Chapter IV  Preliminary experiments and analysis

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1. Introduction

The definition of monitoring parameters to quantify sewing efficiency and feedback variables for control systems are essential to accomplish the objectives of the project team and of this work.

In this chapter the results obtained up to this point, and the most significant conclusions about the phenomena occurring during sewing, will be studied. The expectation about control and monitoring of sewing variables will be analysed.

The knowledge acquired in this preliminary analysis has been used to define a first set of features and computations that are obtained automatically by the sewability test panels described in chapter V.
2. Needle penetration variables

2.1. Analysis of needle penetration efficiency

Needle penetration is one of the sewing process parameters that has been studied in previous research work [4][7].

Based on the analysis of the results obtained, the processing methods have been further developed in this work. The spectral filtering method has been proposed as an alternative method to the elimination of parasitic components in the signals acquired by the needle-bar sensor. The whole measurement process has been streamlined and adequate graphical display tools were developed.

In this section an insight is given on the process with experiments that have been conducted using the initial approaches to signal processing (see 2.3). These show the behaviour of the needle penetration variables in different situations and have been described in [8][10][11][13].

The first observation that can be made on needle penetration signals is that one penetration can significantly differ from another (Figure IV- 1)

The example clearly shows the different behaviour of penetration force from stitch to stitch. This effect is expected because the fabric structure is not homogeneous, so the needle can penetrate through different points on the fabric: yarns, spaces between yarns and yarn crossings, naturally producing different penetration forces.

Figure IV- 1: Pre-processed needle-bar signal, three penetrations represented. Shaded areas represent the phases in which the needle is inside the fabric.

Figure IV- 2 shows a typical needle penetration waveform, obtained on a medium-weight denim fabric with a needle of size 90.
A detailed analysis of the angles at which penetration and withdrawal occur has led to a division of the needle penetration process in three phases:

1. First contact of needle tip with the fabric, a first force peak is produced;
2. The needle passes through the fabric. The shaft penetrates and produces a second peak;
3. The needle inverts its movement and the fabric holds the needle, producing a third, inverted force peak (a valley).

Each stitch is divided in the three phases described and features are calculated in these phases. The most representative features are the peaks/valley and power. The latter is able to describe the signal for the whole phase interval, whilst the peak measurement delivers a value that is measured on a single sample and may not be able to reflect what is happening during the remaining time.

After this processing, the feature values extracted may be represented in two ways:

- A graph in which the values for each feature are represented according to their chronological order;
- A 3-dimensional graph, in which a point is plotted for each stitch, being its coordinates the 3 feature values extracted from the stitch.

Although the two representations are complementary, the latter has led to very interesting results concerning the needle penetration behaviour in relation to materials, needle size and other factors. Figure IV-3 shows the 3D graphs obtained with two different needle sizes (70 and 90) on a light plain weave fabric and on a denim fabric, acquired at low sewing speed (350 spm).
Figure IV-3: 3-dimensional representation of peaks/valley extracted from needle penetration signal. Needle size 70 (blue) and 90 (red) on a light plain weave (left) and on a denim fabric (right).

The figures show a clear distinction between the two different needles, being the difference in penetration force produced on the light plain weave fabric more evident than in the denim fabric.

The 3-D graph has the ability to exhibit the clustering of values produced by a certain sewing condition. It has been observed that the clustering and the patterns generated by different sewing conditions depend on material characteristics and other sewing factors, namely number of plies, needle size, etc. The correct interpretation of the patterns and its quantification can lead the way to the automatic monitoring of needle penetration. Some examples are presented next.

---

1 The angles of the following graphs have been chosen to emphasize the effects that are to be shown. Using the software, the graph may be interactively rotated, which makes it much easier to observe the patterns than in a printed document.
As shown in Figure IV-4 a clear clustering is also observable among peaks/valley of penetration force when sewing a different number of fabric plies. When comparing the values obtained in this case (peak and power values) with those presented in Figure IV-3 it is possible to notice a higher linear dependency between the values in the different phases.

In fact, when the needle passes through a thicker zone of the fabric the penetration forces are higher in all of the three phases, whereas when it passes through a thinner part lower values of penetration forces are encountered. This is an expectable phenomenon but may be impaired if the needle produces damage on the fabric: In this case, a high force would only exist until the breaking of the yarn(s) occurs, the linear dependency would be lost for subsequent penetration phases.

The next example compares penetration forces obtained under the same sewing conditions and fabric structure but with different fabric finishing (softening).
In this situation, the shift of the average penetration force values is only clear in a quantitative analysis. However it is evident in the graph that one of the fabric samples produces a higher spread of values. This spread is also considered a parameter of significance to describe the penetration process. It depends highly on the properties of the material that is being sewn (and thus on the material’s sewability), but needle condition (namely tip damage) may also influence this parameter.

To evaluate the influence of needle condition on penetration forces, a needle has been deliberately damaged, (rubbing its tip). No concern on the exact type of damage produced on the needle has been put into this experiment - it was used to test the ability of the system to detect differences between the two needles. Figure IV-6 shows the outcome of this experiment.

Figure IV-5: Penetration peak force patterns for two different finishing processes (blue and yellow) obtained with an interlock knitted fabric. Sewing speed 3500 spm, 90 needle size, two plies.
The damaged needle produced lower penetration forces and power values than the new needle. This fact seems like a contradiction, but it is explainable by the type of damage that has been produced on the needle tip. If the needle has been sharpened to produce a cutting edge, then penetration forces will be lower than with the new needle.

This means that the simple measurement of penetration force values has to be complemented with other parameters to fully describe the efficiency of the process. One of these parameters is the linear dependency of values between phases. Another parameter may be the relation between the values in the individual penetration phases.

When a needle penetrates without affecting the fabric's structure, the fabric will oppose resistance to the needle during the whole penetration and withdrawal process. Moreover, some relation between the forces or power of the penetration signal in the different penetration phases can be expected.

If the needle breaks one or more yarns, lower values are expected in the remaining phases of the process. A preliminary evaluation of this fact has been carried out defining a feature ratio used as a shape factor for the penetration signal:

\[ R_{mn} = \frac{F_m}{F_n} \]  

(1)

where

\[ F_m \]  

Feature Value in phase \( m \)
This ratio has been computed on the data obtained with a damaged and a new needle (Figure IV-6) for peak and power values. Although showing some difference in the peak ratios, power ratios have been found to distinguish the two situations more clearly, as shown in the following figures.

Figure IV-7: Ratio of power values between phases 1 and 2, new and damaged needle

Figure IV-8: Ratio of power values between phases 1 and 3, new and damaged needle

Figure IV-9: Ratio of power values between phases 1 and 2, new and damaged needle

The graphs presented show that \( R_{12} \) and \( R_{13} \) are lower for the new needle, whilst \( R_{23} \) seems to remain similar in average. Assuming that using the damaged needle, the yarn has been cut in phase 1 of penetration, the forces in phase 2 and 3
would be lower than with a new needle. This would produce higher $R_{12}$ and $R_{13}$ ratios for the damaged needle, whilst the $R_{23}$ would remain equal.

To enable additional studies on needle penetration efficiency the following tools were developed and have been implemented in specific processing routines:

- Display tools: Chronological and 3-D graphing;
- Measurement of absolute values;
- Parameters able to describe spread of values;
- Ratios of feature values;
- Linear correlation between feature values.

Prior to the implementation, however, a fundamental issue had to be analysed: the optimisation of the measurement process regarding the pre-processing of the needle-bar signals. This study is presented in the next sections.

2.2. Physical set-up of the sensing device, consequences

As described earlier, the effect of needle penetration and withdrawal is measured using a piezoelectric sensor introduced into the needle-bar. This means that three effects are present on the signal picked up by the sensor:

1. Forces necessary for the needle-bar’s motion;
2. Forces produced on the needle-bar by thread motion;
3. Forces produced by the interaction between needle/thread and fabric.

2.2.1. Forces related to needle-bar motion

The forces produced by the link mechanism (a crank-connecting rod) used to produce the linear oscillating movement of the needle-bar are observed as an imperfect sine wave. (Figure IV- 10)

Some disturbances due to mechanical imperfections of the machine are clearly visible. These tend to disappear at higher speeds (Figure IV- 11), which can be explained either by mechanical absorption or by loss of response of the sensor. The smoother signal at high speeds also emphasizes the fact that the signal is not
a pure sine wave, but contains harmonics besides those produced by isolated discontinuities.

Spectral analysis confirms this observation and shows that the signal’s spectral content slightly changes with sewing speed. This can be observed in Figure IV-12, where spectra of signals acquired at three different speeds are depicted.

