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Finite Element Analysis of a Novel Tensegrity-Based Vibratory Platform

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Abstract

The study aims to conduct the finite element analysis (FEA) of a novel tensegrity-based vibratory platform by using IronCAD software. and analyze its deformation under external forces to verify if the platform can generate the required advancing motion. Firstly, the structure and operating principles of the proposed platform are introduced. Subsequently, individual parts are created using IronCAD software and assembled to form a solid model of the entire platform. Finally, employing Multiphysics for IronCAD, FEA is conducted to analyze the platform's displacement under different external forces, as well as to examine its natural frequencies and mode shapes. The simulation results indicate that the proposed platform effectively moves a part in a specified direction. Additionally, the maximum stress remains below the yield strength. Moreover, the mode shapes corresponding to the initial 3 natural frequencies contribute to the advancing motion.

Keywords: tensegrity, vibratory platform, vibratory conveyor, IronCAD, finite element analysis

1. Introduction

A conveyor (feeder) is a machine capable of intermittently or continuously transporting materials along a specified path. And, a vibratory conveyor utilizes an oscillating device to generate vibrations for intermittent material advancing. A vibratory platform refers to a vibratory conveyor with 3 degrees of freedom, hence it can advance parts in any arbitrarily specified direction on the horizontal plane [1]. It can be employed for operations such as material classification, orientation, and separation, serving as a commonly used automatic feeding device. Its distinction from typical continuous belt conveyors lies in its generation of intermittent reciprocating vibrations, causing parts to slide on the trough and move forward.

Vibratory conveyors possess advantages such as compact structure, the ability to orient parts, and to handle high-temperature or small-volume materials [2], making them indispensable automation machinery in production lines. They are extensively used not only in industries involving the transportation of bulk materials like food, chemicals, and mining, but also suitable for conveying various small parts such as IC, electronic components, and mechanical hardware. Vibratory conveyors can be categorized into bowl and inline types, shown respectively in Fig. 1 [3] and Fig. 2 [4], based on the relative motion between parts and the track.

Tensegrity [5] is a structure composed of continuous tension elements (cables) and discontinuous compression components (rods or struts). It possesses advantages such as lightweight (high volume-to-mass ratio, low inertia), energy efficiency, high strength-to-mass ratio, low cost, easy assembly and disassembly, high controllability, significant expandability, and high rigidity-to-mass ratio. It is often applied in various constructions, particularly suitable for large-scale structures like bridges, domes, deployable masts, and antennas [6]. Fig. 3 [7], illustrates a type of tensegrity structure that is lightweight yet capable of bearing substantial loads (high strength). Tensegrity structures are also employed in various robot designs.

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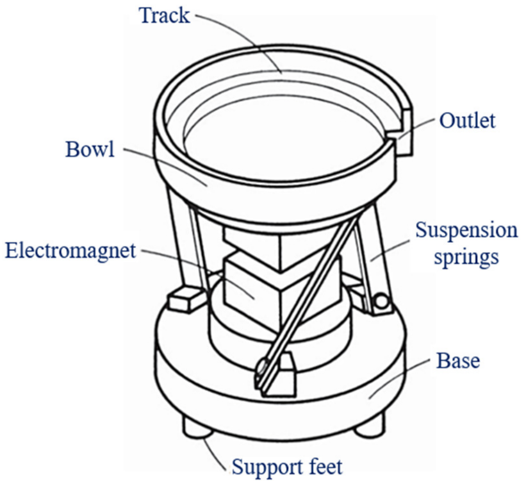


Fig. 1 Vibratory bowl conveyor [3]

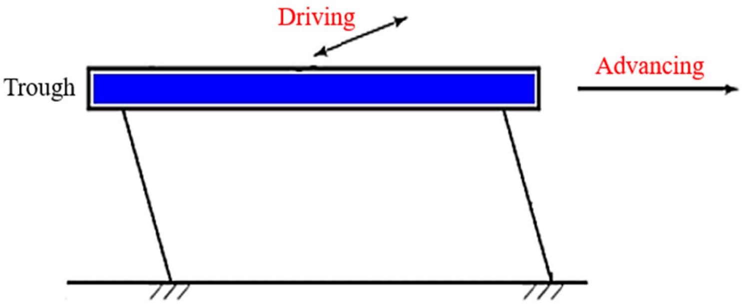


Fig. 2 Inline vibratory conveyor [4]

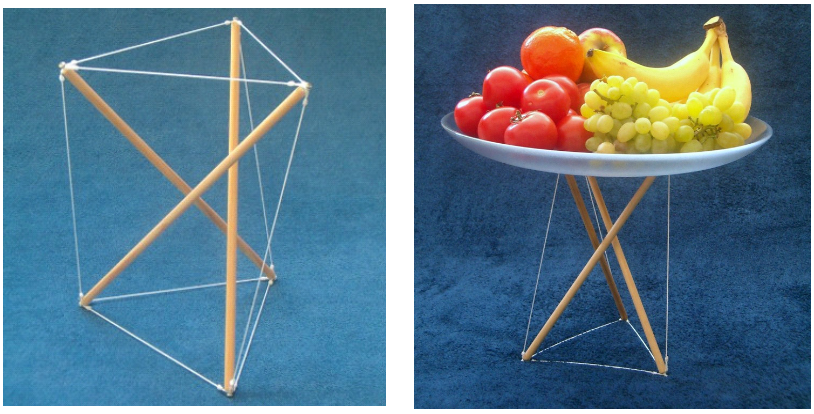


Fig. 3 Tensegrity [7]

