DESIGN AND DEVELOPMENT OF A NOVEL CIRCULAR WARP KNITTING MACHINE

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Abstract

This paper reports the design, manufacture and test of an innovative method of producing warp knitting fabrics, using a circular disposition of the needles rather than linear needle bars. By using the novel truncated-cone needle-bed concept instead of a cylindrical one, the needles slide simultaneously in radial and vertical directions to combine the reciprocating and swinging motions into one. Initially a mechanical prototype machine was designed, built and successfully tested to prove the knitting mechanism and its interaction with the patterning rings. The second prototype has a mechatronic patterning mechanism, hence increasing the patterning capabilities significantly, and enabling changing fabric pattern change during knitting without requiring long machine stoppages and cam changes.

Keywords*: circular warp knitting, machine design, knitting mechanism, mechatronic patterning*

1. Introduction

Warp knitted fabrics are normally made by linear (flat-bed) warp knitting machines containing two needle bars, one for each side of the two-layered fabric, joined on the edges by yarns knitting on each bar to produce a circular fabric. Warp knitting technology has failed to enter the circular knitting market, due to its complexity in achieving warp-knit structures in circular configuration. This paper reports the design and development of an efficient and innovative method of producing tubular warp knitting fabrics, using a circular configuration of needles rather than linear needle bars.

Flatbed warp knitting machines employ three main mechanisms to produce stitches. Namely, (i) a reciprocating motion of the needles in the vertical plane to form and cast off stitches, (ii) a swinging motion to move the yarns from the front to the back of the needles (and vice versa), and (iii) a shogging motion to produce overlaps and underlaps parallel to the plane in which the needles are laid.

The knitting needle cycle for a flatbed warp-knitting machine can be described in six stages (Figure 1). Starting with the needles at their highest position and having the previous loops around their stem, at stage (1) the threads are swung from the back to the front of the needles. At the *overlap* stage (2), a thread is laid under the hook of the needle by performing a sideways *shog* from one needle space to the next. The threads are then swung to the back of the needle at stage (3). The needles then start to move downwards at stage (4). The loops from the previous cycle that are located under the needle latch cause the latches to close as the

*Formerly Teaching Company Associate at Loughborough University in conjunction with Tritex International Limited needles continue to move down, eventually reach the top of the needles, are *cast-off* and pulled down by the fabric tension. At the *underlap* stage (5), the threads are shogged again, this time behind the needles. As the needles rise again at stage (6), the threads in the hooks push open the latches, move further down with respect to the needles and hence become the newly formed loops.

