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Design and Experimental Validation of a Pneumatic Sheet Metal Bending Machine

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Abstract— In this paper, the design, analysis, and testing of a pneumatic sheet metal bending machine are presented. The objective of the work is to design a low-cost, energy-efficient bending machine using pneumatics and a rotating base. The methodology is divided into three sections: calculation of the forces required, design of the machine using 3D CAD, and construction of the machine. The features of the machine include the use of an aluminum framework, a motorized lead screw clamp at the top to hold the workpiece, a servo rotating base, two pneumatic pistons at the top to apply the pressing force at the point where the bending is required, and one at the bottom with a bending tool to apply the bending force. The workpiece is made of a 1 mm thick aluminum alloy. First, the clamping force required to hold the workpiece is determined, considering the friction, and then the bending force required to bend the workpiece to the required angle is determined. Next, the machine will be designed in CAD to accommodate these forces and motions. Finally, the prototype will be built and tested to determine the bending accuracy. From the results, the machine can be able to bend 1 mm aluminum up to 90° with acceptable accuracy within a 5% error. This can be done at a pressure of less than 5 bar. This paper has contributed to the understanding of the design framework for the pneumatic press brake that can be used as a reference for an undergraduate project. The results obtained match the theoretical values.

Keywords— Pneumatic pistons; Lead screw; Clamp; Servo rotating base; Sheet metal bending

I. INTRODUCTION

Sheet metal bending is one of the most popular metals forming processes that are used in various manufacturing industries to produce structural components. Generally, conventional bending processes can be carried out through hydraulic or mechanical press brakes. This is because these machines can produce high forces while ensuring the accuracy of dimensions during the forming processes. However, these machines require complex hydraulic systems, high installation costs, and high energy consumption during continuous operation. On the other hand, pneumatic machines can be a potential substitute for light to medium-duty forming processes due to their simple construction, low maintenance costs, and fast response. Past research on the development of pneumatic bending equipment showed the potential of compressed air-driven forming systems for sheet metalworking processes [1][2]. However, pneumatic actuation systems are normally associated with less energy efficiency compared to hydraulic systems due to energy loss in the compression, regulation, and exhaust of compressed air processes [3][4]. Past research on the energy efficiency of pneumatic systems used in industrial processes showed that the overall energy efficiency of these systems ranges between 6% and 18% [5][6].

Recent research has been directed toward improving the performance and efficiency of pneumatic systems through the improvement of actuator sizing, pressure optimization, and the development of sophisticated control strategies. Simulation studies have confirmed that the selection of appropriate cylinder dimensions and pressure can minimize the consumption of compressed air while ensuring sufficient output forces [7][8]. In addition, various researchers have investigated energy-efficient pneumatic systems through pressure-based cutoff techniques, optimized valve timing strategies, and the development of sophisticated control techniques to minimize energy dissipation in pneumatic drives [9][10]. Exergy analysis techniques have also been used to identify energy dissipation points in pneumatic systems and to propose techniques to improve thermodynamic efficiency [11][12]. In parallel with this research direction, research in sheet metal forming has explored better techniques in bending, incremental forming techniques, and modeling of deformation to minimize the required bending force as well as increase the dimensional accuracy [13][14]. Advanced analytical and numerical techniques have also been explored to investigate the springback effect as well as optimize the bending parameters for thin sheets made from different sheet metals, especially those made from aluminum alloys used in lightweight structures [15].

Hence, there is a considerable research gap to be filled with regards to the development of integrated pneumatic bending systems that can offer the benefits of both mechanical design optimization and energy-efficient pneumatic actuation. Recent studies have highlighted the importance of experimental verification of pneumatic forming equipment and the development of more compact and cost-effective machines to cater to the requirements of small-scale manufacturing and experimentation [16]. In this context, the current study has been conducted to focus on the analytical evaluation of a pneumatic sheet metal bending machine that can offer high-efficiency bending of thin aluminium sheets with minimal structural complexity. The proposed system will comprise a rotating base with a servo motor, a clamping system with a lead screw mechanism, and a bending tool with a pneumatic system. The research will involve the application of theoretical calculations for forces, 3D CAD modeling, and the creation of a prototype to test the feasibility of the proposed system.

