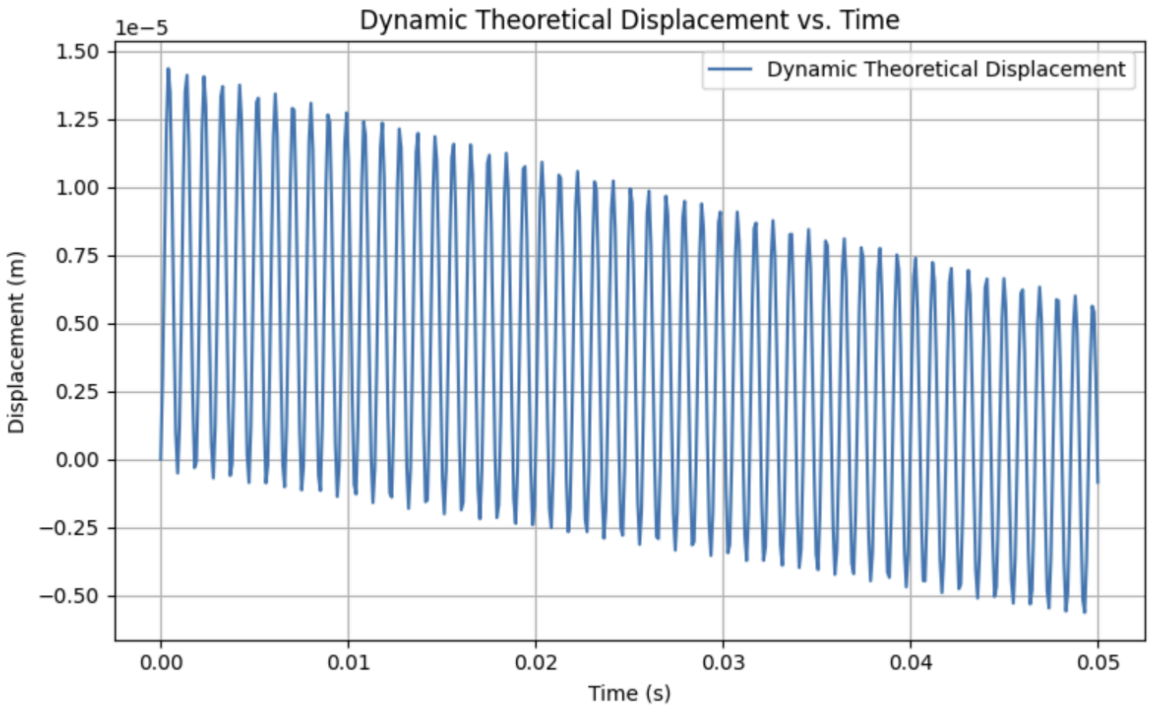

Fig. 7 Center displacement when simulation time equal to 0.05s

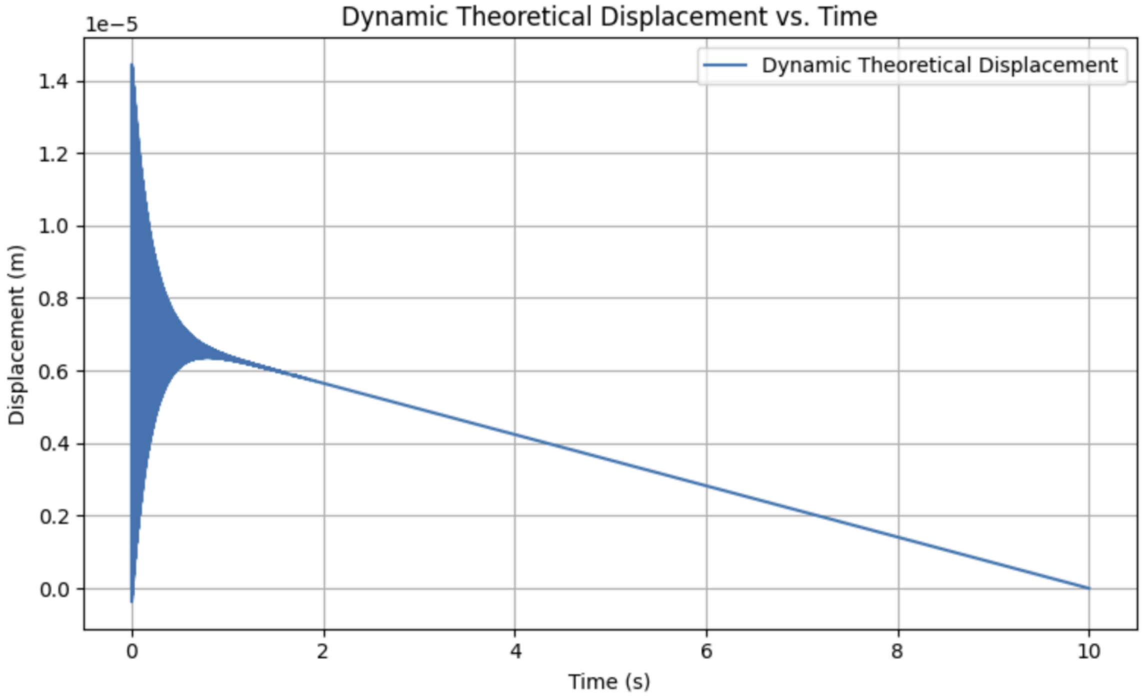

Fig. 8 Center displacement when simulation time equal to 10s

Based on the figures above, our team observed that as the simulation time increases, the range of oscillation gradually decreases. Furthermore, as the time approaches infinity, the displacement curve transitions from a wave-like pattern to a flat line, indicating that the system has reached its equilibrium state.

Conclusion

This study focuses on the deformation behavior of spider silk when flying insects collide with it from a biomimetic perspective. We simplify the spider web model into an octagonal structure. Through computer simulation, we want to study the deformation characteristics of the spider web structure under impact conditions. By simulating and analyzing the deformation characteristics of spider silk under impact conditions, we hope to learn the mechanical properties of spider silk and contribute to the design of elastic materials. The material and structure of a spider web are exceptionally strong, ensuring it does not break when capturing small insects. Its remarkable elasticity allows it to absorb and dissipate the forces exerted on it, causing the web to oscillate as it gradually releases the applied force. Notably, the maximum displacement of the web during oscillation is only -1.436×10^{-7} m, which is extremely small compared to its length of 0.01 m and radius of 0.03 mm. This minimal displacement highlights the web's exceptional ability to maintain its structural integrity under stress.

References

[1] M. Chen, Z. Wang, K. Li, X. Wang, and L. Wei, “Elastic and Stretchable Functional Fibers: A Review of Materials, Fabrication Methods, and Applications,” Advanced Fiber Materials, vol. 3, no. 1, pp. 1–13, Jan. 2021, doi: https://doi.org/10.1007/s42765-020-00057-5.