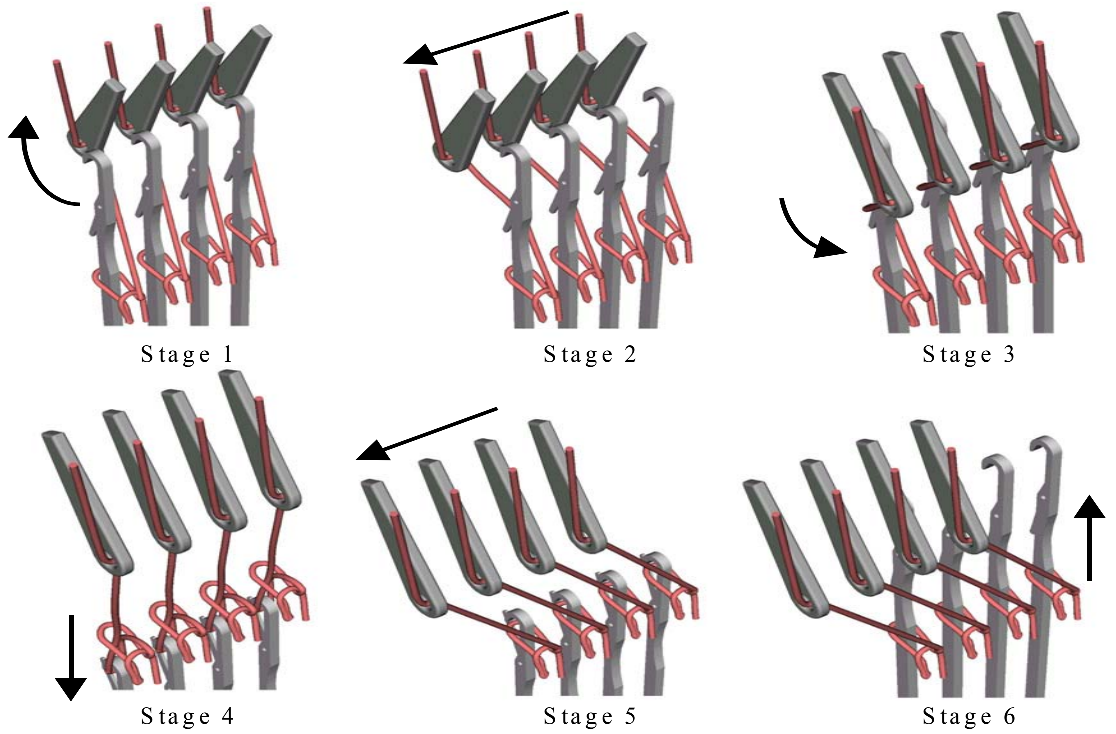

Figure 1. Stages of warp knitting as performed on a flatbed machine

During the **underlap** the needles are in their lowest position. Each thread should travel from the point where the last stitch has been cast off to the new position just past the target needle. Its end position should be such that the target needle rises in front of the thread. It should also be at an appropriate height to enable the thread to pass under the needle hook when the overlap is performed.

The **overlap** motion begins after the needle has risen to its highest position. During the overlap, which wraps the yarn around one needle only, the thread is positioned under the needle's hook, and sufficiently near the stem to ensure the needle picks up the thread on its downward motion. The yarn path will depend on whether the overlap is performed in the same direction as the preceding underlap or in the opposite one.

2. Circular warp knitting machine concept

Patterning mechanism requires a swinging motion to move the yarns from the front to the back of the needles (and vice versa). The swinging motion that achieves this in flatbed knitting machine is not possible in the circular configuration; therefore a totally novel approach is required to achieve this motion of the yarn.

A slotted (or 'tricked') truncated-cone needle-bed (Figure 2), a novel concept, is suggested rather than the traditional cylindrical needle-beds used in circular weft knitting machines.

This design enables the needles to slide in the tricks (slots) cut in the surface of a truncated conical needle bed. The needles, sliding at an angle in the tricks on the conical surface, would move the hooked end of the needles radially inward as they ascend and outward as they descend, combining the two of the successive motions required for the knitting cycle in one: reciprocating in the vertical direction of the needles and swinging of the threads in the radial direction. The appealing advantage of this concept is that there is no need for an extra mechanism to perform the swinging motion of the needles that is required from a warp knitting cycle.

