Design of an automated wood-pallet machine

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ABSTRACT

This article discusses an applied engineering project on the design and test of a wood-pallet machine that was supervised and sponsored by the Technology Application Center (TAC) at Old Dominion University. A hydraulic-power machine was designed to press six metal plates simultaneously onto six end surfaces of a wood pallet, which is used to stack items during movement or storage. Operation of this machine significantly reduces the manual hammering from four minutes to forty-five seconds. Students were guided to design the mechanical components and hydraulic power system. The animating software uses Automation Studio and Autodesk Inventor to simulate the system during the design stage before the machine is fabricated. Design equations are also evaluated in this article.

INDEX TERMS

Automation design, Hydraulic control, PLC, Pneumatic control

I. INTRODUCTION

Engineering Technology curriculum is a combination of a hands-on and minds-on approach to real-world application designs. This project is a product of the Automation and Control course in the curriculum of the Mechanical Engineering Technology under the Department of Engineering Technology at Old Dominion University. The course has the following objectives: [1]

1. Pneumatic components and pneumatic circuit designs.
2. Feedback from electrical sensors and related ladder diagrams.
3. Introduction to Programmable Logical Controllers (PLC) [2]-[3] and programming.
4. Integration of pneumatic, electrical, and hydraulic components with PLC programming design.

In addition to the two-hour/week lecture, a two-hour/week lab is part of the course to integrate the hands-on applications that involve mechanical, pneumatic, and electrical components in ladder diagram designs, and PLC programming. This lab has three main sections: (1) four weeks of pneumatic applications, (2) four weeks of pneumatic components, electrical sensors, and ladder diagram designs, and (3) five weeks of PLC programming designs/implementations [2]-[3]. This TAC project comes from the demands of a local industry that are very similar to the course objectives. Linking the course objectives the students are required to learn using real-world applications giving students needed industrial experiences before graduating and entering the work force. The joint faculty and student project presented in this article is one of the applied research models that demonstrate the design and fabrication of a hydraulic-powered wood-pallet machine.

The wood pallets are made of wood plates jointed by nails and are used to stack manufactured products for shipping and storage. To ensure strength and protection, the construction of the wood pallet uses metal nail plates on both sides that are shown in the upper left and lower right side in Figure 1. This construction is detailed in Figure 2 and 3. There are a total of six nail plates used in each wood pallet construction. Usually, the operation was done by manual hammering, which required extensive time and labor costs. The operation was noisy and not a good fit in many areas. To resolve these problems, a hydraulic-powered machine was designed to press the six nail plates onto the sides of the wood pallet simultaneously in order to reduce the noise and speed up the construction process.