In 1962, Fuller [5] coined the term Tensegrity, derived from the combination of “Tension” and “Integrity”. Concurrently, Emmerich [8] and Snelson [9] introduced the concept of tensegrity structures. As early as 1920, Ioganson proposed structures similar to tensegrity [10]. In 1978, Calladine [11] became the first to devote himself to academic research on tensegrity. Initially, studies on tensegrity primarily focused on its structural aspects. Tensegrity structures can alter their shape by adjusting the lengths of the tensioned cables, making them applicable as mechanisms. Moreover, they require minimal energy input to modify cable lengths, thus exhibiting high energy efficiency [12]. Consequently, over the past 30 years, numerous scholars have been drawn into studying tensegrity mechanisms’ applications in architecture [13-15].

In 1997, Oppenheim and Williams [16] were the first to propose altering cable length to drive tensegrity and achieve tensegrity mechanisms. In the same year, Skelton and Sultan [17] introduced a specific controllable tensegrity spatial structure where components could execute functions such as load-bearing, sensing, actuation, and closed-loop control simultaneously. In 1999, Sultan et al. [18] designed an astronomical telescope using tensegrity. In 2000, Sultan et al. [19] designed a flight simulator based on tensegrity and validated its feasibility through simulations. In 2006, Paul et al. [20] proposed robots structured with a triangular tensegrity prism (TR3) and a Quadrilateral tensegrity prism (TR4) demonstrating their ability to locomote through experiments, showcasing lightweight, high strength, and fault-tolerance advantages.

In 2009, Rovira and Tur [21] established generalized equations of motion to explore the movement of tensegrity robots. Regarding parallel mechanisms constructed with tensegrity in 2002, Tran [22] introduced a 3-3 series (top platform joints - base joints) tensegrity parallel mechanism, replacing flexible elements with cables and springs, and using a flat top and bottom, as illustrated. Marshall [23] further replaced the rigid elements in Tran’s [22] tensegrity parallel mechanism with pneumatic/hydraulic cylinders, studying a 6-degree-of-freedom tensegrity parallel mechanism. Baker and Crane III [24] performed static analysis and top platform orientation analysis on a 3-degree-of-freedom tensegrity parallel platform.

Shekarforoush et al. [25] conducted static analysis on a 3-3 tensegrity parallel mechanism. McCarthy [26] highlighted tensegrity as one of the three major research directions in mechanisms and robotics for the 21st century. In recent years, there has been significant research on tensegrity robots, including studies on prism-based tensegrity robots, spherical tensegrity robots, humanoid tensegrity robots, spherical tensegrity robots, etc. In 2022, Liu et al. [27] conducted a detailed literature analysis on tensegrity robots.

From the above literature on vibratory conveyors and tensegrity, it's evident that tensegrity possesses many advantages such as lightweight (low inertia), energy efficiency, high strength-to-mass ratio, low cost, easy assembly and disassembly, high controllability, significant expandability, and high rigidity-to-mass ratio. These advantages make it well applicable to vibratory conveyors that are large-scale, lightweight (with fast response), energy-efficient, easy to assemble, disassemble, and adjust. In addition, there has been no study devoted to tensegrity-based conveyors

The purpose of this study is to conduct the finite element analysis (FEA) of a tensegrity-based vibratory platform using IronCAD software, to analyze its movement under external forces. Initially, the structure of the tensegrity-based vibratory platform is presented. Subsequently, using IronCAD software, individual components are created and assembled to form the solid model of the entire platform. Finally, utilizing IronCAD software's built-in Multiphysics, FEA is performed to analyze the platform's movement under different external forces, and also examine its natural frequencies and mode shapes.

2. The Proposed Tensegrity-Based Vibratory Platform

This study presents a 3-degree-of-freedom vibratory platform constructed using tensegrity, as depicted in Fig. 4. It enables planar conveyance of parts in specified directions and at controlled speeds. Comprising an upper trough (highlighted in magenta) and a base (blue), it is connected by four tensioned cables (green). Due to the characteristics of tensegrity, it can maintain at its static equilibrium position while also capable of generating motion. Thus, by controlling the periodic variation in the lengths of the surrounding three cables, the upper trough will oscillate, facilitating part conveyance in specified directions on the platform. The developed conveying platform is suitable not only for the precision conveyance of small parts but also for high-speed transport. Moreover, tensegrity is well-suited for large-scale machinery, making it applicable for the construction of large extendable conveyor platforms.

