Multidisciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: P17221

Design of Formula SAE Carbon Tube Winder

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Abstract

The strength and durability of a composite part is highly influenced by how the part has been manufactured. While hand layup techniques provide sufficient strength and durability for many composite parts, it is a poor choice for axisymmetric parts as the consolidation and debulk process of a hand-layup can cause unwanted defects such as fiber wrinkling and voids. Automated processes such as filament winding are much better suited for producing wound composite tubes. A filament winding machine and process was designed, built, tested and verified that met the manufacturing needs of the customer.

Background

Composite tubes are an integral part of creating a lightweight open-wheeled racecar. Many structures on the car require composite tubes including the drive shafts, steering shafts, suspension arms, and wings mounting. Currently, the Formula SAE team at RIT is the only team in the United States that uses composite driveshafts, giving them a significant advantage over their competitors. These tubes were fabricated at RIT in the past using hand layup techniques, but it was found that this technique was not suitable for creating robust tubes. The Formula SAE team is currently buying tubes from a third party, however, these tubes are expensive and overbuilt for the team's needs. This results in both cost savings and mass efficiency penalties for the team. Having an improved filament winding process in-house would greatly help the Formula SAE team by providing the opportunity to manufacture optimized, quality composite tubes for the car at an affordable cost. This automated filament winding machine eliminates the need for low-quality hand layup techniques while also not forcing the team to purchase expensive and structurally overbuilt tubes.

Various off-the shelf tube winders were benchmarked as a means to analyze cost and compatibility for the Formula SAE team and determine the worth of this undertaking as an engineering project. The demand for a Formula SAE specific filament winder was validated as all other options were out of the realms of budget, compatibility, or size for the team. This project is a machine that winds carbon fiber tubes in-house for the Formula SAE team. The machine is designed to be adaptable, allowing the team to create tubes of various layup orientations and diameters. Being able to fabricate tubes in-house will save the team money and allow for fully custom tubes to be produced. Along with an assembled and fully operational filament winder, the FSAE team is also to be provided with a detailed user manual, operational training, and tooling to produce FSAE driveshafts. The machine fits within a maximum footprint requirement set by the team for ease of storage along with being within the team's allocated budget for the end product.

Process: Electrical/Software

The machine as designed can be viewed as 5 major sub-systems that interact together to produce the carbon fiber tubes: Frame, Cross Feed, Tensioning, Spindle, and Electronics systems.

The frame features a large main plate that supports the spindle, spindle drive motor and electronics mounting on the headstock side. 2 Tubes running parallel to the spindle axis provide support for a tailstock that supports the far end of the mold. A billet bar on the opposite side of the machine end plate supports the Cross Feed system.

The cross feed system provides longitudinal positioning of the fiber by moving the whole tensioning system parallel to the axis of the spindle. The main component of the cross feed system is the linear bearing that spans the length of the frame. This low friction bearing allowed for a small NEMA 14 to be used as the bearing was assumed to be frictionless. The stepper motor is mounted in a fixed position on the frame and uses a belt drive to move a carriage on the linear slide which holds the tensioning system.

The Tensioning system features a spool holder with an adjustable tensioning spring to preload the spool. As the fiber winds off the spool it passes into a pay-in eye that aligns the fiber with to a common plane. Guide rollers are used to position the fiber before passing into the resin bath that applies wet resin to the dry fiber. A dip roller keeps the fiber submerged briefly before it passes two resin wipers that remove excess resin. As the fiber approaches the mold, it is guided into its final location via a pay-out eye.

The spindle system controls the rotational positioning of the mold and consists of two major parts. The headstock side consists of a 3 jaw chuck to hold the mold, driven by a NEMA 34 stepper motor via a belt driven pulley with a 2:1 reduction. The tailstock end features an adjustable quill and a morse taper to support common off the shelf live centers to provide support for the far end of the mold.

The Electronics system consists of two independent motor drivers and power supplies to drive the stepper motors of the crossfeed and spindle systems. Control signals for the motor drivers are created via a single Arduino Uno. A CAM software is used to generate the geometric paths that the crossfeed and spindle paths must take to wind a tube. The instructions that this software generates are fed to the arduino via USB. The arduino is loaded with an open source GRBL software that interprets the instructions to create the proper machine motion paths.

After assessing the needs of the customer, the engineering requirements were determined. The engineering requirements and their design values can be seen below in table 1.