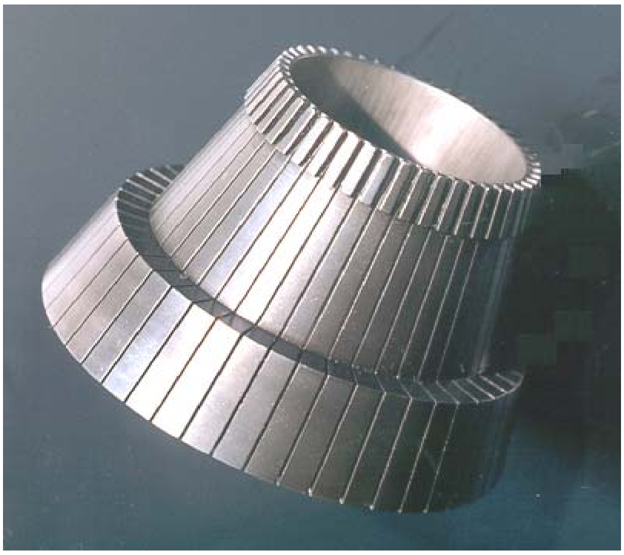

Figure 2. Truncated cone needle-bed

The fact that the tricked truncated cone is a concept where the whole swinging mechanism can be avoided, as it combines both the swing and the vertical reciprocation in the same movement, made it an excellent solution to the problem, outweighing all other possible concepts considered. It can not only increase the speed at which a stitch is produced, but more importantly it also simplifies the yarns movement, that will now only involve the tangential motion of threads relative to the needles.

The shogging motion (moving threads across a certain number of needles to the desired needle position) can be achieved by rotation of patterning rings that guide the yarns that are threaded through radially perforated eyelets. The rings must perform two distinct rotations (overlap and underlap) during a machine cycle. The direction and amplitude of the rotations will depend upon the fabric structure being created. However, an overlap will always be carried out over one needle only, while an underlap can be under several needles and could therefore require a larger rotation of the rings. A knitting pattern chain comprises a number of rotational movements of the rings in synchronisation with the main mechanism responsible for reciprocating the needles in the tricks on the truncated conical needle-bed. The greater the number of rings, the greater the patterning possibilities. However, the amount of space to place them and the complexity of the yarn paths generally restrict the number of patterning rings that can be accommodated in a machine.

3. The design of the mechanisms

This section covers the main issues that affect the design and the performance of the mechanisms in which the new circular warp knitting machine is based.

3.1 The needle reciprocating mechanism

A cam and follower mechanism was chosen to reciprocate the needles because it is a simple and precisely repeatable method of transforming rotational motion into a combination of linear rises, dwells and returns. This mechanism reciprocates the needle support ring in the vertical plane, which in turn moves the needles by sliding them along the tricks (Figure 3). This concept enables the designer to have full control over the shape of the displacement curve, ie the length of the dwells, rises, amplitude of stroke, etc.

The design of the rise-dwell characteristic of the cam is very important in the warp knitting machine application, as it provides the synchronisation with the patterning mechanisms and the maximum speed of the machine depends on its optimisation. The dwells in the knitting cam profile represent the section of the revolution of the cam where the underlaps and overlaps will be carried out by the patterning mechanisms. During the dwell period, the set of needles will remain stationary as the threads are wrapped around them by the patterning rings. The dwell that represents the underlapping period that occurs after lowering the needles is normally longer than that represents the overlapping period, as a knitting pattern can include longer underlaps, but the overlap always wraps the thread over one needle only.

