Feb. 21, 1967 D. S. RATHJE ETAL 3,304,705

FILAMENT WINDING APPARATUS

Filed Sept. 16, 1964

3 Sheets-Sheet 1

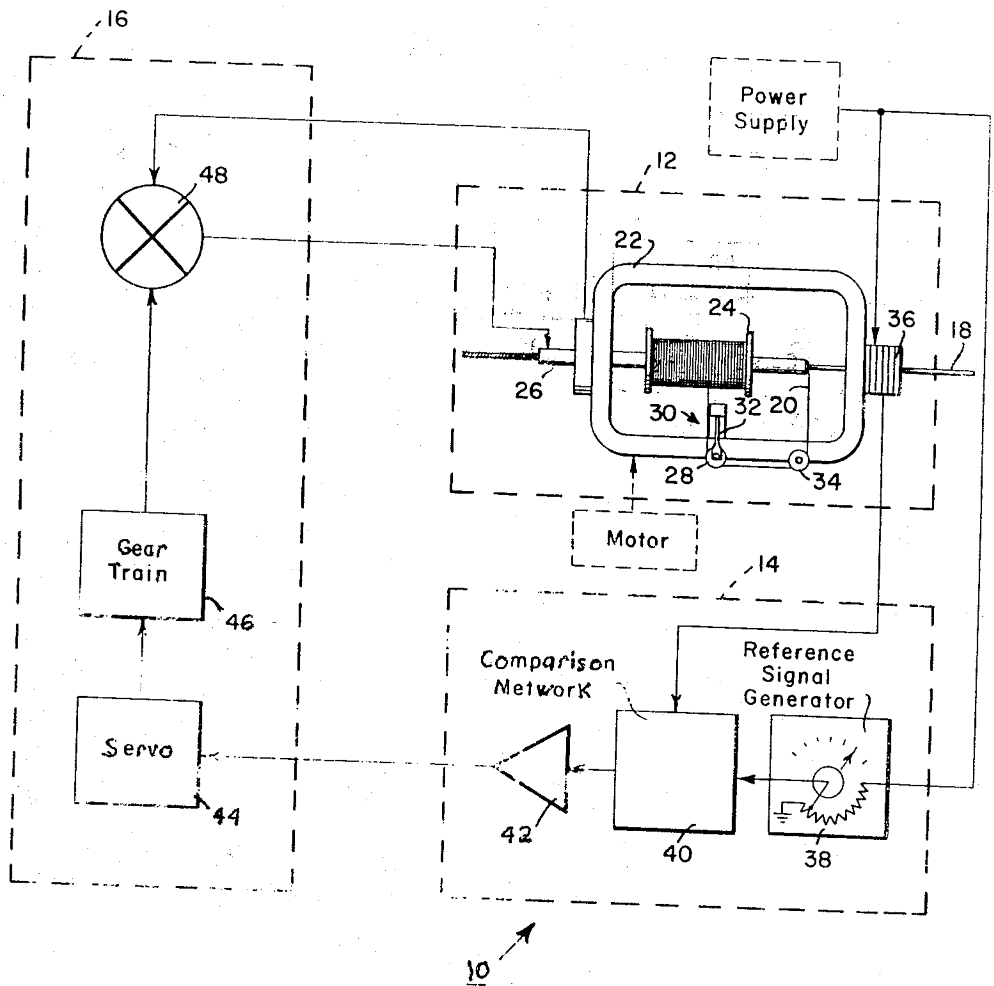


Fig. 1.


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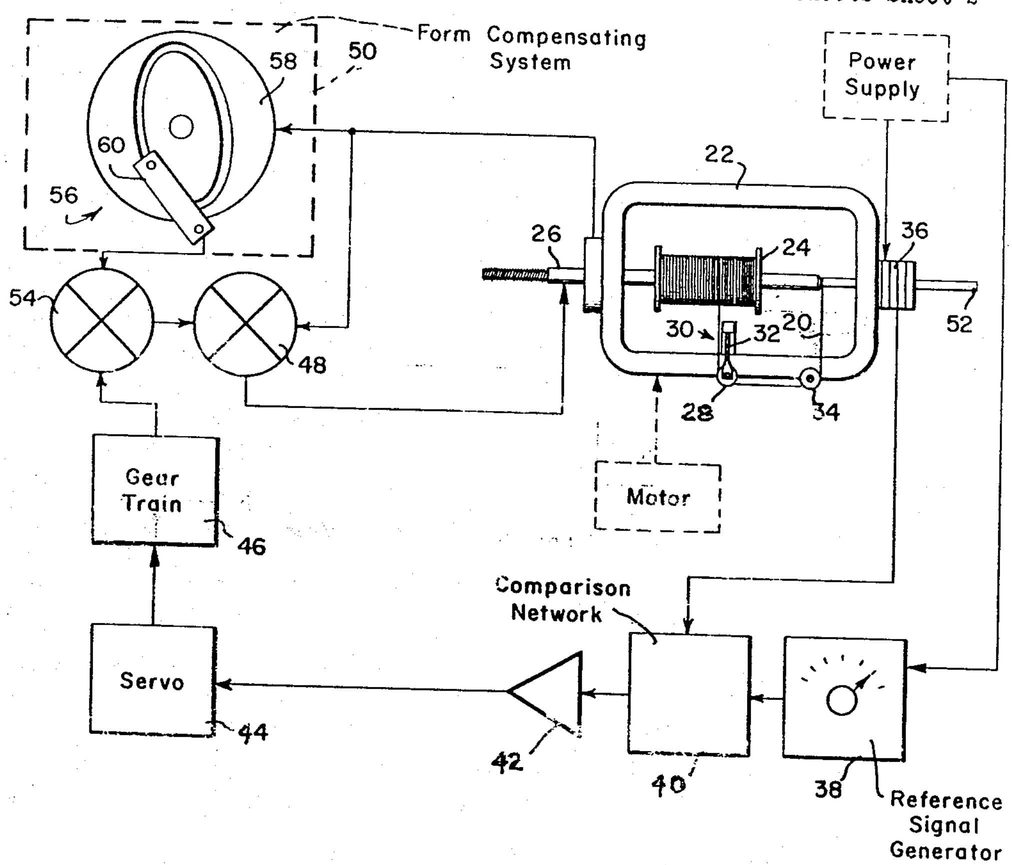


Fig. 2a.

