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Design and Development of Small-Scale Modular Needle Punching Mechanism

Siti Nur Dini Samsul[1], Muhammad Farid Shaari[1]*

[1] *Department of Mechanical Engineering Technology/Faculty of Engineering Technology Universiti Tun Hussein Onn Malaysia, 86400, Pagoh, Johor, MALAYSIA*

*Corresponding Author: mdfarid@uthm.edu.my
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Abstract

With the increasing demand for nonwoven textiles in industries such as automotive, healthcare and refining. There is a clear need for cost-effective and versatile technology. This study describes a compact small-scale modular needle punching mechanism for experimental use and low-volume manufacturing. The machine is sized (766 mm × 800 mm × 545 mm) with three motors and quick needle change, making it more practical and user-friendly. To evaluate and ensure the strength of the structural design for better durability, Finite Element Analysis (FEA) was used. The findings demonstrate the potential of this machine as a sustainable, cost-effective and adaptable alternative for nonwoven material processing.

1. Introduction

The growing demand for sustainable and environmentally friendly textiles has stimulated interest in nonwoven fiber technology. However, traditional needle punching machines used in nonwoven fiber production are usually large and expensive, making them unsuitable for small-scale or experimental applications. This reduces their accessibility, especially for educational institutions, researchers and small enterprises. As a result, there has been a recent high demand for alternatives that create small-scale, flexible and cost-effective sizes to promote innovation and drive sustainability in the textile industry.

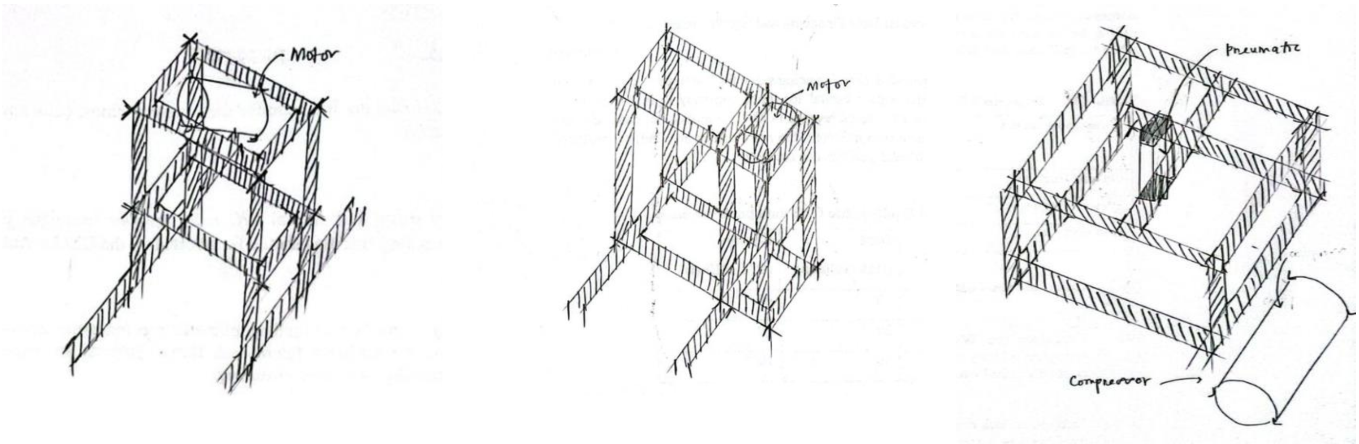
The primary goal of this project is to design and build a small-scale modular needle punching mechanism appropriate for experimental investigations and small production batches. The system should be simple to use, inexpensive, and capable of manual or semi-automated operation to facilitate the testing of biodegradable and recycled fibers. This research covers conceptual design, thorough mechanical design with simulation (FEA), manufacturing, and functional testing of the mechanism. The machine's modular architecture allows for component replacement or improvements without rebuilding the entire system, making it suited for both academic research and early-stage product development.

2. Methodology

The process for this project included many essential steps, beginning with the development of the needle punching mechanism. This phase was dedicated to analyzing the constraints of existing machines and proposing a solution that is small, modular, and cost-effective. Sketches and basic models were created to test various design concepts.

2.1 Conceptualization

This process was done by examining the existing commercial needle punching machines, especially in terms of their large size, complex design, and high cost. Based on these observations, the three-design phase gave the main goal of producing a machine that was medium-sized, easy to operate, modular, and more suitable for educational use, prototyping, and small production. Through several intensive discussion sessions and rough sketches, various ideas were devised. To ensure the design met real-world needs, market research and comparisons with existing products helped shape and refine the final concept. Figure 1 below shows several designs in different solution principles to produce new conceptual alternatives.

