(REFEREED RESEARCH)

DEVELOPMENT OF A TEST DEVICE FOR MEASURING TENSILE PROPERTIES OF FABRICS

KUMAŞLARIN GERİLME ÖZELLİKLERİNİN ÖLÇÜMÜ İÇİN BİR TEST CİHAZININ GELİŞTİRİLMESİ

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ABSTRACT

A tensile tester for textile materials has been designed, manufactured and its performance tested. Horizontal construction is preferred in the design. Servo motor and ballscrew drive is used in the drive of movable clamp and elongation of test sample is calculated from servo motor motion and gear-ballscrew kinematics. Tension is measured by load cells of different measuring intervals. Software routines have been developed for different tests including load-elongation (or stress-strain) curve, tension change under constant elongation, creep test and force and elongation lost under cyclic loading. It is shown that load-elongation curves obtained from the developed device and Instron 4301 are close to each other. But some deviations exist. This is taught to be due to the bending in the movable clamp and mechanical imperfections. With the improvement of rigidity of the device and mechanical imperfections, the device is expected to give test results of commercially available ones in the market.

Keywords: Tensile properties, tensile tester, test device design, load-elongation curve, creep test, dynamic loading test, stress relaxation

ÖZET

Tekstil malzemeleri için mekanik özellikleri ölçen bir test cihazı tasarlanıp imal edildi ve performansı test edildi. Hareketli çenenin tahrikinde servo motor ve bilyalı vida mekanizması ile gerçekleştirildi ve hareketli çenenin yer değiştirme miktarı servo motor hareketi ve vida dişli kinematiğinden hesaplandı. Gerginlik ölçümü ise dğişik ölçüm aralıklarına sahip yük hücreleri ile gerçekleştirildi. Yük uzama eğrisi, sabit uzama altında gerginlik değişimi, creep testi ve tekrarlı yük altında kuvvet ve uzama değişimi gibi testler için yazılım modülleri geliştirildi. Yapılan testlerde cihaz ve Instron 4301'den elde edilen yük uzama eğrileri birbirine yakın olarak elde edilmesine rağmen bazı sapmaların halen mevcut olduğu görülmektedir. Hareketli çenedeki eğilme ve sistemdeki mekanik zayıflıklar (boşluk, açıklıklar vs) bu sapmanın temel sebebi olarak değerlendirilmiştir. Cihazın rijitliğinin artırılması ve mekaniğinin iyileştirilmesi ile piyasada mevcut olan ticari cihazlar seviyesinde test sonuçlarının elde edilebileceğini değerlendirmekteyiz.

Anahtar Kelimeler: Gerilme özellikleri, gerilme özellikleri test cihazı, test cihazı tasarımı, yük uzama eğrisi, sünme testi, dinamik yükleme testi, gerilme gevşemesi

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1. INTRODUCTION

Mechanical properties of textile materials are significantly affected by loading and elongations arising during production and end use [1, 2]. The mechanical properties are measured to determine elastic, plastic and viscoelastic behavior of textile materials. Quality and expected performance of textile materials are decided by the parameters obtained from load-elongation or stress-strain curves [3, 4]. Elastic modulus, breaking load, breaking elongation, work of rapture, permanent elongation and time dependent tensile properties are the main parameters determined by load-elongation curves [5, 6, 7].

There are two principles used in test devices to obtain load-elongation curves. The first principle is that textile material is elongated at a constant speed and tension induced in the material is measured by a load cell. In this way, load-elongation curve is obtained by recording the tension for each value of elongation. In the second principle, load is increased and elongation is recorded for each value of the load and load-elongation curve is drawn. Universal test devices available in the market use the first principle in which textile material is hold by two clamps at a certain distance called sample length [8]. While one of the clamps is fixed the other is driven by a servo motor or servo hydraulic actuator [9, 10]. Tension of test sample is measured by a load cell for small increments of elongation. Load-elongation curve is drawn between elongation and the measured tension.

This paper presents a research work aiming at design and manufacturing of a test device for measuring tensile properties of textile materials, mainly fabrics. Development of test device includes mechanical design, electronic and electromechanical design and software development for different tests. The test device employs constant elongation principle and uses servo motor drive of movable clamp. Horizontal design principle where load cell is connected to fixed clamp is adopted in this test device as different from other test devices. Also, in addition to basic tensile tests like breaking load, breaking elongation, elastic modulus and work of rapture, this device includes the tests like tension decrease under constant elongation (stress relaxation), elongation under constant tension and dynamic or cyclic loading tests.

2. DESIGN REQUIREMENTS

The test device has been designed to meet the following working conditions.

Speed interval of movable clamp: 0-300 mm/min (adjustable speed).

Tension measuring interval: 0-500 N, 0-2000 N, 0-5000 N (dependent on measuring interval three different load cell are employed)

3. DESIGN METHOD AND RELATIONS

3.1. Mechanical Design

Figure 1 shows main units of the proposed test device. As seen from the figure, motion is transmitted from the servo motor (M) to ballscrew (2) via a gear mechanism (1) having speed ratio of 1:25. Nut (4) is mounted on the ballscrew. Ballscrew is pivoted to the frame from front and rear side of the device. Moveable clamp (7) is fixed to the nut. Therefore it moves together with the nut. Fixed clamp (6) is pivoted axially to the frame of the device. Right end of the fixed clamp is connected to the load cell (L) and load cell is connected to the device frame from right hand side. Hence the force exerted to the fixed clamp is directly transmitted to the load cell.