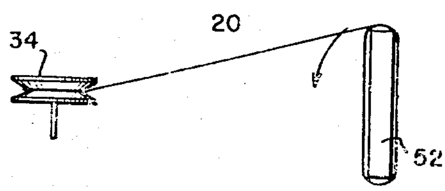


Fig. 2b.

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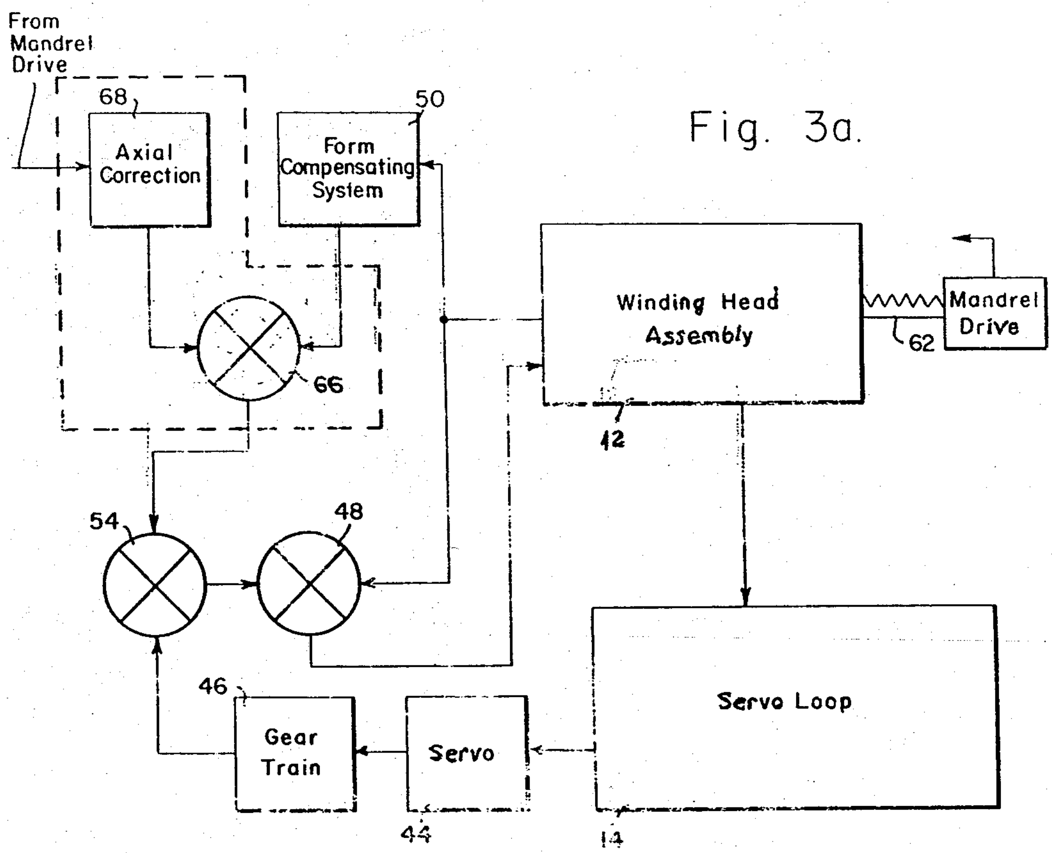



Fig. 3a.

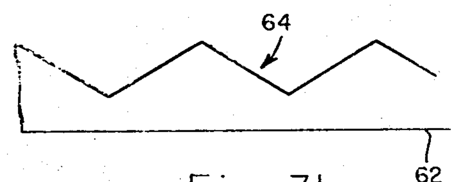



Fig. 3b.

Fig. 4.

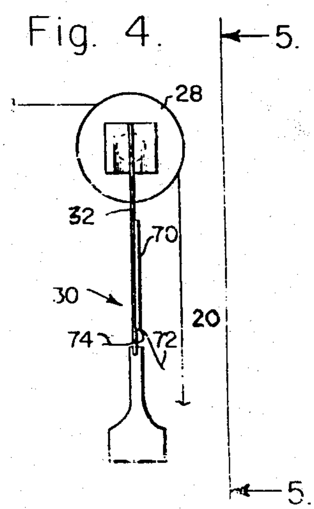
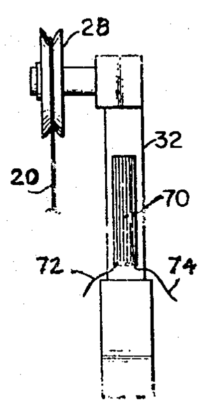



Fig. 5.

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3,304,705
FILAMENT WINDING APPARATUS

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Filed Sept. 16, 1964, Ser. No. 396,903
12 Claims. (Cl. 57—18)

The present invention relates to a filament winding apparatus and more particularly to an apparatus for winding a helical coil on a core.

Within the scope of the present invention, the term filament is to be considered to be composed of any material capable of sufficient flexibility to be wound on a core or other form of any given cross section. Although the invention has generally applicability, it is particularly directed at apparatus for winding a wire helically about a core, the resulting product having utility as a wound electrical resistance element.

As taught in those patents, typical prior art coil winders include a rotating winding head, concentric and coaxial with a continuous form or mandrel. Rotatably mounted in the winding head is a concentrically mounted supply spool of filament which is to be wound about the mandrel or core. As shown in the prior art, filament is taken from a supply spool, is directed to a mechanical tensioning arrangement, and is wrapped about a mandrel or form. The winding head rotates at relatively high rotational velocities and the mandrel moves in the axial direction at a rate which is synchronized to the rotation of the winding head so that the filament is uniformly coiled in a helix about the mandrel.

