Design and Development of a 4-Axis Filament Winding Machine

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Abstract— The objective of this study is to design and develop a 4-axis filament winding machine, which has portable, lightweight, low costs, high-efficiency and inexpensive control system features compared to the previous and present machines. The previous and many current filament winding machines consist of two axes hence two more axes will be added to our design. The 4-axes are for; rotation of mandrel, the longitudinal movement of carriage, the pay-out eye angular motion and the transverse carriage movement. The commonly used filament materials are glass or carbon fibres, which are impregnated in a bath with resin as they are wound onto the mandrel or product liners.

Keywords: 4-Axes, Filament Winding, Automated Winding System

I. Introduction

Filament winding is a process in which filament under tension, is wound over open cylinders or close-ended structures (pressure vessels). It involves winding filaments over a mandrel which rotates about the spindle while a delivery eye which is mounted on a carriage, traverses horizontally, across the line through the axis of the rotating mandrel, laying down fibers in the desired pattern. Machines with over four (4) axes are usually used for advanced commercial applications. Computer controlled filament winding machines need the employment of software system to come up with the winding patterns and machine methods.

II. Problem Summary

Many filament winding machines which are currently used in industries, consist of two axes, hence, they cannot be able to wind filament at the longitudinal ends of closed vessels.

The few, 4-axis filament winding machines which are in use today, are expensive, bulky and complicated.

III. Working

The mandrel rotates about the spindle (X-axis) while a delivery eye on a carriage traverses horizontally (Y-axis) in line with the axis of the rotating mandrel, laying down fibers to the desired pattern. Once the rotating shaft is completely coated to the required thickness, the resin is cured.

The simplest winding machines have 2 axes of motion, the mandrel rotation and the carriage transverse motion (usually horizontal).

Depending on the resin system and its cure characteristics, the rotating mandrel is often placed in an oven or placed under radiant heaters until the part is cured. Once the resin has cured, the mandrel is removed or extracted, leaving the hollow final product. For some products such as gas bottles, the 'mandrel' is a permanent part of the finished product forming a liner to prevent gas leakage or as a barrier to protect the composite, from the fluid to be stored.

Filament winding is well suited to automation, and there are many applications, such as pipe and small pressure vessel that are wound and cured without any human intervention. The controlled variables for winding are; fibre type, resin content, winding angle, tow or bandwidth and thickness of the fiber bundle. The angle at which the fibre is wound, has an effect on the properties of the final product. A high angle "hoop" will provide circumferential strength, while lower angle patterns (either polar or helical) will provide greater longitudinal /axial tensile strength.

IV. Methods of Filament Winding System

A. *Resin Bath-Based Impregnation.*

Conventional wet-filament winding is used to manufacture fibre-reinforced components such as pipes and pressure vessels. It is the wet type of filament winding in which resin is kept in a basin, from which a filament of any material like FRP, Plastic, etc. which is to be wound on a pipe, pressure vessel or a pipe is passed.

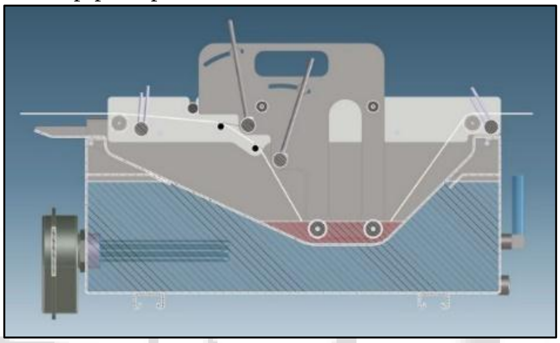

Fig. 1: Resin bath-based impregnation

B. *Dry Type Winding*

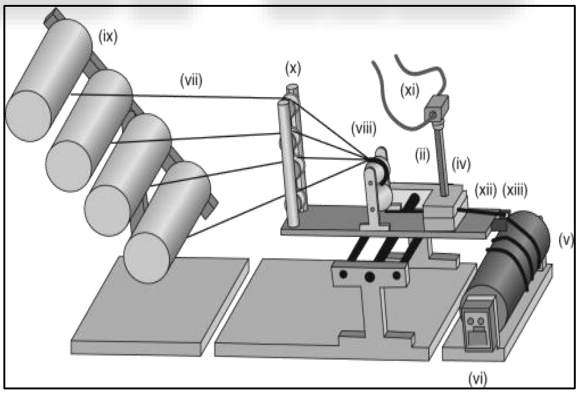

Fig. 2: Dry winding

In this method, the fibers are impregnated with resin before winding, hence another term for the method, prepreg.

