ABSTRACT

Jin Ho Lee, Warp Breaks Detection in Jacquard Weaving using MEMS (under the direction of Dr. Abdelfattah M. Seyam and Dr. George L. Hodge)

Microelectromechanical systems or MEMS technology has gone from an interesting academic exercise to an integral part of many applications in several industries. However, little work has been done in researching applications for MEMS in textiles.

Research related to warp breaks has been limited to monitoring break frequency and the reason associated with breaks in order to improve warp yarn quality. While this approach led to improvement in weaving efficiency, warp breaks still represent a major problem, especially for today’s high-speed weaving machines. Researchers have been trying to develop commercial automated systems to repair warp breaks with no success. The goal of this study is to explore inexpensive methods to detect warp breaks using nontraditional technique that would pave the way to automate warp break repair. To achieve the goal, a system that can detect warp breaks using MEMS accelerometers as sensors was developed for Jacquard weaving. The MEMS accelerometers were mounted on harness cords of a Jacquard tie.

MEMS output acceleration signals components in the vertical and horizontal directions were analyzed using time and frequency domains. The signals were acquired while warp ends
are running and at the moment of intentional breaks. The analysis led to a successful
detection of warp breaks especially using the horizontal acceleration component that is
mainly due to harness cord vibration.

Three experimental designs were conducted to investigate the effect of weave design, warp
yarn type, and warp yarn tension on the output signal strength which is measured by
amplitude in time domain. It was found that warp break for weave with longer floats
showed (shedding motion operates in open shed principal) stronger output signal as
compared to plain weave. Increasing warp tension caused an increase of the output signal
strength. The output signal increased with increase in yarn modulus.
Warp Breaks Detection
in Jacquard Weaving using MEMS

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1. Introduction

Due to low productivity, the weaving process represents one of the bottlenecks in the pipeline of woven fabric production. Developments in weaving machinery have targeted increases in speed and the degree of automation. Today’s weaving machines run ten times faster than those machines of few decades ago. It seems that the weaving speed is very close to its limit [34, 36]. In regards to automation, several milestones have been achieved during the last decade. Today’s weaving machines are equipped with automatic filling repair, automatic pattern change, adaptive control systems of filling arrival time in air jet weaving, quick style change, and pre-programmable variable weaving speed and variable pick density. One of the main challenges to a fully automated weaving machine is the development of mechanism(s) to automated warp break repairs. While there have been several attempts, which will be reviewed later, to achieve the task of automatic warp repair, none of these has been commercially successful.

The traditional method of drop wires stopping the weaving process when a warp yarn breaks is still widely used. Recently, laser-based warp stop motions were developed to replace drop wires since drop wires cause excessive wear on warp yarns [11]. In such a system a laser beam is located under the warp sheet. The system detects a yarn break with assumption that the yarn falls down and interrupts the laser beam. This system is successful when using heavy yarns. While these methods are important to prevent increase in yarn breaks (due to entanglement of the broken ends with other yarns) and thus cause potential
quality and production problems, the repair of the breaks requires operator intervention. After each warp yarn break, the operator has to find the broken ends, remove the end attached to the fabric, elongate the end attached to the warp beam, draw the end through its harness wire and reed dent, then restart the weaving machine. This takes from two to five minutes per break depending on the operator skill, woven fabric structure, and machine parameters. This repair time of broken warp yarns constitutes an expensive cost due to the loss in production of high-speed weaving machines. Automation of warp break repair would reduce labor cost and increase weaving efficiency.

Warp breaks occur when the load on a warp yarn exceeds its breaking strength. Obviously, breaks occur at the weakest link of a warp yarn. Yarn preparation processes (winding, warping, sizing, drawing-in, and tying-in) are designed to reduce/eliminate the warp yarn weak spots. The rigor of weaving, however, causes the warp to undergo complex field of stresses (cyclic tension, abrasion, impact, etc.) during weaving. Various studies have been made using different approaches to predict warp yarns break rate and break locations. It was found that most of the warp breaks take place between the stop motion and the fell of the cloth. This is due to the fact that the abrasion by harness and reed operates on the warp yarns in the shedding zone and the tension of warp yarns due to shedding is not uniform during the weaving cycle and along and across the warp sheet. The results of research investigations regarding weaving stop analysis [9, 33] have led to better understanding of the reasons behind stops and seek ways for improvement. Weaving efficiency can be increased by improvement in warp and weft preparation processes, and
control of yarn tension during weaving. The warp break repair time is still demanding even with the use of most sophisticated yarn preparation and weaving equipment.

Recent advances in electronics, sensor, computing, and control technologies have led to simplified machine designs and reduction in the cost of automation. With the wide growth of MEMS (Micro-Electro-Mechanical Systems) sensing and actuating can be achieved by micro-size electronics. The potential of using MEMS combined with small robotic devices in weaving machines to automate warp break repair in Jacquard weaving is the subject of this research. The Jacquard weaving is selected due to: (1) Jacquard fabrics markets include industrial, decorative, upholstery, which are niche markets and (2) the warp ends are electronically controlled individually with harness cord for each yarn. The harness cords could function as one of the elements that perform automatic warp repair.

Chapter 2 reviews the literature in relevant subjects: Jacquard weaving machines, warp break, and its detection method. The objectives of this research and the plan to achieve the goals are presented in Chapter 3. Chapter 4 describes how the warp break detection system using MEMS accelerometers was developed. Three experimental designs were executed. Details of the experimental designs are given in Chapter 5. Chapter 6 is dedicated for signal analysis of the MEMS output signals in time and frequency domains. Results of the experimental data are presented and discussed in Chapter 7. In Chapter 8, algorithms to automatically detect warp yarn breaks are presented. In Chapter 9, conclusions based on the experimental findings are given and future research areas are suggested.
2. Literature Review

2.1. Jacquard Machine Development

In the early 1800s, Jacquard shed formation mechanism, which produces intricate woven designs, was invented by Joseph Jacquard [45]. This revolutionary invention allowed patterns to be woven without the intervention of the operator. The Jacquard mechanism was added to the top of the weaving machine to control warp yarns and form shed according to weave design. A series of punched cards, which are chained together, ran continuously through the mechanism. The Jacquard mechanism was able to move individual warp yarns up and down according to the weave pattern that is punched into the cards. Researchers have endeavored to increase the speed, and reduce the labor cost of weaving. As a result, Jacquard machines have evolved to gain features such as single-acting, center shed, double acting single cylinder, double-acting double cylinder, open shed, semi-open shed, twilling, and efforts have been made to reduce the number or size of the cards required for a given patterns [45].

A Jacquard machine is divided into three main parts: the engine, the harness, and the mechanism that links the engine to the weaving machine. The engine consists of hooks, knives, needles, springs, and carton device. The harness consists of neck-cords, harness cords, harness eye, and spring [37]. In single-lift Jacquard, the shed formed by raising the hooks (i.e. upper shed moves while the lower shed is stationary), which takes time and high speeds are unattainable. Ainley Jacquard or center shed was invented in 1876 which
remedied this limitation. The center-shed Jacquard improves the shedding speed comparing to a single-lift Jacquard. In the center shed the bottom and top sheds are moving simultaneously a matter that reduces the shed formation time to a half as compared to single-lift [35, 45].

In 1854 John and William Crossley introduced a Jacquard which is classified as double-lift and single-cylinder (Figure 2.1) by using two hooks per one set of warp yarns and two sets of knives [45]. Double-lift Jacquards have an advantage over single-lifts in the saving of power since double-lift operates center shed, less wear per a hook/knife, and higher weaving speed due to the selection of hooks for the next weaving cycle while one set of knives is active. Double-lift double-cylinder (Figure 2.2) can run at faster speeds as compared to the double-lift, single-cylinder Jacquard [45] since one cylinder can be moved while the other is selecting the hooks of the next weaving cycle.

Open shed Jacquard, invented in 1889 by Cheetham and Sutcliffe, made it possible to reduce friction and warp breaks. In this case, a hook is raised up and kept up as long as it needs to be up according to weave design. This is done by lowering knives while retaining elements keep the needed hooks up [35, 45].

In 1860 M. Bonelli employed electricity to replace punched cards to move the needles and hooks according to weave design. The reason behind this development is to reduce Jacquard mechanism parts. With fewer parts and electronic signals the shed formation
could be performed much faster. Today, electronic Jacquard is the standard. In electronic
Jacquard (Figure 2.3), the hooks (warp yarns) are selected electronically by command signals
generated from a computer (Jacquard controller) through electromagnets [10, 22]. Electronic
Jacquard can be installed to the high-speed shuttleless weaving machines to manufacture
intricate woven fabrics. This combination allowed Jacquard fabric producers to weave fabrics
at the speed of producing commodity fabrics.
Figure 2.1 Double-lift single cylinder Jacquard [45]
Figure 2.2 Double-lift double cylinder Jacquard [45]
At ITMA’ 99 Grosse and Staubli showed new Jacquard machines in prototype stage, the UNISHED and the UNIVAL 100. At ITMA’ 2003 they continued to show their Jacquard machines. While the Grosse’s UNISHED is still at the prototype stage, the UNIVAL 100 has been made available for sale. The principle of shed formation of the two machines is different but they have achieved common goals, reduction in the Jacquard engine parts. Both of these machines are based on individual control of each warp yarn [36].
Figure 2.4 and 2.5 show Grosse’s UNISHED and the shed formation principle [36]. The shed formation in the UNISHED is achieved by leaf springs. Each leaf spring is connected to a heddle that controls one warp end. The leaf springs, which are controlled by actuators, control the bottom shed as well as the top shed (positive Jacquard shed type). The configuration of the Jacquard head and the individual control of each heddle (or warp end) allow the heddles to be set vertically. These settings permit the elimination of harness cords, magnets, hooks, pulleys, springs, and the gantry. This results in lower building and air conditioning costs. The Jacquard head is mounted directly on the side frames of the weaving machine (Figure 2.4) thus making Quick Style Change (QSC) possible in Jacquard weaving since it is easy to exchange the entire Jacquard head including the heddles [36].
The shed formation in the UNIVAL 100 electronic Jacquard machine is achieved by controlling each individual warp end by a stepping motor. The harness cord (or warp end) selection is performed electronically and hence fabric design is achieved in the same way as any current electronic Jacquard system. The dimensions of the Jacquard head (the Jacquard
head and tie width is the same as the width in reed) and the control of individual warp end by a stepping motor permit the harness cords to be set vertically. The design of the UNIVAL 100 permits the elimination of hooks, knives, magnets, and pulleys since each harness cord or heddle is directly attached to a stepping motor. The UNIVAL 100 was weaving mattress ticking and switching this with table cloth using automatic pattern change feature. The rate of filling insertion was 2,460 m/min.

The UNIVAL 100 commercial machine seems to have been advanced significantly. In fact the machine ran the highest rate of filling insertion in Jacquard weaving history. The UNIVAL design provides the weavers with new opportunities that have never been available before in Jacquard shedding. With such a system the shed height can be easily set, several sheds can be formed, etc. All settings can be conducted electronically through a user interface without the need of mechanical adjustments. Another significant feature of the UNIVAL is its independency from weaving machine drive since it has its own drive without mechanical coupling to the weaving machine. In a press release, Staubli indicated that the UNIVAL modular construction enables Jacquard capacity range of 5,120-20,480 warp threads (stepping motors). Figure 2.6 shows the UNIVAL Jacquard machine that was set at the Staubli stand at ITMA 2003 [36].
2.2. **Warp Tension Simulation and Measurement**

In Jacquard weaving technology, each warp yarn is individually controlled by a harness cord, and while forming the shed, the yarn experiences certain cyclic tension. Warp tension is one of the parameters to be carefully controlled in order to avoid warp breaks under excessive tension and unsatisfactory shed geometry in low tension. Warp breaks affect the productivity of the weaving machine and may cause potential fabric defects. Therefore it is very essential to reduce the warp break rate to improve weaving efficiency and fabric quality.

Literature disclosed numerous publications in the area of warp tension modeling and measurements as well as warp breaks. For the nature and extent of tension variation, Snowden [42] used three methods of recording tension: (1) Load on the weight lever, (2) Tension of individual warp yarns, (3) Optical recording of the individual warp tension by
cathode oscillograph tensionmeter. The first method of lever system was to measure the force on the back rest against the warp sheet. The second method consisted of three pulley system that is commercially used now. The third method was designed to obtain the pattern of tension variation of individual warp yarns. These methods provide useful tools to study the effect of warp tension on weaving efficiency, the optimum tension and the setting to obtain such optimum, and the effect of warp tension on fabric properties. Using these methods, Snowden [42] found that with increase of warp tension, fabric width from the fell to the take-up roller decreases. Warp crimp decreases and weft crimp increases with increased warp tension. He also indicated how the pattern of variation and the peak tension are affected by shed geometrical parameters, weave interlacing, height of back rest, and closeness of setting [42].

Mirjalili S. A. [27] developed a model to predict warp tension and its variation during weaving to study the effect of machine parameters, material and fabric properties, on warp tension. The model was simulated by computer programming in a projectile weaving machine. It was assumed that tension variation of yarns had a linear relation with the elongation of the yarn (yarns are elastic). All the yarn elongations were determined from geometry of the shed, which is affected by relative locations of lease rods, harnesses, and cloth fell. The calculated tension variation was compared with actual measurement of warp tension by a shell strain gauge and displacement of a back rail was compared with actual back rail movement by L.V.D.T. (Linear Variable Differential Transformer). It was found that the results obtained from measurement are in a good agreement with the model.
Claudia and Günter [6] demonstrated that differences in warp tension setting affect certain fabric properties because fabric quality is dependent upon machine settings. Their investigations were conducted with a view of influence of whole warp sheet tension on single warp yarn tension, air permeability, and fabric basis weight. They showed that excessive single warp tension increases the warp break rate while too low tension causes warp yarns to cling together which causes machine stops. With increase of warp tension, the air permeability decreases due to increase in thread density. As warp tension becomes higher, fabric basis weight increases. Therefore, they concluded that the same fabric woven at different warp tension can cause variation in single warp yarn tension, air permeability, and fabric basis weight. In order to achieve expected and constant quality of fabric, machine settings must be kept the same to produce the same fabric. To avoid differences in fabric properties woven in several weaving machines, it is necessary to employ proper measurement techniques on weaving machines with suitable electronic control systems.

Bandara and Mirjalil [3] mounted a strain gauge on a warp yarn and a sinusoidal signal was obtained in response to actuator movement which was experimentally built. They assumed that the device response is linear with the small variation of warp tension and the large amplitude of warp tension variation mostly involved in weaving cycle does not show linearity. From their experimental studies, it was found that a strain gauge could measure significantly the dynamic yarn tension with a high degree of linearity.
Wolters and Gries [47] used neural networks to develop a model that predicts warp tension in terms of loom settings and woven fabric data. The model aim is to improve machine setting and fabric quality by optimization of warp yarn tension (Figure 2.7). After simulation of the warp tension, prediction of the warp tension was processed by neural networks through varied weaving machine settings. Then, the simulated warp tension was assessed by criteria for the evaluation of the machine setting. The neural network system (Figure 2.8) would be able to predict good warp tension sequences with data collected in weaving mills.