In prior art systems, the relatively simple friction or drag type tensioning systems utilized have not attempted to solve problems created by wide variations in winding speeds, trapped wire, non-uniform spool diameters, and variations in the free wire available from the spool. As the filament is unwound from the supply coil, the filament being taken from the reel moves axially which introduces changes or variations in tension due to the inertia of the spool which is otherwise free to rotate.

Various mechanical linkage systems have been proposed to maintain filament tension but, at high speeds, the mechanical tolerances and speeds of response are such that the efficiency of the linkage system is not much better than that of drag tension systems.

Another problem encountered in using prior art coil winding systems, especially in winding of extremely fine gauge wires on heavier gauge mandrels to produce precision resistance elements, has been the variation in turn-to-turn spacing when wire is being wound at speeds approaching 5000 r.p.m. Although the problem is not severe with fairly heavy gauge wire filaments, diameters of approximately 1 mil or greater, it has been found desirable to attempt to maintain a relatively uniform spacing between adjacent turns to prevent shorting of adjacent turns and to maintain constant resistance per unit length. When very fine wires, less than 1½ mils, are being wound on a mandrel at winding speeds of the order of 5000 r.p.m., it has been discovered, that when friction tensioning systems are used, wide variations are noted in the turn-to-turn spacings. Consequently, spacings less than one mil are difficult, if not impossible to achieve uniformly on a long term basis. It is suspected that the cause of variation in turn-to-turn spacing may be due to the resiliency of the filament wire being wound and the effect of changes in tension upon the point at which the wire contacts the mandrel. At relatively low tensions, the wire may extend in a substantial arc with a relatively large loop of wire disposed between the friction head and the point of wrap. Alternatively, when tension is relatively high, there is virtually no slack in the filament wire and the

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point of wrap is, for all intents and purposes, at a point tangent to a straight line from the tensioning mechanism to the mandrel. If the lateral motion of the mandrel is maintained at a constant speed, then changes in tension will change the point of attachment and, consequently, the turn-to-turn spacing will vary widely.

In the past, therefore, to avoid wide variations in filament tension, to maintain relatively constant turn-to-turn spacing, to attempt to control the linear resistivity of the wound mandrel, and to attempt to overcome the effects of the inertia of the supply spool, filament wires of less than 1 mil were wound at winding speeds substantially less than 5000 r.p.m., and the speed varied almost directly with the wire size, smaller diameter wires being wound at slower speeds.

Further problems in maintaining filament tension are encountered when a filament is to be wound about a form of non-circular cross section. The conventional approach to this problem has been to hold the supply spool stationary and rotate the form, while advancing the form or spool laterally. In designing apparatus which does not rotate the form, but which advances it laterally only, revolving the winding head about the form, the problem of a point of wrap of non-constant length creates great variations in tension during each revolution of the winding head. Further, if such a non-uniform winding form also has variations in cross section that are cyclical with respect to lateral motion of the form, then still further changes in tension are produced during the winding operation.

It has also been the practice in certain prior art winding machines, that the supply spool be arranged to run freely in the direction of winding head rotation at a rotational velocity slightly greater than that of the winding head. To arrange the supply spool oppositely so that, by rotation of the winding head, wire is taken from the spool, the spool would have to be driven substantially at the rotational velocity of the winding head to prevent accumulating a loop of wire with each rotation of the winding head.

In other prior art machines, the supply spool is permitted to run freely and tension is regulated by frictional drag members in the idler pulleys that direct wire travel from the take-off spool to the core or mandrel. Such an arrangement would, over a period of time, introduce changes in wire tension since, at start up, the inertia of the supply spool acts as a dead weight on the wire, resulting in a relatively high degree of tension until the spool came up to speed. The tension then decreases until only the frictional drag of the rotating spool results in tension in the wire. However, as the mass of the supply spool decreases with the utilization of wire, the spool may tend to speed up and equal or over-run the velocity of the winding head, resulting either in a completely slack supply or substantially reduced tension in the wire to the tensioning mechanism.

Although the preferred embodiment of the present invention is shown and described in conjunction with a machine for coiling resistance wire in a helix on a mandrel, it is clear that the present invention has utility in other machines which are adapted to wind one or more filaments on a core of any sort. Further, although the preferred embodiment has been shown with a supply spool concentric with the winding head, it is well within the scope of the present invention to have one or more supply spools eccentrically, mounted and driven accordingly. Certainly, such would be the case in machines wherein filaments are wound upon a form whose diameter exceeds the inner diameter of the core of a supply spool.

In order to maintain a constant tension in a filament being wound, and to overcome the problems inherent in prior art mechanisms, the present invention provides a servo-controlled differential mechanism for driving the supply spool at a rotational velocity slightly greater than that of the winding head in order to feed wire, and yet at a controlled rate such that the tension in the wire is held constant at some desired, predetermined value. This is accomplished by interposing a tension sensing member in the path of filament travel which, in conjunction with a transducer, can signal the deflection of the interposed member and the tension in the winding proportional thereto. The tension sensing member also introduces a slight buffering effect in that it will yield under sudden increases in tension, shortening the wire travel path.

A reference voltage is generated which is carefully calibrated to provide signals corresponding to the signals produced by the sensing member throughout the desired range of tension. An error amplifier compares the reference signal and the sensing signal and generates an error signal to a servo amplifier which in turn controls a servo motor through a gear train into one input of a mechanical differential. The second input to the differential is provided by the rotation of the winding head and the two motions are additively combined in the differential output which in turn drives the spool.