V. Filament Winding Patterns

A filament winding pattern is a way how filament will be wound on a mandrel. There are mainly three types of winding patterns which are commonly used, and they include;

- Circumferential Winding
- Helical Winding
- Polar Winding.

A. Circumferential Winding

Circumferential winding is also known as girth or hoop winding. Hoop winding is a high angle helical winding that approaches an angle of 90 degrees. Each full rotation of the mandrel advances the band delivery by one full bandwidth.

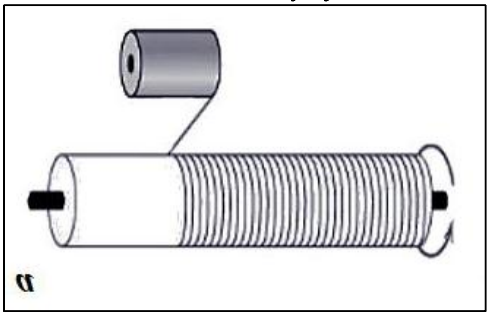

Fig. 3: Circumferential Winding

B. Helical Winding

In helical winding, mandrel rotates at a constant speed while the fiber feed carriage, transverses back and forth at a regulated speed to generate the desired helical angles.

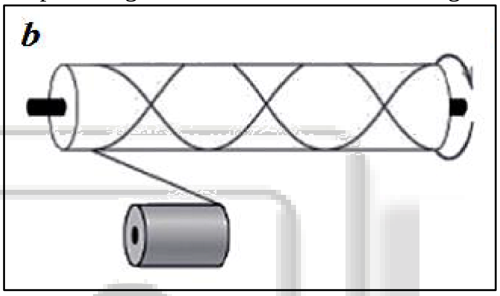

Fig. 4: Helical Winding

C. Polar Winding

In polar winding, the fiber passes tangentially to the polar opening at one end of the chamber, reverses direction, and passes tangentially to the opposite side of the polar opening at the other end. In other words, fibers are wrapped from pole to pole, as the mandrel arm rotates about the longitudinal axis as shown in Figure 4. It is used to wind almost axial fibers on dome-ended types of pressure vessels. On vessels with parallel sides, a subsequent circumferential winding would be done.

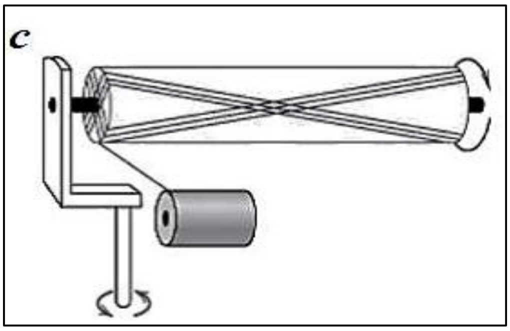

Fig. 5: Polar Winding

VI. AUTOMATED FILAMENT WINDING SYSTEM

The manufacture of filament wound composite products by filament winding consists of many elements. The main elements of filament winding machine are mandrel, machine structure and control system. Filament winding technique and filament wound composite product utterly rely upon filament winding machine types and axes. Multi-axial filament winding machine is the adequate processing technology to fabricate composite products at industrial level.