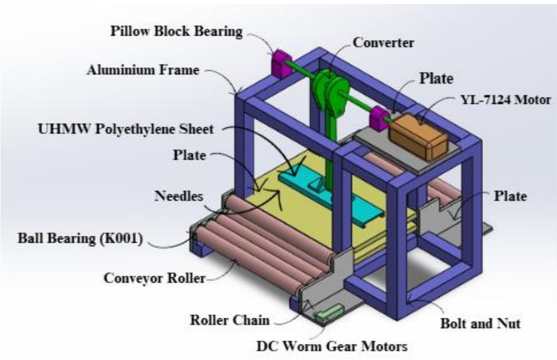


(a) **(b)** **(c)**

Fig. 1 *Several designs in different principles concept*

2.2 Design and Analysis

The suggested needle punching mechanism was modelled in 3D using SolidWorks. Key components of the design comprised the needle module, fiber bed, driving mechanism (motor and crank), and supporting frame. Finite Element Analysis (FEA) was used on structural components, specifically the main shaft, frame, and crank arm, to evaluate strength and safety under operational loads. Simulations indicated that the design could withstand predicted forces while maintaining acceptable stress and deformation levels. Figure 2 below shows an overall view design.



(a)

Fig. 2 *(a) Isometric view*

2.3 Fabrication and Assembly

The machine parts have been manufactured using commonly used manufacturing technologies including CNC, laser cutting, and welding. The materials are inexpensive, extremely durable, and long-lasting. Each individual component is manufactured to a specific design, but modifications were made for accurateness of alignment, appropriate spacing, and even movement through the machine. Modular connections and generic fasteners were used to allow for any future repair or replacement to become an easier process.

2.4 Testing

Functional testing was conducted to validate mechanical performance and needle punching effectiveness. The machine was tested using different fiber samples to observe bonding quality, punching consistency, and operational smoothness. Observations were recorded on punching depth, fiber integrity, and ease of needle replacement. Performance was compared to expectations set during design.

3. Results and Discussion

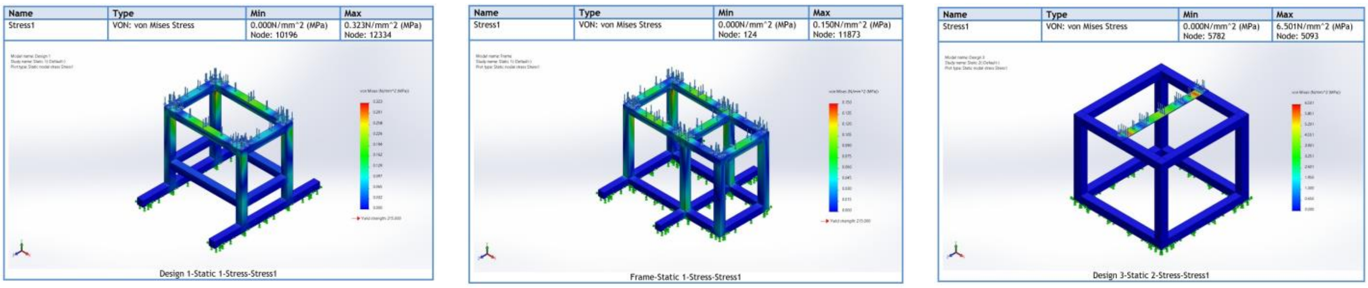
The results of the project indicate that the needle punching mechanism developed for the project achieved the objectives. The final design was successfully built in a compact, modular manner making it suitable for small-scale applications and educational use. The simulation research shows that many of the features were strong enough to withstand the load pressures that any would encounter in operation.

Most of the components were fabricated and assembled without any major adjustments needed to ensure the components worked correctly, aligned properly, and functioned as they were supposed to. In general, the machine performed as it should, and the needle mechanism was working properly through the deposition action. Throughout the course of the performance testing, the machine was able to bind undressed fibers such as jute and wool to produce samples of non-woven fabric of consistent quality. As such, though the machine can be used for practical applications in trials, it can also function in an educational capacity, especially in terms of educating students on the production of textiles sustainably.