When tension in the supply wire exceeds the desired amount, the signal generated by the interposed member is greater than the reference signal and accordingly the error signal to the servo system energizes the servo motor in a sense that would cause increase in the rotational velocity of the supply spool. This rotational motion is applied to one of the inputs of the differential where it is additively combined with the rotation applied from the winding head drive and the combined, increased rotation is applied to the supply spool to increase its rotational velocity relative to that of the winding head, thereby decreasing tension in the wire or filament.

In an embodiment of the present invention, provision is made to wind filaments, on non-uniform cores of other than circular cross section. In such a device, it will be readily appreciated that the point of wrap changes rapidly with the rotation of the winding head, and accordingly, the demand for the filament changes rapidly during a single revolution, which would require a response beyond the frequency range of the servo system. Accordingly, a "correction" generator which, in one embodiment, includes a cam and follower arrangement is provided to generate a compensating motion for any particular elongated form of non-constant cross section in the axial direction.

A mechanical differential is provided which now receives one of its inputs from the correction generator and the other from the servo motor and gear train which corrects filament tension, as above. The output of this differential which receives an input from the winding head and the additive sum of the motions is applied through the output to drive the supply spool.

In yet another embodiment, if a filament is to be wound upon a core having a changing cross section in the axial direction, this too, can be compensated for, if the change is cyclical and repeatable. In this embodiment, a mechanical differential is provided receiving one input from the correcting device which may also be a cam and follower arrangement, and a second input from the apparatus driving the core or mandrel in the axial direction. This mechanical differential output can then be applied as an input to a differential whose other input is supplied by the servo system or, if it is a form of non-uniform cross section which is also varying in the axial direction, then the correcting differential for axial length of the mandrel can be included in the differential "train" so that the ultimate drive to the suppy spool can be the sum of all of the applied inputs.

Accordingly, it is an object of the present invention to provide an improved apparatus for maintaining tension in a filament winding assembly.

It is further an object of the present invention to provide an improved apparatus that is responsive to correct for rapid changes in tension in a high speed filament winding apparatus.

It is yet another object of the invention to provide a tensioning system for a high speed filament winding apparatus which includes a resilient member, interposed in the path of filament travel, that is connected in a servo loop to maintain a predetermined tension.

It is an additional object of the invention to provide an improved tensioning apparatus which includes a servo controlled differential mechanism for applying small changes in rotational velocity to the supply spool of a high speed filament winding apparatus.

It is yet a further object of invention to provide a filament tensioning system in which a transducer interposed in the path of filament travel is connected to control a servo loop including a differential mechanism for driving the supply spool in a sense to compensate for tension changes.

It is yet an additional object of invention of provide a filament tensioning apparatus in a high speed coil winder which compensates, through a differential mechanism, not only for changes in filament tension, but for predictable irregularities in the form of mandrel about which the filament is being wound.

It is yet another object of invention to provide improved apparatus for winding extremely fine filaments at winding speeds of over 5,000 turns per minute while maintaining turn-to-turn spacings of less than the diameter of the filament being wound.

It is yet an additional object of invention to provide in a high speed coil winding apparatus for winding precision resistive elements, a wire tensioning system for correcting and driving the wire supply spool in a sense to maintain the tension at a predetermined value.

It is yet an additional object of the invention to provide a high speed coil winding apparatus for producing precision potentiometer cores having an extremely sensitive tensioning system for driving a filament supply spool at rotational velocities slightly greater than that of the winding head, yet controlled to maintain tension at a predetermined value.

It is still a further object of invention to provide a high speed coil winding system having a tensioning system including a transducer resiliently mounted in the path of resistance wire travel and connected in a servo loop driving a differential core correcting the rotational velocity of the supply spool to maintain tension in the resistance wire at a predetermined value at all times.

The novel features which are believed to be characteristic, both as to organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which several embodiments of the invention are illustrated by way of example. It is to be expressly understood, however, that the drawings are for the purpose of illustration, and description only, and are not intended as a definition of the limits of the invention.

FIG. 1 is a functional block diagram of one embodiment of a filament tensioning system according to the present invention;

FIG. 2 includes FIGS. 2*a* and 2*b* in which FIG. 2*a* is a diagram partially in block form, of an alternative embodiment of the tensioning system of the present invention modified for use in winding coils upon non-circular forms such as shown in FIG. 2*b*.

FIG. 3 includes FIG. 3*a* and FIG. 3*b* in which FIG. 3*a* is a partial block, partial schematic diagram of still another embodiment of the system of the present invention, and FIG. 3*b* is a partial side view of an alternative non-uniform mandrel or form about which the filament is wrapped;

FIG. 4 is a side view of a cantilever beam assembly for determining filament tension according to the present invention; and

FIG. 5 is a front view of the apparatus of FIG. 4 taken along the line 5—5 in the direction of the appended arrows.

Turning first to FIG. 1, there is shown partially in block and partially in schematic form, a portion of a winding system that includes a tensioning system **10** according to the present invention.

As illustrated, the tensioning system **10** includes a winding head assembly **12**, a servo loop **14** and a supply spool drive train **16**.

A form or mandrel **18**, about which a wire or filament **20** is wrapped, is, in a preferred embodiment, coaxial with a winding head **22**. The winding head **22** is driven by a high speed motor through suitable transmission assemblies for example, in a manner shown in U.S. Patent No. 2,334,880, and is, in one embodiment adapted to rotate at speeds in excess of 5000 r.p.m. The filament **20** is taken from a supply spool **24** which, in this embodiment is concentric and coaxial with the mandrel **18** and is also concentric with the winding head **22**. A supply spool drive shaft **26** is journaled in the winding head and provides means for independently rotating the supply spool **24** with respect to the winding head **22**.

Fliament **20** is taken from the supply spool **24** and is passed over an idler **28** which is supported by a transducer **30** that is adapted to detect and signal tension in the filament **20**. In a preferred embodiment, the transducer **30** includes a cantilever beam **32** which introduces a right angle in the path of filament travel, and a second idler **34** which introduces a second right angle into the path of filament **20** travel, from whence it is applied to the mandrel **18**.

