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An Innovative Concept In Weft Insertion Of Projectile Weaving Machine

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Abstract
The common methods of weft insertion in weaving machines are shuttle, rapier, air jet, water jet and projectile insertion. During weft insertion in the weaving process, a variety of demands are to be fulfilled. Besides transportation of the weft yarn, three of the most relevant demands are energy efficiency, productivity and flexibility. These demands are only partially met by the common methods of weft insertion. This paper describes the investigation of a novel method of weft insertion, which combines the advantages of common insertion methods whilst avoiding their deficits. The developed weft insertion is based on the principle of a magnetic force for the controlled transport of the weft yarn. The new method allows a potential energy saving of about 60% compared to a conventional air jet weaving machine. At the same time, industrially experienced weft insertion rates of about 2000 m/min are within reach.

Key words: *Fiber, yarn, fabric formation, materials, production, quality, weaving, weft insertion*

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I. Introduction

Weaving is the most common, as well as the oldest process, for fabric manufacturing. Until now, a fabric was created by crossing warp and weft threads at a right angle, although the insertion method made a large leap during the last two centuries. Nowadays, the most common weft insertion methods are weft insertion by compressed air or water, by rapier or projectile or by shuttle. Air jet weaving grants the highest productivity at a maximum weft insertion rate of up to nearly 4000 m/min (Tsudakoma WLT at ITMA 2015). The high productivity goes along with high energy consumption due to processing of compressed air (12 kWh for a single air jet weaving machine) [1]. In addition, air jet weaving is limited in its ability to process different yarn materials. Remarkably flat or heavy yarn, for example, is difficult or even impossible to process via air jet weaving [2]. Rapier weaving is the most flexible weft insertion method, granting a gentle transport of any yarn material. Due to the high mass of the moving parts and the acceleration and deceleration of the alternating movement of the rapiers, the productivity is limited. To benchmark the productivity of different weaving machines the weft insertion rate is used. The weft insertion rate computes as the product of the weaving width and the number of insertions per minute. Hence, the rate includes both the weft insertion time and rest time for shedding and reed movement. Rapier weaving machines achieve a weft insertion rate of about 1200 m/min. Due to the acceleration and deceleration of the alternating movement, a medium energy consumption of about 6 kWh is necessary [1,2]. The weft insertion granting the lowest energy consumption is projectile weaving with about 4 kWh. The insertion rates are similar to those of rapier weaving. Due to the high acceleration at initiation of movement, an impact load is applied to the yarn.

Only yarns with sufficient tensile strength (such as hightenacity polyester yarn) can be transported by projectile weaving because yarn breakage has to be avoided. Hence, the flexibility of projectile insertion is limited as only processing of yarns with sufficient tensile strength is possible [2]. Table 1 gives an overview of the common weft insertion methods and their characteristics. The values presented refer to common production performance in industrial weaving.1 In the present work, the development of a weft insertion is described as combining the advantages of all common insertion methods while avoiding their deficits. For validation of the developed method, a test bench is designed. In functional tests, a proof of concept is delivered showing that the productivity of air jet weaving is reachable at the low level of energy consumption of projectile weaving. In addition, completely new types of fabric can be manufactured with the ‘‘magnetic shuttle’’ by alternating movement of the weft yarn in the shed.

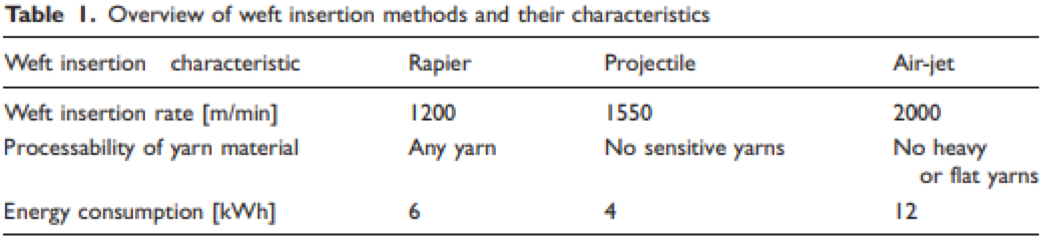

Table 1. Overview of weft insertion methods and their characteristics

Weft insertion characteristic	Rapier	Projectile	Air-jet
Weft insertion rate [m/min]	1200	1550	2000
Processability of yarn material	Any yarn	No sensitive yarns	No heavy or flat yarns
Energy consumption [kWh]	6	4	12