Figure IV-11: Force on needle-bar, acquired at 4818 s.p.m., without fabric and thread

Figure IV-12: Normalized spectra of signals acquired at three different speeds. Harmonics 2 to 17 represented, amplitudes normalized relative to the amplitude of the fundamental component

The graph shows a significant increase of harmonic 3 at higher speeds, an important observation for the filtering analysis that will be presented in a later

---

1 The normalized frequency scale, a feature of the AST software, is obtained by dividing the frequency scale by the fundamental frequency of the signal. The fundamental frequency is the rotation frequency of the machine.
section. Harmonic 2 does not show a monotonic behaviour with rising speed, but reveals to be more significant at low speed.

The amplitude of the motion forces picked up by the sensors is proportional to the square of sewing speed, i.e. to the angular speed of the crank.

2.2.2. Needle penetration and withdrawal forces

Figure IV-13 shows the waveform obtained when a fabric is stitched, superimposed on the waveform presented in Figure IV-10. The machine has been kept unthreaded.

In this case, the resistance of the fabric to the penetration and withdrawal of the needle generates a disturbance on the force signal.

This disturbance represents the effect whose measurement is desired. The ratio of its energy to the energy of the remaining effects is fundamental for an accurate measurement, since the remaining effects have to be filtered without loss of information. In the situation depicted in Figure IV-13, both motion forces and penetration are comparatively low, since speed is low (649spm) and only one layer of a light fabric is being stitched.

2.2.3. Forces related to thread motion

In a stitch formation cycle, there is always an amount of excessive thread that is supplied in order to allow loop or thread interlacing, and that is then pulled back to tighten the stitch. This results in thread being constantly pulled up and down.

The needle itself is used to pull the thread down to the interlacing point, and the thread take up pulls the thread back after interlacing. In both situations, force is produced on the needle-bar. Its effect is shown in Figure IV-14.
The additional disturbance produced by thread forces makes the measurement more difficult to carry out, but has to be considered in a real-time situation. An important remark to make is its apparent similarity to the needle thread tension waveforms picked up by the tension sensor. These can possibly be used in pre-processing algorithms to cancel out the undesired effect. Figure IV-14 depicts a situation in which the interaction of needle and fabric is relatively small (very fine fabric, one ply), and is therefore of the order of magnitude of the disturbance produced by thread motion; this is the most unfavourable situation.

Considering the objectives of this work, it is clear that only the interaction between the needle and the fabric is of interest for the measurement. The remaining two effects have to be filtered and compensated for in a pre-processing stage.

It is interesting to observe that the thread is part of the needle in the needle-fabric interaction. In fact, it occupies space around the needle and also produces friction with the fabric. The forces produced by thread motion, though, are uninteresting.

For a real-time, industrial application, all of the three effects have to be considered and accounted for. For research purposes, however, unthreading the machine can eliminate the effect of thread motion. Experimentation is then performed stitching the material without thread, thus eliminating the effect thread motion.

However, in this case, the effect of the thread on penetration itself is neglected. As described in II-1.2.3, sewing needles are devised with a long groove to protect the thread during needle penetration, meaning that the effect of the thread is likely to be insignificant when compared to the interaction between the fabric and the needle by itself. This suggests that the measurement obtained without thread is still able to depict the penetration process adequately. The only situation in which the presence of thread is known to actively influence the penetration is when needle heating occurs; the thread is an important element to dissipate the thermal energy present and its presence may lead to different results.
The effect of motional forces, however, cannot be removed from the acquired signals, and methods for filtering this effect with a minimum loss of useful signal power have to be found.

Thread presence will be neglected in the first stages of this work to allow a simpler pre-processing and more accurate observation of the needle-fabric interaction by itself.

2.3. Possible solutions for signal pre-processing

2.3.1. Angle-scale referenced subtraction of “void” signals

The first approach that was used to eliminate the motional forces consisted of a direct subtraction of a signal acquired without fabric (“void” signal) from a signal acquired using fabric [4] [7]. The difference obtained represented the needle-fabric interaction. The effect of thread forces was eliminated working without thread.

This method has several limitations and restrictions that rendered it inadequate for a real-time application:

> The void signal has to be acquired at the exact sewing speed as the signal from which it is subtracted;

> The seams must be produced at constant speed, because speed variations produce variations of the amplitude and distortion of the x-scale of the signals. Although it is possible to eliminate the latter using synchronized acquisition (see III-6), in practice, amplitude variations cannot be compensated for. This occurs especially when speed variations are quick and large, as occurs in most industrial situations.

> Differences in the offset of the two signals may produce errors.

> Subtraction of the void signal assumes that the motional forces are as stationary in the presence of fabric as they are when the void signal is acquired. As Figure IV-15 shows, this is not the case when penetration and withdrawal forces become significant compared to motional forces. The fabric produces fluctuations of the signal levels that are not present in the void signals.

---

1 Actually, it is possible to conceive a sewing machine with two equal needle-bars and sensors, in which one of them does not penetrate the fabric. One signal could be subtracted from the other. In practice, though, this concept is difficult to implement.

2 In the context of needle penetration analysis only, signals acquired without fabric will be designated as void signals, whereas loaded signals are those acquired with fabric.
In spite of these limitations and in controlled situations this method was used to carry out several studies [7]. A significant improvement to the method was the "Referenced Subtraction" operation [7] that scales the void signal to the time-scale of the useful signal before subtracting it, allowing the compensation of minor speed differences.

2.3.2. Spectral filtering and reconstruction

Although the spectral analysis of void and loaded signals had shown that the penetration effect and the motion forces slightly intersect in the frequency domain, both effects appeared sufficiently separated to allow the use of digital filtering techniques. These should deliver the pre-processed signal that represents useful information only. Once again, the effect of thread forces is eliminated by unthreading the machine.

In an attempt to approximate the filter as closely as possible to an ideal filter, an FFT-based spectral filtering and reconstruction method was implemented.

The first approaches to the definition of the filter's stopband were based on experiments using different sewing speeds, fabrics and number of layers. The resulting definition was based mostly on the analysis of void signals. The aim was to minimize the power and signal peaks detected by phase-processing on filtered void signals. The stopband derived from these studies eliminated the component 0 (DC), 1 (fundamental), 2 and 3. According to the adopted naming convention this is stopband "0-1-2-3".

The results obtained with the spectral filtering method were very similar to those produced by referenced subtraction; distinction between different sewing conditions was possible, although the results were not exactly the same.

The advantage of the spectral filtering method is that it is far more practical and systematic than referenced subtraction. Furthermore, the fluctuation in signal levels that can be observed in Figure IV-14 are slow and thus produce components with a lower frequency than the fundamental frequency of the signal. These can be totally eliminated by a filter that removes the frequency band between dc and the fundamental component.

To quantify the accuracy of the measurement method, a known reference for the desired signal is necessary. In the present case, the desired effect - the pure fluctuation of the signal when fabric is present.
needle penetration forces cannot be isolated, meaning that this evaluation can only be carried out by simulation. This led to the development of a simulation program that will be presented in the next section.

2.4. Simulation of penetration signals and processing methods

2.4.1. Simulation program

To evaluate measurement performance, a program was designed to interactively generate simulated penetration signals and perform the entire processing sequence on them.

Most of the Labview code previously created for signal processing was re-used in this program. The objective of the simulation program is to supply an interface allowing the user to interactively modify the processing parameters and immediately observe the result. The program was complemented with signal generation routines that created simulated penetration signals resembling as much as possible their real counterpart.

The resulting program was named “Anfil”. Figure IV-16 illustrates its structure:

![Figure IV-16: Structure of the Anfil program](image)

Basically, the program compares the result of extracting features directly from the simulated penetration signal, with those obtained after mixing the penetration signal with a void signal and filtering it. In this way, the pre-processing scheme can be optimised. Furthermore, it is possible to export the original signals to text files, filter them in another program, and import the filtered signal in the same format. This allows the trial of alternative filtering methods in place of the FFT-based filtering implemented in Anfil.

Figure IV-17 shows a picture of the program’s user interface, in which the blocks described in Figure IV-16 can be identified. As the studies conducted using this tool evolved, new program code was developed to automate some tasks and to introduce new processing functions.
The Anfil provides the following parameters and methods to evaluate the filtering performance:

- Direct comparison of values, as shown in Figure IV-17, in which the bars in white display the values extracted from the original signal \( F_{\text{original}} \), and the bars in red display the values extracted from the filtered signal \( F_{\text{filtered}} \);

- Gain for penetration \( G_i \)

\[
G_i = \frac{F_{\text{filtered},i}}{F_{\text{original},i}}
\]  

(2);

- Average gain \( \overline{G} \)

\[
\overline{G} = \frac{1}{N} \sum_{i=0}^{N} \frac{F_{\text{filtered},i}}{F_{\text{original},i}}
\]

(3);

- Relative error for penetration \( E_i \)

\[
E_i = \frac{F_{\text{filtered},i} - F_{\text{original},i}}{F_{\text{original},i}} \cdot 100
\]

(4);

- Coefficient of variation of gain \( CV_G \)

\[
CV_G = \frac{\sigma_{\text{Gain}}}{\text{Gain}} \cdot 100
\]

(5);
where

\[ \sigma_{\text{gain}}: \text{Standard deviation of the gain} \]

> Input/Output Correlation (\textit{CORR})

\[
\text{CORR} = \frac{\text{Cov}(F_{\text{original}}, F_{\text{filtered}})}{\sigma_{\text{original}} \cdot \sigma_{\text{filtered}}}.
\] (6)

where

\textit{Cov}: Covariance

\[ F_{\text{original}} \] Set of original feature values

\[ F_{\text{filtered}} \] Set of feature values extracted from filtered signal

\[ \sigma_{\text{original}} \] Standard deviation of original feature values

\[ \sigma_{\text{filtered}} \] Standard deviation of values extracted from filtered signal

2.4.2. Signal models

To define models for penetration signals, real signals were pre-processed using the subtraction method and the result was observed in several situations. The next figure shows examples of a penetration signal obtained in this way.