II. LITERATURE REVIEW

Pneumatic systems continue to be widely used for sheet metal forming due to the simplicity, economic viability, and high speed of actuation. However, the inefficiency of the compressed air supply and oversizing of the actuator lead to low efficiency, ranging from 6% to 18% [1][2]. In the earlier days, research has been conducted on the mechanical aspects of improving the accuracy of the bending process and the reduction of the bending machine's vibration. However, research conducted on the efficiency of industrial pneumatic systems revealed critical inefficiencies, such as the losses due to pressure, control strategies, and the inefficiency of the exhaust gas supply [5][6]. Recent research conducted on the use of the latest pneumatic benders indicates the challenges being faced in the design of the benders, such as the balance of speed, accuracy, and energy efficiency, the use of optimal sizing, control strategies, and the use of energy recuperation strategies.

Literature has shown a move from fundamental mechanical design studies to sophisticated evaluations through simulation techniques, exergy analysis, and intelligent control algorithms. Some studies have used model-based control techniques to assess pneumatic cylinder performance, pressure regulation, and energy consumption under different conditions. Exergy analysis has also been used to identify the inefficiencies associated with pneumatic systems [11][12]. One notable trend in the methodologies used to assess the performance of pneumatic sheet metal bending systems is the adoption of adaptive and digital control techniques, including reinforcement learning algorithms [13][14] and finite element analysis [15].

In the literature, different researchers have documented significant reductions in compressed air consumption with the optimization of actuator sizing, pressure control, and intelligent switching circuits. Energy savings vary from 25% to as high as 85% with the application of throttling control circuits, pressure-based cut-off circuits, or valve timing optimization techniques [7][14][17]. Pneumatic closed circuits with exhaust air reutilization techniques attain efficiency savings between 34% and 72%, thus proving the efficiency of energy recovery techniques [8][11]. Research into servo-pneumatic control systems proves that sophisticated control algorithms can significantly reduce nonlinearities and enhance the accuracy of control during sheet metal bending operations [10][13].

Table 1: Gap Analysis and Focus of Previous Papers

Reference	Focus	Gap Identified
Badger & Lewis (1976)	Three-point pneumatic bender concept	Early design, no focus on efficiency or control methods
Bangaru & Devaraj (2015)	Pneumatic servo positioning energy analysis	Did not address sheet bending application specifically

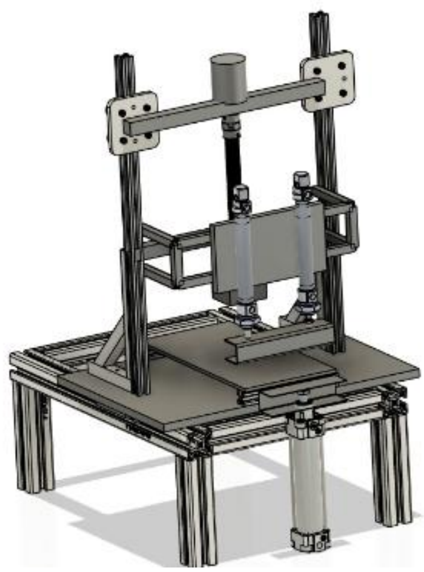
Reference	Focus	Gap Identified
Haikova et al. (2022)	Energy efficiency in sheet bending machines	Proposed methods not yet fully tested on real equipment
Haletskyi & Kasian (2025)	Pneumatic drive efficiency methods	Not tailored to sheet metal bending equipment
Hans (1975)	Air-press brake design	Historic design; lacks modern control or efficiency upgrades

Overall, the body of literature points to a high degree of consensus in terms of the need to improve pneumatic efficiency in sheet metal bending applications. While there are many studies that point to the potential benefits of improving pneumatic efficiency, most of the research deals with the overall potential benefits of pneumatic systems rather than equipment-specific studies on pneumatic sheet metal bending equipment. This provides a strong foundation for future research that will be able to provide experimentally validated energy-efficient pneumatic sheet metal bending equipment.

III. METHODOLOGY

Force Calculations: First, the mechanical requirements are determined. This involves the calculation of the required bending force to achieve the desired bend angle for a given 2 mm thick aluminum sheet, as well as the required clamping force to hold the sheet securely during the bending process. This is done using standard equations for bending, as well as frictional estimates. A suitable actuator, such as a pneumatic cylinder, clamp, and lead screw, is then determined.

3D CAD Drawing: By using Fusion 360 CAD software, a 3D CAD model of the bending machine was designed. The CAD design includes an aluminum frame resting on a flat surface, a rotating circular plate driven by a servo motor, a cross-member at the top with a motor and screw assembly to clamp the material, and pneumatic cylinders. Two pneumatic pistons with a short stroke are placed at the top of the frame near the bending point to push down the plate, and another pneumatic cylinder with a bending tool is placed at the bottom.