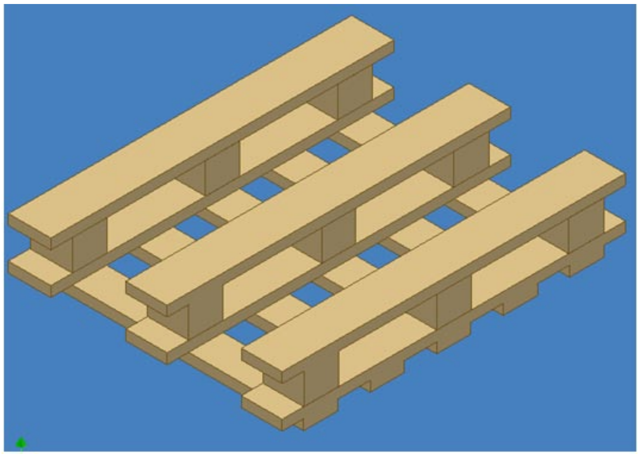

Figure 1. Wood pallet

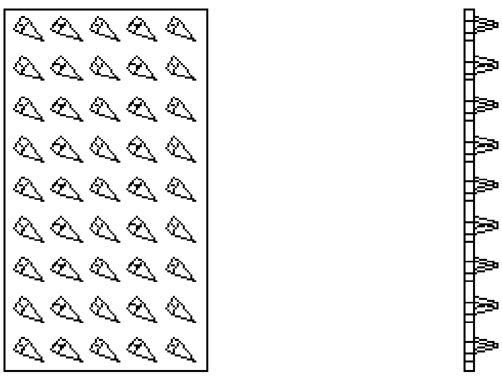

Figure 2. Nail plate

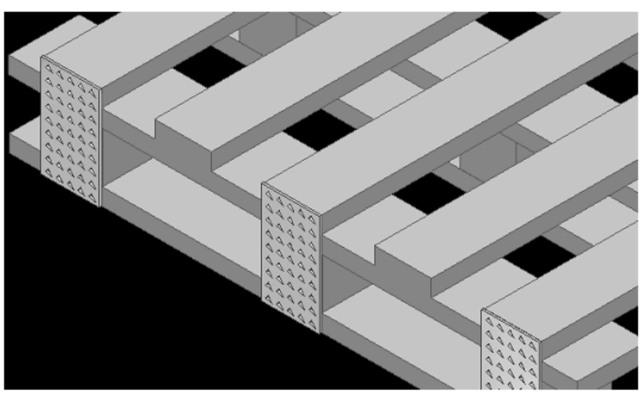

Figure 3. Nail plates fitted onto a wood pallet

II. STUDENTS' ROLES

To better manage this project, students were divided into two groups: mechanical design and hydraulic circuit design. In the mechanical design group, students were responsible for finding the required force needed to press the nails onto the pallet surfaces, designing the press-operation mechanism, and providing the actual dimensions sketch of the designed system. In the hydraulic circuit design group, students were asked to optimize the operation cycle time, determine the diameter dimension for hydraulic cylinders, and design the hydraulic circuit with appropriate electrical sensors.

III. THE DESIGN CONSIDERATIONS

There are different calculations and considerations for the design processes in this project. They are presented in the following order:

A. Nailing Force

A material testing machine [4], as shown in Figure 4, was used to determine the required force to press a plate onto a wood pallet. After several test runs, the results showed that approximately *6,000 lb* is needed to press one nail plate properly onto the wood surface. To accommodate the various natural properties of the wood, *10,000 lb* of the compression force is used based on the design calculation.

B. Diameter of the Hydraulic Cylinder

The diameter of the hydraulic cylinder can be calculated by using the following equation [5]:

$$F = P^* (\pi/4)^* d^2 \qquad (1)$$

where F is the compression force, in this case $F = 10{,}000\ lb$; P is the hydraulic pressure and in this case, $P=1500\ psi$. By substituting these values into equation (1), the diameter of the hydraulic cylinder d is approximately *3* inches.

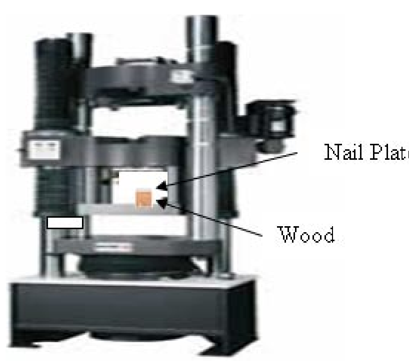

Figure 4. Compression test of the nail plate to a wood pallet

C. Hydraulic Force Mechanism

In order to control the cost of the system, the hydraulic components were placed under a 6'x5'x4' worktable. The press-operation mechanism is shown in Figure 5. The hydraulic force is transmitted from a hydraulic cylinder to a compression head that is located at the top of the worktable. When the double-acting hydraulic cylinder moves forward, a compression force is exerted onto the top of the worktable to press a metallic plate onto a wood pallet. After the cylinder retracts, a clear space is created for easy removal of the wood pallet.

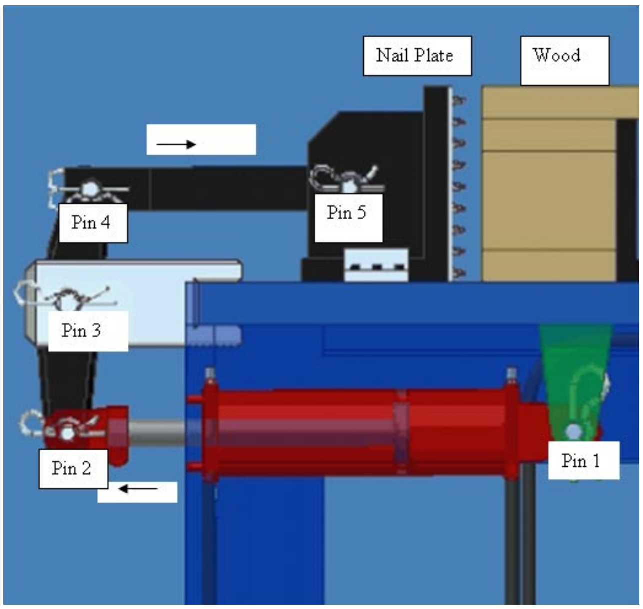

Figure 5. Nailing mechanism

D. Pin Diameter

Diametric size of the five pins in Figure 5 can be calculated from the following equation: [5]