![Figure IV-18: A typical penetration signal, obtained by the subtraction method](image)

Previous studies have shown that the penetration signals have three important phases: Contact, penetration and withdrawal phases [4][7]. These three phases exist in most situations, even when in some cases the withdrawal peak becomes insignificant, as previously stated.

Regarding amplitude and energy in the three phases, some facts have been observed:
> Their values are highly variable, depending on the penetration point (through
yarn, space between yarns, yarn crossings), but force is detected in every
penetration.

> The relation of the individual peak amplitudes among themselves varies with
needle and materials used. It is expected to have some deterministic relation to
the material and sewing behaviour of the needle.

As can be observed in Figure IV-18, the signal contains quick variations and bursts
that are the consequence of the penetration process itself and of electrical and
mechanical noise. These quick variations are contained in higher frequency
bands and will be unaffected by the high-pass filtering optimised in this study. For
the purposes of the study, the simulated penetration signal can thus be a
smoother signal.

Following these considerations, penetration was simulated by composing a signal
in accordance to the three penetration phases. Each phase was simulated by
half a period of a sine wave or triangular wave.

Defining

\[ A_p: \text{ Amplitude of the signal in phase } p \]
\[ \delta_{\text{lower},p}: \text{ Lower phase interval limit of phase } p \text{ [deg]} \]
\[ \delta_{\text{upper},p}: \text{ Upper phase interval limit of phase } p \text{ [deg]} \]

the sine-based penetration signals are defined as

\[
p(\alpha) = \begin{cases} 
A_1 \cdot \sin \left( \frac{\alpha - \delta_{\text{lower},1}}{\delta_{\text{upper},1} - \delta_{\text{lower},1}} \cdot 180 \right) & \delta_{\text{lower},1} \leq \alpha < \delta_{\text{upper},1} \\
A_2 \cdot \sin \left( \frac{\alpha - \delta_{\text{lower},2}}{\delta_{\text{upper},2} - \delta_{\text{lower},2}} \cdot 180 \right) & \delta_{\text{lower},2} \leq \alpha < \delta_{\text{upper},2} \\
A_3 \cdot \sin \left( \frac{\alpha - \delta_{\text{lower},3}}{\delta_{\text{upper},3} - \delta_{\text{lower},3}} \cdot 180 \right) & \delta_{\text{lower},3} \leq \alpha < \delta_{\text{upper},3} \\
0 & \text{outside the intervals}
\end{cases}
\] (7)

Defining interval width \( w \) as

\[ w = \delta_{\text{upper},p} - \delta_{\text{lower},p} \] (8)

the triangular-based penetration will be obtained, for each of the 3 phases \( p \), as

---
^1 There are exceptions, like very open knitwear: Penetrating into a hole may
signify not making contact with the fabric at all.
Varying the amplitudes $A_p$ and the phase interval limits, several signal models have been developed of which the most important are presented and analysed.

1. **Constant amplitude (Cons)**
   This is the first and simplest case, in which the amplitude of each penetration burst is constant and equal to $A_p$ throughout the set of penetrations generated.
   This method is quite unrealistic but revealed some important insights that will be presented later.

\[
p(\alpha) = A_p \begin{cases} 
\frac{2(\alpha - \delta_{\text{lower},p})}{w} & \delta_{\text{lower},p} \leq \alpha < \delta_{\text{lower},p} + \frac{w}{2} \\
1 - \frac{2(\alpha - \delta_{\text{lower},p} - \frac{w}{2})}{w} & \delta_{\text{lower},p} + \frac{w}{2} \leq \alpha < \delta_{\text{upper},p} \\
0 & \text{outside the intervals}
\end{cases}
\]

Figure IV-19: SinCons and TriCons signal models, base amplitude 1000 for all three phases, 4 periods represented

2. **Variable amplitude (Var)**
   In this case, the amplitude is obtained, for each penetration and phase as

\[
A_p = A_{bp} \cdot \text{random}(0;1)
\]

where
$A_{bp}$: Base amplitude value of the signal in phase $p$

A new random number is generated for every phase $p$.

![Graph](image1)

Figure IV-20: SinVar signal model, base amplitude 1000 for all three phases, 4 periods represented

The Var signal model was the first attempt to create varying penetration forces, but still unrealistic considering that needle penetration is not a totally random process.

3. **Variable Amplitude 3 (Var3)**

This variant uses the same random number to multiply the base amplitude, but for the three phases:

$$r = \text{random}(0;1)$$  \hspace{1cm} (11)

$$\begin{cases} 
A_1 = A_{b1} \cdot r \\
A_2 = A_{b2} \cdot r \\
A_3 = A_{b3} \cdot r
\end{cases}$$ \hspace{1cm} (12)

![Graph](image2)

Figure IV-21: SinVar3 signal model, base amplitude 1000 for all three phases, 4 periods represented

In this model the attempt was to maintain variability in the signal, but linking the three phases and creating some dependency between them. This is

$^1$ The “random(0;1)” function provided by Labview generates random numbers between 0 and 1 with a uniform distribution.
justified by the real process: a thicker zone on the fabric will generate higher penetration forces in all three phases when compared to a thinner one. Still, in real signals this dependency is not as strong as in the SinVar3 model.

4. **Variable amplitude 4 (Var4)**
This model assumes a constant amplitude “floor” of 1/3 the base amplitude and a variable amplitude within the remaining 2/3. Like the Var model, a new random number is generated for each penetration and phase.

\[ A_p = A_{bp} \left( \frac{1}{3} + \frac{2}{3} \cdot \text{random}(0;1) \right) \]  

(13)

![Figure IV-22: SinVar4 signal model, base amplitude 1000 for all of the phases, 4 periods represented](image)

The Var4 model is very close to reality as penetration force is always present in the three phases of penetration. Although discarding the dependency between the three phases, this model is adequate for filtering optimisation, as will be analysed later.

5. **Variable amplitude 5 (Var5)**
This type of signal is very similar to the Var4 model, with the difference that every 5 penetrations the generated amplitudes are multiplied by a factor of 5.

![Figure IV-23: SinVar5 model, base amplitude 1000, 23 periods represented](image)

This signal model was created to simulate irregular or open material structures, in which very different resistance is opposed to penetration depending on the fabric zone that is penetrated by the needle. The objective of this model is to
test the performance of the pre-processing algorithms in the detection of these singular values.

6. Variable amplitude 7 (Var7)
In the Var7 signal model, pulse width is varied. Amplitude variation is generated in the same way as in the Var4 model, and the same type of law is used to modify the width of the phase intervals defining

\[ w_{p} = w_{bp} \cdot \left( \frac{1}{3} + \frac{2}{3} \cdot \text{random}(0;1) \right) \] (14)

The objective of varying the pulse width is to simulate the real case, in which there is not always a smooth pulse extending over the whole phase, but a shorter pulse or multiple short pulses. As will be seen in the next section, shorter pulses are easier to reconstruct after a high-pass filtering operation, since the energy is moved into higher frequency bands, when the pulse becomes shorter.

2.4.3. Phase intervals
Based on the observation of numerous real signals and by the examination of the stitch formation cycle, the following phase intervals were determined:

Table IV-1: Phase intervals used for the simulated penetration signals

<table>
<thead>
<tr>
<th>Phase</th>
<th>( \delta_{\text{lower}} )</th>
<th>( \delta_{\text{upper}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>258°</td>
<td>300°</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>360°</td>
</tr>
<tr>
<td>3</td>
<td>360°</td>
<td>460°</td>
</tr>
</tbody>
</table>

These angles were defined according to the calibration of the synchroniser, that delivers a pulse when the needle is at its lowest point in the trajectory. As shown in Table IV-1, phase 3 of the stitch cycle lies beyond 360°, which is related to the calibration of the synchroniser. For practical reasons, in the Anfil program angles larger then 360° are not accepted. Phase 3 is thus generated by a phase interval of 0 to 100°, preceding phase 1 and 2.