Figure 2.7 Schematic representation of the optimization process [47]
2.3. Warp Break

Warp yarn break occurs due to excessive tension greater than the strength of the yarn. Also, friction on the warp yarns and repeating beat-up are factors to reduce the yarn strength as warp yarn passes from the beam into the cloth fell [43]. Lord [24] compared the warp yarn properties before and after weaving. Considering the yarn evenness, the two cases seem to be similar, but there is a reduction in yarn mass after weaving. In his subsequent research, Lord [25] noted that the most important change was the change in load-elongation characteristics (Figure 2.9), and benefits of sizing would be removed as long as the excessive tensions are loaded on the warp yarns.
Brown [5] classified the warp break into eight categories (knots, impurities, chopped ends, abrasion, soft yarn, twisted ends, taped ends and unknown), and observed what type mostly caused the warp break, and assessed each categories to establish the causes of warp breaks. Morton and Pollard [28] also classified the causes of warp breaks into six similar categories. The number of warp break was recorded for the different twist constants. The position of warp breaks was classified and it was noted that most of the breaks took place between the stop motion and the fell of the cloth. Here, it was found that the abrasion by harness and reed was the main cause for breaks. The tension in shedding is not uniform on a warp sheet. Therefore, uniformity of tension would be obtained by eliminating all friction between the yarn and the heald-eye, drop wires and back rest. The effect of twist on warp breaks was also studied by Morton and Pollard [28] and they found out that warp twist affect warp break rate (Figure 2.10), and hence weaving efficiency.
Dolecki [9] also classified the warp breaks in accordance with three main classes: breaks near lumps on the same yarn, breaks near lumps on other yarns, and breaks due to other causes. In this investigation, it was found that warp breaks were associated with lumps, and breaks mostly occur when a lump arrives between harness zone and front shed (Figure 2.11).
Shankam et al [39] performed a study to determine warp break location and frequency in Jacquard weaving by performing in-plant investigation with the aim to design warp break detection system and repair device. Throughout the study, algorithm and design of automatic warp repair devices are dependent on where the broken yarns are located on the weaving machine. When a broken end is found between drop wire and harness tie, the warp yarn needs to be threaded back in its heddle eye and reed dent. On the other hand if a broken yarn is found between the harness tie and the cloth roll, the warp yarns need to be threaded through its reed dent. The warp breaks were manually monitored in two dimensions, and then plotted and recorded as soon as the end of the broken yarn occurred as well as the point where the broken yarn was found.
Figure 2.12 shows the distribution of warp break locations along the warp length. The highest number of breaks has occurred in the region between the harness tie and the fell of the cloth. Figure 2.13 and Figure 2.14 indicate that 76.5% of the breaks occurred between the harness tie and the cloth fell. However, 50% of the broken warp yarns remained in this area and the other 50% were withdrawn to the region between the drop wires and the harness tie. The withdrawal of these warp yarns caused their ends to get out of their heddles. The withdrawal of the warp yarns towards the back of the machine is mainly due to the descent of the drop wire.
Knovačević et al. [23] conducted research that considered the warp yarns tension and elongation at different regions along the warp path. The breaking force taken in different segments was measured using plain, twill and sateen weave in different weaving machines. Warp tension on a weaving machine was divided into six zones. Warp tension was measured by a tensionmeter in zone III (back-rest to drop wires) and Dynamometer was used to test warp tension and cyclic stress.
The following equations show relationships of yarn tension in each region.

\[
\Delta P_{\text{III}} = \frac{P_{\text{III}} - P_{\text{II}}}{P_{\text{II}}} \times 100(\%) \quad (2.1)
\]

\[
\Delta P_{\text{IV}} = \frac{P_{\text{IV}} - P_{\text{III}}}{P_{\text{III}}} \times 100(\%) \quad (2.2)
\]

\[
\Delta P_{\text{V}} = \frac{P_{\text{V}} - P_{\text{IV}}}{P_{\text{IV}}} \times 100(\%) \quad (2.3)
\]

Where \( P_{\text{III}} \) = warp tension between the back-rest and dropwires, \( P_{\text{II}} \) = warp tension between the warp beam and back-rest, \( P_{\text{IV}} \) = warp tension between the drop wires and harnesses, and \( P_{\text{V}} \) = warp tension between the harnesses and fabric fell. Therefore, total relative increase of tension from warp beam to fabric fell is

\[
\Delta P_{\text{VI}} = \frac{P_{\text{VI}} - P_{\text{II}}}{P_{\text{II}}} \times 100(\%) \quad (2.4)
\]

Relative elongation of warp yarns is

\[
\varepsilon_{\text{II}} = \frac{L_{\text{II}} - L_{\text{I}}}{L_{\text{I}}} \times 100(\%) \quad (2.5)
\]
\[ \varepsilon_{III} = \frac{L_{III} - L_{II}}{L_{II}} \times 100(\%) \]  
\[ (2.6) \]

Where \( L_I \) = warp length on the warp beam, \( L_{II} \) = warp length from the warp beam to the back-rest and \( L_{III} \) = warp length from the back-rest to the drop wires, or generally,

\[ \varepsilon_n = \frac{L_n - L_{n-1}}{L_{n-1}} \times 100(\%) \]  
\[ (2.7) \]

In the result, deformation of the warp yarns within zone II to IV showed no differences in tension or elongation at break. On the other hand, the difference in tension and elongation at break among three weaves occurred in cloth zone (V and VI). Toward the fabric fell, elongation at break decreased as well as reduction of the warp tension at break. Therefore, it was concluded that the greatest irreversible deformations of the warp yarns occur in the front shed and in the beating-up zone.

Huh [20] studied the tension variation of warp yarn group with strain gauge sensor. It was found that tension variation is sinusoidal. Data of warp tension at different initial load was acquired. By increase of initial load, variation of warp tension measure during weaving decreased. On the other hand, dynamic tension peak increased (Figure 2.16). Kim [21] recognized that the tension peak of warp yarn group has normal distribution while the tension in a warp yarn depends upon Weibull distribution (Figure 2.17). Earlier, Picciotto and Hersh [31] proved that Weibull distribution provides an excellent fit of tension data. From their research, a weakest-link which was suggested by Peirce [29] was confirmed.
Apart from the contact yarn tension measurement, Cybulska [7] introduced different method based on the video image of yarn surface. The images were taken to observe the change in yarn appearance due to abrasion while the test was being performed. The methods and its software enabled the simultaneous measurement of thickness, hairiness, twist and linear density. In the investigation, analysis of the yarn was observed before destructive load, during successive destruction and at break point. After the yarn was broken, the place of yarn break was identified and twenty-six sections were registered and investigated to determine yarn parameters. From the images (Figure 2.18) obtained during weaving in heddle eye, there appeared to be changes in yarn structure affected by abrasion against the heddle wire. The characteristics of the break locations were also investigated. It was found
that structural parameters (thickness, hairiness, twist, and linear density) of yarn which
subjected to abrasion at break in heddle eye took lower value than mean value. For tension
test, yarn parameters at break took extreme value as minimal or maximal.

Figure 2.18 Image of a yarn during successive abrasion in a heddle eye [7]

2.4. Warp Stop Motion

The main function of warp stop motion is to stop a weaving machine in a very short
period when a warp yarn breaks. Stop motion can be classified into mechanical stop motion,
electrical, and optical stop motion. Mechanical stop motion consists of serrated bars. If a
warp yarn breaks, the drop wire falls down and locks the two bars. The drive movement is
transmitted to a knock-off motion. Electrical stop motion also consists of two bars, but
these bars are used as electrodes with a transformer and a magnetic device. When a yarn
breaks, the drop wire drops and electric signal is transmitted to the circuit which operates the
magnetic knock-off device to stop the weaving machine (Figure 2.19) [8, 19, 30].

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Grob Horgen AG in Switzerland has developed new warp stop motion, KFW4600 and 4800 (Figure 2.20). The warp stop motion can be equipped with contact bars, which have an identical cross-section. The optical indication of warp yarn breaks through a programmable signal-processor can be modified on the weaving machine [18].

Figure 2.19 Schematic diagram of a mechanical warp stop motion [19]

Figure 2.20 Electrical warp stop motion (http://www.grob.com/deutsch/kfw/kfw4600.html)
Optic stop motions were developed to eliminate drop wires due to the friction and
dynamic yarn tension caused by the drop wires during weaving. Protecna Laserstop 4080
optic stop motion [11], for example, is placed under the warp sheet, and generates a laser
beam from one side to another. A laser sensor is placed at the other end. The system
assumes that if a yarn breaks, it falls under its weight and cuts the laser beam. Thus, a yarn
break would be detected. The main drawback of such system is that a yarn does not always
fall down due to support by other neighboring yarns. Additionally, broken yarns may snap
back or forth and entangle with other yarns. This device may be suitable for heavy yarns and
in situations where the warp density is low.

![Figure 2.21 Laserstop - End break detector](http://www.protechna.de/e/laserloom_aufbau_d.htm)

2.5. **Warp Repair Automation**

In pick finding and repair, fully automated systems are available on some looms.
An automatic pick finding motion was developed by using a microprocessor. When a weft
yarn breaks, the next pick is deflected and suctioned away. After clearing the break, the machine can restart [44]. This mechanism can be also attempted to be applied in warp repair automation.

Prat [32] showed an apparatus and method for repairing broken warp yarns during weaving. The apparatus comprises a computerized control system and drawing-in. The moving reed dent counting device is also associated with a device for selecting and feeding an auxiliary yarn. However, this apparatus is not commercially used perhaps due to its complexity and expensive cost.

Figure 2.22 Automatic warp repair apparatus [32]
2.6. MEMS Accelerometer

MEMS (Micro-Electro-Mechanical Systems) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology. MEMS have three important characteristics. The size achieved by semiconductor processing is most apparent. The second characteristic is multiplicity in that MEMS can translates into very low unit costs. The third characteristic is that MEMS enable much closer integration of microelectronics with electro mechanics as the same materials and semiconductor process were used as microelectronics fabrication [1]. Since micromachines are characterized by being small and light weight, technologies for manufacturing and operating MEMS technology are employed in industries and they are expected to be used in broad applications. Table 2.1 shows examples of present and future application areas for MEMS. In practice, MEMS solutions become attractive if they enable a new function, and provide significant cost reduction [26].

The first demonstration of a micromachined accelerometer was introduced in 1979 at Stanford University [26]. All accelerometers share a basic structure consisting of a mass hung in a spring [26]. The primary specifications of an accelerometer are range which is given in g (1G=9.81 m/s²). Capacitive surface-micromachined accelerometer emerged in the late 1980s with low-cost, was designed for automotive applications. Analog Device has been producing ADXL product series. These accelerometers comprise a comb-like structure (Figure 2.23). The comb-like structure balanced from springs forms an inertial mass. Displacement of the mass are measured with respect to electrodes. Any movement of the
mass unbalances the differential capacitor resulting in a square wave (pulse-width modulation) output with the amplitude proportional to the acceleration. Analog devices, ADXL accelerometer currently provides two single axis output. The analog signal is filtered and converted to a duty cycle output which can be transferred to the acceleration with software program.

Table 2.1 Examples of MEMS application [26]

<table>
<thead>
<tr>
<th>Commercial Applications</th>
<th>Military Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invasive and noninvasive biomedical sensors</td>
<td>Inertial systems for munitions guidance and personal navigation</td>
</tr>
<tr>
<td>Miniature biochemical analytical instruments</td>
<td>Distributed unattended sensors for asset tracking, environmental and security surveillance</td>
</tr>
<tr>
<td>Cardiac management system</td>
<td>Weapons arming and fusing</td>
</tr>
<tr>
<td>Drug delivery system</td>
<td>Integrated micro-optomechanical components for identify-friend-or foe system</td>
</tr>
<tr>
<td>Neurological disorders</td>
<td>Head-and night-display systems</td>
</tr>
<tr>
<td>Engine and propulsion control</td>
<td>Low-power, high-density mass data storage devices</td>
</tr>
<tr>
<td>Automotive safety, braking, and suspension systems</td>
<td>Embedded sensors and actuators for condition-based maintenance</td>
</tr>
<tr>
<td>Telecommunication optical fiber components and switches</td>
<td>Integrated fluidic systems for miniature propellant and combustion control</td>
</tr>
<tr>
<td>Mass data storage systems</td>
<td>Miniature fluidic systems for early detection of biochemical warfare</td>
</tr>
<tr>
<td>Electromechanical signal processing</td>
<td>Electromechanical signal processing for small and low-power wireless communication</td>
</tr>
<tr>
<td>Distributed sensors for condition-based maintenance and monitoring structural health</td>
<td>Active, conformable surfaces for distributed aero dynamic control of aircraft</td>
</tr>
<tr>
<td>Distributed control of aerodynamic and hydrodynamic systems</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.23 MEMS accelerometer - ADXL structure
(Analog Devices -http://www.analogdevice.com)
2.7. Application of MEMS in Textile

General accelerometers have been used as monitoring device of vibration. Because of the small size and the low cost, sensor technology can be integrated in textile monitoring system. Regarding the current research, Gahide [12-16] attempted to find applications for MEMS in textile industry. Her concept was based on a strain-gauge sensor for warp break detection with a contact system which was placed between warp beam and stop motions of Jacquard weaving machine (Figure 2.24). Bringing the sensor into contact with a warp yarn allowed monitoring tension. In that warp yarn loses tension at break, the system could stop the weaving machine. While she did not use a MEMS based sensor, Gahide provided design concepts to use such sensors as a mean of monitoring individual warp yarn tension and warp stop motion.

Slusser [41] built a test-bed, Figure 2.25, to simulate shedding motion and mounted MEMS accelerometers on harness cords that were moved by cams. In Slusser’s work [41], the MEMS accelerometers were used as a non-contact tension measurement device. The experiments were conducted with different speeds and warp yarn tension, and the MEMS acceleration signals were acquired by data collection system. To identify a warp yarn break, the yarn was allowed to run and then cut. The difference between the signals before and after cutting was compared. It was found that the accelerometer output detected an increase in acceleration after yarn break. Slusser work was limited to acquiring the vertical component of the accelerometer despite the availability of horizontal acceleration that could be used to better detect yarn breaks. The current work considers the two acceleration components of
MEMS accelerometers. Additionally, the MEMS sensor was mounted on harness cords of a Jacquard weaving machine.

Figure 2.24 Strain gauge sensors in Jacquard machine [12]

Figure 2.25 A test-bed with MEMS accelerometer simulate weaving machine [41]
3. Objectives

Previous research in the area of warp tension measurement and warp break analysis led to a better understanding of the reasons behind warp breaks in terms of yarn quality parameters, weave type, and woven fabric tightness. Through improvement in yarn quality and warp yarn preparation processes (winding, warping, sizing, drawing-in, and tying-in) the number of warp breaks was reduced. The warp breaks, however, still constitute significant downtime and labor cost. With today’s high-speed weaving machines, stopping the weaving process is very costly. Attempts to identifying warp break locations and automatic warp break repair did not succeed commercially due to the complexity and cost of the systems.