Computer-assisted fabrication of composite structures by filament winding has become feasible for manufacturers due to advances in the automation of numerically controlled winders. Considering this fabrication approach, process control usually relies on an advanced software system including computer-aided design (CAD) and computer-aided manufacturing (CAM) functions. Four operational stages can be identified in these software systems:

1) Mandrel geometry definition, comprising the creation or importing of a CAD model of the surface of the mandrel to be wound;
2) Surface path generation, which considers the creation of feasible winding paths on the defined surface of the mandrel while preventing fiber slippage and/or bridging over, for example a concave mandrel surface.
3) 3-D machine path generation, aimed at the generation of a path sequence for the filament winding guide for correct fiber placement on the mandrel surface, while maintaining the defined fiber tension and avoiding any potential collisions with the part or mandrel equipment.
4) Post-processing for the CNC controller, a CAM procedure by which the generated 3-D path data is converted to be interpreted by the filament winding machine controller based on the number and type of axes of motion available on the winding machine.

VII. DESIGN AND DEVELOPMENT OF 4 AXIS FILAMENT WINDING MACHINE

Based on the concept design, the existing machine only needs a little modification design on the clamping system which involves tail stock and chuck. Basically, the design consists of four axes of motion. First axis is the rotation of mandrel, second axis is the longitudinal movement of platform 1, third axis is the transverse movement of platform 2 and the fourth is the controlled motion of the pay-out eye. Four motors will be used to drive the machine, where one motor is a stepper type and the rest are servo motors. The first servo motor is to rotate the mandrel, the second servo motor is to drive platform-1 longitudinally, and the third servo motor is to drive platform-2 in a transverse direction while the stepper motor is to drive the pay-out eye. All the motors can be controlled separately using their drivers.

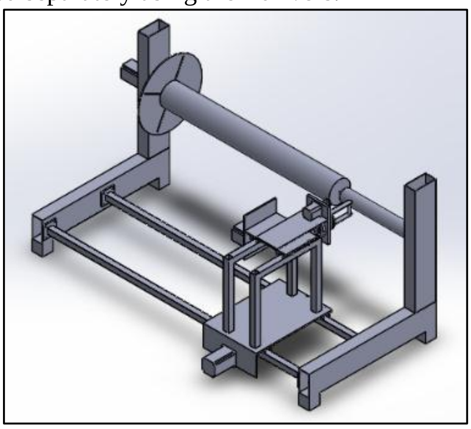

Fig. 6: Proposed design of filament winding machine

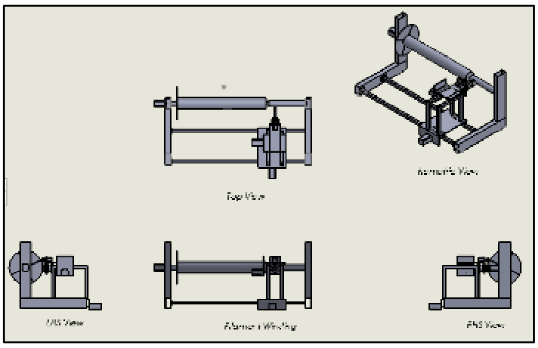

Fig. 7: Different views of the proposed Machine

A. *Objectives of the Winding Machine*

The main objective of this study is to make a filament winding machine which has 4-axes, cheap in price, light in weight, high mobility, easily detachable and highly accurate.

B. *Parts & Controlling Mechanism*

1) *A Sliding Mechanism for X & Y Axes*

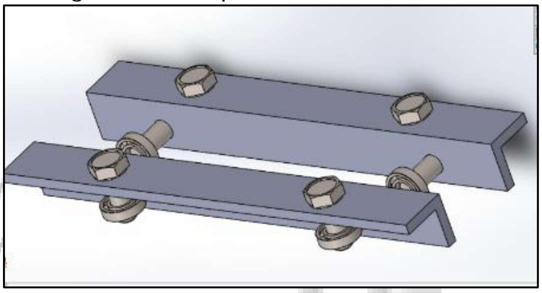

Fig. 8: Indigenous Solidworks model of sliding mechanism for X & Y axis

Fig. 9: Indigenous Fabricated Sliding mechanism for X & Y axis

Materials& Components used.
2 Mild-steel (MS) L-Channel, 6 Bearings, 6 Bolts, 18 Nuts, 4 Washers.
Operations Done. Cutting, Grinding, and Drilling.