ER	Description	Unit of Measure	Threshold Value	Design Value
1	Operator does not need to interact with the moving machine.	Y/N	Yes	Yes
2	Part size capacity	in	3" x 24"	6" x 30"
3	Maximum power draw requirements	W	20A at 110V=2kW	1000W
4	Maximum wrapping angle	Degrees	45	10
5	Wrapping angle precision	Degrees	5	1
6	Filament tension	lbs	Adjustable	0-10
7	Steps required for operator to run	Integer	15	10
8	Total machine cost	Dollars	2000	1503
9	Maximum filament width supported	in	0.125	0.5
10	Maximum spindle speed	RPM	50	100
11	Maximum spindle acceleration	rad/s^2	80	120
12	Spindle speed precision	RPM	1	0.5
13	Spindle position precision	Degrees	5	2
14	Maximum feed speed	in/min	10	100
15	Crossfeed speed precision	in/min	0.5	0.2
16	Machine has a resin bath	Y/N	Yes	Yes
17	Spool capacity	lbs	5	10
18	Stored machine footprint	in	40" x 21" x 24"	51.3" x 19.5" x 20.1"
19	Maintenance interval	hours	10	n/a
20	Part conversion time	hours	1	0.5
21	Maximum part run time	min	60	120
24	Digital or physical interface to start/pause/stop operation	Y/N	Yes	Yes

Table 1: Engineering Requirements

The first requirement came for the customer in the size of the parts that the machine could produce. To meet the current needs the machine needed to accommodate parts up to 3”x24” long. To meet projected future needs the machine would need to be capable of winding tubes up to 6”x30” long. The machine was designed to a value of 6” x 30”.

Inspection of the expected use space of the machine determined that the outlets in the customers were rated for 2200 W (20A at 110V) of power. This was the maximum amount of power that the machine could draw. To allow the machine to be used in other use spaces, the machine was designed to a power consumption of 1000W.

The customers current requirements for tubes required wrapping angles of 45 degrees. Projected future needs showed the possibility of designing parts to wrap angles as shallow as 5 degrees. Since the crossfeed and spindle precision were dependent on the minimum wrap angle, a design value of 10 was ultimately chosen. Values less than this were too constraining on the precision requirements of the spindle and crossfeed.

The wrap angle precision requirement was provided by the customer. For best performance the customer requested a value of 1 degree and allowed for variations of up to 5 degrees. The machine was designed to a wrap angle precision of 1 degree.

The tensioning system was design to have an adjustability from 0-10 lbs to both cover the 0-2lb range and to have additional room to use if it was determined during testing of the machine that more tension than 2 lbs was required.

The max filament was a requirement imposed by the customer. While the current needs indicated wrapping tubes with a maximum filament width of .375" and a minimum of .125", the customer indicated future projections of using filaments with widths up to .500". This requirement drove the size of the tensioning and resin bath components and was designed to .500" to meet both current and projected needs for the customer.

Max Spindle acceleration was chosen to allow the spindle to come from a dead stop to its full speed within 2 full rotations of the spindle. This requirement allows the spindle motor to have completed accelerating by the time that the machine has completed wrapping in the turnaround areas. This requirement ultimately drove the selection of the drive motor based on the torque required to spin the largest expected mold size of the machine per the customer's input. Speed vs torque charts provided by the motor manufacturer were used to determine a motor with sufficient torque at the max spindle speed.

Spindle speed and position precision were based off of the minimum wrap angle and wrap angle precision requirements. Since most common stepper motors use a 1.8 degree step, a 2:1 pulley reduction was used to bring the precision uncertainty due to the motor to .9 degrees. An of the shelf timing belt tooth profile was chosen to reduce the backlash of the system that could not be empirically calculated. This additional loss of precision was estimated to be at maximum of 1 degree bringing the total expected precision to 1.9 degrees, less than the 2 degree target precision.

Max crossfeed speed was based on the maximum run time as indicated by the customer. The resin system indicated by the customer for producing parts had a maximum working time of 120 minutes. The GUI was used to simulate the winding of a 4 layer driveshaft and the part run time was found to be 30 minutes with the spindle speed set at 150 RPM and the max crosfeed speed at 100 inches per minute. This brought the max part run time well within the target of 60 minutes

Spool capacity was based on input from the customer. The packaging of the tow that they currently use is at a max of 10 lbs. This requirement was used in the structural analysis of the tensioning system and the system was designed to handle atleast 10lbs. The customer also specified that the machine could support a tow width of up to .5 inches.