[2] Maria Gessica Ciulla, Alessio Massironi, Michela Sugni, M. A. Ensign, S. Marzorati, and Mahdi Forouharshad, “Recent Advances in the Development of Biomimetic Materials,” Gels, vol. 9, no. 10, pp. 833–833, Oct. 2023, doi: https://doi.org/10.3390/gels9100833.

[3] A. Powers, “Spider Silk: Sronger than Steel? Nature’s Supermaterial,” Berkeley Scientific Journal, vol. 18, no. 1, 2013, doi: https://doi.org/10.5070/bs3181020651.

[4] K. M. Babu, “Spider silks and their applications,” *Silk*, pp. 235–253, 2019, doi: https://doi.org/10.1016/b978-0-08-102540-6.00010-3.

[5] M. K. Jawed and S. Lim, *Discrete Simulation of Slender Structures*. 2022.

[6] O. M. O’Reilly, “Kirchhoff’s Rod Theory,” *Interaction of mechanics and mathematics*, pp. 187–268, Jan. 2017, doi: https://doi.org/10.1007/978-3-319-50598-5_5.

[7] N. Nasir, F.-O. Lehmann, P. Schützner, S. Mat, and N. Mohd, “Dynamics of body kinematics of freely flying houseflies responding to air turbulence,” *Journal of Asia-pacific Entomology*, Dec. 2019, doi: https://doi.org/10.1016/j.aspen.2019.09.002.

[8] F. K. Ko, S. Kawabata, M. Inoue, M. Niwa, S. Fossey, and J. W. Song, “Engineering Properties of Spider Silk,” *MRS Proceedings*, vol. 702, 2001, doi: https://doi.org/10.1557/proc-702-u1.4.1.

[9] Europe PMC, “Europe PMC,” *Europepmc.org*, 2016. https://europepmc.org/article/PMC/2658765?utm_source=chatgpt.com (accessed Dec. 10, 2024).

[10] S. H. Zhang, G. L. Zhang, J. S. Liu, C. S. Li, and R. B. Mei, “A fast rigid-plastic finite element method for online application in strip rolling,” *Finite Elements in Analysis and Design*, vol. 46, no. 12, pp. 1146–1154, Dec. 2010, doi: https://doi.org/10.1016/j.finel.2010.08.005.

[11] “Newton-Raphson Method - an overview | ScienceDirect Topics,” *www.sciencedirect.com*. https://www.sciencedirect.com/topics/mathematics/newton-raphson-method