II. Theoretic approach for the combination of favorable insertion characteristics

A central motivation to develop a new weft insertion method is the requirement of low energy consumption. As an initial approach to reduce energy consumption, the energy balance of a weaving machine is evaluated. The energy Ein that enters the system equals the energy Eout leaving the system (1)

$$E_{\text{in}} - E_{\text{out}} = 0 \qquad (1)$$

Ein comprises the throughput m_ weft and m_ warp of yarn material and the power Pweft as well as Pwarp necessary for the transport of the yarn material (2)

$$E_{\text{in}} = \dot{m}_{\text{weft}} \cdot P_{\text{weft}} + \dot{m}_{\text{warp}} \cdot P_{\text{warp}} \qquad (2)$$

Eout comprises the throughput m_ fabric of the fabric and the power Pfabric necessary for the transport of the fabric as well as the energy Eloss, which is dissipated due to effects such as friction or turbulent air flow during weft insertion (3)

$$E_{\text{out}} = \dot{m}_{\text{fabric}} \cdot P_{\text{fabric}} + E_{\text{loss}} \qquad (3)$$

For a reduction of the necessary input energy Ein, the weft insertion energy is to be reduced. As the throughput m_ weft is to be maximized to be maintained, the maximum productivity the power Pweft is to be minimized. This reduction can be achieved by reducing the force Fweft necessary for the transport of the weft yarn, because P is a function of F.Pweft is proportional to the momentum Mweft and the rotational speed ninsertion needed for the execution of weft insertion. Hence, Pweft is proportional to the force Fweft

$$P_{\text{weft}} = M_{\text{weft}}\, 2\,\pi\, n_{\text{insertion}} = F_{\text{weft}}\, r\, 2\,\pi\, n_{\text{insertion}} \qquad (4)$$

The composition of Fweft depends on the principle of yarn transport during weft insertion. A reliable yarn transport can only be achieved if Fweft is applied at the yarn throughout the complete duration of weft insertion. In air jet weaving, Fweft is applied at the yarn by the air stream, which is generated by the main nozzles and maintained in the reed channel by the auxiliary nozzles . In water jet weaving, Fweft is induced by the amount of water that is applied at the end of the weft yarn. For a sufficient response of the yarn toward Fweft applied by a streaming media, the yarn has to show a certain set of characteristics (such as low weight and a sufficient hairiness). Hence, the requirement of high flexibility in the mean of processability of any yarn material cannot be fulfilled with an insertion method that is based on streaming media [3]. In projectile weaving, Fweft is applied at the yarn by the clamping of the yarn into the projectile. The projectile is instantly accelerated to its maximum speed of up to 60 m/s. Hence, a high acceleration at initiation of the movement takes place, resulting in a high wear of the weft yarn. Projectile weaving is suitable for spun and filament yarns in the range of 6.4–200 tex [4] . An instant acceleration has to be avoided in order to maintain the processability of any yarn material, as only yarns with sufficient tensile strength can be transported at high values of acceleration. As the transport with streaming media is to be avoided, a device that is in contact with the yarn throughout the transport over the weaving width is to be used. Fweft has to be applied continuously on this device to ensure a moderate acceleration of the yarn. The transporting device will be called ‘‘projectile’’ in the following, whereas it is not a device that is brought into movement in a ballistic manner because instant acceleration is to be avoided. Furthermore, there shall not be similarity to the common projectile weaving intended by using a ‘‘projectile’’ in this work. In Figure 1, a force balance of the projectile and the transported weft yarn is displayed. In Figure 1, it can be seen that $F_{\text{insertion}}$ is the force necessary to move the weft yarn from the insertion side over the fabric width to the opposite side. $F_{\text{insertion}}$ is composed of the force Fyarn induced by the weft tension, the inertial force F_{inertia} (induced by the resistance against the movement into insertion direction during acceleration), the air resistance force FCW and the frictional force F which is induced by the normal force FN applied on the projectile by the contact with the guiding surface (5)

$$\vec{F}_{\text{insertion}} = \vec{F}_{\text{yarn}} + \vec{F}_{\text{inertia}} + \vec{F}_{C_W} + \vec{F}_{\mu} \qquad (5)$$