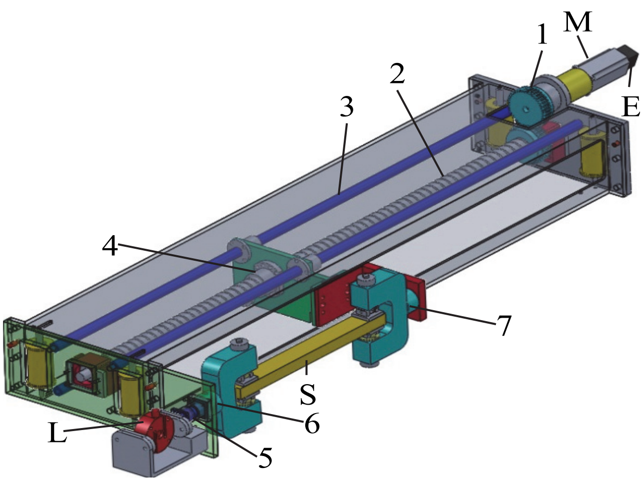


Figure 1. Main units of the proposed test device

3.1.1. Design calculations

Calculation of maximum torque of servo motor

Servo motor is selected to meet safely the speed and tension measuring interval of the device. For this purpose maximum tension which the device is expected to measure is reflected servo motor shaft according to the following formula.

$$M_m \omega_m = F_c V_c + Power\ Loss \quad (1)$$

Nut speed (V_c) can be written as follows considering the gear and ballscrew kinematics.

$$V_c = \omega_m ih/2\pi \quad (2)$$

Replacing V_c in Equation 1 with its equivalent leads to Equation 3.

$$M_m \omega_m = F_c \omega_m ih/2\pi + Power\ Loss \quad (3)$$

Power loss from motor to the nut will be represented by efficiency factor. In this case, Equation 4 is obtained.

$$M_m = F_c ih/2\pi 10\delta \quad (4)$$

Where

M_m: Maximum torque of the motor (Nm)

F_c: Maximum force which device is expected to measure (N)

i: Gear ratio

h: Pitch of the screw (mm)

δ: Total transmission efficiency of gear and ballscrew-nut mechanisms (%)

Speed interval of servo motor

Servo motor should meet the requirement of 0-300 mm/min clamp speed interval of the device. From Equation 2, motor angular velocity (ω_m) can be written as follows

$$\omega_m = 2\pi V_c/ih \quad (5)$$

Pitch of the ballscrew and gear ratio have been chosen as 5 mm and 1/25 respectively. Motor maximum speed and maximum required torque are determined as follows. Total efficiency of motion transmission system is taken as 50 %.

$$\omega_m = 2\pi x 300/\left(\frac{1}{25}x5\right)$$

$$\omega_m = 9424\ rad/min$$

$$\omega_m = 157\ rad/s = 1500\ rpm$$

$$M_m - 5000x\left(\frac{1}{25}\right)x5/(2\pi x10x50)$$

$$M_m = 0.318\ Nm$$

A servo motor of 400 W with 1.27 Nm continuous torque and 3000 rpm running speed has been selected for the drive of the test device. Maximum speed allows the movable clamp to return to the sample length distance quicker (at twice the speed of maximum test speed). Technical data of selected servo motor and ballscrew is given in Table 1 and Table 2 respectively.

Table 1. Technical parameters of the servo motor [11]

Rated output power (kW)	0.4
Rated torque (Nm)	1.27
Maximum torque (Nm)	3.82
Rated speed (rpm)	3000
Maximum speed (rpm)	5000
Gear ratio (Helical planet-sun system)	1/25
Transmission efficiency (%)	85
Encoder resolution (ppr)	10000

Table 2. Technical parameters of the ballscrew [12]

Screw shaft diameter (mm)	32
Pitch or lead (mm)	5
Travel distance error (µm/mm)	±50/300
Dynamic rated load (kN)	19.3
Static rated load (kN)	36.3
Axial rigidity (kN/µm)	5
Transmission efficiency (%)	93

Load cells are designed for certain measuring intervals. For measuring yarn and fabric tensile properties, load cells of different measuring interval are employed to acquire the required resolution from the measurements. Because of this, a load cell of 0-500 N measurement interval has been chosen for yarn testing and 0-2000 N and 0-5000 N load cells have been chosen for fabric testing. Technical data of the load cells are given in Table 3.

Table 3. Technical data of the load cells [13]

Product code	STCS50	STCS200	TB500
Capacities (kg)	50	200	500
Minimum division (g)	5	20	100
Accuracy class (according to OIMLR60)	C3	C3	C3
Combined error (%)	≤±0.02	≤±0.02	≤±0.02
Maximum excitation voltage (DCV)	15	15	15
Rated output (mV/V)	2±0.1%	2±0.1%	2±0.1%

Construction of clamps and mounting of load cell

Clamps are designed to hold the specimen without slippage. For this purpose, metal clamp surfaces are covered with a frictious and soft material (8) [14]. Upper side of the clamps are moved downwards by leadscrew-nut mechanism (9) to provide enough pressure (Figure 3).

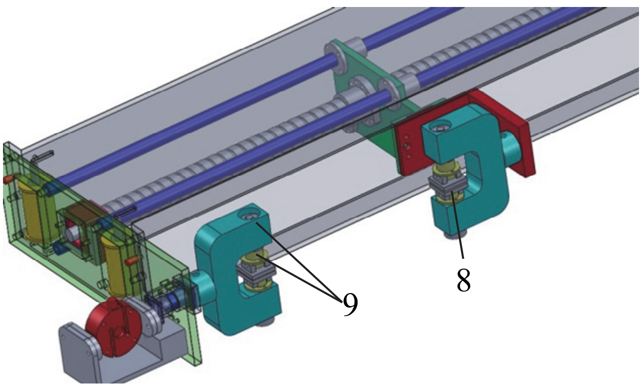


Figure 3. Fixed and movable clamps

Load cell is connected to the fixed clamp by a metal element (10) through an axial bearing (5). Attention has been paid to the inline arrangement of clamps holding specimen and load cell center to make the force induced in the specimen affect to the load cell in axial direction. Figure 4 shows the mounting of the load cell to the fixed clamp.