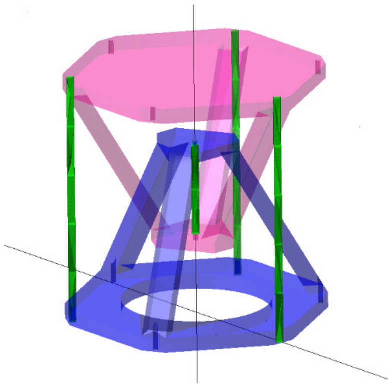


Fig. 4 3-degree-of-freedom tensegrity-based vibratory platform

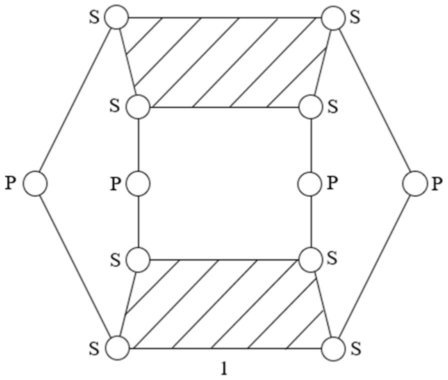


Fig. 5 4-SPS kinematic chain

For performing the analysis of the degree of freedom, each cable of the tensegrity in Fig. 4 is replaced by a pair of binary links (a dyad) connected by a sliding pair (P), and each connection between the cable and the upper trough or the base is replaced by a ball joint (S). Fig. 5 shows its kinematic chain which is a 4-SPS parallel mechanism. This number of the machine element (N) is 10, the number of joints with 1-degree-of-freedom (J_1) is 4, and the number of joints with 3-degree-of-freedom (J_3) is 8. Substituting the above to the spatial degree-of-freedom formula, it yields

$$F = 6(N-1) - 5J_1 - 3J_3 = 6(10-1) - 5\times4 - 3\times8 = 10 \tag{1}$$

Even though the degrees of freedom are 10, there are 4 redundant spinning degrees of freedom due to the presence of ball joints at both ends of the 4 dyads, which do not affect the input-output motion. Hence, the actual degrees of freedom are 6. If the number of the input is 3, there will be 3 unconstrained degrees of freedom, utilized for the automatic adjustment of the tensegrity's equilibrium position. For instance, in Fig. 4, when the outer cables of the tensegrity are tightened, a lateral displacement of the upper trough will automatically return to the static equilibrium position. This characteristic precisely suits the reciprocal motion requirements of a vibratory conveyor, where the return stroke requires no additional input energy, thereby saving energy.

3. Solid Modelling

Due to IronCAD's advantages of ease of use, rapid modeling, and straightforward analysis, it is chosen for the FEA analysis. The modeling steps are outlined as follows:

(1) Modeling the lower base plate: The base is drawn as an inscribed hexagon within a circle (as shown in Fig. 6), with a diameter of 88mm and a height of 4.8mm (as depicted in Fig. 7).

(2) Modeling the lower base struct: The dimensions of the structs are length: 8mm, width: 4.6mm, height: 60mm, rotated counterclockwise by 120 degrees (as shown in Fig. 8). The rest of the pillars are then duplicated using a circular array (as seen in Fig. 9).

(3) Modeling the upper base plate: Using the plane formed by the tops of the three pillars, create a hexagonal upper plate (as illustrated in Fig. 10) with a thickness of 3mm (as shown in Fig. 11).

(4) Cable hole drilling: Create a hole of 1mm diameter at a distance of 1mm from the edges, and then generate the rest of the holes using a circular array (as depicted in Fig. 12), and establish a hole with the same diameter at the center of the upper plate (as seen in Fig. 13).

(5) Upper base: Copy the lower base, then rotate it clockwise by 180 degrees around the X-axis, and finally rotate it clockwise by 60 degrees around the Z-axis (as shown in Fig. 14).

(6) Cable modeling: Create four cylinders (cables) connecting the eight holes of the upper and lower bases. Assign the cables the material properties of nylon.

Fig. 15 shows the completed solid model of the entire proposed platform.