This equation can be specified by the dimensions (front surface APr, mass mPr), velocity vPr and acceleration aPr of the projectile. In this equation, the constants (density of air, air, gravitation g) are given at standard conditions. The air resistance coefficient cW is assumed to be 0.5 as valid for rectangular front surfaces within streaming media. The frictional coefficient is assumed to be 0.2 as valid for two bodies in contact with each other that are both made of steel (6)

$$F_{\text{insertion}} = F_{\text{yarn}} + m_{\text{Pr}} \cdot a_{\text{Pr}} + \frac{\rho_{\text{air}}}{2} \cdot A_{\text{Pr}} \cdot c_W \cdot v_{\text{Pr}}^2 + m_{\text{Pr}} \cdot g \cdot \mu \qquad (6)$$

For a reduction of Finsertion, the mass of the projectile, the front surface, the air resistance and the friction have to be reduced if at the same time the velocity is to be increased. The force induced by weft tension is not to be changed, as a minimal value of this force has to be maintained to ensure a stretched state of the weft yarn at the beating-up of the reed. The required tendencies of the variables of weft insertion have been determined. For the movement of the projectile over the fabric width at a high velocity, the projectile has to show the following characteristics: low mass mPr (results in reduced inertia and friction); small size (results in small front surface APr and thus reduced air resistance); low friction coefficient m (results in reduced friction). Firstly, a number of mechanisms for the induction of Finsertion can be discarded. Hence, a permanent junction of the projectile with a rigid mass, which is in permanent contact with the machine frame at the entrance side, is not further regarded. This mechanism, which is used in rapier weaving, is discarded for its components of heavy mass being moved. Transport of the yarn via streaming media is discarded due to requirements of flexibility and energy consumption, as mentioned before. Furthermore, the impulsive induction of force into the projectile at the beginning of the movement (like in common projectile weaving) is discarded. As the mass in contact with the yarn is chosen to be very light, an impulsive induction of force would result in a yarn whose path over the weaving width is chaotic and uncontrollable. A permanent induction of force over the weaving width is thus to be maintained for the use of a very light projectile.

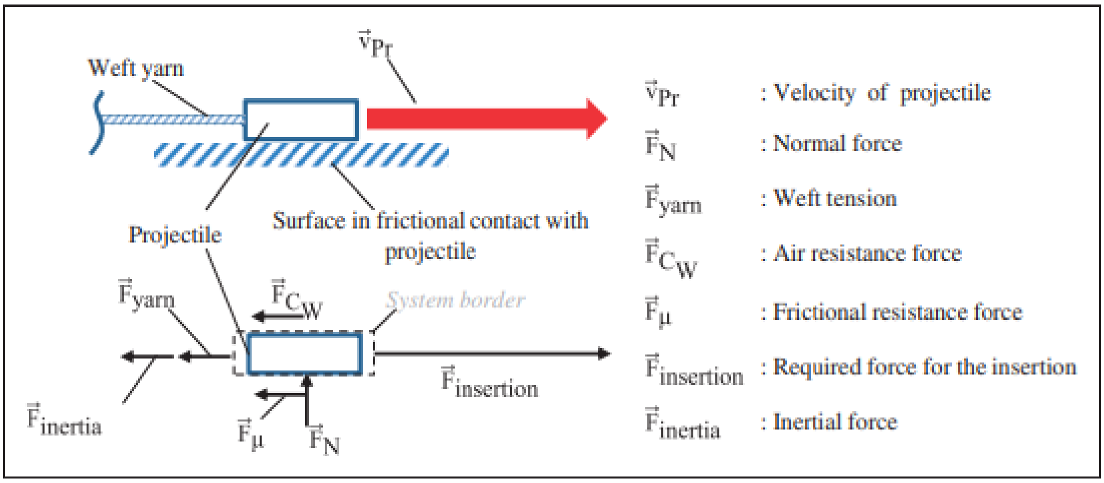

Figure 1. Force balance of the projectile and the transported weft yarn.

Due to the warp yarns, which may not be penetrated, a remote and contactless induction of force is to be generated. A force sufficient for such dynamic movement as needed for weft insertion at the targeted speeds can only be induced by field energy. Such field energy can be provided by magnetism, which is the chosen mechanism for this work.