Current warp break monitoring systems function as means to stop the weaving process when a warp yarn breaks. A drop wire is still the most inexpensive means to monitor warp breaks. It is a passive method and harmful to the warp yarns since the drop wire sits on the warp yarn thus causing abrasion and increase in tension due to drop wire mass and vibration. Drop wires are not used in weaving fabrics with delicate warp yarns such as low denier continuous filament yarns. Newly developed optic systems have limitations that they only work with heavy yarns and low warp densities.

The new developments in MEMS and Jacquard weaving may provide an opportunity to monitor warp yarn tension and breaks using non-contact method and potentially automate warp breaks repair. The objectives of this research work are to:
1. Develop instruments (hardware and software) to detect and locate warp yarn breaks in Jacquard weaving using MEMS accelerometers.

2. Perform signal analysis and evaluate the sensitivity of the instruments in detecting warp breaks through evaluation of the MEMS output signals in time and frequency domain.

3. Determine the effects of warp yarn tension, yarn type and weave structure on the MEMS accelerometer signal strength at the moment of warp yarn break.

4. Identify the limitations of the developed system in warp break detection in terms of warp yarn tension, warp yarn type, and weave design.

5. Develop computer software algorithm to automatically identify warp breaks.
4. Development of Instruments

4.1. Development of Warp Break Detection System

As discussed earlier, using a drop wire as a basic element to detect warp breaks has several limitations. To avoid these limitations, it was decided to develop a method based on a non-contact method to warp yarns to detect warp breaks. In Jacquard shedding each warp yarn is controlled by a harness cord. Since each harness cord is in a direct contact with a warp yarn, instrumentation of harness cords could provide a viable means of warp break detection. MEMS accelerometers have been used successfully in many applications as sensor of motion. These are characterized by their small size, light weight, and the ability to detect motion in two orthogonal directions. MEMS accelerometer sensors are active devices and their signal could be used to detect and identify warp break locations. The signal could also trigger a sequence of actions to activate automated warp break repair elements. For these reasons, it was decided to mount MEMS accelerometers on several harness cords, and to use these as the basic elements in detecting warp breaks.

To detect warp breaks, a system was developed. The full system consists of MEMS accelerometers as sensing devices, data acquisition hardware, data analysis software, an electronic tension device, and a proximity sensor. Additionally, a creel was set behind the machine to supply warp yarns to the instrumented harness cords. This was done to facilitate changing warp yarn type without the need to form a complete warp beam for each warp yarn type, which is a lengthy process.
Four MEMS accelerometers were mounted on selected harness cords of a harness tie operated by a Staubli Jacquard head, which was mounted on an ELTEX rapier weaving machine of one meter wide. Figure 4.1 and 4.2 show a schematic diagram and image of the developed system, respectively.
Figure 4.1 Schematic diagram of the warp break detection system
Figure 4.2 Image of the developed warp break detection system
4.1.1. MEMS accelerometer

The MEMS accelerometer, ADXL202AE (Analog Devices) used in this study, is a dual-axis (X- and Y-axis) acceleration measurement system built on a single monolithic IC. It contains a sensor and signal conditioning circuitry to implement open-loop acceleration measurement mode. For each of X- and Y-axis, an output circuit converts the analog signal to a duty-cycle-modulated digital signal. The signal is shown in Figure 4.3. The signal can be decoded with a capability of measuring both positive and negative accelerations. In this work, only the signal of the duration $T_1$ was considered.

![Figure 4.3 Pulse width modulation signal](image)

Acceleration in the Y-axis direction, one of dual axis acceleration component $A_Y$ is determined as follows:

$$A_Y = \frac{T_1 / P - K_1}{K_2}$$

(4.1)

- $A_Y$ = Y component of acceleration vector, dimensionless units of gravities
- $K_1$ = Constant, dimensionless
- $K_2$ = Constant, dimensionless
- $P$ = Period of PWM signal, seconds
- $T_1$ = Duration of high-going pulse, seconds
\[ T_3 = \text{Duration of low-going pulse, seconds} \]

Same equation can be used for the X-axis acceleration.

The constants \( K_1 \) and \( K_2 \) are variable that depend on circuit components (capacitor, and resistors). The MEMS manufacturer publishes the values of \( K_1 \) and \( K_2 \) in terms of circuit components selected. The circuit components were selected to have 0.5 for \( K_1 \) and 0.125 for \( K_2 \). With the acceleration conversion program developed by the author based on the equation above, the acceleration values (Figure 4.3), operating at duty cycle of 2 ms was determined. The unit of acceleration is G, gravity (9.8 m/s\(^2\)).

**Circuit configuration**

MEMS accelerometer pin layout is described in Figure 4.4 and Table 4.1. ADXL202AE consists of 8 pin layout. The accelerometer can measure static acceleration forces. The output drives a duty cycle modulator (DCM) stage through a resistor. At this point a pin is available on each channel to allow setting the signal band width of the device by adding a capacitor. This filtering improves measurement resolution and helps prevent aliasing.

After being filtered using a low-pass filter, the analog signal is converted to a duty cycle modulated signal. A single resistor sets the period for a complete cycle, \( T_2 \). Zero acceleration (0 G) produces nominally 50% duty cycle. The acceleration signal can be determined by measuring the length of the \( T_1 \) and \( P \) pulses. \( T_1 \): Length of the ON portion of
the cycle, P: Length of the total cycle, Duty Cycle: Ratio of the ON time (T₁) of the cycle to the total cycle (P), Pulse width: Time period of the ON pulse.). An analog output voltage can be obtained either by buffering the signal from the X filter and Y filter pin or by passing the duty cycle signal. The ADXL202AE operates with supply voltages from 3.0 to 5.25 V.

![Figure 4.4 Pin layout](image)

Figure 4.4 Pin layout [48]

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ST</td>
<td>Self-Test</td>
</tr>
<tr>
<td>2</td>
<td>T2</td>
<td>Connect R Set to Set T2 Period</td>
</tr>
<tr>
<td>3</td>
<td>COM</td>
<td>Ground</td>
</tr>
<tr>
<td>4</td>
<td>Yout</td>
<td>Y-channel Duty Cycle Output</td>
</tr>
<tr>
<td>5</td>
<td>Xout</td>
<td>X-channel Duty Cycle Output</td>
</tr>
<tr>
<td>6</td>
<td>Yfilt</td>
<td>Y-Channel Filter Pin</td>
</tr>
<tr>
<td>7</td>
<td>Xfilt</td>
<td>X-Channel Filter Pin</td>
</tr>
<tr>
<td>8</td>
<td>VDD</td>
<td>3 to 5.25 V</td>
</tr>
</tbody>
</table>

Table 4.1 Pin layout descriptions [48]
**Circuit construction**

A circuit design in Figure 4.5 and Figure 4.6 was designed by Slusser [41]. The dimension of the PCB (Printed Circuit Board) was cut with 8.6mm x 12mm. The red tabs at the top side allow access to ST, T2, Common, VDD, Y out and X out. The blue tabs at the bottom side allow access to X filter and Y filter. Yellow box in lower center represents the position of MEMS accelerometer. Blue rectangle in the center represents the path of harness cord where the circuit was attached. Figure 4.7 shows the measurement of the output signal by an oscilloscope. The square wave given in Figure 4.7 is converted into acceleration to be used in this research.

![Figure 4.5 ADXL202AE circuit map](image)

Figure 4.5 ADXL202AE circuit map
Figure 4.6 ADXL202AE circuit after soldering

Figure 4.7 Oscilloscope output
Mounting the accelerometers on harness cords

Four MEMS accelerometers have been constructed and were mounted on four selected harness cords (Figure 4.8). In order to mount the MEMS accelerometers, the back side of each MEMS accelerometer, was pasted by glue along a groove created on a harness wire (connected to each instrumented harness cord) to accommodate the sensor. The harness cords were intentionally selected in the front row, so that the MEMS accelerometers could be easily mounted. Each MEMS accelerometer was attached below the cord sleeve and above the harness eye (Figure 4.9) so that the MEMS accelerometer is not in contact with the reed during weaving. The wires (see Figure 4.8) are attached to the comber board by sticky tapes to keep them away from the reed and the harness cords during weaving.
Figure 4.9 View of harness
4.1.2. Data acquisition system

The MEMS accelerometers were wired to a data acquisition board which is especially designed for counter-timer (event counter). MEMS accelerometers generate pulse-width-modulation (PWM) signal, which is transferred into data acquisition board (PCI-6602: National Instruments™ http://www.ni.com). The counter/timer is a basic unit of hardware functionality on a measurement device. The more counter/timers there are on a device, the more counting/timing operations the device can simultaneously perform. Two ms based pulse width (500 Hz) of MEMS accelerometer were easily measured in that each 32-bit counter can count up to $2^{32}-1$, and pulse widths were measured with 80 MHz resolution. Counter/timer which is represented as low-to-high, or high-to-low, transitions of the input signal can count events as they take place.

To coordinate the signals of the four MEMS accelerometers a reference point of time scale need to be identified. To achieve this, a proximity sensor of type PRX 102-18NE (Figure 4.10) was mounted on the loom frame in front of the reed to detect the beat-up event that is used to identify the start of each weaving cycle. The sensor was wired to PCI-MIO-16E, analog DAQ board via SC 2043 SG, signal conditioning board. The proximity sensor was adjusted to give a peak output signal at the moment of beat up which is identified as the triggering point. The beat up event is considered as the start of the weaving cycle. Figure 4.10 shows the proximity sensor and the reed at the triggering moment.
4.1.3. Software system

A program was developed to acquire analog signals from proximity sensor and to convert the pulse width by using LabVIEW™. During running trials, the program simultaneously read both analog output and PWM signals, and saved the data as ASCII text files according to their time log. The data were analyzed offline. In event counting, since the MEMS accelerometer only provided a pulse width modulation (pulse-width and semi pulse-width), the modulations had to be converted into acceleration from four MEMS accelerometers. Finally, four type of value (pulse width for X, semi-pulse width for X, pulse width for Y and semi-pulse width for Y) were obtained and converted into accelerations. Regarding ASCII text files, they contain four types of values: pulse width for X and Y, and acceleration in X and Y totally with 8 columns. These ASCII files would be used in post-analysis to detect intentional warp yarn breaks. After signals were acquired, Fast Fourier Transform (FFT) was performed on the raw time domain data to obtain frequency domain
The MEMS signals were analyzed for yarns before and after the intentional breaks. The difference between the two signals indicated break detection. Figure 4.11 shows the overall diagram of the developed computer simulation to process the acquired data.

4.1.4. Tension device

A tension meter, type DTMX-500 with sensitivity range of 0.1 to 500 cN, and 2Hz sampling rate. The purpose of the tension meter is to monitor single warp yarn tension prior to data acquisition from MEMS sensors to make sure the tension level has reached the equilibrium. More details are provided in Chapter 5.
4.1.5. Creel

To facilitate changing the experimental warp yarn tension and type, an IZUMI creel (Figure 4.12) was used. The creel, which was located behind the weaving machine to feed the experimental warp yarns, was equipped with 20 spindles and the tension control device. In this work the tension was varied to achieve a yarn tension range of 1 cN/tex to 2.5 cN/tex. The tension control is accomplished by using a servo motor supplied with the creel.

![IZUMI creel](image)

**Figure 4.12 IZUMI creel**

All experimental yarns fed from the creel were not threaded through drop wires since the purpose of this research work is to use the MEMS accelerometer to detect warp breaks. The yarns fed from the creel were put on packages, which fit the creel holders, using IZUMI winder.
4.2. Development of warp break location system

This system is designed to identify the location of a warp break by pointing at the reed dent corresponding to a broken warp yarn using Motion Control System (Figure 4.13 and Figure 4.14). The system employs linear stepper (or servo) motor, controller, amplifier, and motion control software. Motion systems include a power driver or amplifier unit that converts the control signals from the motion controller board into current and voltage power signals for the motor. The following sections provide detailed description of the system components.

Figure 4.13 Warp break location system
Figure 4.14 Schematic diagram and reed dent finder module
4.2.1. **Linear Servo Table**

Motion systems control includes drive servomotors and/or stepper motors. The factors to be considered while selecting the motor type were: number of motors, axes of motions, size of motors, position of the motors and feedback systems involved. In this system, 406 LXR series linear servo motor (Parker automation) was used.

4.2.2. **Power Drive**

Motion systems include a power driver or amplifier unit that converts the control signals from the motion controller board into current and voltage power signals for the motor. The power drive is a fully integrated motor driver unit, while the motion controller is a universal motion interface that gives the connectivity needed for discrete wiring to third-party amplifier, driver, and power electronics devices. GV6-U6E (Parker automation) was used as a power driver and UMI-7764 (National Instruments) was used as a universal connector. Since the power drive has a different pin layout from the motion controller, the universal connector was used for compatible communication.

4.2.3. **Motion controller hardware and software**

For the motion control system, PCI-7344 (National Instruments) was acquired and interfaced with the servo system. Based on the parameters obtained from tuning, a simple program was developed using LabVIEW™. In order to move the servo table, reed specifications need to be known. The reed used has the following specifications:
Reed number: 6.259 dents/cm

Total number of dents: 624

Reed width: 99.695 cm

The servo resolution for the motion control is 5 micron (0.005 mm). Thus, the linear servomotor moves 199,390 points (99.695/0.0005) to travel on reed width. There are 319.5 (199,390/624) points per reed dent. The developed LabVIEW program based on the reed specifications is shown in Figure 4.15. This program has a performance of velocity, acceleration control, and blended motion sequences that provide multiple data point for linear servo table to move a certain point commanded. Referring to the reed dent specifications and resolution of linear servo motor, the target pointer position that is corresponding to warp break is calculated from:

\[
 x = N_d x_w / E_d + N_d / 2
\]

Where \( x \) is pointer target position (reed dent corresponding to warp break), \( N_d \) is the number of points per dent (319.5 in our case), \( x_w \) is a number identifying the broken end, and \( E_d \) is the number of warp yarns per dent (2 in our case).

The position \( x \) is pointed at by the pointer (Figure 4.14) that is controlled by the system to show the weaver the location of the warp break. In an automated system where the warp yarn needs to be drawn through the reed dent, the system could be used to move the threading needle to the target position. The ratio \( x_w / E_d \) must be an integer and can be obtained by rounding up (if needed) the result in order to get the reed dent position corresponding to the broken end. The warp break location system needs to be interfaced
with the MEMS accelerometers in order to get $x_w$ of a broken warp end. The ratio $N_d/2$ is added to position the pointer in the middle of the dent.