A physical limitation imposed on the machine from the customer was the overall size of the machine. Based on the expected use area of the machine, an initial requirement of a machine no larger than 40"x21"x24" (L x W x H) was imposed. To meet the requirement for part capacity, the machine had to be designed slightly longer and is at a designed size of 51.3" x 19.5" x 20.1". Further discussion with the customer indicated that this size will still allow the machine to be easily stowed in the use area.

There are two primary goals of the electrical subsystem. The first goal is to allow the user to interface with a computer to create a winding pattern. In our use case, this winding pattern will typically be for a pipe. The second goal is to allow the user to interface with the motors. Specifically, the generated winding pattern dictates the motion of the motors.

Special winding software called ComposicaD generates winding patterns. This software is very complex and has a variety of inputs that can be configured. First, the machine parameters must be configured. This includes information relating to the physical configuration of the machine. This includes parameters such as the distance from the payout eye to the mandrel, the diameter of the mandrel, the length of the mandrel, the length of the crossfeed, and the maximum and minimum velocities and accelerations of the motors, among other parameters. After the machine parameters are configured, the parameters for winding can be configured. This includes parameters such as the wrap angle, the width of the fiber, and the amount of layers, among other parameters. Before generating a winding pattern, the output of the winding file must be configured in ComposicaD. For this machine, the output must be a subset of G-code. (Some standard G-code commands are not supported by this machine and they must be removed from the output file in order for the file to load correctly.) After all parameters are configured, a winding file is generated in the form of a text document that contains G-code.

The second goal is to allow the user to interface with the motors. The text file containing G-code must be used to control the crossfeed motor and the spindle motor. The system that does this consists of several parts: (1) An Arduino Uno running GRBL, (2) a computer running Universal G-Code Sender, (3) motor drivers for the spindle and crossfeed, (4) stepper motors for the spindle and crossfeed, (5) power supplies for the spindle and crossfeed.

The first part of the system is an Arduino Uno running GRBL. This is the part of the system responsible for converting G-code into motor signals that can be used by the stepper motor drivers. GRBL is an open-source G-code parser and CNC controller. G-code is input into GRBL and GRBL outputs motor signals. GRBL only supports a subset of G-code, however, it supports all commonly used G-code commands. GRBL is capable of running 3-axis CNC machines. In this case, it only has to run a 2-axis machine. GRBL can be configured to match the requirements of the system, and the capabilities of the motors. Some essential configuration includes setting the maximum velocities and accelerations of the motors. If this is not set correctly, the motors can miss steps. The motors also need to be calibrated such that incrementing the both the crossfeed and spindle motors by 1 unit in G-code causes the crossfeed to move 1mm and the spindle to move 1 degree.

The second part of the system is a computer running Universal G-Code Sender. This program is the method by which the user can stream G-code to the Arduino running GRBL. The user has the option of sending individual G-code commands, or streaming entire G-code files. This program has useful features, including estimating the winding time remaining, allowing the program to be paused, stopping the program, and setting a home position.

The third part of the system is the motor drivers for the spindle and crossfeed. These drivers receive output signals that come from the Arduino after it processes the G-code. Each motor has a PUL and DIR. When the pulse signal receives a pulse, the motor increments one step. The state of the DIR signal (high or low), determines which direction the motor will rotate (clockwise or counterclockwise). The direction of rotation is also based on the wiring of the stepper motors. This can easily be reversed if the user wishes to switch the association between the DIR signal and the motor direction.

The fourth part of the system is the stepper motors. A NEMA 34 stepper motor is used for the spindle, and a NEMA 14 motor is used for the crossfeed. These motors are wired to and driven by the stepper drivers.

The fifth part of the system is the power supplies. There is one power supply for the driver of the crossfeed motor, and there is one power supply for the driver of the spindle motor. The power supplies plug into standard wall outlets and provide 16V-1.3A and 48V-2A for the crossfeed driver and spindle driver respectively.

Results and Discussion

The most efficient way to quantify the performance of this project is to analyze the tubes that it produces. The result of the torsion test on the single ply 45 degree wrap angle part was a breaking torque of 1937 inch pounds. This value is just shy of 3% less than the customer predicted value of 2000 inch-pounds, which is a very promising result. There are a couple caveats regarding this measurement to be discussed in depth below. The approach this section of writing will take is to discuss how well the customer requirements were met. The can be viewed in tabulated form in Table 2 on the next page.