III. Methods of magnetic weft insertion

In the past, there have been a number of attempts to transport the weft yarn by magnetic force. These approaches can be distinguished as those resulting in an instant acceleration of the yarn and those using a continuous movement for smooth acceleration of the yarn. The approaches resulting in instant acceleration are not further regarded for the reasons mentioned above. The discarded methods are described, for example, by Grieshaber and Juskjo, Demtro¨der6 and Mirjalili [5-7]. One principle of active guided magnetic weft insertion is based on the effect of magnetic levitation. The first patent of this so-called maglev-weaving was applied by Birtwell in 1953 [8]. For weft insertion, the yarn is clamped in a magnetic projectile. The projectile is then moved by a continuously adjustable transversal travelling electromagnetic field through the shed (as shown in Figure 2, left). While all maglev approaches combine the use of a permanent magnetic projectile, they vary in the design of the reed and the alignment of the electromagnetic parts [8–10]. Another actively guided magnetic weft insertion uses a magnetic projectile in combination with a circulating belt. The weft yarn is clamped in a permanent magnetic projectile. Permanent magnets are attached to the belt, which is aligned beneath the shed. If the magnets then move along the shed, their magnetic field interacts with the magnetic field of the projectile and drives the projectile through the shed. The different concepts vary with the use of external guiding-elements or a special shaped profile-reed for guiding the projectile through the shed. Figure 2 displays a possible set-up of a weaving machine using a magnetic timing belt for weft insertion. This method of weft insertion is mentioned in a number of patents. A proof of concept has not yet been published. The first patents related to magnetic weft insertion via a circulating timing belt were published in the 1970s [11–13]. From the late 1980s onwards, further patents were submitted by Chuang et al., describing magnetic weft insertion via a circulating timing belt [14,15]. The striking advantage of weft insertion via the magnetic timing belt is the use of continuous movement for the transport of the yarn while avoiding the necessity of a complex and high dynamic control of electromagnetic fields, as imperative in maglev-weaving. Due to the principle of using a continuous movement, which only has to be accelerated at initiation of the fabric production process, a massive potential of energy saving can be achieved. To investigate and overcome the challenges of weft insertion via the magnetic timing belt, a demonstrator was designed and assembled with which functional tests were carried out. The conceptual design and validation of magnetic weft insertion via the magnetic timing belt is described in the following sections.