Figure 4.15 Front Panel (LabVIEW™) of Reed Dent Finder Module
5. **Experimental Work**

5.1. **Materials**

Range of yarns was acquired to be used as experimental warp yarns that are fed from individual packages loaded on the creel to the instrumented harness cords. Since warp yarn tensile properties are expected to influence the MEMS output signal, the yarns were selected to cover wide range of tensile properties to assess the sensitivity of the developed system in detecting warp breaks. The selected yarns are:

- 73.81 tex (16/2 cc), 100% cotton yarn
- 39.37 tex (30/2 cc), 50% cotton/50% polyester yarn
- 73.81 (8/1 cc), 100% polyester ring spun yarn
- 124 tex, 100% polyester flat filament yarn
- 69.67 tex, Spectra flat filament yarn

To get an objective assessment of the system sensitivity to yarn tensile properties, the yarns’ tensile properties were measured using MTS Sintech tester. The yarn tensile evaluation was conducted following ASTM D2256 [2]. Fifty samples from each yarn were cut with 25 cm gage length. Two load cells were used: 2.27 kg (5 lb) load cell was used for spun yarns and 453.59 kg (1000 lb) load cell used for filament yarns. Figure 5.1 shows the typical load-extension curves of the experimental warp yarns.
Table 5.1 shows the mean values, standard deviation, and coefficient of variation of the tensile properties of the experimental yarns. Table 11.1-11.5 show the tensile properties individual observations.

The main warp supplied by the warp beam (Figure 4.12) is 124 tex, 100% polyester flat filament yarn which is one of the experimental warp yarns. Four of the main warp yarns were replaced by other experimental warp yarns when needed. The warp density is 31 ends/cm (78.5 ends/inch). The filling yarn was kept unchanged for all experimental runs. The filling yarn 31.2 tex (18/1 cc) ring spun cotton yarn. A constant pick density of 11.8 picks/cm (30 picks/inch) was also kept unchanged.
Figure 5.1 Load-extension of the experimental warp yarns
Table 5.1 Tensile properties of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>Peak Load (cN)</th>
<th>Elongation at Peak Load (mm)</th>
<th>%Starin at Peak Load (%)</th>
<th>Energy to Peak Load (Kg-mm)</th>
<th>Modulus (cN/Tex)</th>
<th>Tenacity (cN/Tex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton 73.81</td>
<td>Mean</td>
<td>935.36</td>
<td>75.20</td>
<td>29.60</td>
<td>43.27</td>
<td>104.16</td>
<td>12.67</td>
</tr>
<tr>
<td></td>
<td>Stdv</td>
<td>39.40</td>
<td>3.71</td>
<td>1.47</td>
<td>3.72</td>
<td>3.41</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>CV(%)</td>
<td>4%</td>
<td>5%</td>
<td>5%</td>
<td>9%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Cot/Poly 39.37</td>
<td>Mean</td>
<td>666.08</td>
<td>18.56</td>
<td>7.31</td>
<td>5.43</td>
<td>290.47</td>
<td>16.92</td>
</tr>
<tr>
<td></td>
<td>Stdv</td>
<td>28.84</td>
<td>0.56</td>
<td>0.23</td>
<td>0.42</td>
<td>4.28</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>CV(%)</td>
<td>4%</td>
<td>3%</td>
<td>3%</td>
<td>8%</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>Poly RS 73.81</td>
<td>Mean</td>
<td>1547.59</td>
<td>108.72</td>
<td>42.80</td>
<td>116.75</td>
<td>123.54</td>
<td>20.97</td>
</tr>
<tr>
<td></td>
<td>Stdv</td>
<td>58.14</td>
<td>7.48</td>
<td>2.95</td>
<td>14.08</td>
<td>5.01</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>CV(%)</td>
<td>4%</td>
<td>3%</td>
<td>3%</td>
<td>8%</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>Poly Fila 124.00</td>
<td>Mean</td>
<td>8209.63</td>
<td>29.45</td>
<td>11.60</td>
<td>122.03</td>
<td>964.19</td>
<td>66.21</td>
</tr>
<tr>
<td></td>
<td>Stdv</td>
<td>175.44</td>
<td>0.94</td>
<td>0.37</td>
<td>6.12</td>
<td>44.77</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>CV(%)</td>
<td>2%</td>
<td>3%</td>
<td>3%</td>
<td>5%</td>
<td>5%</td>
<td>2%</td>
</tr>
<tr>
<td>Spectra 72.22</td>
<td>Mean</td>
<td>20502.92</td>
<td>10.52</td>
<td>4.14</td>
<td>91.00</td>
<td>9960.36</td>
<td>283.90</td>
</tr>
<tr>
<td></td>
<td>Stdv</td>
<td>1223.72</td>
<td>0.54</td>
<td>0.21</td>
<td>10.81</td>
<td>348.12</td>
<td>16.94</td>
</tr>
<tr>
<td></td>
<td>CV(%)</td>
<td>6%</td>
<td>5%</td>
<td>5%</td>
<td>12%</td>
<td>3%</td>
<td>6%</td>
</tr>
</tbody>
</table>
5.2. Experimental designs

Three experimental designs were structured to achieve the objectives that are dealing with the parameters that are believed to impact the MEMS output signal. The parameters are warp yarn tension, warp yarn type, and weave. The following sections describe the details of the three experimental designs.

5.2.1. Effect of weave structure

This experiment (Table 5.2) was aimed at investigating the effect of weave structure at constant yarn tension for the polyester filament yarn of linear density of 124 tex on MEMS output signal prior to yarn break, at the moment of break, and after break. The tension level was selected within the practical range used in the industry. The weave structures selected represent broad range of basic weaves used in developing Jacquard patterns.

Table 5.2 Experimental design 1: Effect of weave structure

<table>
<thead>
<tr>
<th>Weave Structure</th>
<th>Material</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>2x2 RH Twill</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4x4 RH Twill</td>
<td>124 tex, 100% polyester filament yarn</td>
</tr>
<tr>
<td></td>
<td>8H Warp Satin</td>
<td></td>
</tr>
</tbody>
</table>

5.2.2. Effect of yarn type

This experiment (Table 5.3) was aimed at investigating the effect of yarn type, at constant yarn tension of 1 cN/tex, on the MEMS output signal. The types of yarns selected are used in the industry for different markets such as cut resistant fabrics, home textiles,
upholstery, and ladies dresses.

Table 5.3 Experimental design 2: Effect of yarn type

<table>
<thead>
<tr>
<th>Weave Structure</th>
<th>Material</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>73.81 tex, 100% cotton spun yarn</td>
<td>1 cN/tex</td>
</tr>
<tr>
<td></td>
<td>39.37 tex, 50%cotton/50% polyester ring spun yarn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>73.81 tex, 100% polyester spun yarn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>124 tex, 100% polyester filament yarn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>69.67 tex, Spectra filament yarn</td>
<td></td>
</tr>
</tbody>
</table>

5.2.3. Effect of yarn tension

This experiment (Table 5.4) was aimed at investigating the effect of warp yarn tension and weave on the MEMS signal. Yarn type was kept constant. The four tension levels selected are those used in practice. Tension levels vary with warp and pick density in practice.

Table 5.4 Experiment design 3: Effect of yarn tension

<table>
<thead>
<tr>
<th>Weave Structure</th>
<th>Material</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>124 tex, 100% polyester filament yarn</td>
<td>1.0, 1.5, 2.0, 2.5 cN/tex</td>
</tr>
<tr>
<td>4x4 RH Twill</td>
<td>124 tex, 100% polyester filament yarn</td>
<td></td>
</tr>
</tbody>
</table>

5.2.4. Additional experiments

During the runs of three above experimental designs the experimental warp yarns were cut using a sharp pair of scissors. In practice, yarns may break due to excessive tension.
Other situation that requires investigation is the detection of slack yarns. Slack yarns may cause clinging and/or difference in the produced fabric appearance. Additional experiments were designed to address these situations. Two experimental yarns and two weaves were selected for the additional experiments. A total of eight runs were executed (2 yarns X 2 Weaves X 2 cases). Table 5.5 shows the variables of the additional experiments. The excessive yarn tension was achieved by preventing the yarn feed (by holding the yarn package and stop its rotation). The slackness case was done by over feeding the yarn. For each case the tension was monitored using the tension meter.

Table 5.5 Experiment design 4: dynamic variation of tension

<table>
<thead>
<tr>
<th>Weave Structure</th>
<th>Material</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>73.81 tex, 100% polyester spun yarn</td>
<td>Case 1: Slack/Pull with no breaks</td>
</tr>
<tr>
<td>8H warp satin</td>
<td>124 tex, 100% polyester filament yarn</td>
<td>Case 2: Pull to breaking point</td>
</tr>
</tbody>
</table>

5.2.5. Preparation of weaving machine and instruments for experimental runs

Due to creep of warp yarns caused by the tension for a long period of time, it is essential to establish a procedure to get the warp tension to the preset level or equilibrium. This is necessary to obtain meaningful data from the MEMS sensors. The following steps are executed for each run or set of runs (in case of conducting more than one run back to back):
1. Feed a single experimental warp yarn from the creel to each instrumented harness cord

2. Run the weaving machine (a constant speed of 245 picks/minutes was used for all runs)

3. Monitor one of the experimental warp yarn tension for 3-5 minutes (this is sufficient time to reach equilibrium value of tension as it can be seen from Figure 5.2)

4. Start data acquisition from MEMS sensors

5. Break experimental warp yarns using sharp pair of sharp scissors after 10-30 seconds from the start of data acquisition

6. Stop data acquisition and weaving machine

Weaving machine has to be run for several minutes for the warp yarn tension to reach its steady state because the warp yarn tension declines when the machine stops for long periods due to creep behavior. The tension meter was set to measure yarn tension in the area between drop wires and the warp beam. Figure 5.2 shows an example of the tension variation for the polyester filament yarn constructed to a plain weave. In this example the preset tension is 1 cN/tex with corresponding total tension on the yarn of 124 cN at steady state since the yarn tex is 124. The tension in Figure 5.2 was very low at the start up of the weaving machine due to stopping for long time. It is obvious from the tension trace that the warp yarns experienced creep a matter that caused the extreme low tension. The servo motor was run to achieve the target tension shown in the tension traces of Figures 5.2-5.5. The
tension traces of Figures 5.3 – 5.5 show the tension adjustment to reach target tension for back to back runs (no creep).
Figure 5.2 Tension variation after long stop prior to DAQ run
Figure 5.3 Tension adjustment in polyester filament yarn, plain weave, 186 cN
Figure 5.4 Tension adjustment in polyester filament yarn, plain weave, 248 cN
Figure 5.5 Tension adjustment in polyester filament yarn, 4x4 R.H. Twill, 124 cN
6. **Signal analysis**

Prior to actual measurement of harness cord acceleration, it is necessary to establish the actual time-acceleration relationship from measured time-displacement of a harness cord. The actual time-acceleration relationship is used to benchmark the MEMS output signal to ensure proper functioning. To determine the actual time-displacement relationship, the weaving machine manually driven and the time-displacement relationship was determined for a harness cord. A mark on the harness cord was observed for displacement measurement for 30 degree increment of the main shaft. The shape of the time-acceleration relationship was deduced from time-displacement. The procedure was done for plain weave and 4x4 R.H. twill weaves.

Slusser [41] work using a test bed measurement system indicated that the vertical component of the MEMS accelerometer increased slightly when a warp yarn breaks. While an algorithm could be developed to differentiate between the MEMS output for no break and break, this may requires several weaving cycles a matter that could cause unacceptable defects or additional warp yarn breaks. Slusser’s work was limited to a motion that produces plain weave. It was decided in this investigation to study the MEMS vertical and horizontal components for a range of weaves. The vertical component of MEMS signal is due to the known motion given to the harness cords by the Jacquard shedding mechanism. The horizontal component of MEMS signal is, however, due to vibration of the harness cord. The vibration pattern was thought to be different when yarns are up than when they break. Time and frequency domain could reveal the difference.
6.1. Determination of harness cord time-displacement relationship

Figure 6.1 shows the time-displacement curve of the weaving cycle in a plain weave for every 30 degrees of the main shaft. The displacement here is measured in terms of angular rotation of the main shaft. The angle of the main shaft could be converted to time for a given weaving speed. The figure also indicates the main events that take place every weaving cycle. The maximum displacement of a harness from the shed leveling point is 3.5 cm. This gives a maximum shed size of 7 cm. Table 6.1 shows the start and end of the main weaving events.

Table 6.1 Main weaving events

<table>
<thead>
<tr>
<th>Events</th>
<th>Start / End (angular degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beat up</td>
<td>30 / -</td>
</tr>
<tr>
<td>Lay backward motion</td>
<td>30/90</td>
</tr>
<tr>
<td>Lay dwelling</td>
<td>90/340</td>
</tr>
<tr>
<td>Lay forward motion</td>
<td>340/390</td>
</tr>
<tr>
<td>Filling insertion</td>
<td>210/340</td>
</tr>
</tbody>
</table>

Figure 6.2 shows the time-displacement of 4x4 R.H. Twill weave repeat. It is clear from the figure that the shedding motion is open-shed type in which harness cords stay up (or down) as long as it is required to be up (or down) for successive picks according to the weave design. Figure 6.2 indicates a bump per a weaving cycle of the upper shed. The bump formation is caused by the contact of the knife with the hook when the knife reaches its most
upward position (refer to Figure 2.3). The contact between the knife and the hook in upper shed mode causes the spring to extend and the harness cord to move up when the knife moves up. The reason of the bump is to allow the release of the hook from the retaining hook to allow the movement of the hook downward in case of forming bottom shed following an upper shed. The bump is not required in case of float at the lower shed since the retaining hook is not engaged with the hook. The knives, in case of lower shed, are moving opposite to each other smoothly without contact with the retaining hooks (Figure 2.3).

From the two time-displacement relationships of Figure 6.1 and Figure 6.2 determined for plain and 4x4 R.H. Twill weaves, the time-displacement for any weave could be determined. The two relationships were used to generate the time-displacement relationships of the weaves selected for this study as it will be seen in the next section.
Figure 6.1 Time-displacement of plain weave
Figure 6.2 Time-displacement of 4x4 R.H. twill weave
6.2. Displacement, velocity and acceleration

Since MEMS accelerometers provide acceleration value corresponding to harness movement according to the weave structure, time-displacement can be converted to time-acceleration by differentiation with respect to time twice. Based on the measurements of time-displacement relationships of Figures 6.1 and 6.2, the ideal plots of acceleration, velocity, and displacement in time domain were generated for the weaves used in this investigation. Figure 6.3 - Figure 6.6 show these plots.

Figure 6.7 shows the superimposition of the MEMS raw output data (dynamic) and the predicted time-acceleration relationships (from time-displacement hand driven measurements) for the weaves employed in this investigation. The MEMS vertical acceleration output signals of Figure 6.7 were obtained by running the weaving machine with Polyester filament yarns threaded in the heddle eyes of the instrumented harness cords. The figure shows a good agreement between the ideal acceleration plots (red) which were predicted from measurements of time-displacement and the measurement (black) obtained from MEMS output signal.