The transducer **30** is electrically connected to a power supply and signals from the transducer **30** proportional to and representative of filament tension are provided through a slip ring brush assembly **36**.

The slip ring brush assembly **36** is electrically connected to the servo loop **14** which includes, as shown in block form, a reference signal generator **38** and a comparison network **40**. In one embodiment the reference signal generator includes a precision potentiometer or other variable resistance means which is connected to the power supply. The reference signal generator **38** is designed to produce a signal equivalent to that provided by the transducer **30** under different loads and which will be proportional to and representative of desired tension. Thus, by a suitable adjustment, the reference signal generator **38** can be calibrated directly in filament tension by applying measured tensions to the filament and comparing the output of the transducer **30** with that of the reference signal generator **38**. After calibration, desired tension settings can be made directly to the reference signal generator **38**. The output of the reference signal generator **38** is applied to a comparison circuit **40**, the other input to which is provided from slip ring and brush assembly **36** and an error signal will be generated having a magnitude and polarity corresponding to and representative of the difference between actual tension in the filament **20**, as measured by the transducer **30**, and the desired tension in the filament **20** as signalled by the reference signal generator **38**. In one embodiment, positive error signals indicated greater than desired tension and negative error signals indicated less than desired tension.

The output of comparator **40** is applied to a servo amplifier **42** whose output is applied to a servo motor **44**. Servo motor **44** is a part of the supply spool drive train **16**. The mechanical, rotational output of servo motor **44** is applied through a gear train **46**, including appropriate reduction gears. The output of the gear train **46**, is applied to one input of a two-input mechanical differential **48**, whose output is made to be the sum of the applied inputs. The second input is provided from the winding head **22** and the output of the differential represents the sum of the applied rotations.

Any type of differential driving mechanism may be employed that will algebraically add the rotation of the servo motor gear train **44, 46**, to the rotation of the winding head **22**, and the output is applied to the supply spool drive shaft **26** to rotate the supply spool **24**.

In operation, the apparatus is arranged so that the core or mandrel **18** is applied to pass through the winding head in the axial direction at a relatively slow rate of feed. The winding head is driven to wrap the filament **20** in a helix about the mandrel **18**. The path of filament **20** travel extends from the point of wrap on the mandrel **18** to the second idler **34**, the first idler **28** and over the cantilever beam **32** to the point of take-off from the supply spool **24**.

As the winding head **22** rotates, the rotational motion is applied to the second input of the mechanical differential **48**. Assuming that no correction for tension is present, then that rotational motion is directly applied to the supply spool drive shaft **26** and the supply spool will be driven at substantially the same rotational velocity as the winding head **22**.

As filament **20** is wound about the mandrel **18**, additional filament must be drawn from the supply spool **24** and, to the extent that a pull or tension is applied to the filament **20**, the cantilever beam **32** will be deflected as the supply spool resists any increase in rotational velocity over that of the winding head **22**. Accordingly, the tension will build up in the filament and a signal from the transducer **30** will be applied through the brush slip ring assembly **36** to the comparator **40** which then generates an error signal of a polarity indicating an increase in tension.

This error signal is applied to the servo amplifier **42** where it is amplified and applied to the servo motor **44** and its connected gear train **46**. The signal to the servo motor **44** and gear train **46** generates a rotation in the direction of the winding head motion and this is then added to the first input of the mechanical differential **48**.

The output of differential **48** then is the sum of the applied rotations and the drive to the supply spool is then increased, speeding up the supply spool **24**.

So long as the tension in the filament **20** is the desired tension, then the output of the transducer **30**, when compared to the output of the reference signal generator **38**, in the comparator **40** will provide a small offsetting, or "zero" error signal which is applied through the servo system to drive the supply spool at a slightly greater velocity than the winding head, to permit the filament to unreel without setting up undesired oscillations in the servo part of the system as the result of overshoot in the correction.

If the supply spool **24** speeds up and the tension decreases, the desired tension signal from the reference signal generator **38** will be the greater and the error signal will be of the opposite polarity. This error signal when amplified and applied to the servo **46**, tends to apply a rotational input to the differential which is effectively subtracted from the winding head input tending to slow the supply spool **24** and thereby causing an increase in filament tension.

An alternative embodiment is shown in FIG. 2 which includes, in addition to the systems elements of FIG. 1, a form compensating system **50** to permit uniform tension on a filament that is being wrapped about a non-uniform form or mandrel. As shown in FIG. 2*a*, a rectangular bar **52** is shown as the mandrel, and as can be seen in FIG. 2*b*, this shape imposes a non-uniform demand upon the filament supply system, which, if uncorrected, could result in wide variations in filament tension.

To help compensate for this variation in demand, a second mechanical differential **54** is provided. The second mechanical differential **54** is connected to receive one output from, as shown here, a cam follower unit **56** that includes a slotted cam **58** and a crank type follower **60**, which is suitable for winding speeds of up to 2000 r.p.m. For higher winding speeds, a more sophisticated compensating system would be required such as a gear train utilizing elliptical gears, of perhaps a hydraulic servo system. The cam **58** is driven in synchronism with the winding head **22** and provides a first input to the second mechanical differential **54**. The second input to the differential **54** originates from the servo motor **44** and the gear train **46** as described in connection with FIG. 1, above. The output of the second differential **54** is applied to one of the inputs of the first differential **48**. The second input to the differential **48** comes from the winding head **22**, and the combined output of the first differential **48**, is as before applied to the supply spool drive shaft **26**, so that in this embodiment, the rotation of the supply spool **24** is the resulting summation of the rotational motion of the winding head **22** and the corrections applied by the servo motor **44** and the gear train **46**, and by the cam follower unit **56** of the compensating system **50**.

In FIG. 3*a*, there is illustrated still another alternative embodiment for maintaining a constant uniform tension on a filament which is to be wound upon a non-uniform core **62** of cyclically varying cross section. For example, FIG. 3*b* illustrates a portion of such a form **62** which in this case is a rectangular continuous strip having a repeating saw tooth pattern **64**.