$$F = S_{sw}*(\pi d^2/4) \quad (2)$$

where *F* is the force from the hydraulic cylinder, in this case *F = 10,000 lb*; S_{sw} is the allowable shearing stress; and d is the pin diameter. Using maximum shear stress theory, S_{sw} can be found based on the following equation [5]-[6]:

$$S_{sw} = S_{ys}/(2*Fs) \quad (3)$$

where S_{ys} represents the yield strength of the pin, in this case, S_{ys} *=100,000 psi* is selected; *Fs* is the safety factor and set to *2*. Therefore, S_{sw} *= 25,000 psi* is obtained from equation (3). Substituting these values into equation (2), the pin diameter can be found as *0.71* inches. For convenience, *d = 0.75* inches is selected.

E. Dimensions of the Vertical Link

The vertical link is the linkage between Pin 2 and Pin 4 and presented in Figure 5. It experiences a bending stress generated by the hydraulic force. The bending stress is calculated with the equation as [5]-[6]

$$\sigma_b = K \frac{MC}{I} \quad (4)$$

where σ_b is the bending stress; *K* is the stress concentration factor; *M* is the bending moment; *C* is the distance from the neutral axis of the link section to its outer surface; and *I* is the moment of inertia of the link section.

To use the maximum normal stress theory in this design, σ_b can be determined from the following equation [5]-[6]

$$\sigma_b = \frac{S_{ys}}{F_s} \quad (5)$$

where S_{ys} is tensile yield strength of the material and F_s is the factor of safety. In this application, AISI 1040 steel with *90,000 psi* in tensile strength is selected. Assuming F_s *=1.5*, the allowable working bending stress is used as *60,000 psi*. Also from stress-concentration-factor tables, *K* can be found as *1.8* [5]-[6].

The center distance between Pin 2 and Pin 3 is forced to be set at *7.5 inches* due to the limited available space on the worktable (see Figure 5). As a result, the bending moment *M* is calculated as [5], [6]

$$M = 7.5 \times 10{,}000 = 75{,}000 \text{ lb-in} \quad (6)$$

Where I can be found from the following equation [5], [6]:

$$I = \frac{1}{12} bh^3 \quad (7)$$

where b is the thickness of the plate, in this case *b = 2.0 in* and *h* is the width of the link. Both *b* and *h* are shown in the parentheses of Figure 6. C in equation (4) is one half of the width of the link, therefore *C= (1/2)* h*. By substituting these values into equation (4), the link width h can be found as *2.6 inches.* The design sketch is presented in Figure 6. Figure 7 demonstrates these six press-operation mechanisms when mounted on the worktable.