2.4.4. Properties of the signal models
To assess the properties of the signal models created, the SinCons model, as the simplest case, is analysed.
It is possible to decompose this signal in three half-periods of a cosine wave. The sum of signals in the time domain results in a sum in the frequency domain. Each of the three half-period cosines can be modelled as the multiplication of a square pulse by a pure cosine, as represented in Figure IV-24.

\[ f(t) = h(t) \cdot g(t) \]  
\[ f(t) = \text{rect}(\frac{t}{\tau}) \cdot \cos(2\pi f_0 t) = \text{rect}(\frac{t}{\tau}) \cdot \cos(\omega_0 t) \]  

with

- \( f_0 \): frequency of cosine
- \( \omega_0 \): Angular frequency

The Fourier transform of \( f(t) \) can be obtained by the convolution of the spectra of the multiplying functions:

\[ f(t) = h(t) \cdot g(t) \iff F(\omega) = H(\omega) * G(\omega) \]
The transform of the square pulse is given by

\[ H(\omega) = \tau \text{sinc} \left( \frac{\omega\tau}{2} \right) \]  

(18)

whereas the transform of a cosine function presents an impulse function at \( \omega_0 \) and \( -\omega_0 \) and is described by

\[ G(\omega) = \pi \left[ \delta(\omega - \omega_0) + \delta(\omega + \omega_0) \right] \]  

(19)

Applying the convolution equation

\[ f(x) * g(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(x - \lambda)g(\lambda)d\lambda \]  

(20)

the following expression is obtained

\[ G(\omega) = \frac{\tau}{2} \int_{-\infty}^{\infty} \left[ \delta(\omega - \lambda - \omega_0) + \delta(\omega + \omega_0) \right] \text{sinc} \left( \frac{\lambda\tau}{2} \right)d\lambda \]  

(21)

Considering the properties of the impulse function, the integrand has nonzero value only when \( \lambda = \omega - \omega_0 \) and \( \lambda = \omega + \omega_0 \). The convolution between the impulse and the sinc functions results in a shift of the sinc functions to the frequencies of the impulses:

\[ G(\omega) = \frac{\tau}{2} \left[ \text{sinc} \left( \frac{\omega - \omega_0}{2}\tau \right) + \text{sinc} \left( \frac{\omega + \omega_0}{2}\tau \right) \right] \]  

(22)

In the specific case of the half-cosine generated by the simulation program, the following relation verifies

\[ \tau = \frac{T_0}{2} = \frac{1}{2f_0} = \frac{\pi}{\omega_0} \]  

(23)

and thus equation (22) can be rewritten as

\[ G(\omega) = \frac{\tau}{2} \left[ \text{sinc} \left( \frac{\omega\tau - \pi}{2} \right) + \text{sinc} \left( \frac{\omega\tau + \pi}{2} \right) \right] \]  

(24)

Figure IV-25 shows the two sinc functions that are being summed to obtain the final spectrum:
As can be seen, the spectrum is a sum of two sinc functions centred on the frequency $\omega = \pm \frac{\pi}{\tau}$. This means that the centre of each sinc function will move into higher frequencies and the signal will contain more energy in higher frequency bands when the pulse width $\tau$ decreases. This can be observed in Figure IV-26.

---

**Figure IV-25:** Spectrum of half-cosine pulse as sum of two sinc functions

**Figure IV-26:** Spectrum of half-cosine pulse with different pulse widths
Another important property of the spectrum is that it presents zeros at the frequencies \( f = \pm \frac{3}{2\tau}, \frac{5}{2\tau}, \frac{7}{2\tau} \) [14].

Although this development has been performed on a finite pulse using the Continuous Fourier Transform, it is also applicable to the Discrete Fourier Transform and to periodic signals.

The periodic half-cosine pulse waveform used for simulation of the penetration signals is represented in Figure IV-27.

For simplicity, it will be assumed that \( T_{sc} \) is an integer multiple of \( \tau \). In this case, the spectrum of the function that is being multiplied by the square wave is a pure cosine and presents a single component at frequency \( f = \pm \frac{1}{\tau} \).

The resulting spectrum has the same shape as the one presented in Figure IV-26, but with discrete harmonics repeating at every frequency \( f = \pm \frac{n}{T_{sc}}, \ n = 0,1,\ldots \), as shown in Figure IV-28.
It is quite clear that the frequency distribution of energy depends on the width of the pulse, $\tau$, just like in the non-periodic case. This is a very important issue, because the filtering process proposed extracts a stopband defined by specific harmonics of the periodic signal. This means that the amount of energy that is eliminated from the signal, and thus the distortion caused by the filtering process, depends on the pulse width.

Penetration signals generated by Anfil have neither a constant amplitude nor is the period of the signal an integer multiple of the pulse width. This means that the base function that is being multiplied by a square wave has a spectrum that is not as simple as the spectrum of a pure cosine function. Nevertheless, the conclusions drawn about the effect of pulse width apply because they result from the spectrum of the square wave.

There is still a last very important effect of the convolution worthy of note. The convolution of the base function's spectrum with a sinc function has the effect of repeating the base function's spectral information over the whole frequency spectrum, albeit scaled by the sinc's amplitude. This means that even after filtering individual harmonics, the information of the base signal is still concealed in the resulting signal and may possibly be recovered.

2.4.5. Effect of spectral filtering on the different signal models

This analysis has been performed using the Anfil program and the 0-1-2-3 stopband defined in the first experiments. The features were extracted with zero correction to compensate the elimination of the dc component.

Although the Anfil program can generate sine or triangular-shaped signals, early trials showed insignificant differences in measurement performance when changing the shape of the signals. The sinusoidal shape was then chosen for the study.

The most important factors for the errors produced by the measurement process are the amplitude and pulse width distributions.

Amplitude variation is one of the most important factors influencing performance. It has been found that error is constant when amplitudes are constant, and tends
to spread when variability of the amplitudes increases. Figure IV-29 and Figure IV-30 illustrate the relative error for 30 penetrations on signals with increasing amplitude variability: the SinCons, SinVar4 and SinVar models. The signals were generated with the same base amplitude in all of the stitch cycle phases.

![Figure IV-29: Relative error in peak measurement over 30 penetrations, SinCons vs SinVar4 signals](image)

![Figure IV-30: Relative error in peak measurement over 30 penetrations, SinVar signal. Left graph zoomed in, right graph zoomed out](image)

The SinVar signal sporadically produces some very high relative errors. These are due to very low input values, where even a low absolute error may produce a high relative error. (Three of the values visible in Figure IV-30 are actually outside of the range depicted)

It is clear that amplitude variation has to be taken into account, which means that the SinCons model is not adequate for the optimisation of the measurement process. Particularly, the ratio of amplitudes between phases has a major influence on the measurement result. This will be studied in further detail in 2.4.7.

Considering that the needle penetration process is not totally random, other models with variable amplitude should be preferred to the SinVar model. In this circumstance, it is important to examine the following factors and their effect on measurement performance:

> Dependency of the amplitudes between phases, which can be simulated with the SinVar3 model
> Variable pulse width, simulated by the SinVar7 model

The SinVar3 model implements dependency between phases generating a single random amplitude for the three phases within a stitch cycle. As can be seen in Figure IV-31, measurement performance is much better using the Var3 model than the Var4 model. Actually, the dependency will generate a much less variable signal, as amplitude varies only from cycle to cycle, as opposed the Var4 model.
This means that an optimal filter for Var4 will also be adequate to a Var3 type penetration model. Moreover, the dependency implemented in the SinVar3 model is not as evident in real signals.

To analyse the effect of pulse width variation the SinVar7 model was studied. In this model, the width of the penetration bursts is varied. As already stated, shortening the pulses moves energy to higher frequencies, and the signal is less affected by the filtering process.

To confirm this statement, spectra for periodic half-period cosine pulses of different width have been generated and are illustrated in Figure IV-32.

For comparison purposes, the three signals have been normalised to the same energy. The energy $E$ of a half-period cosine pulse of amplitude $A$ and width $w$ can be calculated as

$$E = \frac{A^2}{2} \cdot w$$  \hspace{1cm} (25)

If the pulse width is changed by a factor of $d$

$$w_{\text{new}} = d \cdot w$$  \hspace{1cm} (26)
energy is maintained by equalling the energy of the two pulses, which leads to the following expression:

\[
\frac{A^2}{2} \cdot w = \frac{A_{new}^2}{2} \cdot w_{new} = \frac{A_{new}^2}{2} \cdot d \cdot w
\]

The new amplitude will be computed as

\[
A_{new} = \frac{A}{\sqrt{d}}
\]

Figure IV-32 clearly shows that shortening pulses results in a transfer of energy from lower to higher frequency bands, with a larger bandwidth. This effect should also be present when comparing a SinVar4 signal with its normalized SinVar7 counterpart.

Figure IV-33 compares the spectra of these signals, generated using the phase intervals presented in Table IV-1. The average width of a SinVar7 signal is \(2/3\) of its SinVar4 counterpart (see eq.(14)), thus its energy has been normalised to the SinVar4 signal using \(d=2/3\).