In this embodiment, a third mechanical differential **66** is provided which receives as one mechanical input, the output of a second compensating or axial correction system **68** which is driven by a connection to the form or mandrel drive mechanism which advances the mandrel through the winding head assembly **12**. Typical mandrel drives are shown in Marlowe, above. The compensating or axial correction system **68** may be substantially similar to the form compensating system **50**, and may include a cam and follower arrangement.

The third differential **66** has its second input connected to the output of the form compensating system **50**. The output of the third differential **66** now serves as the input to the second differential **54** and the remaining elements of the system are connected as in FIG. 2*a*.

The series of differentials can be considered, generally, as one form of compensating and correcting means which is wholly mechanical. Other embodiments would include combinations of electrical and mechanical elements, even all-electrical embodiments can be devised by one skilled in the art.

A suitable transducer element **30** is shown in FIGS. 4 and 5 which are a side and front view, respectively, of the cantilever beam member **32** of FIG. 1. As shown in more detail, the cantilever beam **32** has affixed to one face, a signalling element which, in a preferred embodiment is a strain sensitive gauge **70**, bonded to the body of the cantilever beam **32**. Suitable electrical leads **72**, **74** connect through the slip ring brush assembly **36**, to a suitable power supply and balancing network (not shown) so that the cantilever beam member **32** can provide signals which are proportional to the deflection of the beam. As will be clearly seen, the cantilever beam deflection is entirely due to tension in the filament **20** as it makes the turn from the supply spool **24** to the second idler **34**.

It will be apparent to those skilled in the art that the particular circuits comprising the reference signal generator **38**, the comparator **40**, the servo amplifier **42** and servo motor **44** are well known in art and accordingly, no particular circuits have been set forth. Similarly, the details of mechanical gear trains **46** and mechanical differentials are equally well known and will not be discussed in detail herein. Further, the selection of a particular cam follower combination to compensate for non-uniform cross sections or for a cyclically varying form are well within the skill of the artisan and need not be discussed in detail herein other than to state that such mechanical compensating systems are easily provided without the exercise of inventive skills.



It is also within the skill of the art to provide suitable electrical compensating circuits whose outputs, when electrically combined with that of the servo amplifier **42**, would compensate for variations in the shape of the mandrel and for cyclical variations in the mandrel as a function of axial position of the mandrel. In such an embodiment, only a single mechanical differential need be provided, one input of which would be supplied by the servo motor and gear train, and other input of which would be the winding head. The output of the differential would be applied to drive the supply spool.

Broadly, in operation, as the filament is wound about the form or mandrel, any tensions introduced by the movement of the point of wrap on the form can either be mechanically or electrically compensated and corrected for, as a function of some combination of winding head rotation and mandrel movement.

The tension in the filament resulting from the unwinding of the filament from the supply spool is compensated for by a servo loop which continually senses the tension in the filament and compares the tension, represented by a signal from a reference signal generator. An error signal is then produced which, when applied to a servo amplifier-servo motor combination and gear train through a mechanical differential, continuously corrects the supply spool drive to maintain the filament tension at the predesired value. Any tensions introduced by non-uniformities in the mandrel or movement of the point of wrap on the form can be compensated for either electrically or mechanically and these compensations can be superimposed on the corrections already generated.

Although the apparatus as described and shown is useful in the winding of resistance wire in a helix to form a resistive element, similar apparatus could be used, using other types of filaments and cores for the winding of musical instrument strings. Also, in embodiments wherein the form or mandrel is of an unusually large cross section, larger than the inner diameter of a filament supply spool, the filament supply spool could be mounted eccentrically on the winding head. The drive to the supply spool would be reconnected accordingly, and might eliminate the need for the mechanical differential, and the servo motor gear train could be mounted on the winding head to drive the supply spool directly. In this embodiment, if non-uniform cross section mandrels are used, electrical compensation would be preferable. In this case, the electrical output is applied directly to the servo loop of the supply spool.

Thus, there has been shown a novel system for maintaining a predetermined tension on a filament on a winding apparatus having several embodiments. The tension on the filament is sensed and, through suitable transducers, a signal is generated which can be used to correct for variations from desired tension by varying the rotational velocity of the filament supply spool through a suitable servo loop including an error generator, an error amplifier, a servo motor, gear train and mechanical differential.

What is claimed as new is:

**1.** In a high speed winding apparatus for winding a filament about a core, the apparatus having a winding head rotatable about the core, a filament supply spool rotatably mounted on the winding head and means for rotating the winding head at relatively high rotational velocities to form a coil about the core, apparatus for maintaining a predetermined tension in the filament comprising:

tension sensing means coupled to the winding head and interposed in the path of filament travel and adapted to provide a signal proportional to and representative of the tension in the filament being wound on the core;

tension reference means adapted to provide a signal proportional to and representative of a desired, predetermined tension in the filament;

error sensing means coupled to said tension sensing means and said tension reference means for providing an error signal proportional to and representative of a deviation in measured tension from desired tension; and

servo correcting means connected to said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool during rotation of the winding head to modify the filament tension in accordance with said error signal, whereby said servo means affects the rotational velocity of the supply spool to change the filament tension in a sense tending to decrease the magnitude of the error signal.

2. In a high speed coil winding apparatus for winding wire about a mandrel, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted on the winding head and means for rotating the winding head at relatively high rotational velocities for winding a helical coil on the mandrel, apparatus for maintaining a predetermined tension in the wire comprising:

tension sensing means coupled to the winding head and interposed in the path of wire travel and adapted to provide a signal proportional to and representative of the tension in the wire being wound on the mandrel;

tension reference means adapted to provide a signal proportional to and representative of a desired, predetermined tension in the wire;

error sensing means coupled to said tension sensing means and said tension reference means for providing an error signal proportional to and representative of a deviation in measured tension from desired tension; and

servo correcting means connected to said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool during rotation of the winding head to modify the wire tension in accordance with said error signal, whereby said servo means affects the rotational velocity of the supply spool to change the wire tension in a sense tending to decrease the magnitude of the error signal.