[Figure 1: Fusion 360 CAD model of the prototype]

Prototype Building: Next, the actual prototype is built based on the CAD design. For the construction, the framework is made of aluminum beams and plates for maximum lightness and rigidity. A flat aluminum plate is attached to a bearing, which is rotated by a servo motor. A stepper motor with a lead screw is placed at the top. Two air cylinders for clamping at the top, where the bend point is, are placed above the sheet. Similarly, one air cylinder with a steel punch tool is placed at the bottom for the bending action. This methodology ensures that the design is based on actual quantitative force analysis, thereby creating a working prototype.

IV. THEORY AND CALCULATIONS

Bending Mechanics

The bending process in sheet metal forming can be modeled as a three-point bending operation in which a concentrated force is applied at the center of the sheet while it is supported at two points. The required bending force depends on the material properties, sheet thickness, bend length, and die opening. A commonly used empirical relation for bending is expressed as:

$$F = K \times L \times t^2 \times UTS / V \quad \ldots(1)$$

where F represents the required bending force, L is the bending length of the sheet, t is the sheet thickness, UTS is the ultimate tensile strength of the material, V is the die opening width, and K is a constant that depends on the bending method and angle. For a 90° air bending process, K typically varies between 1.2 and 1.5. Considering an aluminum sheet of thickness 1 mm with an ultimate tensile strength of approximately 110 N/mm², a bend length of 100 mm, and a die opening of about eight times the sheet

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thickness, the required bending force is calculated to be approximately 1.8 kN.

Clamping and Friction

During the bending operation, it is essential that the sheet remains securely fixed to prevent sliding or misalignment. The clamping force must be sufficient to generate friction between the sheet and the clamping surfaces so that the sheet does not move during bending. The condition for preventing slip is expressed as:

$$N \approx F\_bend / \mu \quad \ldots(2)$$

where μ represents the coefficient of friction between the contacting surfaces and N is the normal clamping force. For aluminum–steel contact surfaces, the coefficient of static friction typically ranges between 0.9 and 1.2 under dry conditions. Based on the calculated bending force, the minimum clamping force required lies in the range of 10–25 kN, considering practical safety factors. The torque T required to rotate the lead screw against the thrust load F is given by:

$$T = F \times (d_m/2) \times (L + \mu\pi d_m) / (\mu\, d_m - \mu L) \quad \ldots(3)$$

where d_m is the mean diameter of the screw, L is the lead of the screw, and μ is the thread friction coefficient.

Pneumatic Cylinder Force

The bending force itself is generated using pneumatic cylinders operating at controlled air pressure. The theoretical force produced by a pneumatic cylinder is determined from the basic relation:

$$F = P \times A \quad \ldots(4)$$

where P is the supplied air pressure and A is the effective piston area. For a typical pneumatic cylinder with a bore diameter between 40 mm and 50 mm operating at a pressure of 5–6 bar, the generated force can range between 700 N and 750 N per cylinder. By employing multiple cylinders in the machine design, the total available force exceeds the calculated bending force requirement.

V. DEVELOPING AND WORKING OF THE PROTOTYPE

5.1 Design and Fabrication Stages

The development of the pneumatic sheet metal bending machine involved several systematic stages including conceptual design, component selection, frame fabrication, pneumatic system integration, and final assembly. The objective during prototype development was to construct a compact and structurally stable system capable of generating sufficient bending force while maintaining simplicity of operation and low manufacturing cost.

5.2 Frame Design and Fabrication

The structural frame forms the primary load-bearing component of the bending machine. The frame was designed using aluminum structural members to ensure adequate rigidity while minimizing weight. Aluminum sections were selected because of their high strength-to-weight ratio, corrosion resistance, and ease of machining. The frame was fabricated using rectangular aluminum profiles joined with bolts and brackets to maintain structural alignment.

5.3 Rotating Base Installation

A circular rotating platform was mounted on the machine base to allow controlled positioning of the sheet metal during bending operations. The rotating base is driven by a precision servo motor which enables accurate angular positioning of the workpiece. This feature allows the machine to perform bending operations at different orientations without manually repositioning the sheet.