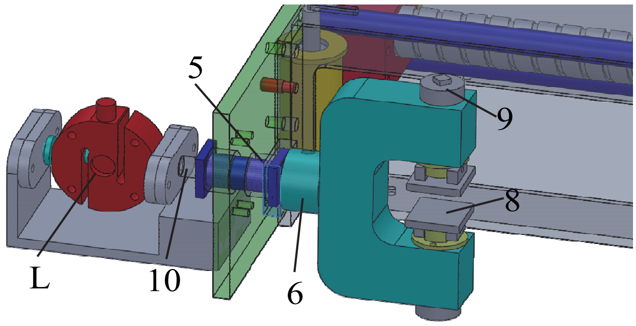


Figure 4. Mounting of the load cell to the fixed clamp

3.2. Electronic Design

Electronic system of the device and signals are shown in Figure 5. Servo motor is controlled and data is read from load cell by a personal computer (PC). Also, digital signals of servo motor encoder are read and recorded by PC. Encoder signals are read to determine the position of servo motor and hence displacement of movable clamp. Communication between servo motor, load cell signal and PC is achieved through a data acquisition card. Technical parameters of the selected data acquisition card (DAQ) are given in Table 4.

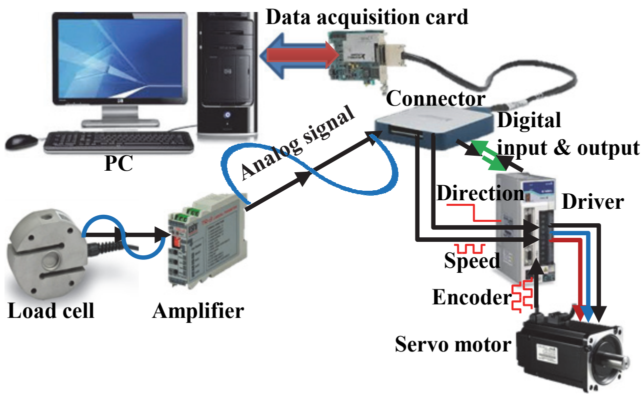


Figure 5. Electronic system of the device and signals

Table 4. Technical parameters of the data acquisition card [15]

Analog input	32 input channels,16 bits resolution 500 kS/s sample rate, ±10 V DC input range, 4095 samples size of buffer (FIFO)
Analog output	4 output channels, 16 bits resolution, 900 kS/s max update rate only one, ±10V DC output range, 8191 samples size of buffer (FIFO)
Digital input/output	48 total I/O and PFI channels for static or timing digital signals, 2.2-5.25 V DC threshold voltage.
Counter input/output	4 total channels, 32 bits resolution, frequency, event counting and encoder measurements; X1,X2 or X4 quadrature encoding with Channel Z reloading for two pulse encoding position measurements, 127 samples size of buffer per counter (FIFO), up to100 MHz internal base clock

Control of the servo motor can be done by analog signal changing between 0 to 10 V or digital signals. For different test routines, it is necessary to control both speed and position of movable clamp and therefore of the servo motor. Digital method has been preferred to control the operation of servo motor in this device as it simplifies simultaneous speed and position control.

Following mathematical relations are used in position and speed control of the servo motor. An incremental type of encoder is used as a feedback element for position and speed measurement of the motor shaft. The position of motor and therefore displacement of the movable clamp can be expressed in terms of number of pulse coming from the encoder as follows.

$$N_m = N_p/R \quad (6)$$

$$x = N_m ih \quad (7)$$

where

N_p: Total number of pulse coming from the encoder

N_m: Total number of revolutions of the motor

R: Resolution of the encoder in pulses per revolution (ppr)

x: Displacement of movable clamp (mm)

Total number of pulse required to move the movable clamp to a desired displacement can be calculated from Equation 6 and 7

Lineer speed of movable clamp can be expressed as below.

$$\dot{x} = V_r = n_m ih \quad (8)$$

$$f_p = n_m R/60 \quad (9)$$

Where

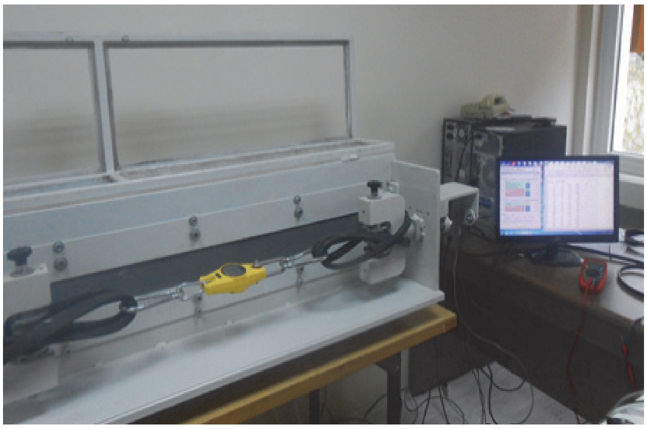
$\dot{x}$: Lineer speed of movable clamp (mm/min)

f_p: Pulse repetition frequency for driving servo motor (Hz)

n_m: Motor rotational speed (rpm)

Hence, pulse frequency necessary to drive the motor is determined by Equation 9.

Load cell needs to be calibrated on the device for the measurements. An electronic force scale has been used for the calibration of the load cell. After connecting the electronic force scale between fixed and movable clamps as shown in Figure 6, the movable clamp was moved in steps and gain of the load cell amplifier was adjusted so as to match load cell output signal and indicated force value by electronic force scale. After fixing the gain, calibration curve was obtained up to 300 kg as in Figure 6. Calibration curve is obtained as a linear curve as indicated in the ASTM E74−13a [16].