![Figure IV-33: Harmonics of SinVar4 vs SinVar7 signal models. Normalised energy](image)

The previous statement is confirmed: the SinVar7 signal contains less energy in harmonics 1 to 5, and more in higher frequencies than the SinVar4 signal. The consequence of this fact to the filtering analysis is that in the SinVar7 model, less energy will be filtered by a high-pass filter with a stopband at the first 3 harmonics. This is the reason why the SinVar4 model, as a “worst-case” model, is used in further analysis.

The SinVar4 model is thus a “worst-case” situation and was chosen to be used in the optimisation of the filtering process. An example of a signal generated with this model and the result of the filtering process are depicted in Figure IV-34. The

---

1 The extracted harmonic amplitudes are shown instead of the whole spectrum for easier observation of the graph.
existence of a measurement error is evident and its minimisation will be further detailed.

2.4.6. Detection of singular values: The SinVar5 model

One of the important aspects of needle penetration monitoring is the detection of singular values. In certain types of defects or machine malfunctions, a singular force value should be detected by the system. This can happen in several situations, e.g. when the needle crosses a thicker point of the material (a cross-seam, for example), when it is damaged after hitting another component of the machine (the looper or hook), or when it breaks the yarn.

The measurement system should not only correctly measure the force value, but it should also be able to indicate the stitch where it occurred. This indication is particularly useful to enable the identification and analysis of the abnormal stitch on the seam.

Preliminary experimentation with the Anfil program, using the SinVar5 signal model, has shown that the filtering process does not compromise the detection of singular values. However, measurement becomes distorted in the vicinity of these singular values.

Figure IV-35 shows the peak value of phase 2, extracted from the original and from the filtered signal. As can be seen, the singular values are detected from the filtered signal in the correct period of the signal.
A close observation of Figure IV-36 shows an increase of gain in the period immediately following the singular value.
Similar results are obtained with different stopbands; just as the remaining values, the singular values are attenuated in proportion to the number of components that are eliminated from the signal.

2.4.7. Effect of amplitude ratios on the measurement error

After setting up the Anfil program, the effect of the filter on the output was experimented with. One of the immediate conclusions drawn was the dependency between the output and the ratio of the amplitudes of the three penetration bursts.

As an example, SinCons type signals with two different amplitude ratios (1:1:1 and 1:3:2) are filtered with a 0-1-2-3 stopband. Figure IV-37 shows the gain for the peak value, resulting for every stitch and phase.

The variable distortion of the signal can be justified by the removal of the DC component alone.

It can be shown that the average value of a sine half-period is

$$\bar{x} = \frac{A}{\pi}$$

(29)

Thus, the average of the composed SinCons signal can be written as
The average value subtracted from the signal by elimination of the DC component is dependent on the amplitudes of the three sine half-periods of which the signal is composed. The end result will therefore depend on the ratio of the three amplitudes. The elimination of the fundamental and harmonics has the same effect, that is, an amplitude-dependent distortion of the output signal.

Extending this approach to a SinVar and other signals in which amplitudes vary from stitch to stitch, it is possible to understand that the result depends not only on the amplitudes within the period (=stitch), but also of the amplitudes in the remaining periods.

This confirms that with a variable input signal, variable measurement errors are produced; the spread of the error is dependant on the spread of the input signal. A SinCons signal therefore presents a measurement error that is constant over all stitches, whilst a SinVar signal presents a variable error from stitch to stitch.

This conclusion is very important to the analysis of real penetration signals. One of the studies to be performed is the analysis of the ratio of penetration and withdrawal forces in the three phases, seeking for rules to monitor needle penetration. Bearing in mind that the error is variable from stitch to stitch, it will be difficult to monitor needle penetration on a “local” stitch basis. Instead, needle penetration must be observed statistically over a whole set of stitches, unless a method is found to correct the mentioned errors.

The elimination of the dc component can be compensated with zero correction, but the elimination of the AC components is more difficult to be dealt with.

In the Anfil program, in which the penetration signal is known, the following scheme has been implemented to perform an amplitude correction:

- Signal Generation
- Measurement of amplitudes (base amplitude or stitch by stitch measurement)
- Generation of SinCons signal with measured amplitude ratio
- Filtering
- Feature extraction and gain calculation
- Generation of SinCons signal with measured amplitude ratio
- Filtering
- Feature extraction
- Compensation with 1/gain

Figure IV-38: Amplitude correction in the Anfil program

In this amplitude correction scheme, an auxiliary SinCons type signal is generated using the same amplitudes as the signal to be compensated. The program will then generate the SinCons signal, measure the gain produced by the filter and feature extraction method, and compensate the main signal with this gain. The compensation can be done on a stitch-to-stitch basis, using the amplitudes generated for each stitch, or on an average basis using the base amplitude. The end effect is very similar.

The proposed method is, of course, totally effective for SinCons signals. For variable signals, it corrects the average error but is still unable to improve error variability. Amplitude errors remain on a stitch-by-stitch basis (due to the interdependency between stitches), but the result is correct when observed from a statistical point of view. Figure IV-39 compares the relative error for 30 cycles of...
a SinVar4 signal with and without amplitude correction (correction was performed on a stitch-to-stitch basis).

![Graph](image)

Figure IV-39: Relative error produced on peak measurement of a SinVar4 signal with (right) and without amplitude correction (left).

In a practical situation, however, the amplitude of the penetration signal is unknown, and this amplitude correction scheme cannot be used.

2.5 Evaluation of alternative methods

Several alternative signal processing techniques were evaluated using trial software and the Anfil program. Some of these techniques are complex and would demand a great effort for a comprehensive study. The development of the appropriate signal processing routines to be integrated into the AST software would also be onerous. The results found did not justify this effort.

A preliminary study of adaptive filters led to the conclusion that these structures may be configured to produce an appropriate behaviour for some situations, but the randomness of the needle penetration signals is not well managed by them.

Some attempts were made to train a filter to extract a needle penetration signal, obtained with referenced subtraction, from the original signal. This was carried out using a trial version of the Neurosolutions application, of NeuroDimension, Inc., that proposes some linear adaptive filter structures. No interesting results were found in this first approach.

The use of the wavelet transform to decompose, filter and reconstruct the needle penetration signals was studied using a trial version of the Autosignal application from Autodesk.

The wavelet transform was tested with the signals generated by the simulation program. The transform is able to show the signal’s frequency content over time, being very suitable for non-stationary signals as the ones that are being analysed.

However, the objective of this work is to compute features on subsets of the penetration signal, which cannot be done on basis of its spectrum. Some attempts were made to use the spectral filtering method based on the wavelet instead of the Fourier transform, but the resulting filtered signals were practically the same as the ones obtained with Fourier.

Some miscellaneous methods (time-warping and signal nulling), were also evaluated. The effect produced on the signals made it even more difficult to filter the signal and accurately extract the desired values.

Using the Neurosolutions software package, the possibility of a post-correction of values after spectral filtering and feature extraction was evaluated. Some interesting results were found that encouraged a further development of this complementary processing method.
A neural network was then trained to correct the values obtained with the spectral filtering method. This work [5] is briefly described in section 2.7. Some of the work carried out in the preliminary evaluation of the alternative and complementary processing methods is described in detail in Annex D.

2.6. Optimisation of Spectral Filtering and Reconstruction using the Fourier Transform

After experiments with the wavelet transform and miscellaneous techniques, it was decided that FFT-based spectral filtering would be the most immediate and feasible method to use in this work. The objective is now the optimisation of the filter's stopband in order to reduce the inertial force component as much as possible, whilst minimising the error in the extraction of the penetration features. The effectiveness of zero correction when extracting the feature values is also considered.

2.6.1. Introduction

Planning of experiments was firstly based on knowledge of the signals acquired in preliminary experiments, using different fabric structures and sewing speeds. The most important factors to observe are in this context the following:

> The shape of the penetration signals. The SinVar4 model was found to be the most useful in filtering optimisation;
> The variation of needle-bar motion forces with sewing speed;
> The amplitude ratio between motional and penetration forces (signal-to-noise ratio). Considering that motional forces are (mechanical) noise, the purpose of the filtering method is to eliminate the noise whilst preserving the useful signal. The result of the filtering operation is always better with lower signal-to-noise ratios;
> The ratio between the penetration signal amplitudes in the different stitch cycle phases.

This study was conducted in two stages. In the first, void signals were filtered using different stop-bands and features were extracted with and without zero correction. The residual feature values still detected after filtering were computed. These should be as low as possible.

In a second stage, simulated penetration signals were filtered directly, with different stopbands, and once again processed with and without zero correction. Several parameters were computed to assess the error produced on the measurement of the penetration signal’s features by the filtering process. In this stage experiments were conducted using the SinVar4 signal and varying amplitude ratios. The same study was conducted in parallel with SinCons signals for comparison.