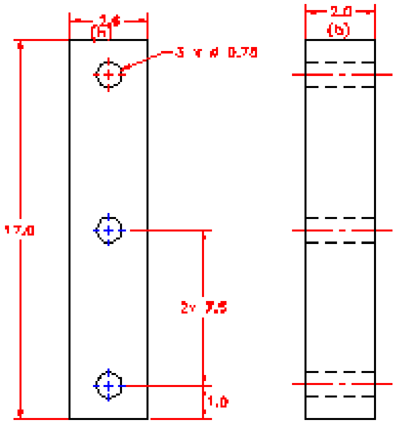

Figure 6. Design of the link

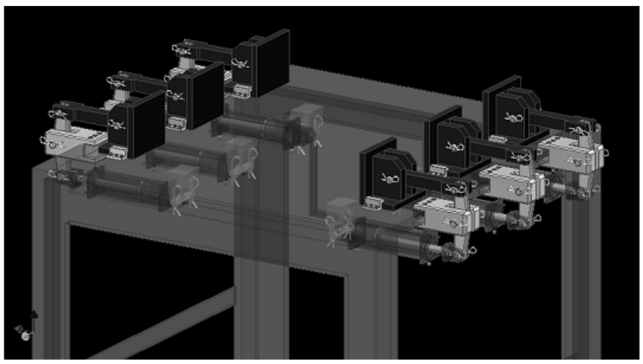

Figure 7. Six hydraulic nailing mechanisms

F. Flexible Locking Mechanism

In order to hold the wood pallet on top of the worktable during the pressed nailing process, a special locking mechanism is necessary. Because the wood pallets are made manually, the distance between the two inner surfaces used to locate the pallets can vary as much as 1/4 inch. This variable factor is presented as "Varying Distance" in Figure 8. To protect the pallet from being bent or damaged by the compression force during the nailing process, a flexible locking mechanism is designed to solve this problem. As shown in Figure 8, the design has a fixed end on one side and a flexible end on the other to accommodate the problem of Varying Distances. Figure 9 shows the principle of the locking operation. The moving mechanism at the end of the worktable is opposite the hydraulic compression force, and the locating surface on the flexible end will remain in the locked position during the press-operation process.

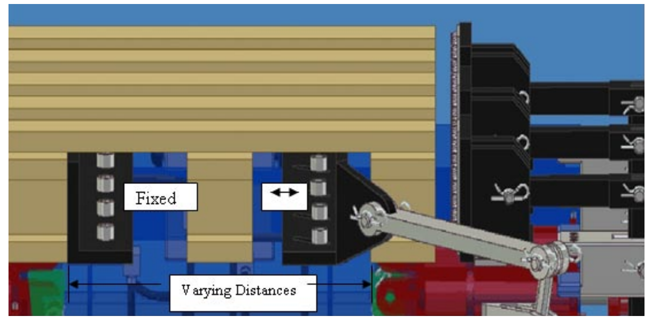

Figure 8. Locking mechanism of varying inner distances of the wood pallet

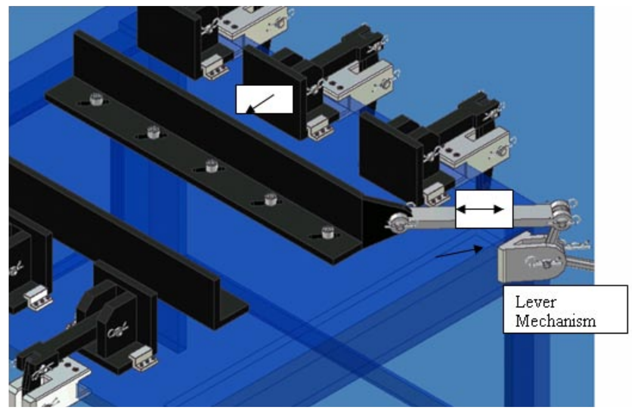

Figure 9. The automatic anti-reverse lever mechanism

G. Compression Head

There is a permanent magnetic plate mounted on the compression head. This magnet is used to hold the metal nail plate, as shown in Figure 10. Each compression-head face has extra room to accommodate the nail plate to be aligned with the wood pallets.

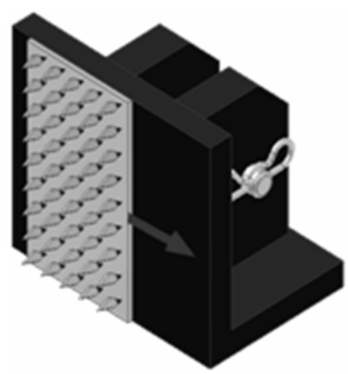

Figure 10. A nail plate on the magnetic compression head

H. Hydraulic System Design

Students are required to use the simulation software called Automation Studio [7] for the hydraulic circuit design, as shown in Figure 11. The operation steps of the designed circuit are: (1) A Normally

Open (N.O.) Push Button PB1 is pressed to activate SOL1. (2) When SOL1 is activated, it will activate the right position of the 4/2 directional control valve. The hydraulic fluid will push the double-acting cylinder in the forward direction to generate the press operation. (3) A Normally Closed (N.C.) Push Button PB2 can be pressed at any time to deactivate SOL1 and move the cylinder back to its retracted position for any desired or emergency situation. (4) When overloaded, the pressure relief valve will open and the fluid will be drained directly into the reservoir to release the pressure of any overpressure condition.