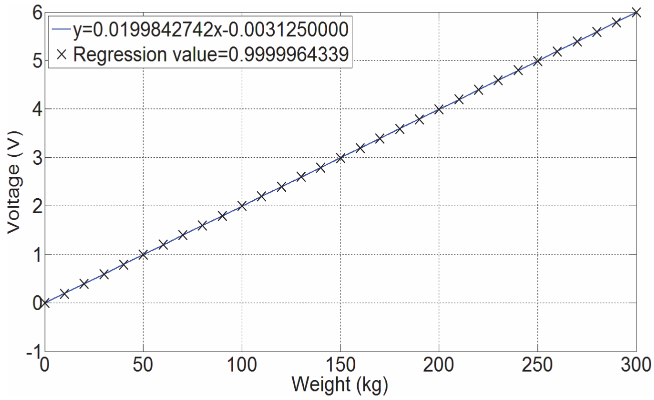


Figure 6. Use of electronic force scale for calibration and the calibration curve

3.3. Software Development

Simplified algorithm of software developed for the device is given in Figure 7. In the first step movable clamp is brought to the home position corresponding to test length by driving the servo motor. After each test, position data of the movable clamp is recorded to a data file. Before starting a new test, this data is read by computer and servo motor is driven so as to bring the movable clamp to the home position. Then data acquisition parameters are initialized and test parameters are entered. In the third step, different test routines are executed. This step includes tests of load-elongation (or stress-strain) curve, tension change under constant elongation, creep behavior and force and elongation lost under cyclic loading [17, 18]. Software module for each test are developed separately and executed when selected. In the final step, the test data is presented in graphical form and movable clamp is driven to its home position. Software routines were written using MATLAB Data Acquisition Toolbox [19, 20].

Figure 8 shows the flowchart of data reading module used in all test routines. Sensor signals are read continuously and stored in a buffer memory of DAQ card. This routine checks the availability of data in the buffer and if available it transfers all the data in the buffer to a file in computer hard disk. This software module has internal check about the value of data coming from the load cell. If it falls below a predetermined value, routine is stopped because it understands the break of fabric sample.

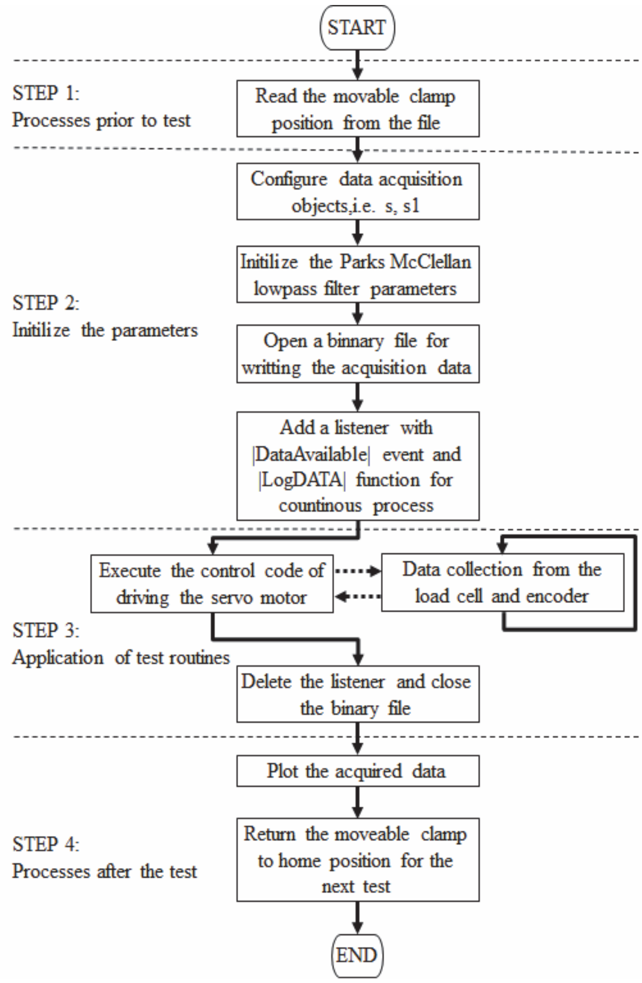


Figure 7. Simplified algorithm for the device software

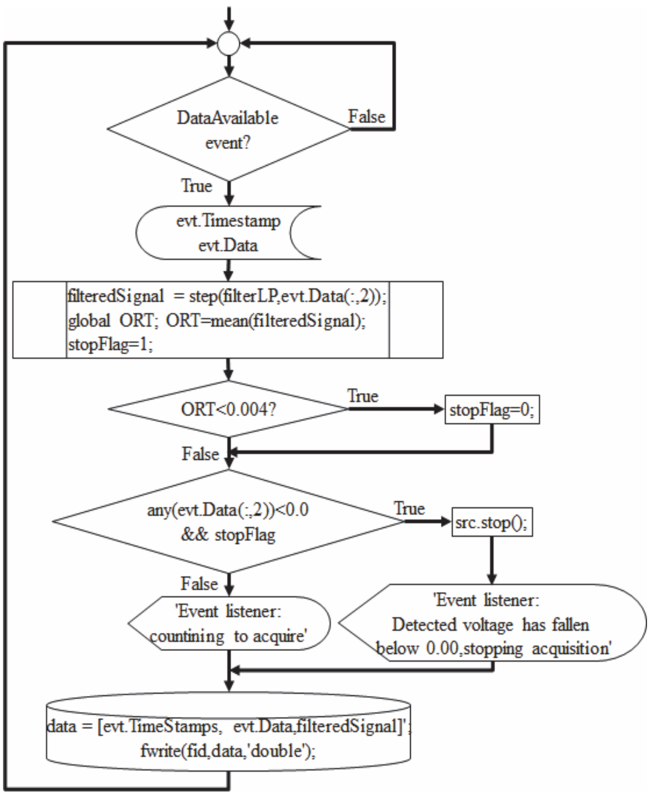


Figure 8. Data reading algorithm

Figure 9 shows the flowchart for load-elongation test. In this test, motor is driven at a specified speed and data is read from load cell and encoder on the servo motor shaft until the test specimen is broken. After completion of the test, load-elongation curve is plotted by the load cell data and elongation calculated from servo motor encoder data.