2) *Base Frame Structure Development*

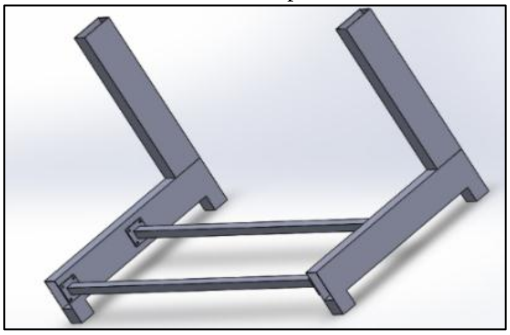

Fig. 10: Base frame Solidworks model

It is a part on which, both moving platforms (Carriage and Deliverly head platforms), chuck, tail-stock, rack & pinion assembly and motors are placed.
Materials & Components used.
4 Rectangular MS Pipes, 2 Stainless Steel (SS) Square Bars, 4 Rectangular MS Plates, 4 small MS Pipes, 4 Bolts, Nuts & Washers, Timing Belt, Bondtite, Wooden Strip, 3M Double Tape.
Operations Done. Drilling, Welding, Cutting, Sticking, Grinding.

Fig. 11: Fabricated Base frame

3) *X-Axis Platform*

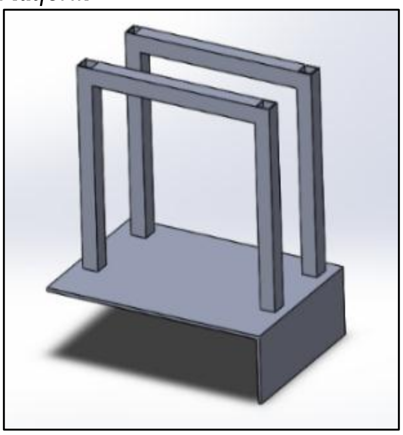

Fig. 12: X axis Platform Solidworks Model

It is a moving platform on which, the deliverly platform, end-eye, rack & Pinion are Installed.
Materials & Components used.
4 MS Square Pipes, 2 SS Square Pipes, Rectangular MS Plate, Wooden Strip, Timing Belt, 3M Double Tape, 2 Bolts & Nuts, 2 Springs.
Operations Done. Drilling, Welding, Cutting, Grinding.

Fig. 13: Fabricated X axis Plate form

4) Mandrel and Rack & Pinion Mechanism.

Fig. 14: Fabricated Mandrel holder

Material & Components Used.
Bearing, Bolt & Nut, MS strip, Washer.
Operations Done. Turning (Lathe), Drilling, Welding, Grinding.

5) Rack & Pinion Mechanism.

Material and Components used.
Aluminium timing pulley, Timing belt, wooden strip, Metallic pins, bondtite.
Operations Done. Cutting, sticking, drilling, tapping.

Fig. 15: Rack and Pinion Mechanism

6) Rotary Mechanism for Mandrel and Guide Bracket

Fig. 16: The Fabricated chuck mechanism

Since already made chucks on the market are heavy and costly, which increases the net price of the project, we designed a lightweight & cheap chuck.
Materials & Components Used.
Aluminum Pulley, 4 Bolts.
Motor Shaft Extension made of MS.
Operations Done. Turning (Lathe), Surface Finishing, Drilling, Tapping.

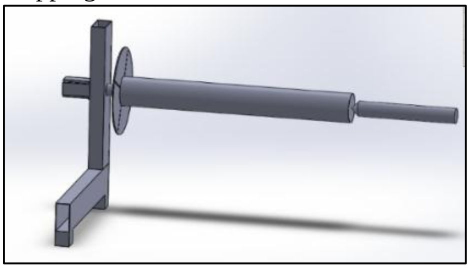

Fig. 17: Chuck with motor assembly (Solidworks model)