Figure 6.8 shows the same data as Figure 6.7 with the difference that MEMS output data were filtered using low pass filter at 8.75 Hz (525 min\(^{-1}\)). This value exceeds the loom speed in picks/min and number of weave repeats/min for any weave used to avoid any loss of important information.
The data of Figures 7.7 and 7.8 reveal some difference in the actual and the ideal signals. The difference is obvious in the plain weave signal in the positive part of the acceleration (harness cord is moving downward). The ideal signal shows one positive peak, while the actual shows two positive peaks and one negative peak in between. The reason for the two positive peaks can be explained by the knives motion in plain weave. In such weave the left hook of a harness cord is moving continuously upward and downward by the left knife (Figure 2.3) while the right hook is engaged to the retaining hook. The right knife becomes in contact with the right hook when the harness cord at its most downward position causing the harness cord to be raised slightly. This detail was not captured during determining the time-displacement of Figure 6.1 since the displacement was determined every 30 degrees of the main shaft. The data of Figures 7.7 and 7.8 prove that the system is measuring what is expected.
Figure 6.3 Ideal plot of plain weave

Figure 6.4 Ideal plot of 2x2 R.H. Twill
Figure 6.5 Ideal plot of 4x4 R.H. Twill

Figure 6.6 Ideal plot of 8H warp satin
Figure 6.7 Comparison of MEMS output with expected time-acceleration relationship for plain (top plot), 2x2 R.H. twill, 4x4 R.H. twill, and 8-Harness Satin
Figure 6.8 Comparison of MEMS filtered output data with expected time-acceleration relationship for plain (top plot), 2x2 R.H. twill, 4x4 R.H. twill, and 8-Harness Satin
6.3. Vibration

6.3.1. Vibration of Stretched String

Assume a stretched string (a warp yarn or harness cord in our case) is given a motion. The string will vibrate with certain amplitude in trying to get to the rest position. Increasing the string tension leads to higher force and speed that pulls the string away from its rest position a matter that leads to higher string frequency. Vibration waves are created as a result of string motion. Modes of wave vibration are shown in Figure 6.9 and more details regarding the formation of waves are given elsewhere [17]. It can be shown that

\[ T = 4Mf^2L^2 \]  \hspace{1cm} (6.1)

where

\[ f = \text{fundamental frequency (first mode of vibration see Figure 6.9) [Hz or s}^{-1}] \]

\[ L = \text{string length between fixed points (i.e. bridge and nut) [m]} \]

\[ T = \text{string tension [kg·m/s}^2]\]

\[ M = \text{string mass per unit length [kg/m]} \]
Figure 6.9 First four vibration modes of a string fastened at both ends [17]

Figure 6.10 and Table 6.2 show relationship between string tension and frequency for the polyester filament yarn (124 tex). The yarn tension values of Table 6.2 are these used in experimental design of Table 5.4. The mass per unit length \( (M) \) of this yarn is constant and can be calculated from the yarn tex, which is defined as the weight in grams of 1,000 meter. Thus \( M = 124/1000 \) or 0.124 g/m. Substituting value of \( M = 0.124 \) into Equation 6.1, we get:

\[
f = \frac{\sqrt{T}}{0.704L}
\] (6.2)

Four yarn lengths should be considered; \( L_1, L_2, L_3, \text{ and } L_4 \) of Figure 6.11. The four lengths were considered since the yarn is threaded through or supported by different weaving machine elements. While the yarn is not well gripped at the points of contact with machine elements, this may provide basis for understanding the output data in frequency domain of the MEMS accelerometers.
Figure 6.10 Relationship between string tension and frequency

Figure 6.11 Diagram of warp yarn path through/over machine parts
Table 6.2 Data generated from equation 6.1

<table>
<thead>
<tr>
<th>Tension (cN/tex)</th>
<th>Total Tension (cN)</th>
<th>L (m)</th>
<th>f (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>L₁ = 0.13</td>
<td>121.6</td>
<td></td>
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<tr>
<td></td>
<td>L₂ = 0.85</td>
<td>18.6</td>
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<tr>
<td></td>
<td>L₃ = 0.98</td>
<td>16.1</td>
<td></td>
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<tr>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>L₃ = 0.98</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>L₄ = 1.48</td>
<td>16.9</td>
<td></td>
</tr>
</tbody>
</table>
6.3.2. Damped Vibration

Free vibration with damping is described by the following equation:

\[ m \ddot{x} + c \dot{x} + kx = 0 \]  \hspace{1cm} (6.3)

Where

\( m \): mass

\( c \): damping constant

\( k \): spring constant

\( x \): displacement from the equilibrium

If the system is under-damped, for the initial conditions of \( x_0 \) and \( \dot{x}_0 \), the solution of the equation above is:

\[ x = Ae^{-\zeta \Omega_d t} \sin(\omega_d t + \psi) \]  \hspace{1cm} (6.4)

where

\[ A = \sqrt{(x_0 \omega_d)^2 + (\dot{x}_0 + \zeta \omega_n x_0)^2} / \omega_d \]  \hspace{1cm} (6.5)

\[ \psi = \tan^{-1} \left( \frac{x_0 \omega_d}{\dot{x}_0 + \zeta \omega_n x_0} \right) \]  \hspace{1cm} (6.6)

\[ \omega_d = \sqrt{1 - \zeta^2} \omega_n \]  \hspace{1cm} (6.7)

\( x_0 \): initial position

\( \psi \): phase

\( \omega_n \): natural frequency

\( \omega_d \): harmonic motion of frequency

\( \zeta \): damping factor
Ideal signal is the single frequency signal which can be seen in Figure 6.12. In mass-spring system, many problems involve transient signals such as viscous damping due to impulse effects. Figure 6.12 shows that mass is displaced by an amount $x_0$ from its static equilibrium position and then released with zero initial velocity. The maximum amplitude occurs when the product $A e^{-\zeta \omega t}$ and $\sin(\omega_d t + \psi)$ is a maximum. Rewriting the equation with $(\omega_d t)$ as the independent variable and equating $dx/d(\omega_d t)=0$ for maximum, we have

$$x = A e^{-\zeta \psi /\sqrt{1-\zeta^2}} \sin(\omega_d t + \psi)$$ (6.8)

$$\frac{dx}{d\omega_d t} = A e^{-\zeta \psi /\sqrt{1-\zeta^2}} \left[ -\frac{\zeta}{\sqrt{1-\zeta^2}} \sin(\omega_d t + \psi) + \cos(\omega_d t + \psi) \right]$$ (6.9)

Hence the maximum amplitude occurs at

$$\tan(\omega_d t + \psi) = \sqrt{1-\zeta^2} / \zeta$$ (6.10)

Figure 6.12 Free vibration with damping [46]
In Figure 6.12, let \((\omega_d t_1)\) and \((\omega_d t_2)\) correspond to the maxima \(x_1\) and \(x_2\). The last equation indicates that \(\tan(\omega_d t_1 + \psi) = \tan(\omega_d t_2 + \psi)\). Hence \((t_2 - t_1) = 2\pi / \omega_d\) is a period and \(\sin(\omega_d t_1 + \psi) = \sin(\omega_d t_2 + \psi)\). The consecutive amplitude ratio is

\[
\frac{x_1}{x_2} = \frac{Ae^{-\zeta \omega_0 h}}{Ae^{-\zeta \omega_0 t_2}} = e^{\zeta \omega_0 (t_2 - t_1)} = e^{\zeta \omega_0 (2\pi / \omega_d)} = e^{2\pi \zeta / \sqrt{1 - \zeta^2}}
\]

(6.11)

The natural logarithm of the ratio is called the logarithmic decrement \(\delta\). Hence

\[
\delta = 2\pi \zeta / \sqrt{1 - \zeta^2}
\]

(6.12)

Based on the equation above, the number of cycles \(n\) is given by the expression

\[
\frac{x_1}{x_2} = N = e^{n\delta} \quad \text{or} \quad \delta = \frac{1}{n} \ln N
\]

This logarithm of the ratio, is defined as [46]:

\[
\delta = \frac{1}{n} \ln \left( \frac{x_0}{x_n} \right)
\]

(6.13)

\[
\delta = 2n \pi \zeta / \sqrt{1 - \zeta^2}
\]

(6.14)

Where

- \(x_0\): initial position
- \(x_n\): \(n^{th}\) position
- \(\zeta\): damping factor

The logarithmic decrement is a measure of the damping factor \(\zeta\) and it provides a convenient method to measure the damping in a system [46].

The logarithmic decrement and the damping factor were used in this investigation to
characterize the data of warp breaks and correlate them to warp yarn tensile properties. Both of these values characterize the break signal how fast the vibration signal (due to break) dissipates.

6.4. Time domain analysis and frequency analysis

In order to identify warp breaks using acceleration of harness cord motion as measured by MEMS accelerometers, it is necessary to investigate the time domain and frequency domain before and after warp yarn break. It is highly probable that the break signal can be seen in horizontal direction because the acceleration in this direction is mainly influenced by the vibration of the harness cords while the acceleration in vertical direction is mainly influenced by the law of motion dictated by the Jacquard shedding mechanism. It is expected that a warp break affects the time and frequency domains (Figure 6.13 - Figure 6.15) as detected by the horizontal acceleration signal of the MEMS sensors. Therefore, detection methods should be developed in terms of time and frequency domains analyses. These methods are evaluated in the next Chapter.

![Graph showing hypothetical break signal with different frequency](image)

Figure 6.13 Hypothetical break signal with different frequency
6.4.1. Statistical analysis in time domain

A signal containing different amplitude (before and after yarn break in our case) can be detected by a statistical analysis of time domain data. Statistical parameters of horizontal vibration in time domain can be established for the case of no yarn break. The statistical distribution of the time domain data collected by MEMS could be determined. Assume that the data follow normal distribution. In standardized normal distribution with mean $\mu$ and standard deviation $\sigma$, the probability of acceleration value to be in the range $\mu \pm 1\sigma$ is 68.26%, the probability of the acceleration value to be in the range $\mu \pm 2\sigma$ is 95.46%, and the probability of the acceleration value to be in the range $\mu \pm 3\sigma$ is 99.73%. These limits (upper and lower) could be established as parameters that identify acceleration signal when
yarn is not broken. To obtain the corresponding standardized $Z_i$ values to the acceleration values $X_i$, the following relation is used [4]:

\[
Z_i = \frac{X_i - \mu}{\sigma}
\]  

(6.15)

By selecting upper and lower control limits for the no break case, the data of the break case could be checked against the control limits and thus breaks could be detected.

In this case of signal analysis, the upper and lower limits must be carefully chosen to identify warp breaks. Using $3\sigma$ could lead to a break going without detection. In the case of $1\sigma$ and $2\sigma$, it is possible to get false indication of breaks. Therefore, peak acceleration values could be used to strengthen the decision making regarding a break or no break. The following section addresses this issue.

6.4.2. Peak detection

Peak detection is a basic concept to find a specific peak or valley value in the signal. It is one of the important time domain functions in a signal monitoring. The process is to find the locations and amplitudes of local maxima and minima in a signal satisfying certain conditions. In this study, threshold peak detection algorithm was developed as an additional method to identify warp breaks and hence cooperating with a statistical analysis for the reasons mentioned in the previous section. The algorithm scans the input sequence of the horizontal acceleration data, which were collected at a rate of 550 points/sec for all runs, and
searches for valid peaks (minima and maxima) and keeps track of the indices of the peaks (Figure 6.16). Further information is provided in section 11.4.4. Another threshold was established in terms of number of points (or time width interval) above the threshold. This would allow avoiding false break detection due to shocks (sudden high peak values). The peak can be considered due to warp break if the following two conditions are satisfied:

- The peak is out of the threshold limits, and

- The number of points out of the threshold exceeds the established value.
Figure 6.16 Peak detection diagram
6.4.3. Fast Fourier transform

The MEMS output signals contain different frequencies that can be detected by a frequency analysis. The Fourier transform converts time domain data into frequency domain. It is defined as [40]:

\[ X(f) = F\{x(t)\} = \int_{-\infty}^{\infty} x(t)e^{-2\pi if t} dt \]  \hspace{1cm} (6.16)

- \( x(t) \): Time domain signal in continuous function mode
- \( X(f) \): Fourier transform (frequency domain)

Similarly, the discrete Fourier transform converts discrete-time data into discrete-frequency (DFT) and is given by [40]:

\[ X_k = \sum_{i=0}^{n-1} x_i e^{-2\pi ik / n} \hspace{1cm} \text{for } k = 0, 1, 2, \ldots, n-1 \]  \hspace{1cm} (6.17)

- \( x \): the input sequence
- \( X \): discrete Fourier transform
- \( n \): number of data points

Direct implementation of the DFT requires approximately \( n^2 \) complex operations. However, computationally efficient algorithms can require as little as \( n \log_2(n) \) operations. These algorithms are called fast Fourier transforms (FFT). From the definition of the DFT, the Fourier transform of any sequence \( x \), whether it is real or complex, always results in a complex output sequence \( X \) of the form [40]
\( F\{x\} = X = X_{\text{Re}} + iX_{\text{Im}} = \text{Re}\{x\} + i\text{Im}\{x\} \) \hspace{1cm} (6. 18)

An inherent DFT property is

\[ X_{n-i} = X_{-i}, \] \hspace{1cm} (6. 19)

Which means that the \((n-1)^{th}\) element of \(X\) contains the result of the \(-i^{th}\) harmonic. Furthermore, if \(x\) is real, the \(i^{th}\) harmonic and the \(-i^{th}\) harmonic are complex conjugates:

\[ X_{n-i} = X_{-i} = X_i^* \] \hspace{1cm} (6. 20)

Consequently,

\[ \text{Re}\{X_i\} = \text{Re}\{X_{n-i}\} \] \hspace{1cm} (6. 21)

And

\[ \text{Im}\{X_i\} = \text{Im}\{X_{n-i}\} \] \hspace{1cm} (6. 22)

These symmetrical Fourier properties of real sequences are referred to as conjugate symmetric, symmetric or even-symmetric and anti-symmetric or odd-symmetric.

Based on the frequency response of time-acceleration, MEMS accelerometer provides a specific frequency distribution in different parameters. A normal acceleration (no warp break) signal of harness cords motion would differ from an abnormal signal at warp break according to Figure 6.13 and Figure 6.15. This idea could be applied to detect warp break in frequency response.
7. Results and Discussions

7.1. System testing

7.1.1. Acceleration with no motion

Runs to test the system for circuit noise were performed. The MEMS output data (acceleration in horizontal and vertical directions) were collected without running the weaving machine. Figure 7.1 and Figure 7.2 show a time and frequency domains data. The data of Figure 7.1 indicate that the horizontal and vertical acceleration data lay on adjusted zero gravity. The vertical MEMS acceleration was initially 1 G (9.8 m/s²) on the average and this was adjusted by to zero by subtracting one from each data point. The horizontal acceleration was initially zero and there was no need for adjustment. The frequency domain data show that there is no outstanding peak which led to the conclusion that there is no significant circuit noise.