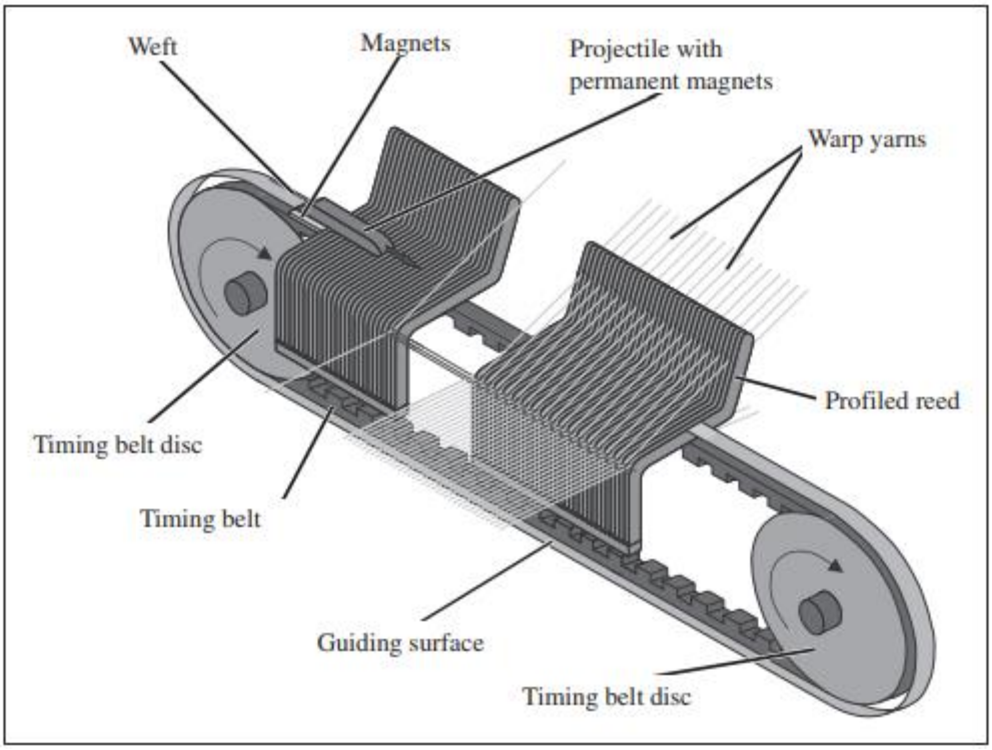

Figure 2. Magnetic weft insertion with a circulating timing belt.

IV. Concept and development of magnetic weft insertion for laboratory scale demonstration

In Figure 3, the functions that are to be fulfilled by the demonstrator are shown. These functions are as follows: weft supply (I.); transport over the reed (II.); selvedge formation (III.); and return of the projectile (VI.). The components that are necessary for the realization of these functions are also shown in Figure 3. Shedding (IV.) and beat-up of the reed (V.) are not shown with this demonstrator. Nevertheless, the design of the reed and its path of movement are designed to ensure a shedding motion as well as transport of the weft yarn to the fabric edge. The manufacturing of a fabric is targeted to be carried out in a further step of the development. Hence, this demonstrator does not show the manufacturing of a fabric. For the weft supply, a device was designed for resembling the device for weft supply in rapier machines. The reed is designed in such a way that it allows the transport of the projectile on a guiding surface, as well as a correct kinematic behavior during beat-up of the inserted weft yarn. The timing belt is equipped with a permanent magnet. Due to the high centrifugal force during rotation at target speeds (e.g. 230 N at 1200 weft insertions per min), a special attachment of the magnets in the belt is necessary, as shown in Figure 4. The attachment consists of a magnet holder that is screwed on one tooth of the timing belt. Therefore, the actual tooth of the timing belt is replaced by a metallic one. The magnetic projectile is equipped with a clamping device and a gliding layer at the bottom surface.

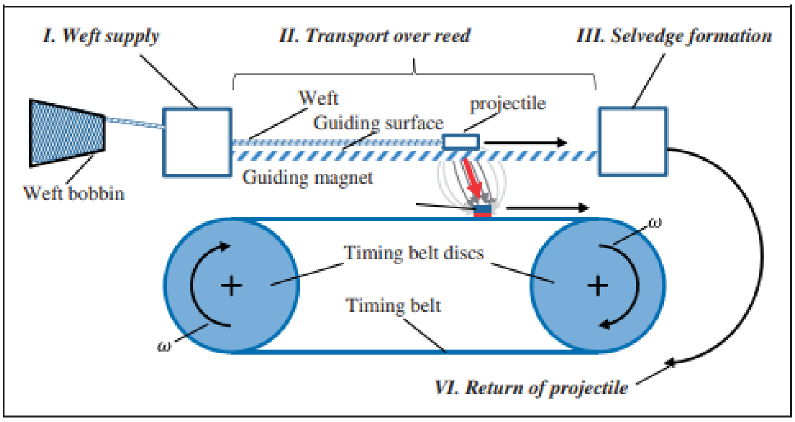

Figure 3. Schematic drawing of the demonstrator for magnetic weft insertion.

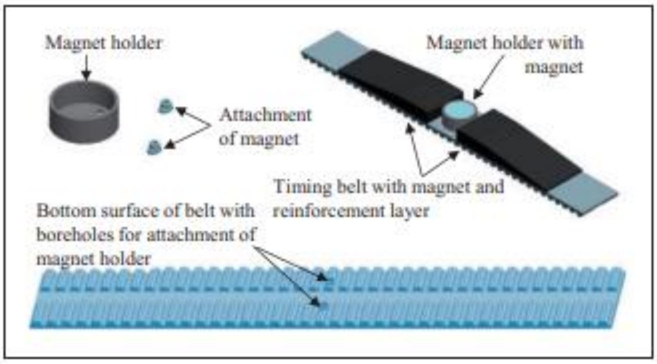

Figure 4. Attachment of magnet in the timing belt.