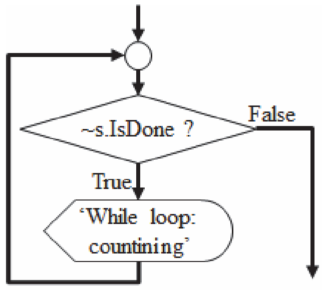


Figure 9. Load-elongation test algorithm

Figure 10 shows flowchart of the software module of tension reduction under constant elongation. Initially test period is entered to the software module and servo motor is driven until elongation or fabric tension reaches to the predetermined level. Then servo motor is stopped and elongation is kept constant during test period and fabric tension is recorded with respect to time. When the test period is completed, tension change with respect to time is plotted as a curve.

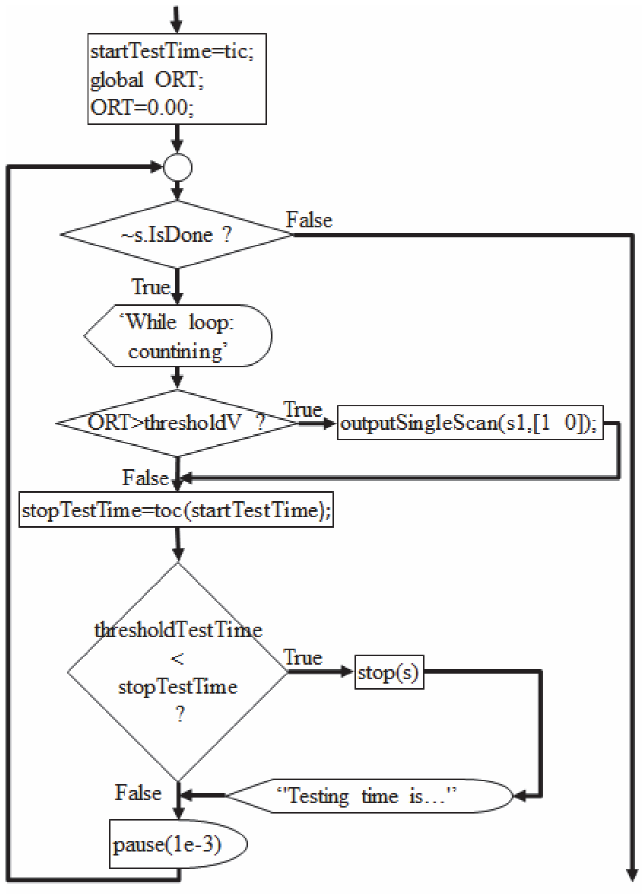


Figure 10. Stress relaxation test algorithm

Flowchart in Figure 11 shows process steps in creep test (elongation under a constant load (tension)). Initially test duration and load are entered to the routine. With a feedback control approach, elongation is applied to fabric by driving servo motor until fabric tension reaches predetermined load. Then fabric tension is read continuously from load cell and compared with the predetermined load. When tension falls below the predetermined level, software drives the servo motor and increases elongation until the predetermined tension level is reached. These process steps are repeated until the end of the test duration or period. After completion of the test, elongation is plotted with respect to time.

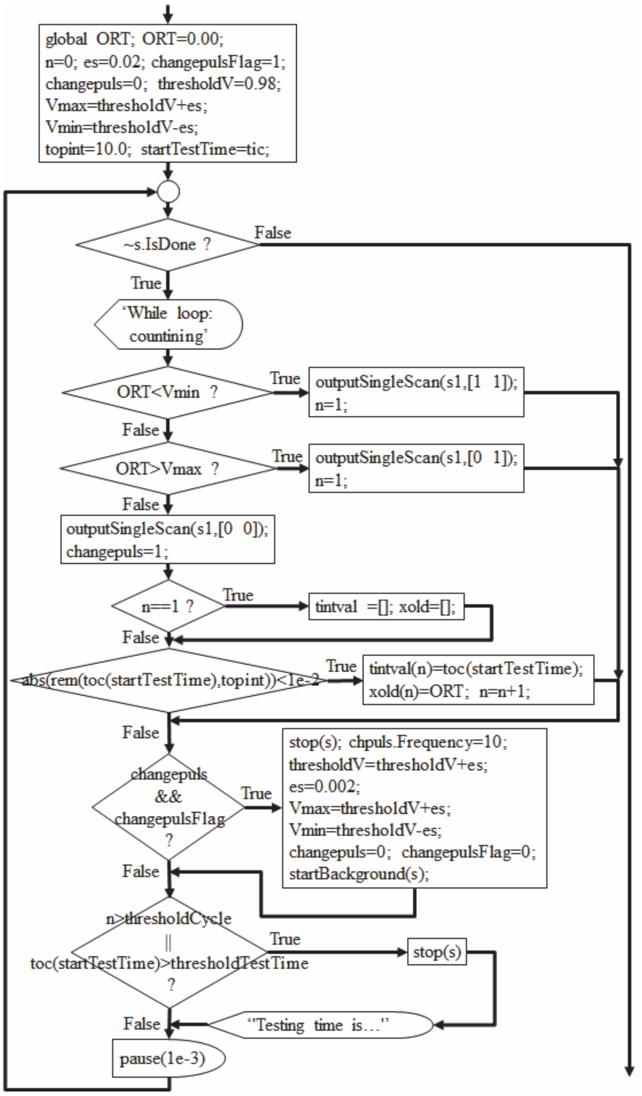


Figure 11. Creep test algorithm

The flowchart in Figure 12 shows the process steps in dynamic loading test in which force and elongation lost under cyclic loading is obtained. Initially number of cycles to be repeated, upper and lower elongation or tension values are entered to the routine [21]. Routine can work in two ways, i.e. dynamic loading within two elongation values and dynamic loading within two tension values [22, 23]. When routine works according to elongation, servo motor continuously drive the movable clamp in forward and backward directions between two predetermined elongation values. During this time, tension is recorded continuously until the end of the test. Finally tension-elongation curve is plotted for each cycle or at selected cycles.