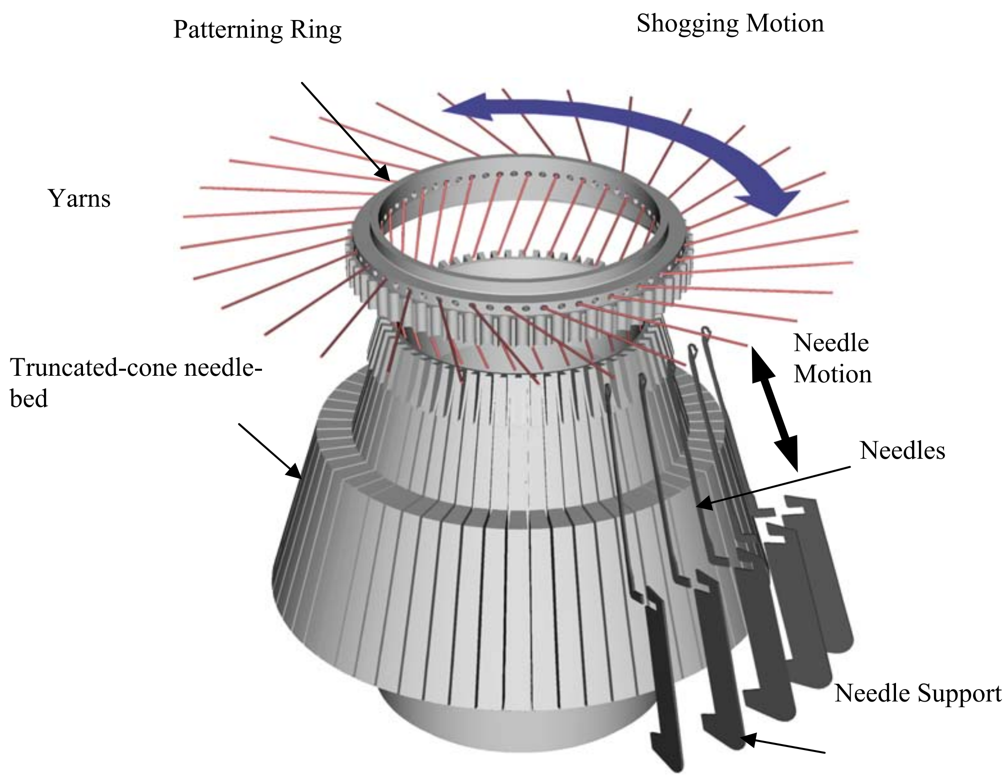

Figure 3. A patterning ring and needles on truncated-cone needle-bed

3.2 The patterning mechanism

The main function of the patterning mechanism is to provide the needles with threads at the appropriate points in the knitting cycle following a specified sequence, which will produce a given knitted pattern. A pattern consists of a number of varying length of underlaps each followed an overlap that wraps the thread over one needle each time. The previously patented patterning mechanism concepts (Borenstein, 1986; Ragosa, 1990) are all mechanically controlled, use two patterning rings driven by open face cams and have a maximum pattern length of twelve machine cycles. The restriction on the number of cycles is due to space limitation. A larger number of machine cycles in a pattern would require a larger cam, but the space that accommodates the cam is constrained.

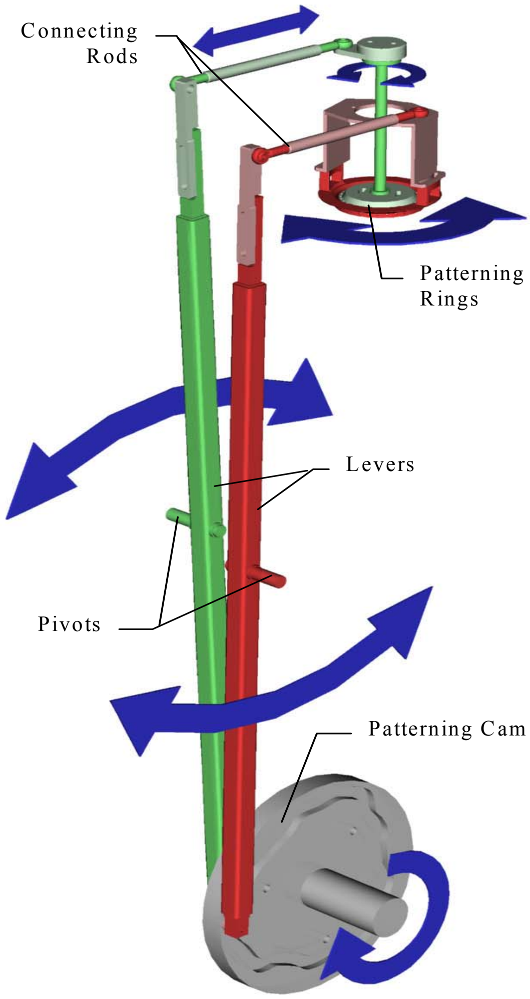

Figure 4. Mechanical patterning mechanism

The patterning mechanism is based on patterning rings through which the yarns are threaded radially (Figure 3). The rings need to be rotated in order to provide the required shogging motion. The shogging mechanism could be seen as the most important mechanism in a warp-knitting machine. This is because it limits the machine's patterning capability. Having isolated the swinging problem from the shogging one, the latter is now simplified to designing a means to rotate threaded rings about their centre in the smallest possible space, but allowing for easy threading of the rings.