3. In a high speed filament winding apparatus for winding filament about a core, the apparatus having a rotatable winding head coaxial with the core, a filament supply spool rotatably mounted concentric with the rotating winding head and means for rotating the winding head at relatively high rotational velocities for winding a helical coil about the core, apparatus for maintaining a predetermined tension in the filament during winding comprising:

tension sensing means coupled to the winding head and interposed in the path of filament travel and adapted to provide a signal proportional to and representative of the tension in the filament being wound on the core;

tension reference means adapted to provide a signal proportional to and representative of a desired, predetermined tension in the filament;

error sensing means coupled to said tension sensing means and said tension reference means for providing an error signal proportional to and representative of a deviation in measured tension from desired tension; and

servo correcting means connected to said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool relative to the rotational velocity of the winding head to modify the filament tension in accordance with said error signal;



whereby a change in the rotational speed of said supply spool changes the filament tension in a sense tending to decrease the magnitude of the error signal.

4. In a high speed coil winding apparatus for winding resistance wire about a mandrel, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted concentric with the rotating winding head and means for rotating the winding head at relatively high rotational velocities for winding a helical coil about the mandrel, apparatus for maintaining a predetermined tension in the resistance wire during winding comprising:

tension sensing means coupled to the winding head and interposed in the path of resistance wire travel and adapted to provide a signal proportional to and representative of the tension in the resistance wire being wound on the mandrel;

tension reference means adapted to provide a signal proportional to and representative of a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means for providing an error signal proportional to and representative of a deviation in measured tension from desired tension; and

servo correcting means connected to said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool relative to the rotational velocity of the winding head to modify the resistance wire tension in accordance with said error signal;

whereby a change in the rotational speed of said supply spool changes the resistance wire tension in a sense tending to decrease the magnitude of the error signal.

5. In a high speed filament winding apparatus for winding a filament about a core, the apparatus having a rotatable winding head coaxial with the core, a filament supply spool rotatably mounted concentric with the winding head and means for rotating the winding head at relatively high rotational velocities for winding a helical coil on the core, apparatus for maintaining a predetermined tension in the filament comprising:

tension sensing means including a cantilever beam coupled to the winding head and interposed in the path of filament travel to be deflected in proportion to filament tension, deflection sensitive transducer means mounted on said cantilever beam and adapted to provide a signal proportional to and representative of the tension in the filament being wound on the core, and means for energizing said transducer means;

tension reference means adapted to provide a signal proportional to and representative of said transducer means signal at a desired, predetermined tension in the filament;

error sensing means coupled to said tension sensing means and said tension reference means for providing an error signal representing a deviation in measured tension from desired tension; and

servo means connected to said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool relative to the rotational velocity of the winding head to modify the filament tension in accordance with said error signal, whereby said servo means, by changing the rotational speed of the supply spool, changes the filament tension in a sense tending to decrease the magnitude of the error signal.

6. In a high speed coil winding apparatus for winding resistance wire about a mandrel, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted concentric with the winding head and means for rotating the winding head at rela-

tively high rotational velocities for winding a helical coil mandrel, apparatus for maintaining a predetermined tension in the resistance wire comprising:

tension sensing means including a centilever beam coupled to the winding head and interposed in the path of resistance wire travel, strain gage means mounted on said cantilever beam and adapted to provide a signal proportional to and representative of the tension in the resistance wire being wound on the mandrel and means for energizing said strain gage;

tension reference means adapted to provide a signal proportional to and representative of said strain gage signal at a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means for providing an error signal representing a deviation in measured tension from desired tension; and

servo means connected to said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool relative to the rotational velocity of the winding head to modify the resistance wire tension in accordance with said error signal, whereby said servo means, by changing the rotational speed of the supply spool, changes the wire tension in a sense tending to decrease the magnitude of the error signal.

**7.** In a high speed coil winding apparatus for winding resistance wire about a mandrel, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted concentric with the winding head and means for rotating the winding head at relatively high rotational velocities for winding a helical coil mandrel, apparatus for maintaining a predetermined tension in the resistance wire comprising:

tension sensing means including a cantilever beam coupled to the winding head and interposed in the path of resistance wire travel, strain gage means mounted on said cantilever beam and adapted to provide a signal proportional to and representative of the tension in the resistance wire being wound on the mandrel and means for energizing said strain gage;

tension reference means adapted to provide a signal proportional to and representative of said strain gage signal at a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means for providing an error signal representing a deviation in measured tension from desired tension; and

servo means connected to said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool relative to the rotational velocity of the winding head to modify the resistance wire tension in accordance with said error signal, whereby said servo means affects the rotational speed of said supply spool to change the wire tension in a sense tending to decrease the magnitude of the error signal.

**8.** In a high speed coil winding apparatus for winding resistance wire about a mandrel, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted on the winding head and means for rotating said winding head at relatively high velocities for winding a helical coil on the mandrel, apparatus for maintaining a predetermined tension in the resistance wire comprising:

tension sensing means coupled to the winding head and interposed in the path of resistance wire travel and adapted to provide a first signal proportional to and representative of the tension in the resistance wire being wound on the mandrel;

tension reference means adapted to provide a second signal proportional to and representative of a said first signal in response to a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means and operable in response to applied first and second signals for generating an error signal having a magnitude and polarity representing the deviation in measured tension from desired tension; and

servo means connecting the supply spool and said error sensing means and operable in response to said error signal for changing the rotational velocity of the supply spool by an amount related to the magnitude of said error signal and in a direction related to the polarity of said error signal to modify the resistance wire tension, whereby said error signal changes the rotational speed of said supply spool to change the wire tension to correspond to the desired predetermined tension.