Figure 7.1 Time-acceleration without weaving
MEMS accelerometer and proximity sensor signal

It was mentioned earlier that the purpose of installing a proximity sensor is to indicate the moment of beat up (or the start of weaving cycles). This moment and the timing diagram of Figure 6.1 could be used to explain signal behavior. Figure 7.3 - Figure 7.6 show the time domain and the frequency domain running the cotton yarn of Table 5.3 in plain weave. In these figures, black line indicates acceleration value and pink line is the proximity sensor signal. As expected for plain weave the vertical acceleration components of MEMS is a sinusoidal while the horizontal acceleration is due to vibration of harness cords. The proximity sensor output signal provided a sharp peak at the moment of beat up. Figure 7.5 shows the frequency domain obtained by FFT for the vertical acceleration component of MEMS. The graph shows high peaks at approximately 2 Hz and 4 Hz. These two main frequencies are corresponding to 120 cycles/min and 240 cycles/min. The weaving machine speed hand dial was adjusted at approximately 245 picks/min. The frequency corresponding to 120 cycles/min is the number of weave repeats/min since the plain weave picks per repeat is 2. The proximity sensor frequency domain signal exhibited also a peak at 4 Hz.
The peaks beyond 4Hz in Figure 7.5 are due to machine vibration resulting from motion of different machine parts. In contrast to the spectrum of vertical motion, spectrum of horizontal vibration in Figure 7.6 shows lower magnitude, and does include main frequencies including weaving speed.
Figure 7.3 Acceleration of vertical motion in plain weave

Figure 7.4 Acceleration of horizontal vibration in plain weave

Figure 7.5 Frequency domain of vertical motion data

Figure 7.6 Frequency domain of horizontal vibration
7.2. Results of experimental designs

7.2.1. Effect of weave

The experimental design to investigate the effect of weave on the output signal of MEMS accelerometers is shown in Table 5.2. Three different runs for each weave (a total of 12 runs) were conducted. For each run time domain data were acquired from MEMS accelerometers as well as the proximity sensor. The tension was adjust and kept at constant value of 1 cN/tex. The experimental yarns were intentionally cut between drop wires and creel using a sharp scissors.

Figure 7.7-7.10 show the plots of time domain data of horizontal acceleration due to vibration (shown in black), and vertical acceleration given to the harness cords by the shedding motion (shown in purple) for the four weaves investigated. Figures 7.11-7.14 show the same data as Figures 7.7-7.10. The purpose of producing Figures 7.11-7.14 is to show the time-displacement, time-velocity, and time-acceleration of harness cords with smoothed red continuous line to show the moment of yarn break and at what mode (dynamic or static) of motion the harness experienced at the time of break. The data of Figures 7.7-7.10 were collected before warp yarn intentional break, at the moment of the break, and after the break. In Figure 7.7 (plain weave) the moment of yarn break is clearly seen at 8.14 sec (identified by arrow) from the horizontal acceleration data and it is characterized by high acceleration value. It is also observed that regardless of weave the break moment is obvious with high horizontal acceleration value in each break occurrence. The acceleration values continue to be high over a noticeable period of time. It should be
mentioned here that in case of plain weave the harness cords are in continuous motion (dynamic) as it can be seen from the data of the vertical acceleration in Figure 7.11. On the other hand 2x2 R.H. Twill, 4x4 R.H. Twill, and 8-H Satin weaves the harness cords are moved up (or down) followed by a dwelling (static) period as it can be seen from the vertical acceleration in Figures 7.12-7.14. The break signal was appreciable from the horizontal acceleration data for all weave types regardless of the time at which the yarn was cut and whether the harness cords were moving (dynamic mode) or stationary (static mode).

The results of Table 7.1 shows the maximum peak of horizontal acceleration at the moment of break for the four weaves, the average of positive peaks before break, and the average of negative peaks before break. Figure 7.15 shows plot of Table 7.1 data. It seems from these results that the static breaks showed higher peak values than dynamic. This may be due to the interference between the vertical and horizontal movements of the harness cords in case of plain weave (dynamic mode). Additionally, the results of Figure 7.15 and Table 7.1 illustrate that the maximum peak at break is much higher than the average peaks before break.

Observing the data of the vertical acceleration of Figures 7.7-7.14 the moment of break can not be seen. This could be attributed to the fact that the harness cords (Figure 4.9) are rigidly supported from the top and the existence or presence of the yarn did not affect the harness cord law of motion significantly. On the other hand, the horizontal vibration increased due to the fact that the presence of the yarn supports the harness cord at the
heddle eye (Figure 4.9) and to some extent restricts the horizontal motion. Once the yarn break occurs the harness length supported is much longer as compared to the presence of the yarn a matter that increases the motion amplitude in the horizontal direction. Moreover the sudden vanishing of the yarn tension component causes the spring to be suddenly compressed (when warp yarn is the negative zone of displacement) or tensioned (when the yarn is in the positive zone of displacement) a matter that causes the spring to bounce. The bounce of the spring causes the most flexible element (the harness cord) to buckle. Buckling, (or slackness) of the harness cord and free harness cord without support combined with the vibration caused by different weaving motions lead to appreciable harness cord horizontal vibration which is transferred to the heddle wire (or MEMS accelerometer).

Based on the above, the size of a hole in the comber board could be optimized to increase the horizontal motion and allow for better break detection if other factors (such as yarn type) prevented the detection.
Figure 7.7 Plain weave - 100% polyester continuous filament yarn, break at 8.14 s

Figure 7.8 2x2 R.H. twill weave - 100% polyester continuous yarn, break at 15.91s

Figure 7.9 4x4 R.H. twill weave - 100% polyester continuous yarn, break at 8.24s

Figure 7.10 8H warp satin - 100% polyester continuous yarn, break at 12.49s
Figure 7.11 Plain weave - 100% polyester continuous filament yarn

Figure 7.12 2x2 R.H. twill weave - 100% polyester continuous yarn
Figure 7.13 4x4 R.H. twill weave - 100% polyester continuous yarn

Figure 7.14 8-H warp satin - 100% polyester continuous yarn
Table 7.1 Highest horizontal acceleration peak at yarn break and average peaks before yarn break

<table>
<thead>
<tr>
<th>Weave Structure</th>
<th>Total Tension (cN)</th>
<th>Average Peaks Before Yarn Break* (G)</th>
<th>Highest Peak Acceleration at Yarn Break (G)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td></td>
<td>0.7261/0.8394</td>
<td>1.9935</td>
<td>Dynamic</td>
</tr>
<tr>
<td>2x2 R.H. twill</td>
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<td>0.6190/0.8485</td>
<td>1.8017</td>
<td>Static</td>
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<tr>
<td>4x4 R.H. twill</td>
<td></td>
<td>0.8937/1.0078</td>
<td>1.8858</td>
<td>Static</td>
</tr>
<tr>
<td>8H warp satin</td>
<td></td>
<td>0.6715/0.6526</td>
<td>1.9152</td>
<td>Static</td>
</tr>
</tbody>
</table>

* Absolute values of positive and negative accelerations

Figure 7.15 Comparison between highest horizontal acceleration peak at yarn break and average peaks before break for different weaves
Figure 7.16 and Figure 7.17 indicate the damping factor and logarithmic decrement of warp break in terms of weave structure. The logarithm decrement and the damping factor were calculated from equations 6.11 and 6.12 (respectively) using the horizontal acceleration data of MEMS sensor. To calculate the logarithm decrement from equation 6.11, the highest amplitude of the horizontal acceleration at a yarn break was determined and considered as $x_0$. The value of $x_n$ was taken as $x_3$ because it was noticed that after three peaks the vibration was masking the break peaks.

The results of Figures 7.16 and 7.17 illustrate that the damping factor and logarithmic decrement reduce with increase of the weave float length (or the number of picks/float). It should be pointed out here that the peaks due to yarn break vanish quicker with an increase in the damping factor or logarithmic decrement (Figure 6.8). The plain weave showed the highest values of damping factor and logarithmic decrement (or the quickest signal due to yarn break to vanish) due to the fact that the harness cord is in continuous motion (dynamic mode). With such continuous motion the vibrations caused by different weaving mechanisms especially shedding motion interfere with the horizontal acceleration peaks due to yarn break. The damping factor and logarithmic decrement for 4x4 Twill and 8-H Satin weaves exhibited lowest values since in forming these weaves the harness cords stay stationary for long period of time. With such still motion the peaks of the horizontal acceleration continues for longer time as compared to plain weave. The relationship between the weave structure and the damping factor and logarithmic decrement must be considered when developing algorithm to automatically detect warp yarn breaks.
Figure 7.16 Logarithmic decrement and weave structure

Figure 7.17 Damping factor and weave structure
7.2.2. Effect of warp yarn type

The effect of yarn type on the MEMS output signal was investigated by conducting the runs of the experimental design of Table 5.3. The yarns were fed from packages held by the creel and yarns were threaded through the heddle eyes of the instrumented harness cords.

Figure 7.18 - Figure 7.22 show the time domain output signals of the MEMS accelerometers of the five yarns. In these figures the acceleration of the vertical motion is shown in red while the horizontal vibration is shown in black. Consistent to what has been revealed in regards to the break detection, the vertical acceleration showed no appreciable peaks at the moment of warp breaks for all types of yarns as it can be seen from Figures 7.18-7.22. The polyester spun yarn, polyester filament yarn, and Spectra filament yarn showed significant change in the horizontal acceleration at the moment of break and during a period of time following the break. The two cotton and cotton/polyester yarns did not show detectable signal at the moment of yarn break. These two yarns were run several times to check whether the results are consistent. The additional runs revealed same results. For the cotton and cotton/polyester yarns of Figure 7.18 and Figure 7.19 the break time was monitored by a stop watch at 6.51 sec and 4.91 sec respectively. The results of this experimental design indicate that the use of MEMS accelerometers to detect warp breaks is limited to certain types of yarns.

The reasons behind the failure of MEMS accelerometer to detect warp breaks of cotton and cotton/polyester yarns could be attributed to the yarn hairiness and tensile
properties. The hairiness causes the yarn to cling to its neighboring yarns and since the break is done intentionally at the back, the piece of yarn from the break location to the cloth fell is supported by the neighboring yarns and did not get sudden slackness. Since the yarn is still threaded in the heddle eye, the horizontal vibration is restricted. The yarn slowly loses its tension and thus does not cause sudden impact on the horizontal acceleration significantly. These two yarns exhibited the lowest tenacities among the five yarns used (Table 5.1). The combination of low tenacity and the hairiness of these yarns could have caused restriction of the horizontal harness cord movement at the time of the break.

Perhaps the most important parameter that influenced the horizontal acceleration is the total yarn tension including tension variation. Since the tension used is one cN/tex, the average yarn tensions of the five yarns are:

- Cotton Yarn: 73.81 cN
- Cotton/Polyester Yarn: 39.37 cN
- Polyester Spun Yarn: 73.81 cN
- Polyester Filament Yarn: 124 cN
- Spectra Yarn: 69.67 cN

During weaving the tension varies due to yarn extension caused by shed opening and closing and beat up. The highest tension variation is experienced by the spectra yarn due to its high modulus followed by the polyester filament yarns. This means that the total tension values for these two yarns are the highest among the five yarns studied. With such high tension, the bouncing of the spring and the buckling of the harness cord and hence the horizontal vibration due to yarn break are more dramatic for these two yarns than the spun yarns.
The results of Table 7.2 and Figure 7.23 support the above comments. The spun polyester yarn showed the lowest maximum peak due to low total dynamic tension (low modulus) and presence of hairiness while the spectra showed the highest peak due to its high modulus (high total dynamic tension) and smoothness.

It should be mentioned here that the actual warp breaks takes place in the area between the cloth fell and the harness tie. Such break locations cause the yarn to get slack quickly since the yarn from the breaking point to the heddle eye is short. This could produce a detectable horizontal acceleration signal at the moment of break for cotton and cotton/polyester yarns. Thicker cotton and cotton/polyester yarns could also show better detectable signal due to high total tension. Further investigation is required to identify the limitation of using MEMS to detect warp breaks of spun yarns.
Figure 7.18 Time-acceleration of cotton spun, plain weave, break at 6.51 sec

Figure 7.19 Time-acceleration of cotton/polyester spun, plain weave, break at 4.91 sec

Figure 7.20 Time-acceleration of polyester spun, plain weave, break at 3.69 sec
Figure 7.21 Time-acceleration of polyester filament yarn, plain weave, break at 8.39

Figure 7.22 Time-acceleration of Spectra filament yarn, plain weave, break at 14.65
Table 7.2 Highest horizontal acceleration peak at yarn break in terms of yarn type

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Total tension (cN)</th>
<th>Average Peaks Before Yarn Break* (G)</th>
<th>Highest Peak Acceleration at Yarn Break (G)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>73.8</td>
<td>0.3225/0.2588</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cotton Polyester</td>
<td>35</td>
<td>0.7352/0.7588</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Polyester Spun</td>
<td>73.8</td>
<td>0.6095/0.9600</td>
<td>1.1111</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Polyester filament</td>
<td>124</td>
<td>0.7261/0.8394</td>
<td>1.9935</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Spectra</td>
<td>69.7</td>
<td>0.6881/0.8382</td>
<td>1.9523</td>
<td>Dynamic</td>
</tr>
</tbody>
</table>

* Absolute values of positive and negative accelerations

Figure 7.23 Highest horizontal acceleration peak at yarn break in terms of yarn type
The relationship between the damping factor and yarn type is shown in Table 7.3 while Figure 7.24 shows the relationship between the damping factor and the tensile properties of experimental yarns. The cotton and cotton/polyester experimental yarns were excluded since break signals for these yarns were too weak to detect. The results of Table 7.3 and Figure 7.24 indicate that the damping factor of warp breaks signals tend to increase with yarn peak load, modulus (total dynamic yarn tension), and tenacity. Additionally, an increase of yarn strain at break caused a decrease in damping factor. The reason behind the quick vanishing of the signal due to yarn break for spectra and polyester filament yarn is the very high $x_0$ values. While $x_0$ and $x_3$ values for these two yarns are higher than the corresponding values for the polyester spun yarn, the ratio of $x_0/x_3$ for the two yarns is lower than the corresponding ratio of polyester filament yarn. Algorithm to automatically detect warp yarn breaks should be better of dealing with the amplitude than dealing with the damping factor.
Table 7.3 Damping factor

<table>
<thead>
<tr>
<th>Yarn Type</th>
<th>Logarithmic Decrement</th>
<th>Damping Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester spun yarn</td>
<td>0.1419</td>
<td>0.0075</td>
</tr>
<tr>
<td>Polyester filament yarn</td>
<td>0.7508</td>
<td>0.0398</td>
</tr>
<tr>
<td>Spectra yarn</td>
<td>0.6470</td>
<td>0.0343</td>
</tr>
</tbody>
</table>

Figure 7.24 Tensile properties vs. damping factor of break signal
7.2.3. Effect of yarn tension

A total of eight runs (4 levels of yarn tension x 2 weaves) were conducted to investigate the influence of warp yarn tension on the MEMS output signals. The details of this experiment are illustrated in Table 5.4. Each of the eight runs was replicated three times. Figure 7.25 - Figure 7.32 show the acceleration data of a replication for each of the eight runs.