The current status of the machine as of 5/11/2017 is that there are constraints to the regions it operates reliably in. The driving restriction is the path of the crossfeed motor, which has a high risk of slipping near the region where the two slide pieces join. A full breakdown of this problem has not been performed, and as of now the best guesses for the root of the root of the problem are either inconsistencies in the track at the joint or motor/belt resonance. The effect is that the machine will not reliably create a part unless it can do so without the crossfeed traveling through this area. This has serious implications as it restricts maximum part size (engineering requirement 2). The required value is 24 inches, and the design value of 30 inches is easily attainable by resolving the issue with crossfeed movement. Until that issue is resolved, the effective max part size is 18 inches.

ER	Description	Unit of Measure	Threshold Value	Design Value	Measured value
1	Operator does not need to interact with the moving machine.	Y/N	Yes	Yes	Yes
2	Part size capacity	in	3" x 24"	6" x 30"	3" x 18"
3	Maximum power draw requirements	W	20A at 110V=2kW	1000W	517W
4	Maximum wrapping angle	Degrees	45	10	45
5	Wrapping angle precision	Degrees	5	1	3
6	Filament tension	lbs	Adjustable	0-10	Adjustable
7	Steps required for operator to run	Integer	15	10	5-10
8	Total machine cost	Dollars	2000	1503	1046.75
9	Maximum filament width supported	in	0.125	0.5	0.125
10	Maximum spindle speed	RPM	50	100	471
11	Maximum spindle acceleration	rad/s^2	80	120	34.9
12	Spindle speed precision	RPM	1	0.5	0
13	Spindle position precision	Degrees	5	2	3 degrees after 1000 revolutions
14	Maximum feed speed	in/min	10	100	324
15	Crossfeed speed precision	in/min	0.5	0.2	0
16	Machine has a resin bath	Y/N	Yes	Yes	Yes
17	Spool capacity	lbs	5	10	10
18	Stored machine footprint	in	40" x 21" x 24"	51.3" x 19.5" x 20.1"	48" x 18" x 24"
19	Maintenance interval	hours	10	n/a	n/a
20	Part conversion time	hours	1	0.5	0.25
21	Maximum part run time	min	60	120	45
24	Digital or physical interface to start/pause/stop operation	Y/N	Yes	Yes	Yes

Table 2: Engineering Requirements

Engineering requirement number 11, maximum spindle acceleration was failed by nearly a factor of four. Despite that, its operational value of 34.9 rad/s^2 allows it to achieve max speed in less than half a second. Considering that ComposiCAD opts to run the machine at an 80% capacity for acceleration for default.

Operation complexity is a requirement that was admittedly difficult to specify. The requirement was quantified by “number of steps that the operator has to perform”. The purpose is clear: a machine requiring a large number of steps to perform is cumbersome and difficult to learn. The issue is that the requirement can be interpreted pretty liberally. The requirement was further specified to refer exclusively to the steps required to produce the part with the machine, therefore excluding steps such as curing the resin or separating the part and mandrel. The unfortunate result is that ComposiCAD is rather difficult to use, even for someone who is familiar with composites. In order to draft up and produce a completely new part, a new pipe project must be created and specified in ComposiCAD which requires many steps. However, the machine can easily be run with files that have previously been created using ComposiCAD. Operating under the assumption that the user already has the output file that they want to use, this requirement was met.

Conclusion and Recommendations

The unofficial theme of this project can be thought off as: an inexperienced attempt at creating a well understood device. Throughout the design process many high level decisions were made via referencing currently existing winders. As a result many things conveniently worked out just as anticipated, while some turned out to be complete oversights. Delays from these oversights pushed the project well beyond its original deadlines. As a blanket statement, many of these delays could have been avoided by a more thorough design process and making specific effort to consider possible future problems. Human nature seems to accept that mistakes provide the best learning opportunities, and so the following will attempt to capture what lessons can be taken away from the project.

To begin, one simple oversight was the incorrect setup of the MA860H stepper driver. In this case, due to improper interpretation of documentation, a control signal was hooked up backwards causing an internal short immediately damaging the driver. Diagnosis showed that the power transistors on the board had been completely fried. Once the mistake had been identified a replacement was ordered resulting in a delay of a week and a cost of 70 dollars. While this straightforward example lacks depth, it communicates the importance of caution and thoroughness. No subsequent wiring mistakes were made for the remainder of the project.