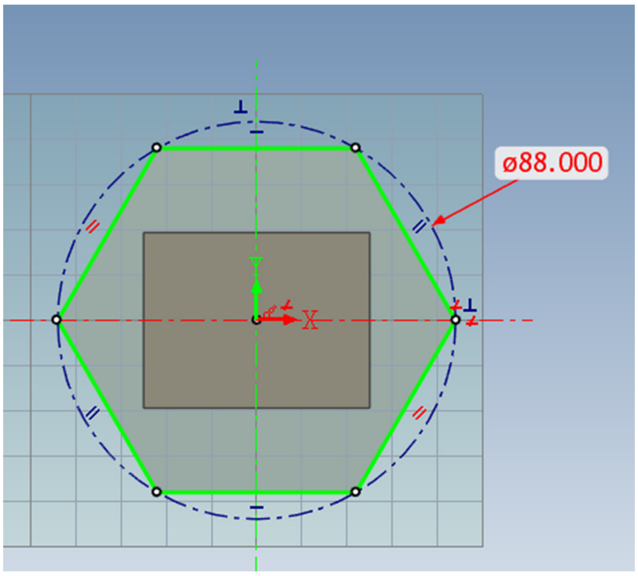


Fig. 6 Low base plate - top view

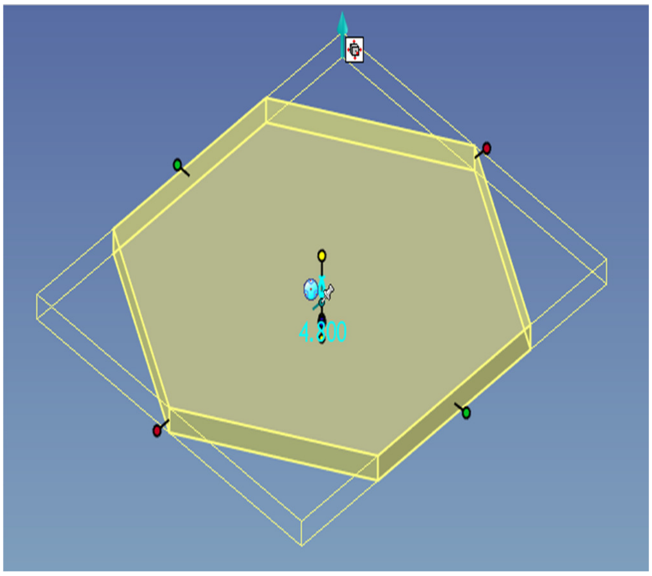


Fig. 7 Low base plate - height

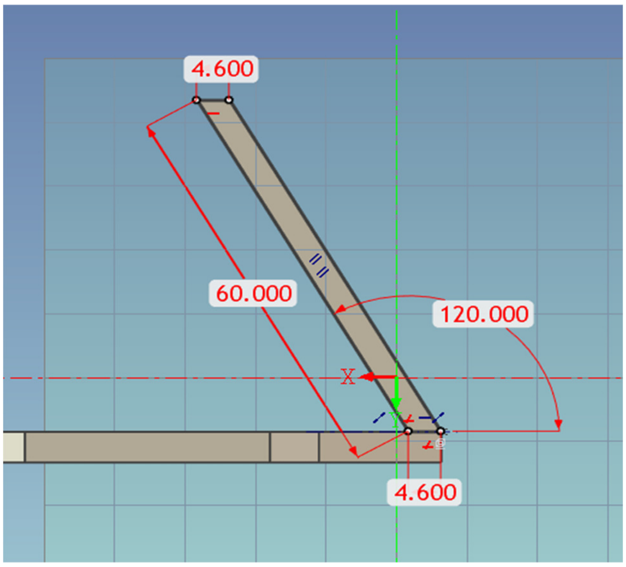


Fig. 8 Dimensions of the Strut

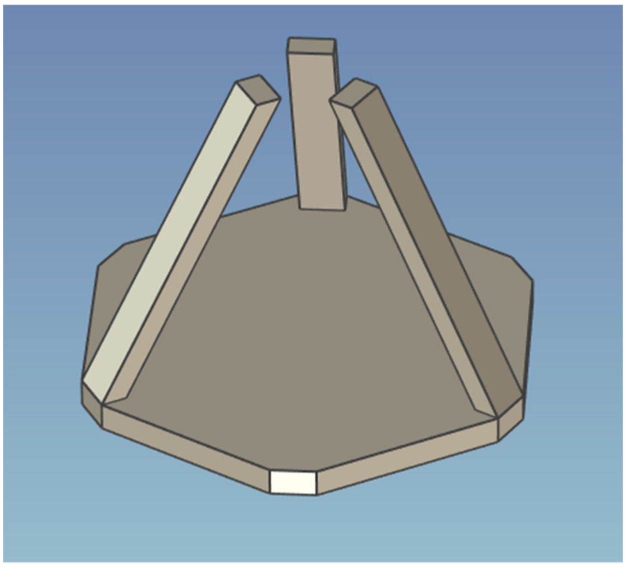


Fig. 9 Strut

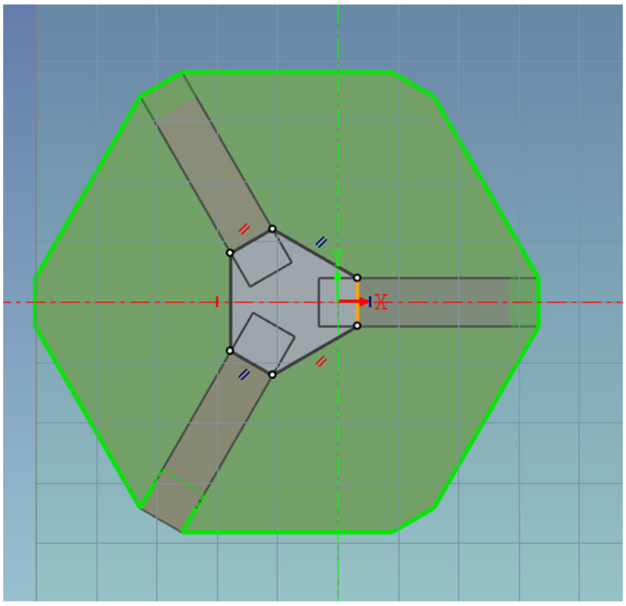


Fig. 10 Top plate - top view

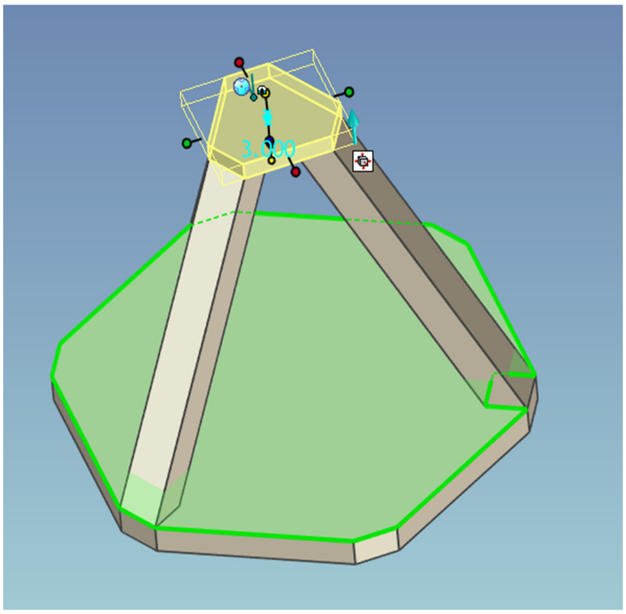


Fig. 11 Top plate - Height

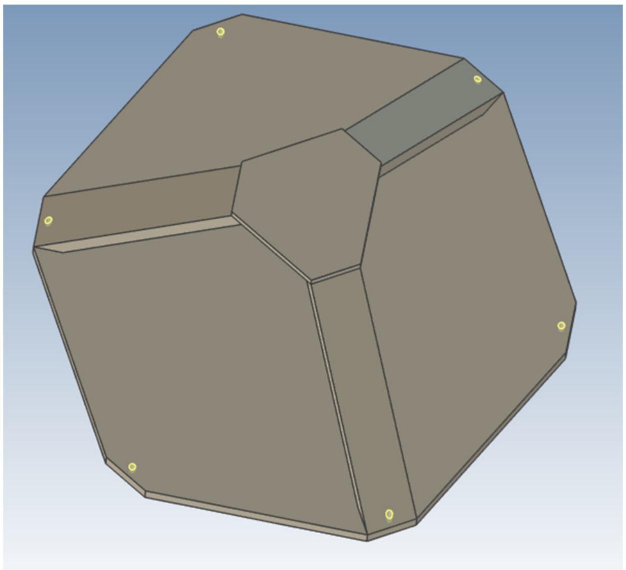


Fig. 12 Outer circumferential cable holes

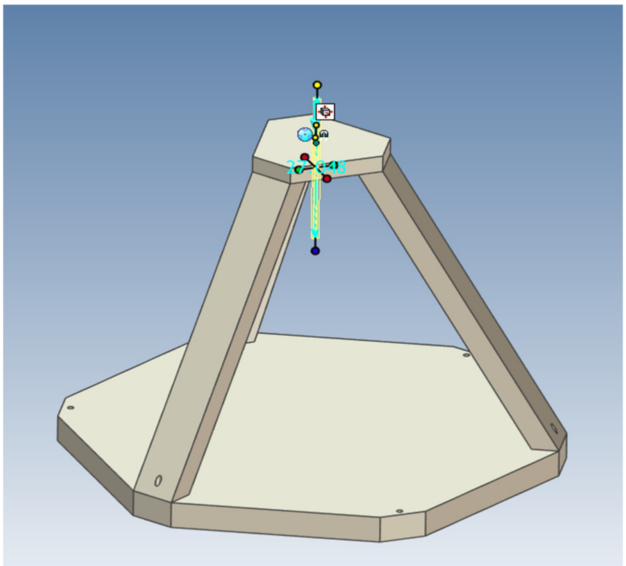


Fig. 13 Central cable hole

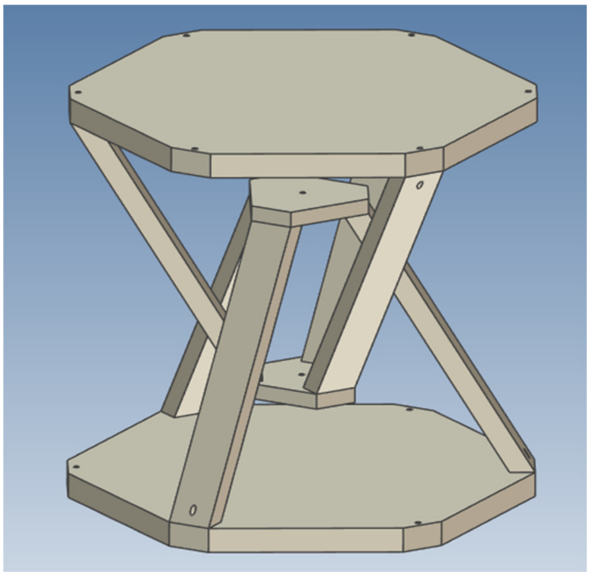


Fig. 14 Upper base

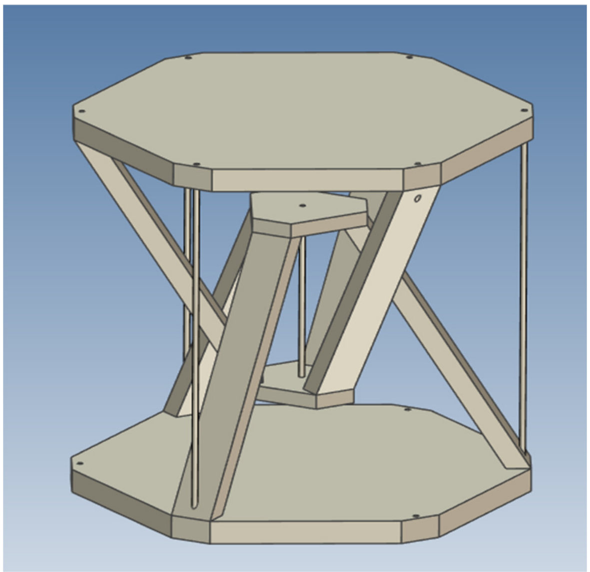


Fig. 15 Solid Model of the proposed platform

4. Finite Element Analysis

Since the proposed tensegrity-based vibratory platform is a compliant mechanism of complex shape, FEA is necessary for verifying its deformation under external loadings. This analysis can investigate the forces (stress) and deformations (strain) of the platform. Additionally, it can analyze the natural frequencies and mode shapes of the proposed platform. The analysis is conducted by using Multiphysics for IronCAD, an FEA simulation tool integrated in the IronCAD interface. The analytical steps are outlined as follows:

(1) Material property setup: The upper and lower base plates of the prototype are planned for production using 3D printing technology. Accordingly, both base plates are designated to be crafted from ABS material, characterized by specific material properties: Modulus of Elasticity, Poisson's ratio, and density, set at 2000 N/mm², 0.394, and 1.02×10^{-6} kg/mm³, respectively. All the cables are composed of Nylon 101, featuring specific material properties: Modulus of Elasticity, Poisson's ratio, and density set at 1000 N/mm², 0.3, and 1.15×10^{-6} kg/mm³, respectively.

(2) Boundary conditions setup: As the lower base remains fixed with the frame, its displacements in the X, Y, and Z directions are set to 0.

(3) Preload setup: Since the cables can withstand tension only, and to maintain platform stability, each cable is prestressed with a tension of 0.3038 N.

(4) Load setup: The load is applied as horizontal forces acting on the circumferential cables, three horizontal forces are 1, 0.5, and 0.3 N, respectively. The resultant force is 0.6244N with a direction of 76 degrees, as shown in Fig. 16.

(5) Meshing: To conduct FEA, the model is meshing with geometry - Solid, element type – Tetrahedra, and element size - 4.4mm. After meshing, the model comprises 17,300 nodes and 69,453 elements.

(6) Analytical Results: With the completion of the above setup, FEA can then be performed. The displacement and stress results are depicted in Figs. 17 and 18, respectively. From Fig. 19, it is found the upper base moves at the specified direction of 74^{o}. The analysis demonstrates that the proposed platform can advance a part in a specified direction under applied loads, and the maximum stress remains below the material's yield strength. The mode shapes at the first 10 natural frequencies are also analyzed and presented in Fig. 20, and it found that the mode shapes corresponding to the first 3 natural frequencies facilitate the advancement of a part. The analysis confirms the successful application of IronCAD software in finite element analysis for the vibratory platform. Its advantages include ease of use, rapid modeling, and simplified procedures.