The features whose errors were computed are the peak value and power, considered to be the most important for the analysis of needle penetration. Moreover, a filtering method optimised for the extraction of peaks and power is also valid for the optimisation of average and power, since average is proportional to the peak value (in the simulated signals, eq.(29)) and energy is proportional to power.

The assessment of performance of the processing method used has been carried out using the following parameters:
> Input-Output Correlation (CORR): Correlation between the sets of features extracted from the original and from the filtered signal (eq.(6)).

> Average of relative error over a set of penetrations (ME):

\[
ME = \frac{1}{N} \sum_{i=0}^{N} E_i
\]

where

\[
E_i: \text{Relative error in penetration } i \text{ (eq.(4))}
\]

\[
N: \text{Total number of penetrations}
\]

> Standard deviation of the relative error (ESTDEV)

\[
ESTDEV = \sqrt{\frac{\sum_{i=0}^{N} (E_i - ME)^2}{N-1}}
\]

This set of parameters slightly differs from the one implemented in Anfil, but the objectives of their use are the same, namely the evaluation of:

> The input-output relation of the filtering and processing method (correlation), describing the linearity of the measurement method;

> The proximity of the output values to the real value (average relative error):

> The spread of the error.

The spread of the error is a very important aspect. The existence of an error is expected, because the filtering procedure will necessarily attenuate the signal. It is, however, desirable that the relative error remain constant, preserving the ratio of values measured within a stitch between the different penetration phases. This ratio is expected to assume some significance in the interpretation of the measurement of needle penetration force.

The standard deviation of the relative error (ESTDEV) has been preferred to the coefficient of variation because it provides a measure of spread that does not depend on the average value of the error. The processing methods compared produce different attenuations of the signal, resulting in different average relative errors. The coefficient of variation, defined as

\[
CV(\%) = \frac{ESTDEV}{ME} \cdot 100
\]

may result in a biased measure of spread since \(ME\) is necessarily different when filtering with different stopbands.

2.6.2. Experiment plan

The measurement process consists basically of a filtering and a feature extraction step. In the tables, the measurement process is indicated with the definition of the
stopband, and the character “C” is added when feature extraction is performed with zero correction.

In all stopbands the fundamental component is included since this is the most significant component of the void signal. The study seeks to determine which additional components should be eliminated for optimal results.

Table IV-2: Conditions for study of void signal filtering

<table>
<thead>
<tr>
<th>Stage 1: Filtering of void signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speeds [spm]</td>
</tr>
<tr>
<td>Stopbands</td>
</tr>
<tr>
<td>Features</td>
</tr>
<tr>
<td>Zero Correction</td>
</tr>
</tbody>
</table>

Table IV-3: Conditions for study of SinVar4 penetration signal filtering

<table>
<thead>
<tr>
<th>Stage 2: Filtering of SinVar4 signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration signal</td>
</tr>
<tr>
<td>Number of data sets</td>
</tr>
<tr>
<td>Amplitudes</td>
</tr>
<tr>
<td>Number of stitches</td>
</tr>
<tr>
<td>Stopbands</td>
</tr>
<tr>
<td>Features</td>
</tr>
<tr>
<td>Zero Correction</td>
</tr>
</tbody>
</table>

To generate different amplitude combinations for the penetration signals, the Anfil program was modified. The base amplitude is divided in $n$ levels and stitches are generated in a way that all combinations of these $n$ levels in the three penetration phases are present in this signal. The total number of stitch cycles generated is thus $n^3$.

The effect of 4 amplitude levels on the generated peak amplitudes can be observed in Figure IV-40. The peak values of a SinCons signal with a base amplitude of 1000 in the three phases is shown. This divides the amplitudes in levels 250, 500, 750 and 1000 and generates 64 combinations.
In the experiments described in this section, 3 stitches per combination, with 4 amplitude levels, were used. This results in a total of 192 stitches, which has been considered adequate. In a preliminary evaluation, results obtained with different data sets and this number of samples have revealed almost equal. Nevertheless, a unique data set has been maintained throughout the experiments to eliminate the effect of sample variability (see Table IV-3).

2.6.3. Filtering of void signals

As described previously, in this stage acquired void signals were processed with different methods. The residual feature values detected in the three penetration phases after filtering are now presented. Ideally, these residual values should be zero as void signals contain no useful information and it is their frequency content that it is intended to be eliminated.

The following figures show the result of this study for peaks.

![Amplitudes of peak values in SinCons signal with amplitude combinations in 4 levels.](image)

**Figure IV-40:** Amplitudes of peak values in SinCons signal with amplitude combinations in 4 levels.

![Residual peak value detected in phase 1 with different processing methods.](image)

**Figure IV-41:** Residual peak value detected in phase 1 with different processing methods
Observing the presented graphs, it is possible to conclude that the 0-1-2-3 and the 0-1-3 stopbands result in the lowest residual peak values. The elimination of the third harmonic is especially important at high speeds, at which this harmonic tends to increase (see 2.2.1, Figure IV-12). The second harmonic plays a role at lower speeds, but at these speeds motional forces are low and tend to have a smaller effect on measurement accuracy.

Zero correction does not improve the result, but with the 0-1-2-3 and 0-1-3 stopbands the difference is not very significant.

The same study was conducted for the signal power in the three phases and the result is presented in the following figures.
Figure IV-44: Residual power value detected in phase 1 with different processing methods

Figure IV-45: Residual power value detected in phase 2 with different processing methods
The result for power measurement is very similar to the one obtained for peak measurement. The 0-1-2-3 and 0-1-3 stopbands seem to be in general the most effective ones for the reduction of mechanical noise, but in this case the 0-1-2-3 stopband produces significantly better results. In most cases, zero correction is not useful, but does not produce significant differences in the 0-1-2-3 and 0-1-3 stopbands.

Whilst being a first factor of choice for the filtering method to adopt in future studies, the data presented in this section assumes another important role. It can be used to determine the “noise floor” present in the measurement of needle penetration at different sewing speeds.

Values obtained from needle-bar force signals should only be considered valid if they are above the noise-floor defined by the average residual values obtained in this analysis. If they lie within the noise levels presented the measurement is blurred and the results should be discarded.

2.6.4. Filtering of simulated penetration signals

The second stage of this study consisted of applying different processing methods directly to simulated penetration signals, without mixing them with void signals. This analysis is useful to determine in what extent the filtering and computation algorithms distort the penetration signal. As described previously, several amplitude ratios were used in order to obtain a generally applicable result.

The evaluation has been made using input/output correlation (\textit{CORR}), mean relative error (\textit{ME}) and Relative Error Standard Deviation (\textit{ESTDEV}). Correlation should be as high as possible, whilst \textit{ME} and \textit{ESTDEV} should be as low as possible but identical between the three phases.

All computations were conducted for SinVar4 signals and SinCons signals. The latter were used for cross-validation and in fact produced similar results.

The following figures show the results obtained for the extraction of peak values.
Figure IV- 47: Input/Output Correlation of the peak values extracted in the three penetration phases using different processing methods

Figure IV- 48: Mean relative error of the peak values extracted in the three penetration phases using different processing methods

Figure IV- 49: Standard deviation of relative error of the peak values extracted in the three penetration phases using different processing methods
The analysis of these graphs should take into account the study of filtering of void signals. Several stopbands have been found inadequate for the final purpose as they present too high residual detection values. The eligible stopbands to be examined more carefully in this section are the 0-1-3 and 0-1-2-3 stopbands.

The correlation values presented in Figure IV-47 clearly show that the best choice is the 0-1-3 stopband. This choice is confirmed by the examination of the error variability described through the ESTDEV parameter.

Under the conditions defined for the generation of the penetration signals, the elimination of the 3rd harmonic doesn’t seem to significantly affect the measurement if the 2nd harmonic is preserved. The choice of the 0-1-3 stopband is thus the best compromise between the elimination of the void signal and the preservation of measurement accuracy.

As for zero correction, it is possible to state that it leads generally to poorer results. However, the values related to the 0-1-3 stopband do not reveal this trend. Differences are insignificant in the correlation values, whilst the error spread measure is more favourable in some situations. An additional benefit of zero correction with the 0-1-3 stopband seems to be a more balanced average error between the three penetration phases.

The same analysis has been performed for the measurement of power in the penetration phases and is presented in the following figures.

![Figure IV-50: Input/Output Correlation of the power values extracted in the three penetration phases using different processing methods](image-url)
The interpretation of power values is not different from the one drawn for peak values. It is thus possible to conclude that the 0-1-3 stopband is the best choice for the processing method.

Using this stopband, zero correction presents good results in the reduction of errors. The use of zero correction is also a safe option, because it provides some compensation for large signal fluctuations.