**9.** In a high speed coil winding apparatus for winding resistance wire about a mandrel, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted concentric with the winding head, means for rotating the winding head at relative high rotational velocities for winding a helical coil on the mandrel, and means for feeding the mandrel at a preset speed in an axial direction, apparatus for maintaining a predetermined tension in the resistance wire comprising:

tension sensing means connected to the winding head and interposed in the path of resistance wire travel, and including strain gage means adapted to provide a first signal proportional to and representative of the tension in the resistance wire being wound on the mandrel;

tension reference means including variable resistance means adapted to provide a second signal proportional to and representative of the first signal produced by said strain gage means at a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means including potential source means for electrically energizing said tension sensing and reference means for providing an error signal in response to applied first and second signals, having a polarity and magnitude representing a deviation in measured tension from desired tension; and

servo means connected to said error sensing means and operable in response to said error signal having a first polarity for increasing the rotational velocity of the supply spool relative to the rotational velocity of the winding head to decrease the resistance wire tension and operable in response to said error signal having a second polarity for decreasing the rotational velocity of the supply spool relative to the rotational velocity of the winding head to increase the resistance wire tension, the magnitude of the increase and decrease being proportional to the magnitude of the error signal, whereby said servo means affects the rotational speed of said supply spool to change the wire tension in a sense tending to decrease the magnitude of the error signal.

**10.** In a high speed coil winding apparatus for winding resistance wire about a mandrel, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted on the winding head and concentric therewith, and means for rotating the winding head at relatively high rotational velocities for winding a helical coil of resistance wire on the mandrel, apparatus for maintaining a predetermined tension in the resistance wire comprising:

tenson sensing means coupled to the winding head, including strain gage means interposed in the path of resistance wire travel and adapted to provide a first signal proportional to and representative of the tension in the resistance wire being wound on the mandrel;

tension reference means adapted to provide a second signal corresponding to the signal resulting from said strain gage means in response to a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means and operable in response to first and second signals to generate an error signal having a polarity and magnitude respectively corresponding to the sense and magnitude of the difference between measured tension and desired tension;

servo drive means connected to said error sensing means and operable in response to said error signal for producing a rotational motion corresponding to a supply spool velocity increment sufficient to produce the desired predetermined tension; and

differental drive means having a first input coupled to the means for rotating the winding head, a second input coupled to said servo drive means and an output coupled to apply rotational motion to the supply spool, said output being equal to the sum of the applied inputs, whereby said differential drive means modify the rotational speed of the supply spool to change the wire tension in a magnitude and direction tending to decrease the magnitude of the error signal derived therefrom.

11. In a high speed coil winding apparatus for winding resistance wire about a mandrel of non-uniform cross section, the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted on the winding head and concentric therewith, and means for rotating the winding head at relatively high rotational velocities for winding a helical coil of resistance wire on the mandrel, apparatus for maintaining a predetermined tension in the resistance wire comprising:

tension sensing means coupled to the winding head, including strain gage means interposed in the path of resistance wire travel, and adapted to provide a first signal proportional to and representative of the tension in the resistance wire being wound on the mandrel;

tension reference means adapted to provide a second signal corresponding to the signal resulting from said strain gage means in response to a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means and operable in response to first and second signals to generate an error signal having a polarity and magnitude respectively corresponding to the sense and magnitude of the difference between measured tension and desired tension;

servo drive means connected to said error sensing means and operable in response to said error signal for producing a rotational motion corresponding to a supply spool velocity increment sufficient to produce the desired predetermined tension;

mandrel compensating means connected to the winding head rotating means including apparatus for generating an output motion to compensate for the nonuniformity of the mandrel cross section during each rotation of the winding head;

first differential drive means having a first input coupled to said mandrel compensating means output motion, a second input coupled to said servo drive means and an output; and

second differential drive means having a first input coupled to the means for rotating the winding head, a second input coupled to said first differential drive means output and an output coupled to apply rotational motion to the supply spool, said output being equal to the algebraic sum of all of the applied inputs, whereby said first and second differential drive means modify the rotational speed of the supply spool to change the wire tension during each rotation of the winding head in a magnitude and direction tending to decrease the magnitude of the error signal derived therefrom and to correct for the non-uniform shape of the mandrel.

12. In a high speed coil winding apparatus for winding resistance wire about a mandrel of non-uniform cross section cyclically varying in the axial direction the apparatus having a rotatable winding head coaxial with the mandrel, a wire supply spool rotatably mounted on the winding head and concentric therewith, means for rotating the winding head at relatively high rotational velocities for winding a helical coil of resistance wire on the mandrel, and means for axially advancing the mandrel apparatus for maintaining a predetermined tension in the resistance wire comprising:

tension sensing means coupled to the winding head, including strain gage means interposed in the path of resistance wire travel, and adapted to provide a first signal proportional to and representative of the tension in the resistance wire being wound on the mandrel;

tension reference means adapted to provide a second signal corresponding to the signal resulting from said strain gage means in response to a desired, predetermined tension in the resistance wire;

error sensing means coupled to said tension sensing means and said tension reference means and operable in response to first and second signals to generate an error signal having a polarity and magnitude respectively corresponding to the sense and magnitude of the difference between measured tension and desired tension;

servo drive means connected to said error sensing means and operable in response to said error signal for producing a rotational motion corresponding to a supply spool velocity increment sufficient to produce the desired predetermined tension;

compensating and correcting means having a first input coupled to the means for rotating the winding head, a second input coupled to said servo drive means, a third input coupled to the mandrel advancing means and an output coupled to apply rotational motion to the supply spool, said ouput modifying the rotational speed of the supply spool during each rotation of the winding head to change the wire tension in a magnitude and direction tending to decrease the magnitude of the error signal derived therefrom to compensate for non-uniformities in mandrel cross section and to modify and correct the compensation with axial movement of the mandrel.

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