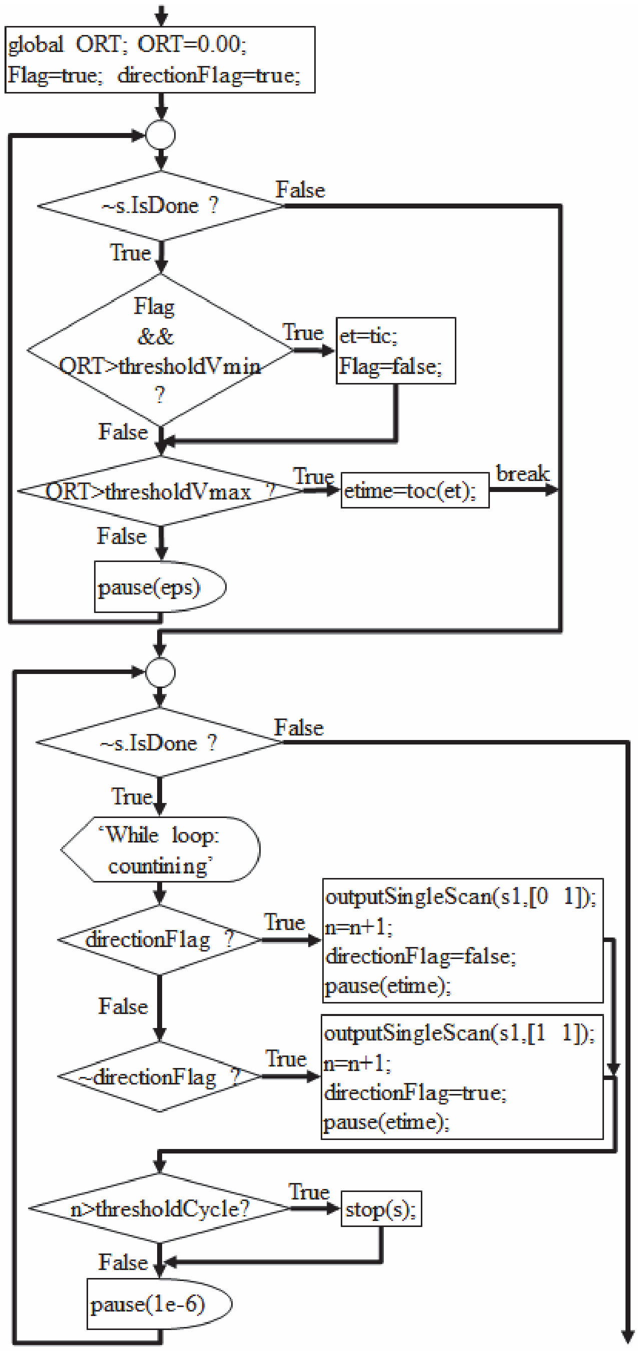


Figure 12. Dynamic loading test algorithm

4. RESULTS AND DISCUSSION

Experimental work to evaluate the performance of the device has been carried out by fabric types given in Table 5 according to test standart TS EN ISO 13934-1/2013.. Fabrics contained both continuous filament and spun yarns of different count and weaves. First trials have been performed with load-elongation curves. To evaluate the measurement accuracy of the test device, load elongation curves have also been obtained using Instron 4301 tensile tester and Titan- universal strength tester. As Titan and Instron 4301 test results were almost the same, comparison has been made by Instron 4301 results. Red curve in Figure 13 to 18 represents load-elongation curves obtained from our device and blue curves belong to Instron 4301.

Table 5. Fabric types used for the tests

Fabric Code	Fabric Weave	Fabric Weight (g/m^2)	Fabric Thickness (mm)	Yarn Composition and Type	Yarn Count		Fabric Density (threads/cm)	
					Weft	Warp	Weft	Warp
Sheeting	Plain 1/1	126	0,26	CO Combed	Ne 30	Ne 30	26	32
Drapery	Satin 5/1	136	0,26	PES texturized intermingled	150 denier	100 denier	25	85
Upholstery-1	Plain 1/1	290	0,45	PES texturized intermingled	450 denier	150 denier	25	66
Upholstery-2	Plain 1/1	450	1,48	PES Chenille	Nm 6	Nm 6	10,5	10
Upholstery-3	Twill 2/2	490	0,80	%40 CO %20 PES %20 CV %20 LI OpenEnd	Ne 10/2	Ne 10/2	17,6	17,6

Figure 13 shows load-elongation curves obtained by Instron 4301 and our device in the first trials. Breaking load is almost the same in both devices while elongations differ significantly. A close analysis has shown some slippage between clamps and fabric sample as well as some bending in the movable clamp. This caused a difference between real elongation of fabric and lineer motion supplied by the motor [24, 25]. To eliminate the slip, surfaces of both fixed and movable clamps have been covered by a frictious material. Also rigidity of mechanical system including movable clamp has been increased. Although slip between fabric and clamps has been eliminated some bending remained in the system. Amount of bending has been determined experimentally under differed load and a coefficient of correction for elongation has been determined [26, 27, 28]. After correcting the elongations with the coefficient of corrections load-elongation curve have been obtained as in Figure 14. As shown from the figure, there is a very good match between Instron 4301 and our device's load-elongation curves. Apart from the match of breaking load and elongations, curves obtained from both devices is almost same.