Initially a mechanical system was designed and built to prove the proposed knitting machine based on the novel conical needle-bed concept and patterning rings (Figure 4). A cam-based mechanism was thought to be advantageous in cost terms but its main disadvantage is the lack of flexibility (each different fabric structure requires a different cam profile). The mechanical system converts the motion created by the patterning cam into a rotation of the patterning ring by means of a mechanical linkage. The configuration and length of the linkage components depend on the physical space available and the dimensions of the machine elements.

The first prototype machine used a 72-needle truncated-cone (Figure 5). A ring rotation of 80^o that is equivalent to 16 needle spaces was considered to be sufficient for most knit structures. The main improvements achieved are the use of enclosed cam followers in the patterning cams, hence reducing shock and vibration attributable to open face cams, and enhancement of the cam performance by using cycloidal profiles for each rise and fall segments to obtain the best results for high-speed applications (Erdman and Sandor, 1991).

The tricked truncated cone concept that combines the vertical reciprocating and radial swinging motions in one simultaneous motion of the needles and its interaction with the shogging motion of the patterning rings are undoubtedly unique to this circular warp knitting machine concept. Prototype machine was built to industrial standards, tested successfully and had gone through successful industrial trials.

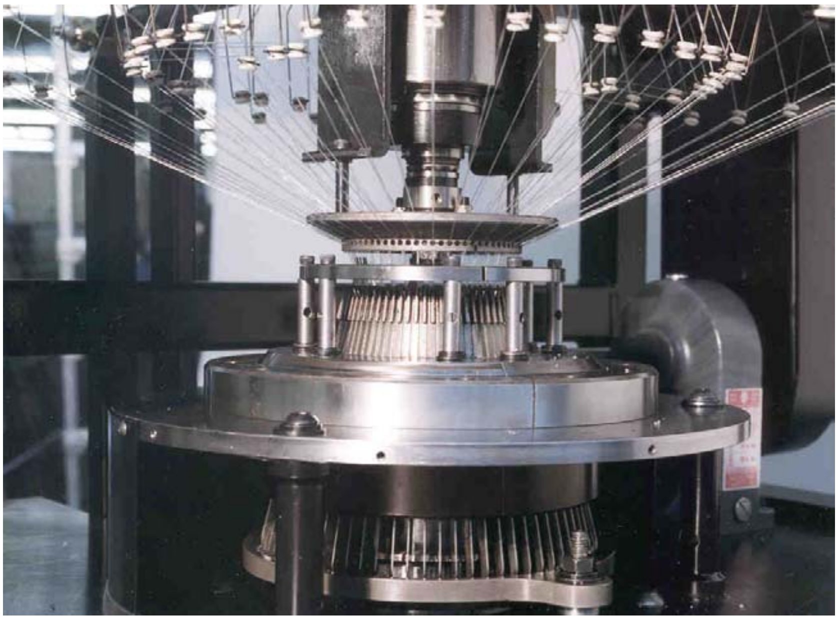

Figure 5. Prototype showing truncated-cone needle-bed and patterning rings

4. The mechatronic solution

The flexibility of the patterning depends on the ease of modifying the motion performed by its shogging mechanism and the length of the pattern chain. With the cam driven mechanism, a change of pattern requires changing the patterning cam.

4.1 The concept

A much more flexible and innovative mechatronic solution to the problem of designing a patterning mechanism for a circular warp knitting machine is to directly drive the patterning rings using servomotors (Figure 5). Servomotors were selected over stepper motors because of the speed of reaction and position control requirements of the knitting application. The servomotor controllers can store programs with the series of movements required by a given fabric design.