Next, an avoidable design mistake occurred when choosing a motor for the crossfeed subsystem. The motor was chosen such that its catalog torque rating would support accelerating the mass of the crossfeed to a functional speed within a certain amount of time. These values were driven by the engineering requirements plus a margin for error. The analysis failed to take into account that as the wrap angle grows (from perpendicular to the mandrel towards parallel to the mandrel) the crossfeed motor begins to experience a portion of the tension on the tow. This is hardly significant at shallow wrap angles, but the machine is primarily intended to wrap at 45 degrees for which this presented a major problem. During the first round of testing it was clear that the motor had insufficient torque and needed to be replaced. The replacement shipped within a week, but the motor housing on the frame had to be rebuilt to accommodate the larger size. This is a clear example of the kind of mishap that is best avoided through peer review or contact with an SME. It is natural to expect that a single person will make some mistakes on a project of this complexity, so countermeasures need to be planned and carried out.

The most unpredictable subsystem of this project was by far the tensioning system. Constructed with the expectation of unforeseen difficulties, the system was built upon a modular pegboard which gave great flexibility to the placement of all tensioning components. Even so, the result was riddled with problems that took numerous iterations to correct. At first, the carbon fiber would fray on the payin and payout eyes. Extreme angles from the spool to the payin eye caused violent jumping of the filament and erratic tow tension. These problems were addressed and resolved before wet fiber winds were even attempted, and those brought a new slew of issues. Resin leaked all over the crossfeed, and the bath needed to be refilled mid-wind. Resin scrapers and a larger resin bath with new rollers had to be constructed. The point of these troubles isn't that there was a lack of engineering process, it is rather that there was a lack of time planning. The very nature of this type of design challenge requires that lots of testing is done in order to produce a final product that will function reliably. Completing initial testing much earlier would have allowed the time required for multiple build and test iterations without challenging the Imagine RIT deadline, and would have thus yielded more time to achieve the level of performance required to produce a functional carbon fiber tube.

Finally, the most accumulated hurdle faced by the team was the winding program ComposiCAD. The decision to attempt to get a winding GUI donated for the project was decided on in the first few weeks both because the Formula SAE team has good resources and because to do anything else would be well beyond the scope of the project. Between four mechanical engineers and two electrical engineers, there was little in the way of resources towards writing anything that complex. However, despite the early success of obtaining a copy of ComposiCAD, no one knew how to use it. It was clear that the success of the project completely rode on the functionality and compatibility of ComposiCAD but figuring out how it worked was a daunting task. The documentation for ComposiCAD isn't catered towards users who are new to winding, and most winding technology is inaccessible in the form of proprietary industry solutions. The electrical engineers spent the most time with ComposiCAD as it most closely interfaced with their subsystems. Lacking an intuitive physical understanding of the winding machine, not much progress was made towards figuring out the software until the complete winder had been assembled. Ultimately, through exhaustive testing and thorough research of the help documentation a valid winding file was produced. The result was lots of lost time, and he key takeaway here is that it was due to communication failure.

There is merit in understanding the successes and pitfalls of the process style employed by P17221. Largely due to formula team experience and individual comfort, the team followed a reactive approach to design, build and test. P17221's guide, Gary Werth, deserves acknowledgement for breaking down and providing insight to this approach. While the design approach during MSD 1 was thorough, as the team moved to construction during MSD 2 the process largely followed a pattern of solving problems as they came up. This approach led to the problem solving skills and dedication of the team carrying the weight of the project. On the other hand, many build and test iterations were required to fully flush out unforeseen problems. In order to successfully function this way, the project would need to adhere closely to a planned schedule which accommodated the tests in high quantity. In P17221's experience, the schedule was not aggressive enough nor followed closely enough to put the project in a good spot before imagine. Performing better to those pitfalls would have given the team the window of time necessary to eliminate the final problems with the crossfeed plus testing the user guide. One example of a technique that would have offset those drawbacks was early prototyping.

References

ComposiCADm. Vers. 2.4.43. Zonhoven, Belgium: Seifert and Skinner & Associates, 2014. Computer software.

Acknowledgments

We would like to acknowledge our customer, The RIT Formula SAE Team, our guide, Gary Werth, and CompisiCAD for their donation of the GUI software package to our project.,