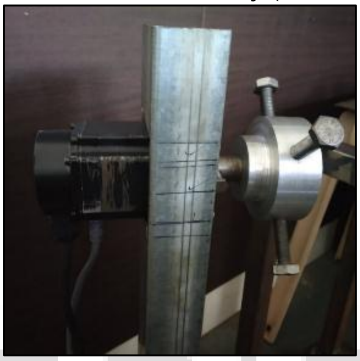

Fig. 18: Chuck with motor assembly

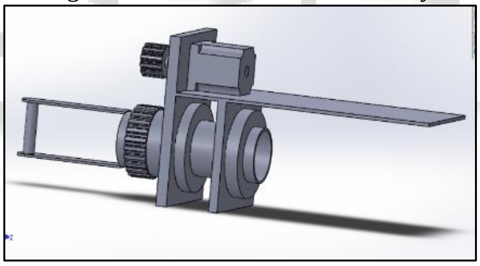

Fig. 19: End-eye mechanism Solidworks model

Fig. 20: Fabricated End-eye Mechanism

C. Controlling Mechanism

1) Three Servomotors and One Stepper Motor

Fig. 21: Servomotor

Hybrid Servo motor 2-Phase
Model number RMCS-1051
Torque Capacity 22kg-cm
Input: 24-48 V, 120 W
Output: 24-48 V.

2) Driver

Fig. 22: Servo motor Driver

Hybrid Servo Motor Driver.
Model number: HSS57
24 VDC

3) Break-Out Board

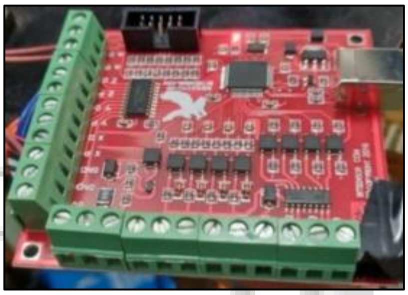

Fig. 23: Break-out Board

This is the image of a Break-out Board, which takes signals from computer and feed it to the driver of the motor. It has a 100 kHz kernel speed & and can work up to 4 axes. We run it with RnR motion Controller Eco-version 2.0.

4) Controller Mach3

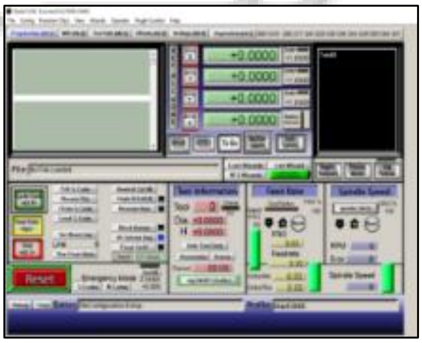

Fig. 24: Mach3 CNC control interface

We developed different codes for different winding patterns, which we loaded to the computer and use MACH3 to communicate with other controlling devices.

5) Switched-Mode Power Supply (SMPS)

Fig. 25: Switched-Mode Power Supply

This SMPS was used to regulate and stabilize power output at 12 V 10A.

VIII. RESULTS, CONCLUSIONS AND FUTURE SCOPE

Fig. 26: Developed 4-axis FWM

A. Salient Features of this Project.

4-axes, light weight, inexpensive, indigenous sliding mechanism, detachability and high modularity, low maintenance

The above salient features give our project a competitive advantage on the market.

B. Conclusion

During the design concept development stage of this project, we mainly used Solidworks part modeling, Assembly and simulation in order to actualize the idea.

Instead of expensive, bulky and fixed filament winding machine, detachable Filament Winding machine with our indigenous sliding mechanism, has been designed and developed, and found satisfactorily working during the test operations.

Linking mechanical knowledge with mechatronics in this project, 4 axes were controlled with servomotors and a stepper motor. The servomotor steps were generated with the help of a 4-axis breakout board and further refined with micro stepping drivers. During the test run, all 4 axes were running satisfactorily according to our indigenous CNC codes.

After designing and developing this project, we have learnt a lot at individual levels in terms of skill sets like welding, and we are convinced that our project will find a competitive space on the market among industries which deal with high pressurized fluids.

C. Future Scope

For future work, more accurate, standardized commercially used 4-axis filament winding machine can be developed based on this first machine. Furthermore, work can be done in the direction of code development for different filament lay angles, size of pressure drums and non-axisymmetric pressure vessels.

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