3.1 Result Concept

Three prospective frame designs for the needle punching mechanism were developed and tested with Finite Element Analysis (FEA) to obtain the best design in terms of strength, stability, and resistance to stress and forces. When a downward load was applied to the first design the von Mises stress value reached 0.323 MPa, stressing was localized around the joints and bolt area, however; it was structurally solid and far less than 215 MPa which is the yield strength of 6063-T6 aluminum alloy. Additionally, the frame was underutilized with respect to its potential strength from materials. While the second design was better in every relatively comparable load situation displaying a peak stress of simulatively 0.150 MPa. Furthermore, stress was spread over the frame reasonably well throughout its body and could equally distribute at key connection points as well. This gradual loading of stress weakened this design less not only comprised it, but also did not exhibit any signs of deformation during the evaluations. Initial structural analysis indicates that the designs' overall stress levels were relatively low, reaching a maximum of 6.501 N/mm^2 in the top center portion of the frame with the most tensile forces. This is a relatively low stress occurrence, and it is still well within the appropriate limits, but it is worth noting the area does have some observable definitive strain, meaning it could potentially be stressed repeatedly and be strained more easily unless it is beefed up.

In evaluating all three designs, reviewed and determined the second design to be the more ideal due to overall material use, structural depth, and most appropriate integration of motor mounting. Adding an expanded frame design to incorporate the new site mounting of the YL-7124 motor at the top of the assembly, certainly improved balance and mechanical integration. The final dimensions of the entire design were 766 mm long, 800 mm high and 545 mm wide, which is very compact even for small space use cases yet mechanically stable. By utilizing hollow extruded products manufactured from the 6063-T6 aluminum alloy, we engineered a lightweight yet resilient frame that can withstand cyclical operational loads, making the final form useful for long-term deployment in research, education, and smaller industrial projects. Figure 3 below shows the stress, strain and deformation for body frame analysis.

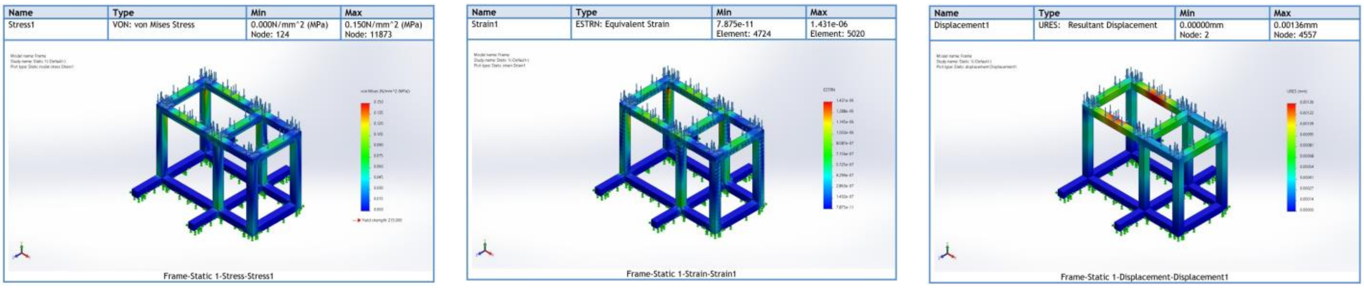


(a) **(b)** **(c)**

Fig. 3 *(a) Simulation first design; (b) Simulation second design; (c) Simulation third design*

3.2 Result Design and Analysis

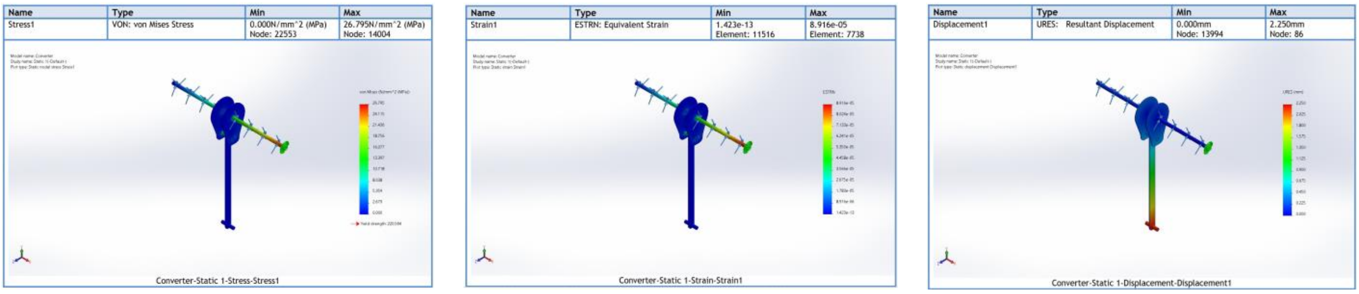
The body frame of the needle punching mechanism was analyzed using Finite Element Analysis (FEA) in SolidWorks to guarantee the structural strength under operating loads. A static load of 300 N was applied to simulate the mechanical loading under machine operational conditions. From the von Mises Stress Analysis, a maximum of 0.150 MPa was found, which is less than the yield strength of the aluminum alloy used (215 MPa) indicating the frame can sustain the force without failure. Strain findings variated from 7.875e-11 to 1.431e-06, with the most strain concentrated at the location of load application, which is typical for mechanical systems in a static load. The maximum recorded movement of the frame was 0.00136mm, indicating a reasonable level of stiffness and essentially no deformation. The results reflected that the frame successfully transferred force to each quantity while maintaining consistent structural integrity for secure, and reliable nonwoven small-scale processing. Figure 4 below shows the stress, strain and deformation for body frame analysis.