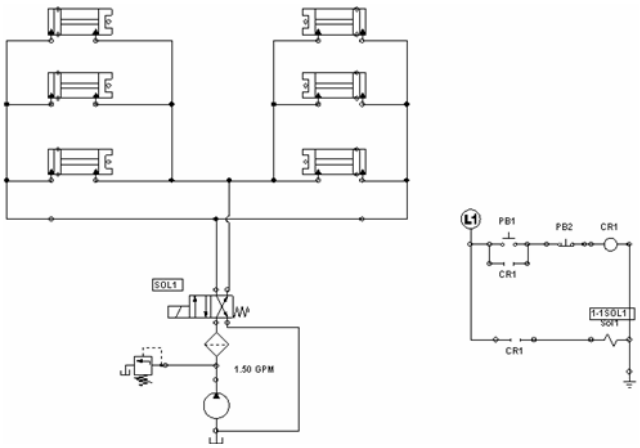

Figure 11. Hydraulic control circuit

I. *Flow Rate of the Hydraulic Pump*

The flow rate of the hydraulic pump in Figure 11 can be calculated in gallons per minute *(GPM)* based on the following equation [8]

$$GPM = \frac{V}{t * 231} \qquad (8)$$

where *V* is the total volume of the hydraulic cylinder in cubic inches; *t* is the operation cycle time in minutes that is set to be *0.5 minutes*; and one gallon equals *231 cubic inches*. The diameter of the cylinder is *3 inches* from equation (1), *V* can be found in the following calculation:

$$V = n * Str * \frac{\pi * d^2}{4} \qquad (9)$$

where *n* is the number of cylinders, in this case *n=6*; *d* is the diameter of the piston and is equal to *3 inches*; and *Str* is the stroke or total displacement of each hydraulic cylinder, in this case *Str= 4 inches*. Substituting these values into equations (9) and (8), the *GPM* can be found as *1.47*. Therefore, a *1.5 GPM* hydraulic pump with fixed displacement is selected in this project.

IV. TEST AND VALIDATION OF THE DESIGNS AND OPERATIONS

Numerous nailing tests were performed to validate the design theory before the machine was delivered to the company. Results showed that there was no damage to the mechanical components. In addition, the whole operation was completed in about forty-five seconds. The hydraulic operation is very quiet and smooth. The overall operational sequences of the system are presented from Figures 12 to 15. The six nail plates positioned on six magnetic compression heads and the wood pallet in the locked position on the worktable is shown in Figure 12. The compression heads pushing six nail plates onto the wood pallet surfaces is revealed in Figure 13. After the press operation, Figure 14 illustrates the retracted position of the hydraulic heads. The wood pallet after the completed nailing process and left on the worktable ready for pickup is demonstrated in Figure 15.