5.4 Clamping Mechanism Development

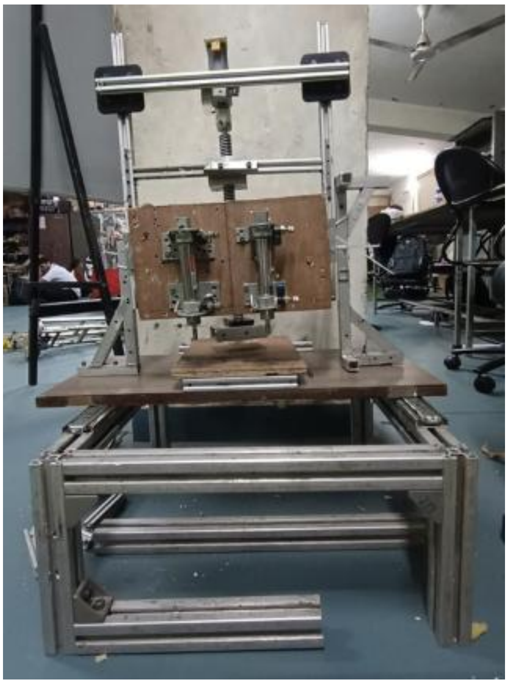
A lead screw-based clamping mechanism was installed above the work table to secure the sheet metal before bending. The lead screw is driven by a stepper motor that converts rotational motion into linear displacement. When the screw rotates, the clamping plate moves downward to press the sheet against the support surface, ensuring that the sheet remains fixed during the bending process.

5.5 Pneumatic System Integration

The bending force is generated using pneumatic cylinders supplied with compressed air through solenoid valves. Two pneumatic pistons are mounted above the bending location to apply downward pressure while another piston positioned beneath the sheet pushes the bending tool upward. The pneumatic circuit includes an air compressor, pressure regulator, control valves, and connecting pipelines. The system operates at pressures between 4–6 bar.

5.6 Final Assembly and Alignment

After fabrication of individual components, the complete system was assembled and aligned. Proper alignment of the bending tool, sheet support, and pneumatic cylinders is critical to ensure uniform bending and avoid uneven stresses on the sheet.



[Figure 2: Actual prototype front view]

[Figure 3: Actual Prototype]

5.7 Working

The working of the pneumatic sheet metal bending machine is based on the combined operation of the clamping mechanism, pneumatic cylinders, and rotating base. Initially, the aluminium sheet is placed on the support platform at the bending location. The operator activates the stepper motor which rotates the lead screw to move the clamping plate downward and firmly hold the sheet in position.

Once the sheet is securely clamped, compressed air is supplied to the pneumatic cylinders through a control valve. The upper cylinders apply downward force at the bending location while the lower cylinder pushes the bending tool upward. The interaction between the upward force of the bending tool and the downward clamping force causes the sheet to deform plastically along the bending line. The bending angle increases as the pneumatic piston extends. When the piston reaches its predetermined stroke length, the sheet achieves the required bending angle, typically 90 degrees. After the bending operation is completed, the compressed air supply is released, allowing the pistons to retract.

VI. RESULTS AND DISCUSSION

To evaluate the performance of the developed machine, experimental testing was carried out using 1 mm thick aluminum sheets. The objective of the testing phase was to determine whether the prototype could generate sufficient force to produce a 90° bend while maintaining dimensional accuracy. During testing, aluminum sheets were placed on the bending platform and clamped using the lead screw mechanism. The pneumatic system was operated at different pressure levels ranging from 3 bar to 6 bar, and the corresponding bending angles were recorded. The results obtained from these experiments are presented in Table 2.

Table 2: Prototype Bending Test Results

Test Batch No.	Air Pressure (bar)	Mean Cylinder Force (N)	Mean Bend Angle (°)
1	3	376	32
2	4	502	54
3	5	628	78
4	6	754	90

The results demonstrate that increasing pneumatic pressure increases the bending force and consequently increases the bending angle achieved in the sheet metal. The experimental results confirm that the designed pneumatic bending machine is capable of bending thin aluminum