(a) **(b)** **(c)**

Fig. 4 *(a) Stress analysis; (b) Strain analysis; (c) Displacement analysis*

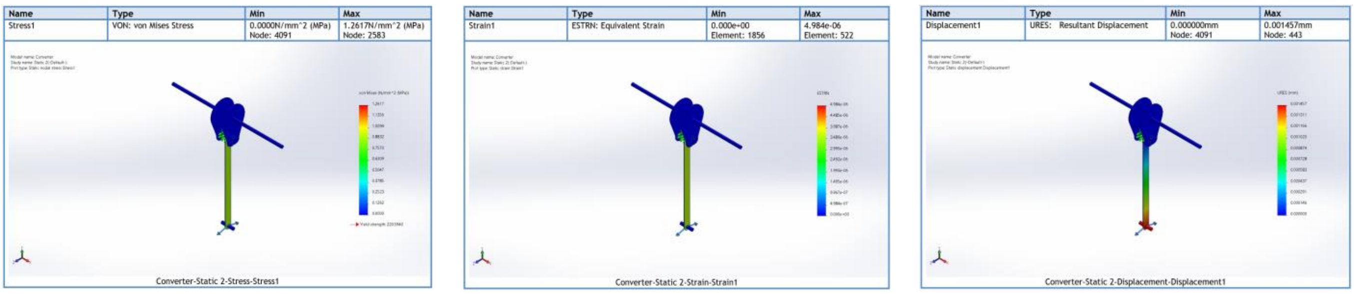
The converter component that drives the motion of the needle was analyzed via FEA under three loading scenarios. Torque (2.5 N·m) bending, downward force (-100 N), and upward force (150 N). The maximum stress under torque loading was 26.8 MPa, and maximum displacement was 2.250 mm. Both stresses and displacements were well within yield limits for the material at 220.6 MPa stress. Figure 5 below shows the stress, strain and deformation for torque analysis.



(a) **(b)** **(c)**

Fig. 5 *(a) Stress analysis; (b) Strain analysis; (c) Displacement analysis*

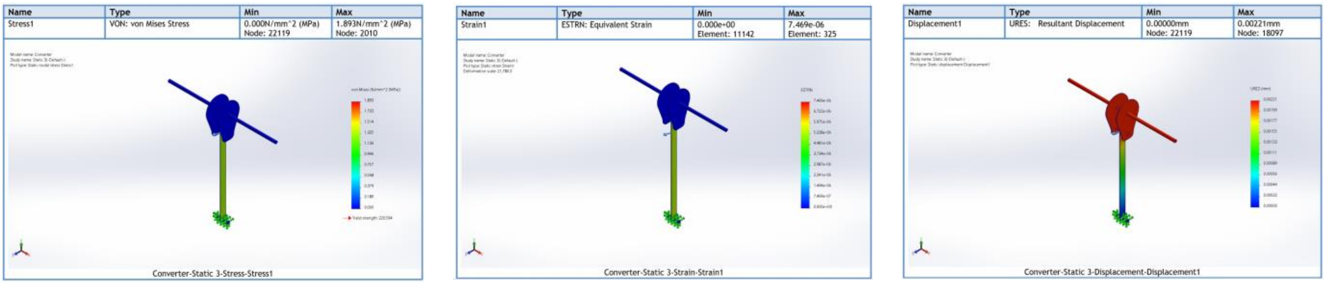
The downward force was concentrated at 1.2617 MPa stress and had a displacement value of 0.001457 mm, which is very small, indicating that it had enough structural integrity. Figure 6 below shows the stress, strain and deformation for downward force analysis.



(a) **(b)** **(c)**

Fig. 6 *(a) Stress analysis; (b) Strain analysis; (c) Displacement analysis*

Overall, the upward load produced an imparted stress of 1.893 MPa while also having a maximum displacement of 0.00221 mm. The level of strains was all acceptable and essentially no catastrophic deformation was apparent. The data indicates that the converter is able to withstand some degree of mechanical loading while assimilating damaging being permanently deformed, thus assisting in assisting in the longevity and reliability of the machine in which the needle-punching device will be mounted. Figure 7 below shows the stress, strain and deformation for upward force analysis.