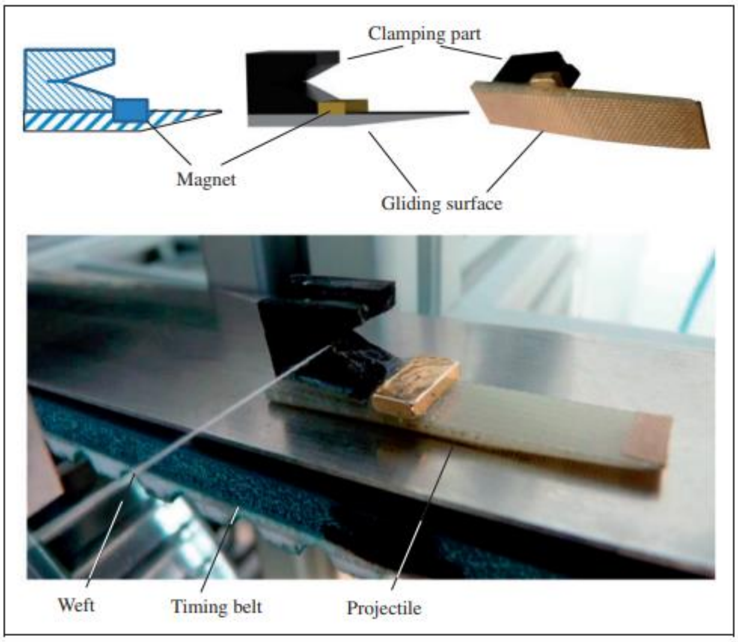

Figure 5. Magnetic projectile and yarn take-up at weft supply

The clamping device of the projectile catches the weft at the weft supply. The projectile and the moment of yarn take-up are shown in Figure 5. The designed demonstrator is shown in Figure 6. The demonstrator comprises the components that are necessary for a complete weft insertion. These components are the weft supply, the reed, a yarn clamping device and a projectile.

V. Validation of magnetic weft insertion in the laboratory scale

The laboratory-scale demonstrator has been validated regarding productivity, energy efficiency and weft flexibility. The first examined productivity parameter is the production speed. The weft insertion rate vWI given in meters of inserted weft yarn per minute ([m/min]) depends on the revolution speed of the engine. For the use of two projectiles simultaneously, a revolution speed of n = 2650 1/min is achieved. For the validation, different set-ups of the test bench have been examined. Table 3 shows the achieved engine speed and the calculated weft insertion rate, which is calculated with the diameter of the pulley dP =190:1mm, the length of the timing belt lB =2.65 m, the weaving width xW = 1 m and the number of projectiles NPr as follows (7)

$$v_{WI} = \frac{n \cdot d_{\mathrm{P}} \cdot \pi}{l_{\mathrm{B}}} \cdot x_W \cdot N_{\mathrm{Pr}} \qquad (7)$$

Whereas xW NPr < lB. applies. In set-up A, only the magnetic belt has been installed. The set-up shows that the chosen engine is able to accelerate the magnetic belt up to the designated weft insertion speed. In set-up B, a high production speed is achieved by operating one projectile in direct contact with the belt or in combination with a non ferromagnetic reed-dummy. However, the sighted weft insertion speed has not been achieved. In both cases, after reaching the maximum engine speed n, the projectile loosened and slipped out of the demonstrator. For set-up C, instead of the projectile, the ferromagnetic reed runs in combination with the magnetic belt. Due to high friction that occurs between the magnetic belt and the ferromagnetic reed, the weft insertion speed was limited to 680 insertions per minute. Set-up D is determined by the full set-up of the magnetic belt, projectile and the ferromagnetic reed. The set-up confirms the Proof of Concept for the magnetic projectile weft insertion with regard to the movement of the magnetic projectile.