The patterning mechanism requires very fast responses and accurate position control. AC brushless servomotors that can meet these requirements at a high machine speed of 1000 rpm were selected (Mermelstein et al 2001) to rotate the three patterning rings used on the second prototype machine via a belt and pulley arrangement, hence considerably reducing the machine parts used. This in turn reduces the mechanical vibrations associated with the cam driven mechanism.

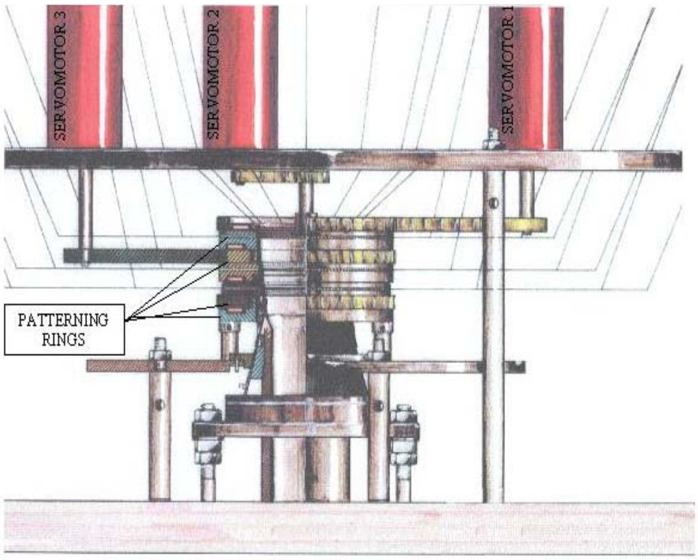

Figure 5. Servomotor drive concept

The servomotor program should include the appropriate dwells in the ring rotation when the needles are being raised or lowered, and a means for synchronisation between the shogging movement and the knitting mechanism should be devised. In addition, changing the knitting pattern can easily and quickly be realised by entering a new set of values into the motion controller memory and involves no changes of mechanical parts.

4.2 The Prototype

The patterning mechanism for the knitting machine was then designed, built and tested. It consists of three rings each controlled by servomotors (see Figure 6). The motors are only linked to the load by pulleys and belts, ensuring an appropriate gear ratio. The mechanism is no longer restricted by mechanical properties of the linkages used in the mechanical design.

The mechanism was tested without yarns and the maximum rotation (80°) was achieved repeatedly in alternating directions, within the specified time of 20 ms, accelerating from zero to 139 rpm in 10 ms and decelerating to zero again in the remaining 10ms, which illustrates the very fast response of the system.

The development of a new knitting pattern is reduced to stepping the motor until it reaches the desired position for each motion and recording those values.

The mechatronic shogging has the potential of creating pattern chains that are only restricted by the size of the memory of the hardware used, allowing hundreds of machines cycles rather than limited numbers that can be accommodated by a cam mechanism. It is a more costly solution but its patterning flexibility and simplicity of its design renders it the best solution concept.

The main knitting mechanism, that is, the one responsible for the needle motion could also be servo-controlled giving further control over the synchronisation between needles and yarns. This has not been implemented in the current design, but it can deploy the method proposed by Yao et al, (2000) to improve the motion characteristics of a cam follower by controlling the cam speed, using servo drives.