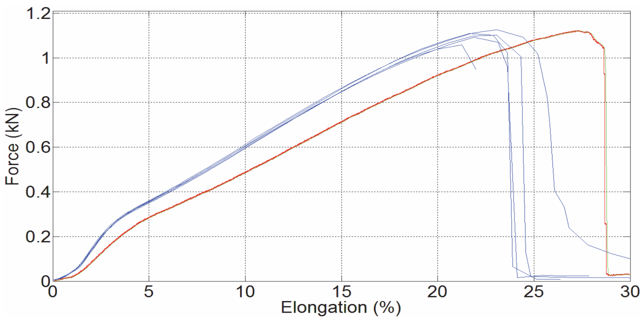


Figure 13. Comparison of load-elongation curve (Drapery fabric)

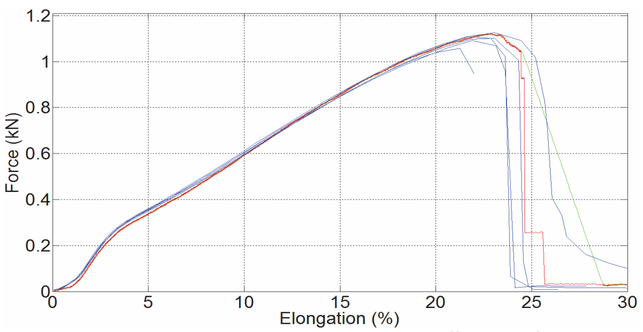


Figure 14. Load-elongation curves with coefficient of correction (Drapery fabric)

Load-elongation curve tests have been extended to other fabrics to test the consistency of the results. Figure 15-18 show load-elongation curves obtained from both devices. As seen from the figures, breaking load is the same in all figures. Despite small deviations, breaking elongation is also obtained very close. Characteristic of load-elongation curves shows a close change despite small deviations in certain parts of the curve.

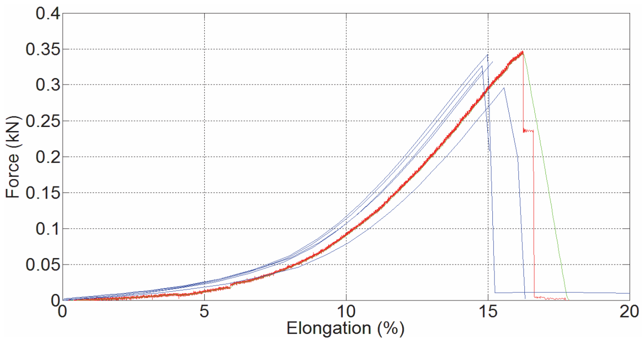


Figure 15. Comparison of load-elongation curve (Sheeting fabric)

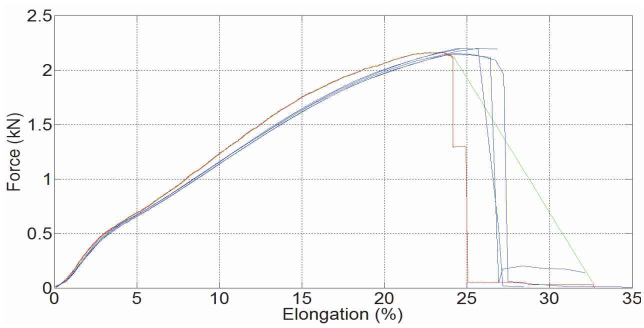


Figure 16. Comparison of load-elongation curve (Upholstery-1)

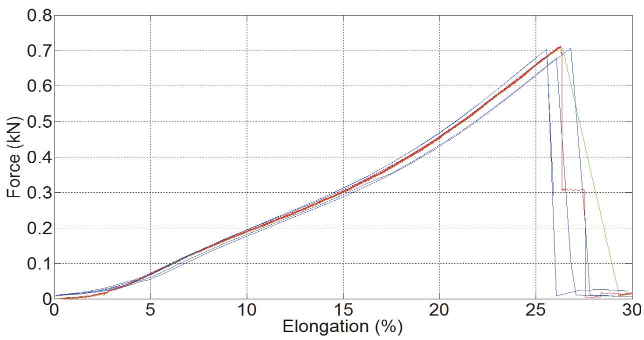


Figure 17. Comparison of load-elongation curve (Upholstery-2)

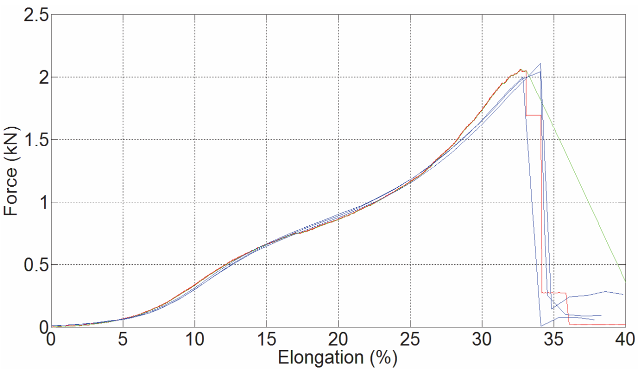


Figure 18. Comparison of load-elongation curve (Upholstery-3)

Considering close results in load-elongation curves between Instron 4301 and our device, other test routines have been applied and results have been obtained as follows. Figure 19 shows the creep test results. Crosses (x) on the curves indicate start of the test. The curve before the cross (x) indicate the elongation until creep test starts. Tests have been conducted for 900 seconds. Elongations for different fabrics correspond to 250 N load. All the curves show some elongation (up to 1,5 %) during 900 seconds.