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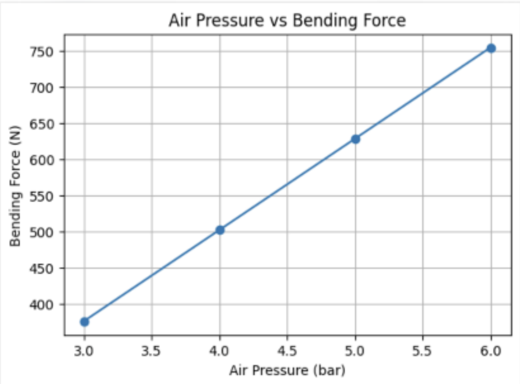
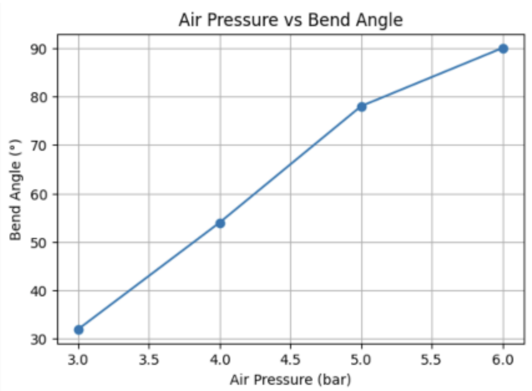
sheets effectively. The theoretical calculations predicted that a bending force of approximately 1.8 kN would be required to deform the sheet to the desired angle. The selected pneumatic cylinders operating at pressures between 4–6 bar produced forces sufficient to achieve this deformation.

Graph 1: Air Pressure vs Bending Force



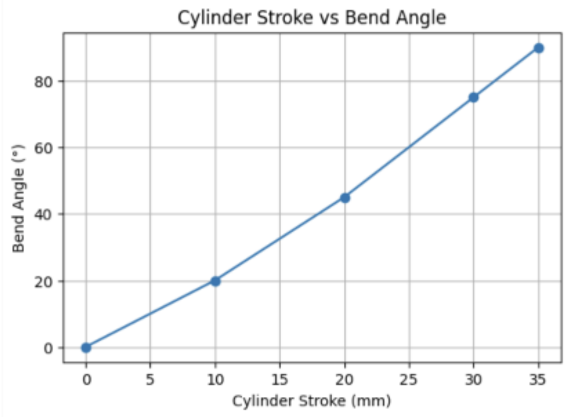
The first graph represents the relationship between the pneumatic pressure and the force generated by the cylinder. The graph shows a linear increase in force with increasing pressure because the force generated by a pneumatic actuator is directly proportional to the applied air pressure and piston area.

Graph 2: Air Pressure vs Bend Angle



The second graph shows the relationship between pneumatic pressure and the resulting bending angle of the aluminium sheet. As the air pressure increases, the bending angle increases progressively until reaching the desired 90° bend at approximately 6 bar pressure.

Graph 3: Cylinder Stroke vs Bend Angle



Another important relationship observed during testing is the variation of bending angle with cylinder stroke. Initially, the bending angle increases rapidly as the piston moves upward. However, as the sheet approaches the final bending angle, the rate of increase slows due to the contact between the sheet and the die surfaces.

The results demonstrate that the machine operates reliably and produces consistent bending results with minimal variation between repeated tests. The clamping mechanism effectively prevents sheet movement during bending, ensuring good dimensional accuracy. Furthermore, the pneumatic system provides several advantages such as faster operation, reduced maintenance, and simpler control compared to hydraulic systems.

VII. CONCLUSION

This research presented the design, development, and evaluation of a pneumatic sheet metal bending machine intended for bending thin aluminium sheets in an efficient and cost-effective manner. The study combined theoretical analysis, CAD modelling, prototype fabrication, and experimental testing to validate the feasibility of the proposed system.

The theoretical analysis demonstrated that a bending force of approximately 1.8 kN is required to bend a 1 mm aluminium sheet. Based on this requirement, suitable pneumatic cylinders, clamping mechanisms, and structural components were selected to ensure reliable machine operation. The calculations also confirmed that the lead screw clamping mechanism can generate sufficient normal force to prevent sheet slippage during bending.

Experimental testing was conducted to evaluate the performance of the developed machine. The results showed that the prototype is capable of bending 1 mm aluminium sheets up to 90° using pneumatic pressures between 5–6 bar. The bending process was found to be smooth and repeatable, confirming that the design calculations and component selection were appropriate for the intended application.

Overall, the proposed pneumatic sheet metal bending machine provides a simple and energy-efficient alternative to conventional hydraulic bending systems for light-duty sheet forming applications. The machine is particularly suitable for educational laboratories, prototyping workshops, and small manufacturing units where compact, low-cost equipment is required.

Future work may focus on incorporating automated control systems, sensors for real-time angle measurement, and advanced pneumatic control strategies to further improve accuracy and efficiency. Additionally, testing with different materials and sheet thicknesses can be conducted to expand the capabilities of the machine.

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