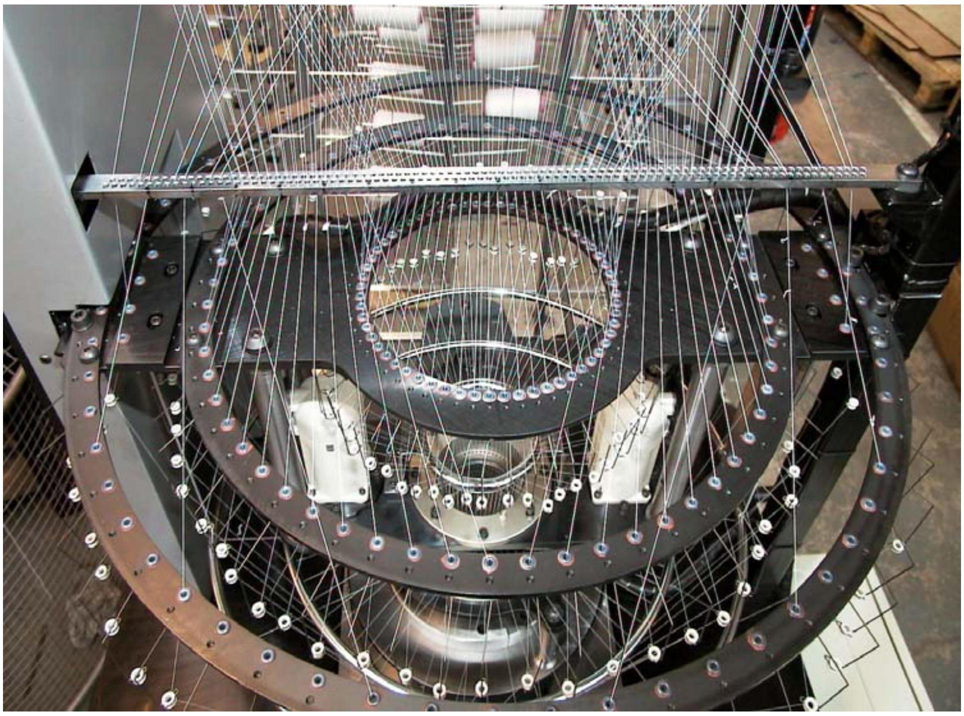

Figure 6. The servomotor driven patterning rings on the prototype machine

4.3 The Yarn Feed Mechanism

Furthermore, a positive yarn feed mechanism was developed to control the feed rate of the yarns to the needles. By changing the feed-rate and the knit-pattern, the diameter of the knitted structure can be controlled and altered as required, offering new fabric formation opportunities. This novel concept opens up many industrial applications from medical textiles to fruit packaging.

4.4 Truncated Cone Optimisation

The use of a truncated-cone needle-bed to enhance the interaction between the needle and yarn movements is one of the main innovations of the circular warp knitting machine design. By using a tricked truncated cone to support the needles, two of the traditional displacements performed by the needles are merged into one.

The prototype machine used a 15^{o} half-cone angle. However it is essential that, the optimum taper angle of the cone, a novel and unique feature of this design, needs to be investigated to find the most efficient interaction between the needle and yarn motions. The optimum inclination of the cone depends on other geometrical factors in the design of the patterning mechanism. Given the complexity of the motions of the needles and yarns in a three-dimensional space the following parameters had to be considered: the position of yarns, the intersection of yarns with different needles, the maximum shogging distance that a given ring can rotate (for a given minimum cone diameter, taper angle, and number of needles), the optimum height of the patterning rings in relation with the top of the tricked cone and the maximum number of patterning rings. All of these geometrical factors in the design of the patterning mechanism are interrelated. It is necessary to develop a parametric mathematical/graphical model to predict the equations that govern the relationship between these parameters and to find the optimum combinations.

5. Conclusions

A new concept of producing warp knitted fabrics using of an innovative circular disposition of the needles has been proven. The truncated-cone needle-bed concept was invented after a thorough research into warp and weft knitting principles and mechanisms, a concept evaluation, and product design specification process.

Initially a mechanically controlled patterning system was used for the first prototype in order to prove the new concepts. Having proven the concepts, a mechatronic system has been developed using AC brushless servomotors to control three patterning rings via a belt and pulley arrangement. This novel concept has significantly reduced the machine parts required and enabled the knit pattern changes to be realised by changing software parameters only. The new design not only makes its patterning capabilities significantly better than any mechanical system; but also meets the response requirements that will allow the machine to be run at 1000 rpm design speed. Prototypes both mechanisms have been manufactured and tested on separate machines.

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