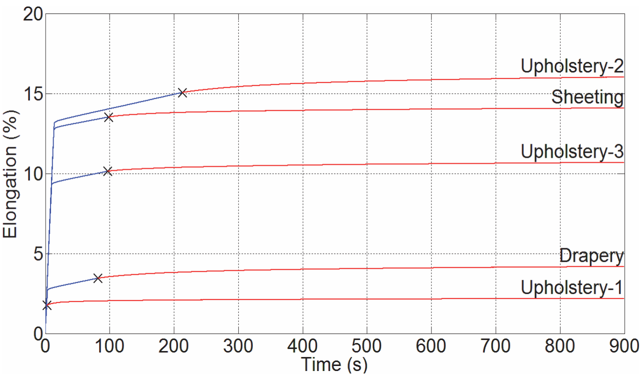


Figure 19. Creep test results

Figure 20 shows tension decrease during 900 seconds after an initial loading. With all fabrics, tension decreases quickly during 10-20 seconds. Then decrease in tension continues at a slower rate [29]. Figure 21 presents same curves in terms of stress (ie., tension/cross section area). Same variation is shown in stress-time curves.

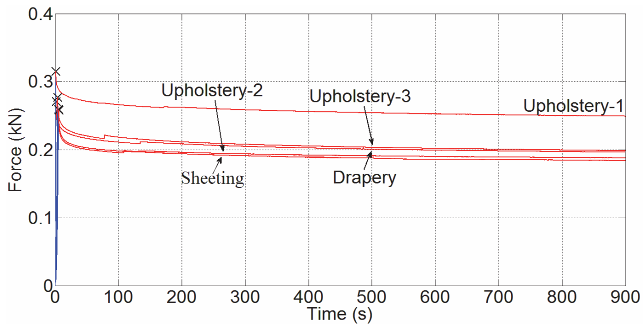


Figure 20. Tension decrease during the test period at constant elongation

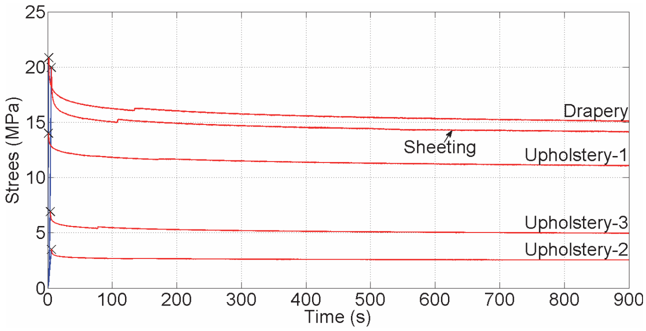


Figure 21. Stress relaxation during the test period at constant elongation

Dynamic loading test results are presented in Figure 22. These test results are only for demonstration purpose and for proving the use of the device in dynamic loading test. Successive 3 cycles forcing shows that load-elongation curve shifts after each cycle. Dynamic loading test results are also given in Table 6 numerically.

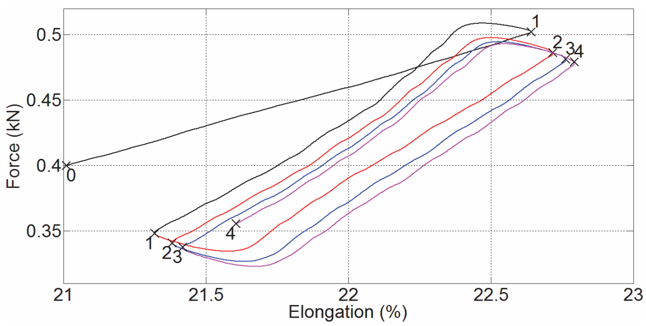


Figure 22. Dynamic loading test results (Upholstery-2)

Table 6. Position control data for dynamic loading test (Upholstery-2)

Number of cycle	0	1	1	2	2	3	3	4	4
Testing time (s)	9,0070	9,8260	10,625	11,428	12,218	13,018	13,809	14,608	15,299
Motion time(s)	free	0,819	0,799	0,803	0,79	0,8	0,791	0,799	0,691
Displacement (pulse)	22610	24649	22714	24663	22746	24688	22769	24709	23028
Displacement (mm)	42.020	45.281	42.641	45.434	42.764	45.524	42.837	45.584	43.212
Elongation (%)	21,010	22,640	21,320	22,717	21,382	22,762	21,418	22,792	21,605
Force (kN)	0,3999	0,5021	0,3483	0,4864	0,3409	0,4814	0,3375	0,4791	0,3555

5. CONCLUSION

A horizontal tensile test device has been designed, manufactured and its performance and suitability for textile tensile testing have been assessed by comparing its load-elongation curves with those obtained from Instron 4301 test device. Early results of load-elongation curves show a significant difference between the two devices. This is found to be due to the slippage between fabric samples and clamps and bending of movable clamp unit and mechanical imperfections. Clamp surfaces have been covered with a frictious and soft material and this measure has prevented the slip between fabric samples and clamp surfaces for the fabric types tested. Movable clamp unit has been reinforced to increase its rigidity. A difference between actual clamp displacement and the calculated one from motor displacement and kinematics of motion transmission system still remained. A coefficient of correction was used to obtain actual elongation from the calculated one and load-elongation curves have been obtained by this way.

Software modules were developed for different tests like load-elongation curve, dynamic loading test, creep test, tension decrease under constant elongation. Software modules have been tested and their proper operation has been demonstrated.

Same breaking load values are obtained from both Instron 4301 and our device. However, there is a small difference in breaking elongation values obtained from the two devices. Although characteristic of load elongation curves of two devices match to a large extent, some deviations still exist.

The future work will focus on increasing rigidity of especially movable clamp unit and eliminating mechanical imperfections. In this way, we expect that the developed tensile test device will reach measurement characteristics of commercial tensile testers in the market.

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