Figure 7.25 - Figure 7.32 show the influence of yarn tension on the MEMS output signals before and after yarn intentional breaks for Plain and 4x4 R.H. Twill weaves. It is clear that increase in the yarn tension caused an increase in the vertical and horizontal accelerations amplitude in case of Plain weave (Figures 7.25-7.28) without yarn break. The effect is not seen in case of 4x4 Twill weave (Figures 7.29-32).

Table 7.4 and Figures 7.33 and 7.34 show a comparison of the horizontal peak accelerations before and at yarn break. The highest peak caused by the yarn break is reduced with yarn tension increase in case of Plain and 4x4 Twill weaves. The difference between the acceleration peaks before yarn break and the highest peak caused by the yarn break is reduced as the yarn tension increases. This finding lead to the conclusion that yarn break may not be detected if the warp yarn tension is too high. Fortunately, yarn tension during weaving is about 1 cN/tex and at this level the difference between the acceleration peaks before yarn break and the highest peak caused by the yarn break is significant for all weaves studied (Figures 7.15, 7.33, and 7.34).
Figure 7.25 Time-acceleration (plain, 1cN/tex, break at 8.39)

Figure 7.26 Time-acceleration (plain, 1.5cN/tex, break at 13.42)

Figure 7.27 Time-acceleration (plain, 2cN/tex, break at 15.90)
Figure 7.28 Time-acceleration (plain, 2.5cN/tex, break at 15.07)

Figure 7.29 Time-acceleration (4x4 R.H. Twill, 1 cN/tex, break at 8.24)

Figure 7.30 Time-acceleration (4x4 R.H.Twill, 1.5 cN/tex, break at 10.75)
Figure 7.31 Time-acceleration (4x4 R.H. Twill, 2cN/tex, break at 11.43)

Figure 7.32 Time-acceleration (4x4 R.H. Twill, 2.5cN/tex, break at 9.78)
Table 7.4 Highest horizontal acceleration peak at yarn break

<table>
<thead>
<tr>
<th>Tension (cN/tex)</th>
<th>Total Tension (cN)</th>
<th>Weave</th>
<th>Average Peaks Before Yarn Break* (G)</th>
<th>Highest Peak Acceleration at Yarn Break (G)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>124</td>
<td>Plain</td>
<td>0.7261/0.8394</td>
<td>1.9935</td>
<td>Dynamic</td>
</tr>
<tr>
<td>1.5</td>
<td>186</td>
<td>4x4 R.H. Twill</td>
<td>0.8937/1.0078</td>
<td>1.8858</td>
<td>Static</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plain</td>
<td>0.8070/0.7056</td>
<td>1.5946</td>
<td>Dynamic</td>
</tr>
<tr>
<td>2</td>
<td>248</td>
<td>4x4 R.H. Twill</td>
<td>0.7389/0.9294</td>
<td>1.4601</td>
<td>Static</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plain</td>
<td>1.3992/1.0788</td>
<td>1.5203</td>
<td>Dynamic</td>
</tr>
<tr>
<td>2.5</td>
<td>310</td>
<td>4x4 R.H. Twill</td>
<td>0.6862/0.7410</td>
<td>1.0833</td>
<td>Static</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plain</td>
<td>1.1483/1.2501</td>
<td>1.3670</td>
<td>Dynamic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.8029/0.8875</td>
<td>1.2511</td>
<td>Static</td>
</tr>
</tbody>
</table>

* Absolute values of positive and negative accelerations

Figure 7.33 Highest horizontal acceleration peak at yarn break (Plain weave)
Figure 7.34 Highest horizontal acceleration peak at yarn break (4x4 R.H. Twill)
Table 7.5 and Figure 7.35 show the damping factor and logarithmic decrement data as functions of yarn tension. The two parameters decrease with increase in warp tension in case of plain weave. The two parameters, however, did not show significant change with tension in case of 4x4 Twill weave.
Table 7.5 Damping factor and logarithmic decrement of tension effect

<table>
<thead>
<tr>
<th>Weave</th>
<th>Tension (cN/tex)</th>
<th>Logarithmic decrement</th>
<th>Damping factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0.7508</td>
<td>0.0398</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>0.5682</td>
<td>0.0301</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.4643</td>
<td>0.0246</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>0.3799</td>
<td>0.0202</td>
</tr>
<tr>
<td>Plain</td>
<td>1</td>
<td>0.3868</td>
<td>0.0221</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>0.4867</td>
<td>0.0258</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.4820</td>
<td>0.0256</td>
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<tr>
<td></td>
<td>2.5</td>
<td>0.4731</td>
<td>0.0251</td>
</tr>
<tr>
<td>4x4 R.H. twill</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.35 Damping factor in different levels of yarn tension

Figures 7.36-7.43 show that frequency and amplitude for different warp yarn tension levels. These figures correspond to Figure 7.25-7.32. It can be noticed that Plain weave (Figures 7.36-7.39) shows significant change in frequency with warp yarn tension. This is not the case, however, for 4x4 Twill weave. Plain weave shows higher frequencies values with
significant amplitude as tension increase beyond 1 cN/tex.

The frequencies calculated using Equation 6.2 and depicted in Table 6.2 are comparable to those shown in Figures 7.36-7-43. While the calculation is based on simple excitation of single stretched string and the warp yarns are subjected to more complex excitation from different weaving events, the frequencies measured by MEMS seem to be affected by the warp yarn vibration due to tension.
Figure 7.36 Frequency data of Polyester Filament Yarn, Plain Weave, 1 cN/tex (124 cN)

Figure 7.37 Frequency data of Polyester Filament Yarn, Plain Weave, 1.5 cN/tex (186 cN)

Figure 7.38 Frequency data of Polyester Filament Yarn, Plain Weave, 2 cN/tex (248 cN)
Figure 7.39 Frequency data of Polyester Filament Yarn, Plain Weave, 2.5 cN/tex (310 cN)

Figure 7.40 Frequency data of Polyester Filament Yarn, 4x4 R.H. Twill, 1 cN/tex (124 cN)

Figure 7.41 Frequency data of Polyester Filament Yarn, 4x4 R.H. Twill, 1.5 cN/tex (186 cN)
Figure 7.42 Frequency data of Polyester Filament Yarn, 4x4 R.H. Twill, 2 cN/tex (248 cN)

Figure 7.43 Frequency data of Polyester Filament Yarn, 4x4 R.H. Twill, 2.5 cN/tex (310 cN)
7.2.4. Slack and pull to break

As mentioned in the experimental section, warp yarns break due to excessive tension and slack yarns cause difference in the fabric appearance. Additionally slack yarns may cause clinging group of neighboring yarns which may cause yarns to break. This section shows the results of experiment devised to reveal whether MEMS accelerometer can in fact be used to detect these two situations. If MEMS accelerometers can successfully detect such situations, prevention measures could be taken by stopping the weaving machine and identify the reason for stopping (excessive or low tension). The experimental design of Table 5.5 was conducted for this purpose.

Figures 7.44-7.51 show the MEMS accelerometer output signals and the corresponding tension traces for each of the four runs. In each of these runs, an experimental warp yarn was slackened gradually and then pulled gradually. The slack and pull were carefully done to avoid yarn breaks (case 1). This can be seen from the tension traces of Figures 7.45, 7.47, 7.49, and 7.51. Observing the time scale of the acceleration and the tension traces, it can be seen that the amplitude of the horizontal and the positive vertical accelerations increase with an increase in yarn tension. This verifies the results of the previous section. It is worth noting that the effect of slack/pull is shown in dynamic mode.

The reason for the increase in the horizontal acceleration can be seen from equation 6.1. Tension increase in warp yarn causes the warp yarn to vibrate faster and hence acceleration gets higher. The motion of the warp yarn is transferred to the harness cord.
The reason for the increase in the positive vertical acceleration with increasing in yarn tension is the influence of warp tension on the spring extension. The harness cord is subjected to a downward force from the spring and upward force from the warp yarn. The warp yarn force is dynamically changing with time which causes a bouncing effect on the spring. The increase in warp tension causes the spring to bounce more dramatically. The negative acceleration is not affected by yarn tension since the warp force and spring force act on the harness cord in the same direction. The lag in time between the tension and the acceleration of Figures 7.44 and 7.45 is due to the use of two data acquisition systems.

Figure 7.44 Time-acceleration (polyester spun yarn, plain)

Figure 7.45 Time-tension (polyester spun yarn, plain)
Figure 7.46 Time-acceleration (polyester spun yarn, 8-H warp satin)

Figure 7.47 Time-tension (polyester spun yarn, 8H warp satin)
Figure 7.48 Time-acceleration (polyester filament yarn, plain)

Figure 7.49 Time-tension (polyester filament yarn, plain)
Figure 7.50 Time-acceleration (polyester filament yarn, 8H warp satin)

Figure 7.51 Time-acceleration (polyester filament yarn, 8H warp satin)
Figures 7.52-7.55 show the MEMS accelerometer output signals for the four runs of pull till break (case 2 of Table 5.5). In these figures the top graphs show vertical acceleration and bottom graphs show vertical and horizontal accelerations. In each of these runs, an experimental warp yarn was gradually pulled till break. Same observations for case 1 are noticed here as well. At the moment of break, however, the vertical positive and the horizontal accelerations are not different from those of the time before break at high tension. Shortly after the break the accelerations reduces dramatically. The results of Figures 7.44-7.55 lead to the conclusion that MEMS can in fact detect excessive yarn tension and could be used to stop the weaving machine and take measures to stop the break before it happen. Additional conclusion is that warp break when operating at high warp tension (in case of weaving high performance yarns such as Kevlar and Zylon) may be detected by making use of the dramatic reduction in acceleration after break.
Figure 7.52 Increase of tension to break (polyester spun yarn, plain)

Figure 7.53 Increase of tension to break (polyester spun yarn, 8H warp satin)
Figure 7.54 Increase of tension (polyester filament yarn, plain)

Figure 7.55 Increase of tension (polyester filament yarn, 8H warp satin)
Figure 7.56 – 7.59 were deduced from the data of Figures 7.44 – 7.55. These figures show the differences in horizontal peak accelerations at different levels of warp tension including zero tension in cN/tex and in cN as well as the peak acceleration at break and after break. These differences could be used to develop algorithms and make decision to stop the weaving process if needed.
Figure 7.56 Highest horizontal acceleration peak of polyester spun yarn (Plain)

Figure 7.57 Highest horizontal acceleration peak of polyester spun yarn (8H-Satin)
Figure 7.58 Highest horizontal acceleration peak of polyester filament yarn (Plain)

Figure 7.59 Highest horizontal acceleration peak of polyester filament yarn (8H-satin)
8. Automatic warp break detection

As discussed in the previous chapter, it was found that the break signal was clearly seen in horizontal acceleration of MEMS sensors. In this chapter analysis of the differences between the data before yarn breaks, at breaks and following the breaks are presented. Algorithms based on these differences to automatically detect warp yarn breaks are developed to make use of the instrumentation developed.

8.1. Warp break detection in time domain

Assume that the horizontal acceleration data points before yarn break follow normal distribution. With this assumption, upper and lower limits can be determined for a set of acceleration data points. In general, the upper and lower limits can be expressed as \( \mu + A\sigma \) and \( \mu - A\sigma \) respectively. The two parameters \( \mu \) and \( \sigma \) are the mean value and the standard deviation of the horizontal acceleration. To decide a value for \( A \), three values were used (1, 2, and 3) to determine which value is more suitable to set the limits. Figure 8.1 shows an example of horizontal acceleration acquired from weaving the polyester filament warp yarn with tension of 1 cN/tex. The weave in this case was plain and 8H-satin weaves. Figure 8.1 shows the three limits used. The upper limits are shown in red horizontal lines while the lower limits are shown in green horizontal lines. Table 8.1 depicts the values of the limits used for 1,000 data points (no yarn break data included). It is obvious from Figure 8.1 that most of the acceleration data (yarn is not broken) lay beyond the limits in case of using \( \mu \pm \sigma \) and \( \mu \pm 2\sigma \).
Most of the acceleration data for the case when the yarn is not broken lie within the range of \( \mu \pm 3\sigma \) and the data corresponding to a broken yarn are well beyond the limits (Figure 8.1). It is obvious, however, that many data points exceeded the limits. Increasing the value of the parameter \( A \) may lead to undetected yarn breaks. To avoid detecting false breaks while considering the value of \( A \) of 3, width threshold technique was used. The technique is provided in commercial software systems. In this technique, each peak that exceeds the limits is detected and its data width (proportional to the number of points above/below the limit) is determined. A peak corresponding to a yarn break has wider data width than that of no break. The results of Table 8.2 indicate this fact.

![Figure 8.1 Peak detection using three limits](image)

Figure 8.1 Peak detection using three limits
Polyester filament yarn, Plain (top) and 8H-satin weaves (bottom)
Table 8.1 Upper/lower limits

<table>
<thead>
<tr>
<th>Limit Type</th>
<th>Plain</th>
<th>8H-satin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper Limit</td>
<td>Lower Limit</td>
</tr>
<tr>
<td>( \mu \pm \sigma )</td>
<td>0.11563</td>
<td>-0.30421</td>
</tr>
<tr>
<td>( \mu \pm 2\sigma )</td>
<td>0.32556</td>
<td>-0.51413</td>
</tr>
<tr>
<td>( \mu \pm 3\sigma )</td>
<td>0.53549</td>
<td>-0.72406</td>
</tr>
</tbody>
</table>

Table 8.2 Peak detection parameters

<table>
<thead>
<tr>
<th>Polyester filament yarn</th>
<th>Time of 1st peak @ Break (sec)</th>
<th>peak Value</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
<th>Data Width of 1st Break Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>8.24</td>
<td>-0.7335</td>
<td>0.5354</td>
<td>-0.7240</td>
<td>22</td>
</tr>
<tr>
<td>2x2 R.H. twill</td>
<td>16.18</td>
<td>1.1512</td>
<td>0.5122</td>
<td>-0.6376</td>
<td>22</td>
</tr>
<tr>
<td>4x4 R.H. twill</td>
<td>12.44</td>
<td>0.8460</td>
<td>0.5302</td>
<td>-0.6066</td>
<td>33</td>
</tr>
<tr>
<td>8H warp satin</td>
<td>12.79</td>
<td>0.4720</td>
<td>0.4602</td>
<td>-0.5542</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Polyester spun yarn</th>
<th>Time of 1st peak @ Break (sec)</th>
<th>peak Value</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
<th>Data Width of 1st Break Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>3.69</td>
<td>1.0014</td>
<td>0.5741</td>
<td>-0.7484</td>
<td>15</td>
</tr>
<tr>
<td>2x2 R.H. twill</td>
<td>5.14</td>
<td>-1.0530</td>
<td>0.6555</td>
<td>-0.6115</td>
<td>15</td>
</tr>
<tr>
<td>4x4 R.H. twill</td>
<td>4.18</td>
<td>-1.9641</td>
<td>0.6030</td>
<td>-0.5455</td>
<td>16</td>
</tr>
<tr>
<td>8H warp satin</td>
<td>5.65</td>
<td>-0.8205</td>
<td>0.6549</td>
<td>-0.6568</td>
<td>8</td>
</tr>
</tbody>
</table>

To determine the critical peak data width of breaks, the data of polyester filament yarn of plain and 4x4 twill weaves were taken as examples. Figure 8.2 - 10 show the peaks of the horizontal acceleration as measured by MEMS accelerometer. The raw data corresponding to these figures are shown in Figure 7.25 and 7.29. Figure 8.2 - 10 show the detection of peaks that meet certain width condition. Figures 8.11 – 8.12 show the relationship between the peak data width and the number of detected peaks. It is obvious from Figures 8.2 – 8.12 that as the data width increases the number of peaks reduces. At certain data width, the peak at break was isolated. Combining the critical data width and the threshold could lead to identifying real warp break signals. By selecting a reasonable
threshold, the number of beaks beyond the threshold would be reasonable and finding the data width for reasonable number of peaks would lead to quick decision on whether a break took place.