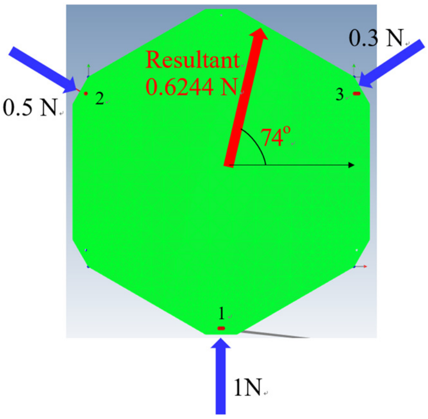


Fig. 16 Applied loads

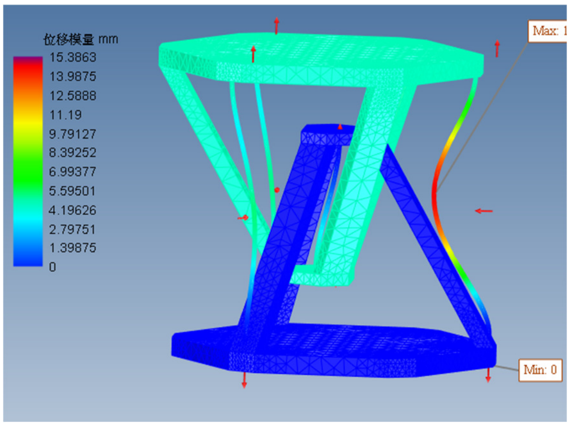


Fig. 17 Displacement

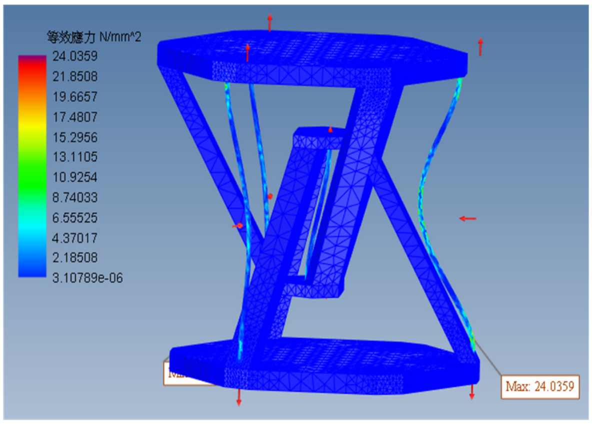


Fig. 18 Stress

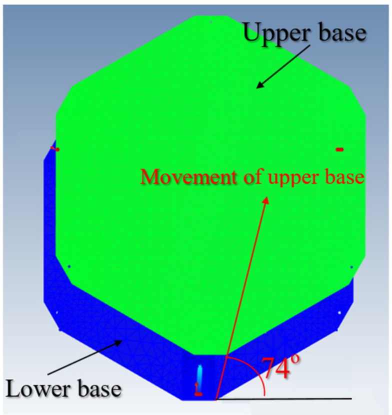
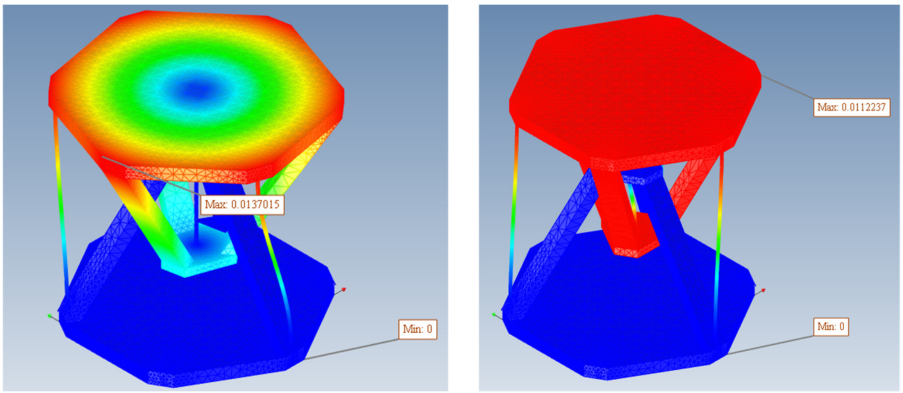
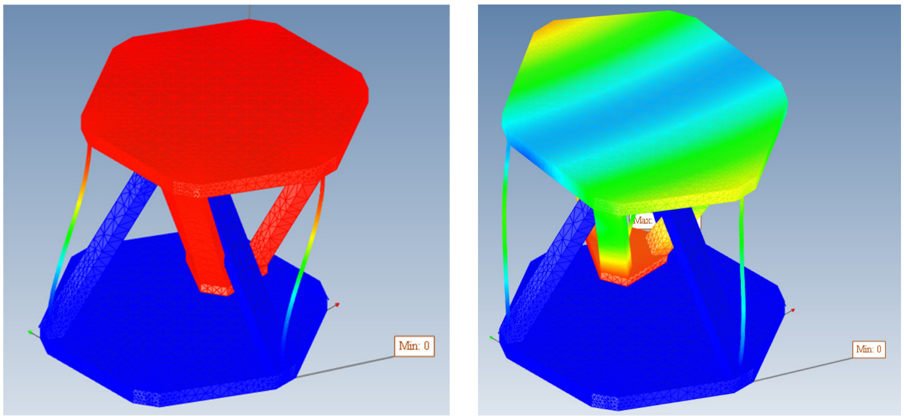