2.6.5. Conclusions and definition of final feature extraction methods

The main conclusions drawn from the analysis carried out regarding the FFT-based filtering and feature extraction are summarised in the following paragraphs:
The 0-1-3 stopband has revealed to be the best compromise between the elimination of the motional force’s components and the preservation of the penetration signal;

Zero Correction is a safe signal processing option and provides good results when used with the 0-1-3 stopband;

Due to the changing spectral contents of void signals, better results are obtained at higher speeds for the same signal-to-noise ratio. In practice, however, and taking into account that motional forces vary with the square of speed, higher speeds will result in lower signal-to-noise ratios and thus deteriorate measurement accuracy;

The measurement should be discarded if the values obtained are close to the residual noise values. Measurement accuracy is acceptable if the values obtained are outside the noise floors defined;

The measurement obtained is an estimate of penetration forces. Errors are variable and impair a stitch-by-stitch analysis, and thus results should be regarded considering sets of values.

2.7. Use of Artificial Neural Networks to correct results

After seeking an alternative method for the filtering process, the idea of using artificial neural networks (ANN) to correct the results after filtering, arose.

ANN’s are networks of processing elements that can be trained to approximate virtually any mathematical function. They are used when an analytical representation of the function is not possible to obtain or when a function is to be defined from noisy or inaccurate data.

The purpose of studying ANN’s in the context of this work is to train a network to approximate the following function:

\[ [y_1; y_2; y_3] = f(x_1, x_2, x_3) \]  \hspace{1cm} (34)

where

\[ x_n; \] Feature value extracted from the filtered signal in stitch cycle phase \( n \)

\[ y_n; \] Original feature value for stitch cycle phase \( n \)

The idea is to filter the signal, extract the feature values and correct them using the ANN.

The existence of such a function is justifiable by the properties of the penetration signals. As already stated the convolution of a base signal with a square wave has the effect of repeating the base function’s spectral information over the whole frequency spectrum. This means that it may be possible to obtain a function to invert the process. Given the complexity of the penetration signal’s spectrum, such a function is very difficult or even impossible to be obtained analytically, but a neural network may be trained to approximate it. In this perspective, the network should also be able to be trained to correct values obtained by other filtering stopbands, as for instance the 0-1-2-3 stopband, that delivers the lowest residual values of inertial forces. This possibility would represent a major advantage.
The Anfil program is an excellent tool to generate training data for such a neural network. Different signal models with varying amplitude ratios can be used to generate a great amount of training data.

Since the field of ANN's is a research subject on its own, this work has been limited to the study of the basics of ANN's, using the capabilities of commercially available software. An overview over the fundamentals of ANN's is given in Annex D.

To test the effectiveness of ANN's in correcting the extracted feature values, an evaluation version of the Neurosolutions application of NeuroDimension, Inc, was used. The interesting results found encouraged the development of a software routine to be integrated in the AST software.

The ANN was implemented using the Matlab software from The Mathworks.[5] This software includes an extensive set of tools for the implementation, training and test of ANN's. Furthermore, some tools are provided for an easy integration of the resulting processing subroutines in a Labview application, which is a fundamental advantage.

A Multilayer Perceptron (MLP) structure with one hidden layer was trained with data sets generated by the simulation program. Two training sets, one for a network for peaks/valley correction and another for power values, were generated considering the following variables:

- Variable amplitude ratios between the three phases in the penetration signal (6 combination levels, 3 periods per combination)
- Void signals at three different sewing speeds (649, 2829, 4818 spm);
- Four signal-to-noise ratios for each sewing speed (1:10, 1:2, 1:1, 2:1)
- SinVar4 penetration signal model;

To account for varying acceleration force amplitude and spectral content, a 4th input, sewing speed, was added. This corresponds to an additional input variable in equation (34).

The performance of the network was very good when trained and tested with simple data sets, all generated with the same shape parameters (same amplitude ratio, sewing speed, signal-to-noise ratio). When using the more general training sets in which all the conditions are varied, the network is still able to converge well on the training set for peak value correction. The networks trained for power value correction produced very bad results and its use was abandoned.

Independent data sets, using different sewing speeds (1387, 3596 and 3964 spm), were then fed to the network as test sets. The results showed that the accuracy is not very different from the one obtained directly after filtering.

In general, correlation appears slightly higher, but the error variability, one of the parameters to be improved, does not reflect this change. In lower signal-to-noise ratios, the values obtained with the neural network are slightly worse than the values after filtering. Average error is in general lower, but not consistently in all sewing speeds. These results lead to the conclusion that the neural network merely produces an offset shift and scaling to the values.

Despite of the limitations of the peaks/valley correction provided by the network, it has been integrated into the sewing test rig’s software as an alternative analysis method and will be later analysed.
3. Stitch formation variables

The objective of this work is to gather all the results obtained by the project team [2][3][6], provide tools for their analysis and integrate them. This integration should enable the evaluation of methods for monitoring and automatic control of thread tensions and thus the stitch formation process.

To evaluate the stitch formation process, the machine was equipped with thread tension sensors and a thread consumption measurement device. This device not only complements the tension sensors, but also adds fundamental information to this subject of study.

The 504 overlock stitch uses three threads: the needle, lower looper and the upper looper threads. Typical waveforms of needle thread tension are represented in Figure IV-53. They were acquired at 3700 spm using the same thread tension adjustment on 2 and 4 plies of a jersey knitted fabric.

![Figure IV-53: Needle thread tension over two stitch cycles. Two (blue) and four (red) plies of a jersey knitted fabric.](image)

Similarly to needle penetration signals, the thread tension waveforms are divided into phases (4 in the case of needle thread tension) and features are computed in those phases. The feature that has been used in most studies conducted is the peak value. Just like in the analysis of needle penetration signals, the results may be displayed in a graph according to their chronological sequence, or in 2-D or 3-D graphs. When 4 feature values are being computed, the 3-D graph may use dot size as the graphic element to represent the fourth coordinate. Later these phases were redefined merging two phases and using just three [2], so that the representation of the 4th coordinate was no longer necessary.

To analyse the relations between peak tension values and pre-tension adjustment in the three threads it was necessary to compute the angle of occurrence of a peak on a specific thread and extract the value of thread tensions on the remaining threads at this angle. This new parameter was called Parallel Value (VP) and is defined as

\[ VP(A,B) = \text{Tension Value of Thread B at peak of Thread A} \]  \hspace{1cm} (35)

The exact quantification of the thread pre-tension adjustment is possible using the newly developed quasi-static thread tension measurement.
To complement thread tension analysis, the author suggested the computation of feature ratios as defined for penetration signals in equation (1). The objective of these feature ratios is to provide a factor able to describe the shape of the signal in each stitch cycle and resulted from the observation of thread tension signals in faulty situations like skipped stitches. Figure IV-54 shows the waveform of the lower looper thread tension signal in a normal stitch and a skipped stitch:

Figure IV-54: Waveform of lower looper thread tension in a normal and a skip stitch

As can be seen, thread tension has reduced significantly in two phases of the stitch cycle and remained almost unchanged in the third phase.

The chronological sequence of the peak tension values in this acquisition for the three phases confirms this observation:

Figure IV-55: Peak tension values in phases 1 to 3 of lower looper thread tension in a seam in which a skip stitch occurred

Figure IV-55 shows that in stitch 15 of this seam a significant decrease of thread tension is present in phases 1 and 2. In phase 3 the decrease is also present, but in a much smaller degree.
This behaviour can be explained by analysing the stitch formation process itself. The tension values produced in phase 1 and 2 are related to the actual interlacing of the threads. They occur when feeding takes place (phase 1) and when the stitch is completely formed and the thread take up tightens it (phase 2). At this point of the sewing cycle the thread loops are released from the stitch formation elements, thread tension suffers a sudden decrease and phase 3 begins. The needle-bar is still pulling thread for the next stitch and produces peak 3.

In a skipped stitch, one of the stitch formation elements misses the thread loop and one or more threads are loose. Tension will thus decrease in both feeding phase and stitch tightening phase. The peak value in phase 3, however, is always present because it is mainly influenced by the movement of the needle-bar and less by the actual thread interlacing.

To detect a skip stitch automatically, the software might monitor the absolute value of peak thread tension in phase 1 or 2 and indicate a defect if it falls under a pre-defined threshold. This approach is straightforward, but the definition of the threshold is difficult. Taking into consideration that absolute values of peak tension depend largely on the material being sewn and on the pre-tension adjustment, a threshold has to be defined for each situation.

An alternative method to this is to use feature ratios, assuming that the peak ratios are independent of thread tension adjustment (a higher pre-tension produces the same increase of tension in all peaks). This would result in constant values for peak ratios regardless of thread tension adjustment.

The ratio \( \frac{P_{k3}}{P_{k1}} \) has been computed on the lower looper thread tension of the data presented in Figure IV-55.

![Figure IV-56: Peak3/Peak1 ratio of lower looper thread tension for seam containing a skip stitch](image)

In this case, the peak ratio exhibits a large difference at the skipped stitch and a threshold could be more easily defined. Moreover it would also be possible to determine which threads failed to interlace.

Further experiments showed that the previous assumption is not always correct and the average peak ratio does in fact change with the tension adjustment used.
Figure IV- 57 shows the peak ratio in needle thread tension for different tension adjustments.