Figure 8.2 Peak detection data width ≥ 3, plain weave

Figure 8.3 Peak detection data width ≥ 5, plain weave

Figure 8.4 Peak detection data width ≥ 10, plain weave
Figure 8.5 Peak detection data width $\geq 22$, plain weave

Figure 8.6 Peak detection data width $\geq 3$, 4x4 twill weave

Figure 8.7 Peak detection data width $\geq 5$, 4x4 twill weave
Figure 8.8 Peak detection data width $\geq 10$, 4x4 twill weave

Figure 8.9 Peak detection data width $\geq 22$, 4x4 twill weave

Figure 8.10 Peak detection data width $\geq 33$, 4x4 twill weave
Figure 8.11 Peak data width vs. Detected peak data points (Polyester filament yarn)

Figure 8.12 Peak data width vs. Detected peak data points (Polyester spun yarn)
Figure 8.13 - 20 show the graphs of horizontal acceleration data for two examples of yarns; polyester spun and polyester filament yarns. Table 8.2 depicts the results of the threshold peak detection of the data of Figure 8.13 - 20. In these figures the upper and lower limits are shown by the red and green horizontal lines. The break peak of Figure 8.13 was clearly noticed and found at 8 sec with acceleration value of -0.7335. The upper and lower limits are 0.5354 and -0.7240.

The results of Table 8.2 and Figure 8.13 - 20 reveal that there is no one simple rule to identify a break. It is expected that for every set of weaving parameters (weave, warp yarn tension, warp yarn type, etc.), the difference between the data widths of break and no break must be decided based on large number of data. Once this is done, the decision of stopping the weaving process based on the established difference can be reached.
Figure 8.13 Peak detection of polyester filament yarn, Plain

Figure 8.14 Peak detection of polyester filament yarn, 2x2 R.H. twill

Figure 8.15 Peak detection of polyester filament yarn, 4x4 R.H. twill

Figure 8.16 Peak detection of polyester filament yarn, 8H warp satin
Figure 8.17 Peak detection of polyester spun yarn, plain

Figure 8.18 Peak detection of polyester spun yarn, 2x2 R.H. twill

Figure 8.19 Peak detection of polyester spun yarn, 4x4 R.H. twill

Figure 8.20 Peak detection of polyester spun yarn, 8H warp satin
8.2. Detection in frequency domain

It is expected that the MEMS accelerometer output signal at warp break has a different frequency from a normal signal. To reveal whether this is true, the horizontal acceleration data were analyzed using a time interval window to evaluate the frequencies during the data collection period. The data were taken for normal run and intentional warp yarn breaks. A LabVIEW program was written to convert the time domain data to frequency domain and monitor these using a time interval window. Figure 8.23 shows a block diagram showing the logic of the program and the entire program code is given in section 11.4.4.

This method was applied to the polyester spun and filament yarns as examples. Figure 8.22 – 41 show the procedure of the frequency analysis through a warp break. The sample size to scan the signal was selected at 550 points (1 sec). The LabVIEW<sup>TM</sup> program scanned continuously (a point added and a point removed) in order to detect the break. For example, Figure 8.22 - 26 show acceleration variation running the polyester filament yarn, plain weave. It is clear from the figures that not only acceleration in time domain is high at the break but also the frequency domain shifted towards higher frequency. Therefore, it can be said that the acceleration variation at a warp break contains a different frequency from before-break and after-break. While the frequency is high at break in case of polyester spun yarn of 8-H warp satin (Figure 8.37 - 41), it is not as dramatic as the polyester filament yarn.
Figure 8.21 Diagram of time interval scanning
Figure 8.22 Polyester filament yarn, plain before warp break

Figure 8.23 Polyester filament yarn, plain at the moment of warp break
Figure 8.24 Polyester filament yarn, plain after warp break

Figure 8.25 Polyester filament yarn, 4x4 before break
Figure 8.26 Polyester filament yarn, 4x4 at the moment of break

Figure 8.27 Polyester filament yarn, 4x4 after break
Figure 8.28 Polyester filament yarn, 8H warp satin before break

Figure 8.29 Polyester filament yarn, 8H warp satin at the moment of break
Figure 8.30 Polyester filament yarn, 8H warp satin after break

Figure 8.31 Polyester spun yarn, plain before break
Figure 8.32 Polyester spun yarn, plain at the moment of break

Figure 8.33 Polyester spun yarn, plain after break
Figure 8.34 Polyester spun yarn, 4x4 R.H. Twill before break

Figure 8.35 Polyester spun yarn, 4x4 R.H. Twill at the moment of break
Figure 8.36 Polyester spun yarn, 4x4 R.H. Twill after break

Figure 8.37 Polyester spun yarn, 8H warp satin before break
Figure 8.38 Polyester spun yarn, 8H warp satin at the moment of break

Figure 8.39 Polyester spun yarn, 8H warp satin after break
9. Conclusions and Future Research

9.1. Conclusions

The objectives of this research were to develop instruments to detect warp yarn breaks in Jacquard weaving using MEMS accelerometers, to evaluate the sensitivity of the MEMS accelerometer installed on harness cords (no contact with warp yarn) throughout signal analysis of the vertical and horizontal accelerations of MEMS and to identify the limitations of the developed system. The objectives were achieved by executing three experimental designs. The collective independent variables of these designs are warp yarn tension, warp yarn type, and weave. Additional experimental design was conducted to reveal the influence of excessive tension/slackness of the warp yarn on the MEMS output signal.

The results of the experimental designs showed that MEMS accelerometers could be used to detect warp breaks except for the cases of hairy yarns with low tensile modulus. Hairy single warp yarns are rarely used in weaving since most of single spun warp yarns are sized. Experimentation with sized spun yarns needs to be conducted to verify this. MEMS accelerometers were found to detect excessive warp yarn tension/slackness. It is known that drop wires do not monitor warp yarn with excessive tension.

Signal analyses of the results indicated that algorithms could be developed to automatically identify warp breaks through establishing threshold of upper and lower limits, peak data width, and frequency analyses of the output acceleration data corresponding to
warp breaks and compare these to data collected before and after break. One or more of these algorithms could be implemented to make a decision to stop the weaving process when a warp yarn breaks, experiences excessive tension, gets slack, or tension reaches very low level. Possible warp break detection algorithm, including excessive tension/slackness, is shown in Figure 9.1.

Figure 9.1 Schematic diagram of warp break detection for excessive tension or slackness
9.2. Recommendations for future research

It is recommended that broader range of yarn types, sizes and tension be used to investigate the range of applicability of MEMS accelerometers in detecting breaks.

The warp break detection system could be integrated with warp break locator system described in Chapter 4. This integration alone could achieve significant time saving by having a system that stops the weaving process when a warp break occurs and physically point at the location of the break.

Since MEMS accelerometers were proven to be successful in detecting warp breaks, automatic warp break repair system based on the proposal by Seyam et al [38] could be developed.
10. References


2. Annual Book of ASTM Standards, Section 7 Vol. 07.01, 2003


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### 11. Appendices

#### 11.1. Tensile Test Results

Table 11.1 16/2 100% Cotton yarn load-extension

<table>
<thead>
<tr>
<th>No</th>
<th>Tex</th>
<th>Peak Load (g)</th>
<th>Elongation at Peak Load (mm)</th>
<th>%Stain at Peak Load (%)</th>
<th>Energy to Peak Load (Kg-mm)</th>
<th>Fiber Modulus (g/Tex)</th>
<th>Fiber Tenacity (g/Tex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73.81</td>
<td>938.38</td>
<td>78.60</td>
<td>30.95</td>
<td>44.54</td>
<td>101.16</td>
<td>12.71</td>
</tr>
<tr>
<td>2</td>
<td>73.81</td>
<td>879.73</td>
<td>68.10</td>
<td>26.79</td>
<td>36.01</td>
<td>105.12</td>
<td>11.92</td>
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<tr>
<td>3</td>
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<td>947.18</td>
<td>75.00</td>
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<td>42.78</td>
<td>104.85</td>
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</tr>
<tr>
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**Mean:** 8377.17  29.45  11.60  122.03  964.19  67.56

**Stdv:** 179.02  0.94  0.37  6.12  44.77  1.44

**CV(%)** 2.14%  3.19%  3.17%  5.01%  4.64%  2.14%
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Mean 20921.34 10.52 4.14 91.00 9960.36 289.69
Stdv 1248.70 0.54 0.21 10.81 348.12 17.29
CV(%) 5.97% 5.15% 5.15% 11.88% 3.50% 5.97%
11.2. MEMS Specifications

The specifications of the Analog Devices ADXL202AE can be viewed at:

http://www.analog.com

Figure 11.1 ADXL 202AE Date sheet (http://www.analog.com)

11.3. Data acquisition system specifications

11.3.1. Computer specifications

CPU: Intel Pentium III 450 MHz, RAM: 256 MB, HDD: 10GB

Windows 2000 (SP1), National Instruments LabVIEW™ version 7

11.3.2. DAQ board specifications


Analog input characteristics:

Number of channels: 16 single-ended or 8 differentials

Type of ADC: Successive approximation

Resolution: 12 bits, 1 in 4,096

Maximum sampling rate (single-channel): 500 kS/s
Digital I/O:
Number of channels: 8 input/output
Max transfer rate: 50 kwords/s, system-dependent
Constant sustainable rate: 1 to 10 kwords/s, typical

Timing I/O:
Number of channels: 2 up/down counter/timers, 1 frequency scaler
Resolution: 24 bits in counter/timers, 4 bits in frequency scaler
Base clock accuracy: ±0.01%
Max source frequency: 20 MHz
Min source pulse duration: 10 ns, edge-detect mode
Min gate pulse duration: 10 ns, edge-detect mode

PCI-6602 (National Instruments)
Timing I/O:
Number of channels: 8 up/down counters
Resolution: 32 bits
Maximum count: $2^{32} - 1$
Base clocks available: 100 kHz, 20 MHz, 80 MHz
Minimum gate pulse duration: 5 ns in edge-detection mode
Minimum pulse width: 200 ns
11.4. Data acquisition programming using LabVIEW™ 7

11.4.1. ADXL202AE and a proximity sensor via PCI-MIO-16E-4 board

PWM from MEMS accelerometer can generate duty cycle and semi-pulse width, which was mentioned in section 4.1.1. Each pulse width is displayed in two dimensions (vertical and horizontal). The PWM is converted into acceleration according to a equations which is provided in ADXL202AE manual (http://www.analog.com). These parameters are displayed in the program panel on the left top of Figure 11.2. After the conversion to acceleration, the acceleration was made to see real-time coordinates in two dimensions on the left bottom. Three graphs in the middle were made to show the final acceleration signal in horizontal and vertical motion, proximity sensor analog output, and their frequencies. Acceleration data were listed in time table on the right side. To support the previous front panel, the following block diagram is shown in Figure 11.3. Three channels are set up in device configuration. Since ADXL202AE MEMS accelerometer provides PWM, the time-counter channels of PCI-MIO-16E-4 were used. One analog input was used for the proximity sensor. This information is sent to loop stages to collect the data with conversion of PWM into acceleration as well as beat-up time. After the program stops, the data are plotted in time and frequency domain. Fast Fourier transform is employed in this analysis as a virtual tool-set (the detail information can be seen at http://zone.ni.com/devzone/devzone.nsf/webcategories/1284E6919C8B33CE862567AF0075696B).

The data saved as ASCII text files which are available in spreadsheet applications. The acceleration data file consists of eight columns to indicate duty cycles and acceleration values.

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Figure 11.2 Front panel
Figure 11.3 Block diagram
11.4.2. Four MEMS accelerometers via PCI-6602 counter/timer

This program was based on the previous program under PCI-MIO-16E-4 board. Since the four MEMS accelerometers were mounted on the harness cords, counter/timer function was intensified with National Instruments PCI-6602 counter/timer board. A program panel in Figure 11.4 shows acceleration signals from four MEMS accelerometers. Real time coordinates are placed beside the time-acceleration plots (Green: vertical motion, Red: horizontal vibration). The duty cycle of PWM is obtained in Figure 11.5. Since the four MEMS accelerometer were used in counter/timer board. The source code was extended from the application on PCI-MIO-16E-4 (Figure 11.3). In Figure 11.6, the block diagram is designed to obtain semi-pulse width. After conversion into acceleration, the statistical values are fundamentally analyzed in Figure 11.7 in order to shift the mean of acceleration to zero because the default is 1 G (gravity) when the MEMS accelerometer stays vertically. The block diagram in Figure 11.8 supports saving the data as ASCII files.
Figure 11.4 Front panel of four MEMS accelerometer DAQ
Figure 11.5 Block diagram of duty cycle measurement
Figure 11.6 Block diagram of semi-pulse width measurement
Figure 11.7 Block diagram of statistical analysis

Figure 11.8 Block diagram to save files
11.4.3. Frequency domain analysis

ASCII files saved by the previous program could be analyzed in frequency domain using Fast Fourier Transform which is introduced in section 6.4.3. Figure 11.9 shows frequency-magnitude and frequency-phase, and supporting block diagram is shown in Figure 11.10. In addition to the frequency analysis, filtering process is coded to smooth the acceleration signal using low-pass filter.

![Figure 11.9 Front panel of frequency analysis](image)

Figure 11.9 Front panel of frequency analysis
Figure 11.10 Block diagram of frequency analysis
11.4.4. Warp break detection in time domain

Based on section 6.4.2, a statistical method was developed to define upper and lower bound. Figure 11.11 shows that the acceleration in horizontal vibration includes warp break beyond upper (red) and lower (green) bound. Figure 11.12 support the detection principle using peak detection. Fundamental information of peak detection is introduced at National Instruments™ developer zone


Figure 11.11 Front panel of warp break detection in time domain
Figure 11.12 Block diagram of warp break detection in time domain
11.4.5. Warp break data scan in frequency domain

As Section 8.2 described the warp break detection in frequency domain, the supporting code is shown in Figure 11.13. In time-acceleration, the sample size is adjustable to scan the data. Frequency plots are demonstrated in Figure 8.22 - 8.39 to investigate the change of frequency and magnitude.

Figure 11.13 Block diagram of warp break data scan in frequency domain