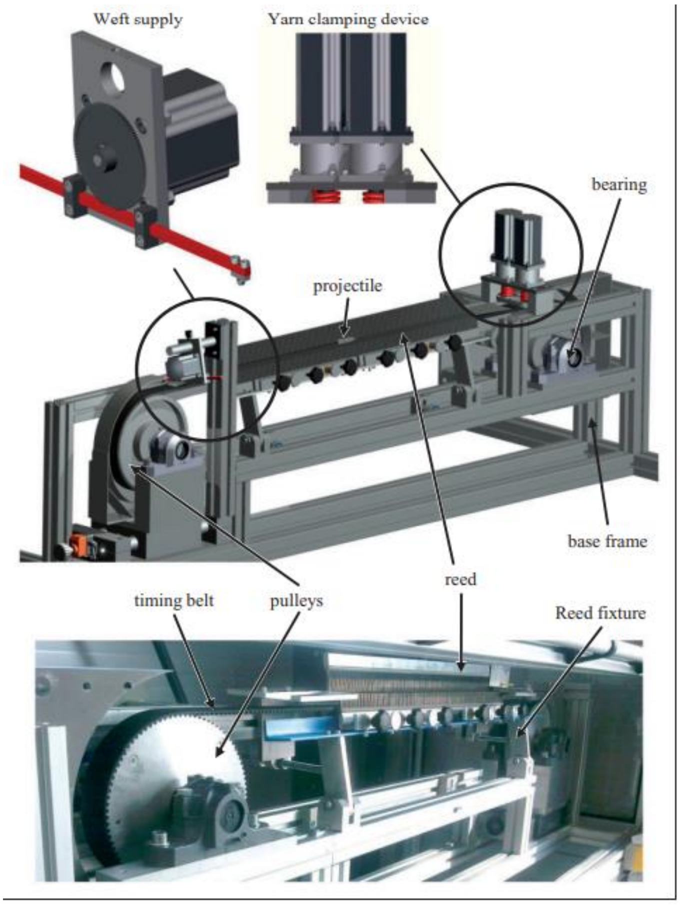

Figure 6. Computer-aided design model and photography of the demonstrator for magnetic weft insertion.

The second investigated productivity parameter energy efficiency is measured via the energy consumption in Wh. The energy consumption is physically defined by the work W, which results as the product of power P and the time interval t = 1 h. The power P is calculated as the multiplication of the voltage U and the current I. Measuring both between the power supply and the servo controller ensures that even dissipation loss of the servo controller is included. As a result, the energy consumption can be calculated using the following formula

$$W = P \cdot t = U \cdot I \cdot 1h \qquad (8)$$

Using a laboratory power supply in combination with an oscilloscope, the current has been recorded for different demonstrator set-ups. The acquired data has been processed using MS Excel. As a result, the energy consumption W for each set-up has been calculated. The results are shown in Table 4. With an engine speed of 1770 r/min, set-up 2 matches the target weft insertion speed. As shown in set-up 3, the use of one projectile increases the energy consumption by 11.3%. Accordingly, the energy consumption of three projectiles can be estimated as 3 x 11.3 = 33.9%. Based on set-up 2, the expected energy consumption for the whole demonstrator using three projectiles in combination with the reed can be assessed according to the following formula

$$W = 112.56\ Wh \cdot (1 + 33.9\ \%) \cdot (1 + 61.7\ \%) \cong 244\ Wh \qquad (9)$$

This estimated value of 244 Wh is clearly below the target energy consumption of 2 kWh and proves that the magnetic projectile weft insertion is a promising approach that can compete against the conventional projectile weft insertion. The last examined productivity parameter is flexibility. Using an actively guided projectile, a weft insertion with a controlled acceleration profile comparable to weft insertion by a rapier should be feasible. Using a special movement profile, a forward and backward motion of the projectile has been achieved. In addition, in Figure 7 it is shown that the projectile prototype is able to catch a manually provided weft yarn and transport it over the entire shed width. A concluding evaluation of the flexibility in comparison with the usual weft insertion systems will be carried out in the further development in which the set-up is transferred to a complete weaving machine.

VI. Conclusion

A demonstrator was designed, assembled and set up. In functional tests, first validations of the magnetic weft insertion via the magnetic timing belt were carried out. In the functional tests for investigation of the movement of the projectile, a rotational speed equivalent to a weft insertion rate of 1500 m/min was achieved with the described set-up. Further research will comprise functional tests of the components that are necessary for the fulfillment of the stated requirements. Hence, a special weft supply and a selvedge formation device will be established. The projectile will be designed to allow processing of any yarn material at minimum friction with guiding surfaces. The complete method of weft insertion will further be transferred into an existing weaving machine to allow shedding and beat-up of the reed to produce a fabric.

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