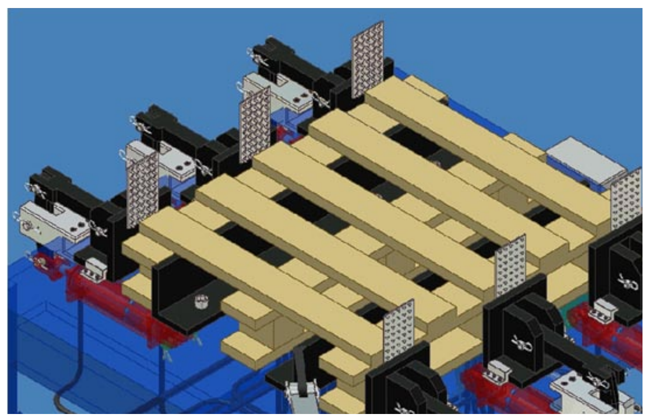

Figure 12. Nail plates placed on the magnetic hydraulic heads

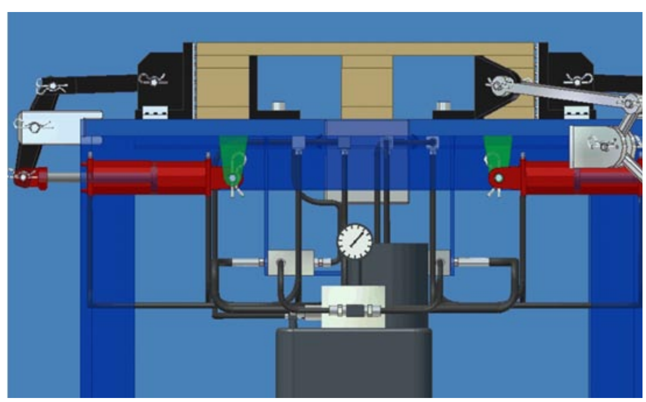

Figure 13. The nail plates pushed onto the wood pallet

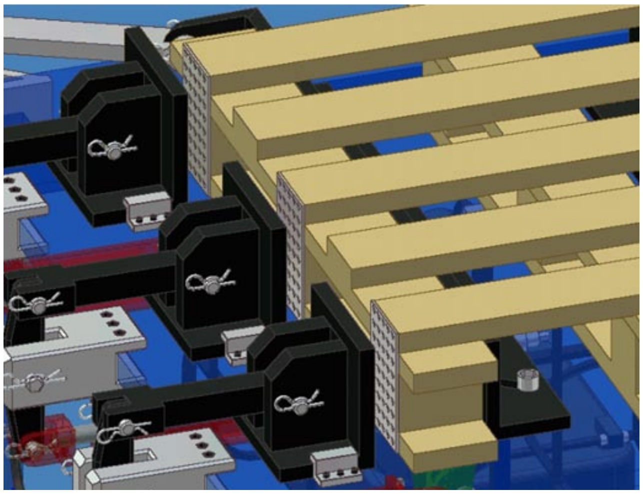

Figure 14. The hydraulic heads in retracted position

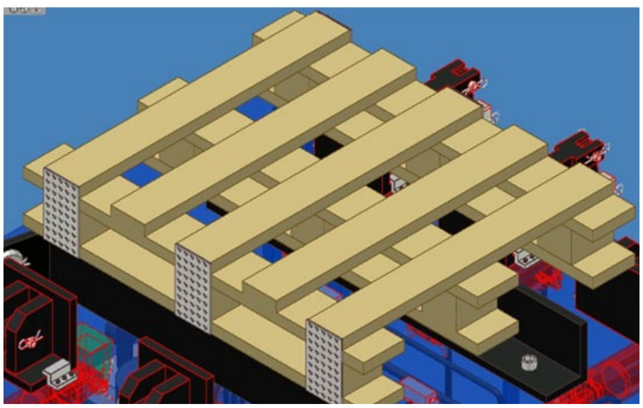

Figure 15. Wood pallet is removed after the operation

V. THE LEARNING EXPERIENCES

There are two additional features that were not in the original plan for this project: (1) the locking mechanism design aimed at securing the wood pallets that have no unique shapes and variable dimensions and (2) the use of stress concentration factor in the machine design.

The locking mechanism was originally designed with two fixed-steel plates to locate a wood pallet during the first operation. Due to Varying Distances between the inner surfaces, pallets could not be tightly locked, and several wood pallets were bent and damaged during the test operations. This leads to a modified design on one side of the locking mechanism to make it movable. The flexible locking mechanism protects the wood pallets and improves the nailing operation.

Carelessly overlooking of the Stress Concentration Factor K in equation (4) of the first design caused the link failure during the system test. The K was included in the revised design equation after the examination of the 3/4" diameter of holes in the link and the problem was resolved.

VI. CONCLUSION

The system was tested many times before it was delivered to the local company. The tested data shows that the designed system is quite reliable and meets the intended design expectations.

This project has fulfilled the goals: (1) It satisfies the client's needs: an automated process for the nailing operation significantly increases productivity and reduces the hammering noises made by manual operation. (2) It provides various design experiences for students: learning how to use the design equations and animation software tools for mechanical components and hydraulic system designs is a valuable lesson. In addition, the modification of the original mechanism design to meet size variations in locking the wood pallets is a good learning experience.

The process of designing, building the system, and using software tools, has triggered students' interest in real-world applications. This integration provides interesting concepts that offer students an enhanced understanding of the links between hardware and software. The potential applications for use with classroom/lab materials make them suitable for future workplaces.

VII. REFERENCES

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