![Graph showing peak ratios for different tension adjustments](image)

Despite this, peak ratios may still be used as a quality indicator. The sequence plotted in red, for instance, contains two values outside the average value. These have been found to coincide with the stitch distortion depicted in Fig.II-9b [2]. They lie in the range of values obtained with a very loose thread tension adjustment that results in a bad quality and distorted seam by itself.

Although peak ratios are not constant with thread tensions, they may still be used to detect skip stitches and other sewing defects. It is likely that the definition of tolerance margins is more flexible using ratios than absolute tension values. Additionally, peak ratios may be able to quantify stitch formation efficiency in some way. Some of these aspects will be analysed in the experiments described in chapter VI.

The measurement of thread consumption has been an important addition to the analysis of stitch formation. Thread consumption is able to indicate if thread tension is correct in both the amount and balance between threads. Figure IV- 58 shows the effect of unbalancing tensions by applying more tension to the needle thread.

![Bar graphs showing thread consumption balance](image)

Figure IV- 58: Thread Consumption balance when increasing needle thread tension (left to right)
As expected the stitch has been tightened at the needle thread and thus needle thread consumption diminished and the consumption in the remaining threads increased.

Given the geometrical parameters of the stitch (fabric thickness, stitch length and width), it is possible to compute an expected value of thread consumption for each thread. It is then possible to compare this expected value to the actual measure and assess the correct adjustment of tensions in both balancing and overall amount.

With the AST software it is possible to obtain a measure of fabric thickness by acquiring a presser-foot reference cycle at low speed. By indication of the seam width (a permanent parameter for a sewing machine) and of the stitch length setting, it is possible to compute the theoretical thread consumption values.

Stitch formation can also be described with the two parameters designated as Stitcheck [2], which take into consideration consumption and thread tension values.

\[
\text{Stitcheck(Tension)} = \frac{P_{2N} + P_{2UL}}{P_{2LL}} \tag{36}
\]

\[
\text{Stitcheck(Consumption)} = \frac{C_N + C_{UL}}{C_{LL}} \tag{37}
\]

where

- \(P_{2N}\): Average of needle thread tension peak in phase 2
- \(P_{2UL}\): Average of upper looper thread tension peak in phase 2
- \(P_{2LL}\): Average of lower looper thread tension peak in phase 2
- \(C_N\): Consumption of needle thread
- \(C_{UL}\): Consumption of upper looper thread
- \(C_{LL}\): Consumption of lower looper thread

The Stitcheck method plots points on an X-Y graph using the two parameters as x and y coordinates, being each point the result of one seam. It was found that values obtained for seams with different tension adjustments cluster according to these adjustments. It is in this way possible to define an area on the graph where all correctly adjusted seams are located, being the remaining ones poorly adjusted seams [2].

In the present work, the use of Stitcheck method was broadened by making the parameter “rotate” around the three thread tensions. Two additional Stitcheck parameters have been created in which the variables of equations (36) and (37) are switched. The denominator of the equation determines on which thread the Stitcheck parameter is based. The Stitcheck parameter based on the needle thread is, for instance, obtained rewriting equations (36) and (37) as:
The results obtained with this new approach are further described in chapter VI.
4. Feeding system variables

The optimisation study of the feeding system led to the development of an active actuator together with control methods and references for this actuation [1].

In order to analyse the effects of this device in the feeding system (as well as the performance in a conventional system) and to automate the methods proposed, several tools were designed and new methods considered and integrated.

In the feeding system analysis two variables are measured: Presser-foot displacement and force on the presser-foot bar.

Typical waveforms of presser-foot displacement in a low and a high-speed situation are depicted in Figure IV-59. The sample span two stitch cycles.

![Figure IV-59: Presser-foot displacement waveforms at a low-speed (2000 spm, green) and a high-speed situation (4700 spm, red)](image)

As represented in the figure, presser-foot displacement can also be divided in phases:

> Phase 1 is the feeding phase, in which the feed-dog emerges from the throat plate and pushes the fabric. The presser-foot should in this phase ideally accompany the vertical component of the feed-dog's movement;

> Phase 2 is the needle penetration phase, in which the presser-foot should hold the fabric firmly against the throat plate.

Figure IV-59 shows that the presser-foot describes different trajectories depending on sewing speed. Especially during phase 2 there is a deviation from the ideal situation: when the feed-dog disappears under the throat plate, the presser-foot bounces and eventually loses contact with the fabric. To describe the behaviour of the feeding system, the peak displacement values are computed in phase 1 and 2 and plotted on an X-Y graph. In this work, the computation of the valley in phase 3 has been suggested. This value can quantify the amount of compression produced on the fabric by the presser-foot during the needle penetration phase. An excessive compression may occur when presser-foot pre-tension is increased to avoid the “bouncing” effect, and can result in damage on the fabric.
The result of extracting the peak displacements can be displayed in a graph representing the chronological sequence of the measured values. Alternatively, the features may be plotted in 2-D or 3-D graphs and the clustering behaviour of the values can be observed.

In the following figure, the results extracted from the sample presented in Figure IV-59 are plotted on a 2-D graph:

![Graph showing peak displacement values in phase 1 and 2 extracted from sample at low speed (2000 spm) and high speed (4700 spm)](image)

Using stitch regularity as criterion, limits for the displacement in both phases were defined as Admissible Displacement Limits (ADL) [1]. The ADL result in a square or a cube when represented on a 2-D or 3-D graph, respectively. In a monitoring system, a seam would be rejected if the displacement values are outside these limits. In the context of a control system, the displacement peak values would be used as feedback variable.

Another way of evaluating presser-foot displacement is proposed in this work. The method uses a reference cycle for the presser-foot, acquired at very low speed, to define the ideal trajectory for the presser-foot and is obtained by a specific tool implemented in the AST software. The difference between the ideal trajectory and the actual one describes the efficiency of the feeding system, and can be used as a feedback variable in a closed-loop control system. Since the deviation from the ideal trajectory is not constant throughout the stitch cycle, it would be possible to adapt the force to the exact instantaneous deviation from the ideal value, over the stitch cycle. The success of this fine control depends mainly on the actuator’s dynamic response.

The measurement of force on the presser-foot is an alternative and complementary tool to analyse feeding efficiency. Although the measurement of two variables creates some redundancy that must be avoided for economic reasons in an industrial equipment, it has provided great knowledge of the feeding process.

The force measured on the presser-foot for the same two stitch cycles represented in Figure IV-59 can be observed in Figure IV-61:
Two effects can be detected when comparing the two signals:

- The amplitude of the waveform is reduced at higher speeds. This means that the transmission of force from the feed-dog to the presser-foot is reduced;
- The waveform acquired at high speeds presents quick drop-offs at several moments of the stitch cycle.

Understanding the physical significance of these two effects is of utmost importance to find methods of diagnosis for this situation.

An approach proposed to quantify the regularity of force is based on a spectral analysis of the force signals[1]. The quick variations present in the high-speed signal result in a different spectral content of the signal. To be precise, energy from the fundamental component is reduced, and higher frequency harmonics increase. The reduction of the fundamental component is the consequence of the reduction of overall amplitude of the signal, but the ratio between the amplitudes of higher frequency components and the fundamental changes significantly, as can be seen in Figure IV-62:

Figure IV-61: Waveforms at force on presser-foot at a low-speed (2000 spm) and a high speed-situation (4700 spm)

Figure IV-62: Harmonics extracted from amplitude spectrum of force signal at a low-speed (2000 spm, green) and a high speed-situation (4700 spm, red)
An automatic diagnosis of this effect can be made by computing the Total Harmonic Distortion (THD) of the signal:

\[
THD = \sqrt{\frac{\sum_{i=2}^{N} A_i^2}{A_1^2}}
\]  

(40)

where

\(A_i\): Amplitude of the \(i\)th harmonic

\(A_1\): Amplitude of the fundamental component

This parameterisation can also be applied to the analysis of the displacement signal. The shape of this signal also moves further away from the shape of a pure sinusoid when the presser-foot starts to bounce, as can be seen in Figure IV-59.

The force waveforms obtained using the active actuator differ in shape from those found with the traditional spring-hinged presser-foot. They exhibit a base frequency of the double of the machine’s rotation frequency. For this reason, distortion parameters computed with reference to other components than the fundamental were considered. A more general definition of harmonic distortion \(D_n\) is given in eq.(41):

\[
D_n = \sqrt{\sum_{i=1}^{N} \frac{A_i^2 - A_n^2}{A_n^2}}
\]  

(41)

where

\(A_i\): Amplitude of the \(i\)th harmonic

\(A_n\): Amplitude of the component \(n\)

Given the shape of the force signals observed with the spring-hinged presser-foot and the version with active actuation, the distortion parameters for the 1\(^{st}\) (fundamental) and 2\(^{nd}\) harmonic may be useful for the description of presser-foot force waveforms.
5. References