Fig. 19 Movement – upper base

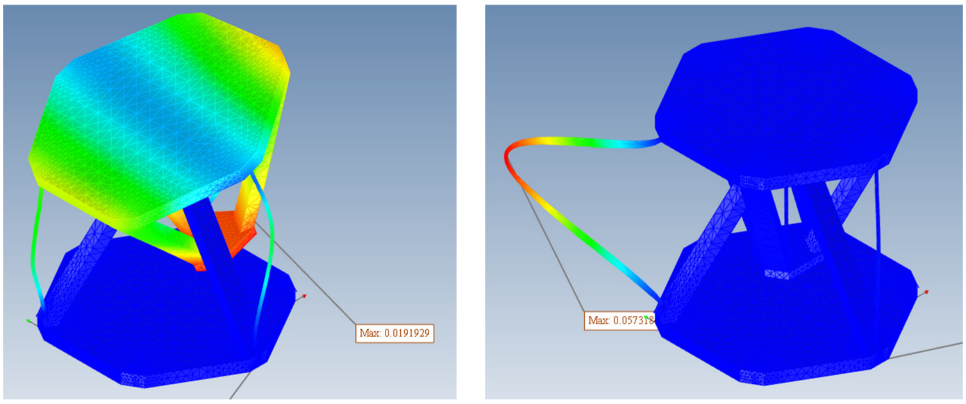


(a) 1st natural frequency (4.33Hz) (b) 2nd natural frequency (5.68 Hz)

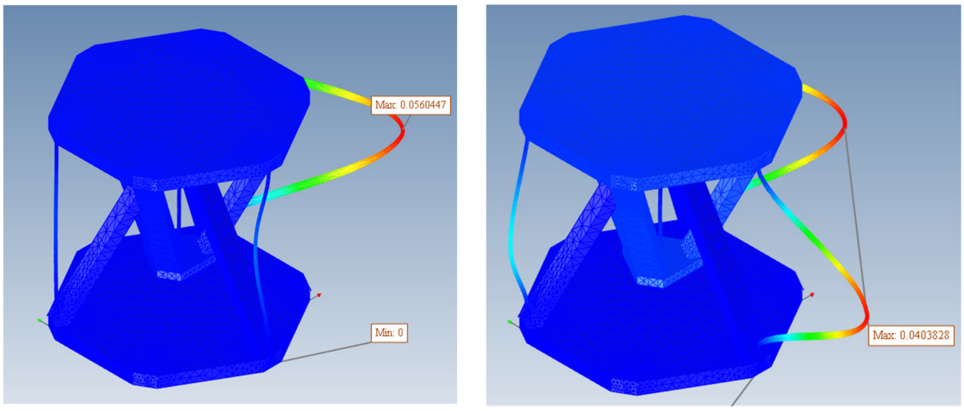


(c) 3rd natural frequency (5.75 Hz) (d) 4th natural frequency (164.94 Hz)

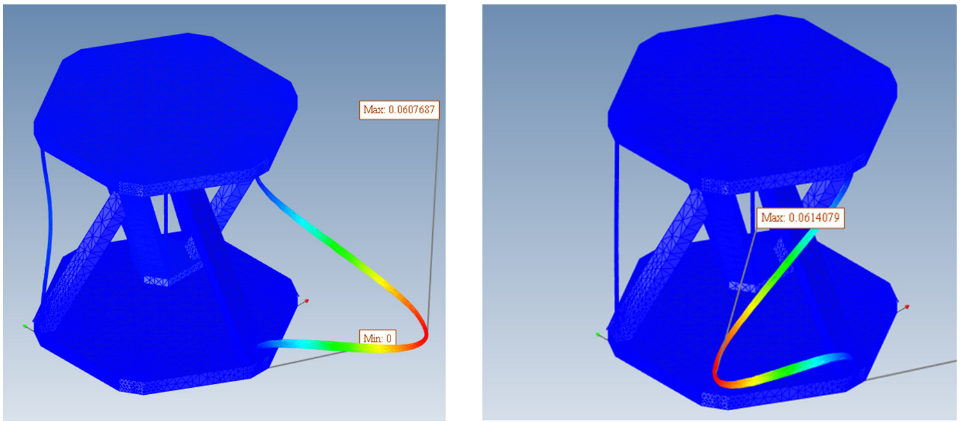
Fig. 20 Natural frequencies and mode shapes



(e) 5th natural frequency (165.89 Hz) (f) 6th natural frequency (193.01Hz)



(g) 7th natural frequency (195.26 Hz) (h) 8th natural frequency (196.89 Hz)



(i) 9th natural frequency (198.23 Hz) (j) 10th natural frequency (201.55 Hz)

Fig. 20 Natural frequencies and mode shapes (continued)

5. Conclusion

This study proposed a novel tensegrity-based vibratory platform. The FEA of the proposed platform was performed by using IronCAD software to validate whether the desired conveying motion could be achieved. The results of FEA indicated that the proposed platform can advance a part on the trough in a specified direction. Hence, it verifies the feasibility of using a tensegrity-based structure as a vibratory platform, and also provides insights for subsequent optimum design. Moreover, IronCAD software offers advantages such as user-friendliness, rapid modeling, and ease of analysis.

Acknowledgment

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Conflicts of Interest

The authors declare no conflict of interest.

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