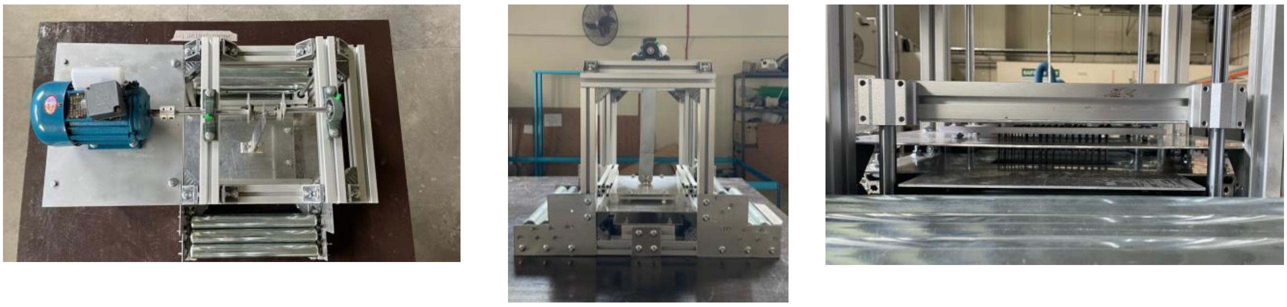
(a) **(b)** **(c)**

Fig. 7 *(a) Stress analysis; (b) Strain analysis; (c) Displacement analysis*

3.3 Result Fabricate and Assembly

The manufacturing and assembly of the small-scale modular punching needle system conformed to the established plan outline. The final assembly, as seen in Figure 8, demonstrates the successful integration of all necessary elements such as the needle system, conveyor roller, main frame, and drive system. The needle unit was directly mounted on the conveyor route from the front and the aluminium; support frame was tightly mounted to assist in maintaining structural stability and decrease the vibration while operating. The exterior layout is also considered to allow the user easy access to the various critical components for operational control and monitoring. The overhead view illustrates the interior layout of the critical components, mainly the motor, drive system and needle board at similar alignments.

This setup is important to ensure that the needle is entering the fabric vertically and properly. When viewed from the side, it is easy to see that the arrangement of the components such as the roller, motor and needle board is in a vertical line, meaning that the needle can move freely through a fabric item without obstruction. Finally, the interior view shows more detail of how the crankshaft, connecting rod and needle board operate at the same time and in harmony with one another. The modular concept is certainly very convenient for access purposes; this would reduce the time taken to access a component to maintain, modify or replace, without having to open the entire machine enclosure.



(a) **(b)** **(c)**

Fig. 8 *(a) Top view; (b) Side view; (c) In front view*

3.4 Result Testing

To ensure that all items performed as functions, the prototype was subject to visual and operational tests. The operation of machine was assessed for operation smoothly, the precision of alignment, and the efficiency of the punching process. As a result from figure 9, there were no mechanical failures or significant difficulties with alignment with all components running smoothly. The converters system took the rotary movement of the motor and produced a linear inline motion, raising and lowering the needle plate as required by the conveyor system, again to ensure that needle penetration was identical and on the correct plane within the fiber materials. The modular construction of the machine allowed for rapid and simple changes. The prototype integration was able to successfully punch nonwoven fiber sheets. The needle bar linear motion was also consistent and well within a safe travel range thus reducing the chance of excess pressure or unwanted touch. There was no severe interference, vibrations or other issues that inhibited operation. The overall test results indicate that the machine performs reliably achieving the intended aims and is ready for improved design or actual use in a small-scale textile production environment.

(a)

Fig. 9 *(a) Front view*

4. Conclusion

Successful design and development of a small-scale modular needle punching mechanism was achieved in this project. The actual machine manufactured in this work realized its purpose of being of small size, simple to use, and suitable for teaching and low volume production. Through design research using FEA to analyze the mechanism's strength in relation to the proposed loads to which it would be subject, the overall design produced a mechanism that has been shown through functional testing, to effectively and efficiently join different kinds of fibers. The project offers a pathway to sustainable textile innovations by providing access to lower cost and smaller scale needle punching for use in smaller business and educational settings. The modular approach supports learning, prototyping and experimentation, and possible future variations or automation. These will all promote sustainability trends of production worldwide and promote future developments in biodegradable textile use.

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