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Asko washing machine components

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ABSTRACT

Nowadays, consumers demand not only appliances with good performance at an affordable price, but go one step beyond asking for innovations that improve their standard of living, as for instance in noise suppression systems and energy consumption, and lately the concern for the environment is gaining strength. The remaining moisture in clothes after spinning is one of the most important aspects in the whole washing process of a washing machine. With an efficient spinning, clothes come out dryer what reduces later periods of drying. Moreover it is also closely related to the energy consumption and the environmental care. Spinning means that the load laundry is dried as the water which is bound to the fabric is forced out because of the centrifugal forces. The water still bound to the laundry is a source to imbalance and following vibrations, and therefore, knowledge about the dynamics of dehydration process could also help during optimization of the suspension. Today, the control of drum rotational speed is based on a set of schemes containing predefined steps and the step selection is performed based on how high the load and imbalance are in the beginning. But spin speed is not the only variable that affects the dehydration process, also the load laundry (both materials and quantity), the processing time and the geometry, number and position of the holes in the drum are parameters that will affect the results of the water extraction process.

The content of this thesis can be divided in two parts. The first part includes the experimentation performed in the washing machine laboratory at Chalmers where the data needed for the second part was acquired. The experiments consist on running different spin profiles in the test rig built at the lab and measure their corresponding water extraction along time. The second part of the thesis consists on building a mathematical model for the water extraction process based on the experimental data acquired in the first part.

The results from the experiments have shown good potential for water extraction improvements in washing machines, and both the mathematical model and the test rig could represent a useful tool for further studies on vibration isolation and energy saving.

Keywords: Spinning, Spin speed, Speed gradient, Load, Clothes, Remaining water, Dehydration process, Experiments, Drum, Outlet tub, Jerry can, Data fitting, Optimization and Mathematical model

Contents

Preface

In this project, theoretical and experimental studies of the spinning process of a washing machine have been done.

The work has been carried out from January 2009 to June 2009, and it's an extension of previous studies related to improve other aspects of washing machines. The project is carried out at the Department of Applied Mechanics, Division of Dynamics, in collaboration with the company Asko Appliances AB.

The supervisor and examiner of the thesis was Professor Viktor Berbyuk from the Applied Mechanics Department at Chalmers University of Technology. I want to thank him for giving me the opportunity to work on this project and also for his valuable guidance and collaborative work. I also would like to appreciate the help of Thomas Nygårds, PhD student at the Department of Applied Mechanics, for help with experimentation and his support during this project. I also have to appreciate the help of Patrik Jansson, Test leader Product development, Asko Appliances AB, for his help providing equipment and important information.

Finally, I would like to thank Charmers University of Technology, University of Oviedo, Asko Appliances AB and my family for giving me the opportunity to study abroad and their unique support.

Göteborg, June 2009

Alberto Merediz

Notations

Roman upper case letters

F_c	Centrifugal force
L_d	Weight of dried laundry
L_w	Weight of wet laundry after spinning
M	Remaining moisture in clothes after spinning
R	Radius
V	Volts signal produced by the load cell
V_t	Tangential component of velocity
W_e	Amount of water in the jerry can at the end of the experiment
W_i	Initial amount of water in the drum
W_j	Amount of water in the jerry can
W_o	Amount of water in the outlet circuit
W_r	Remaining moisture in clothes

Roman lower case letters

m	Mass turning around inside the drum
a_n	Normal component of acceleration
t	Time
w	Remaining water inside the drum as a fraction of unity

Greek lower case letters

α	Correction term for the remaining water inside the outlet circuit
ω	Spin speed of the drum
$\dot{\omega}$	Spin speed gradient of the drum

1 Introduction

The remaining moisture in clothes after spinning is one of the most important aspects in the whole washing process of a washing machine, since it’s really annoying waiting for clothes to air dry, especially during the winter because it could take long time. Using dryer machines after the spinning process is one solution to reduce drying duration, but it’s not desirable because they consume much energy and space. This is why there is a major effort to improve the extraction of water, especially for commercial washing machines, in order to reduce the moisture of remaining water inside the clothes after the spinning process.

Modern washing machines are capable of generating a great drying, reducing the final moisture in clothes after spinning to the forty-six percent. This is a good rate, but a pre-study has showed that there is a possibility for improvements, so it would be wonderful to reduce the remaining water inside the clothes in order to reduce the duration of later drying periods.

1.1 Aim of the thesis

Nowadays people are aware of the necessity to take care for the environment so they request for more efficient products, which represents also a way for saving money. As a result it becomes a task for the companies to come up with more efficient appliances. For that purpose it’s important to improve the internal processes in appliances and as it was said before, one the most relevant ones, is spinning. Therefore the aims of this thesis are:

- To analyze the dehydration process. Since the spinning profile haven’t been changed for many years, from the beginning of the thesis the main objective is to test experiments with different spin profiles and analyze the effects of the different parameters in the dehydration process. If possible it is also interesting to find a spinning sequence that improves the quality if drying, in order to avoid or at least reduce the necessity of later drying processes.

- To build a mathematical model that can predict the spinning behaviour of the washing machine in order to obtain the remaining moisture at any instant of time depending on different parameters. This model could be helpful to test new spinning profiles without the necessity of running the experiments, and also to improve the quality of drying.

1.2 Methodology

The project was split into several phases. In the first phase, a wide literature search on the ways that liquids are extracted nowadays and on processes similar to spinning was done. Second phase was dedicated to design the experiments that were run in the third phase. Finally, in the fourth phase, a mathematical model for the dehydration process was obtained using the Least Squared Error Methodology.

2 Literature Study

As an introduction some information about the components, how a washing machine works and similar processes has been searched.

2.1 Components of a washing machine

Washing machines are very common appliances and nowadays everybody is familiar with them, because there is a washing machine in every home. For a better understanding of the technical terms that are used throughout this thesis, a compilation of the most important components of a washing machine is presented bellow:

- Inner tube or drum: is where clothes are put. In most washing machine brands, this tub has hundreds of small holes that allow the water to flow through to an outer tub. The outer tub is solid and holds the water.

- Motor: The motor drives the drum during the wash cycle and spins the clothes during the spin cycle.

- Dumpers: washing machines use generally three or four passive friction dumpers to isolate the frame from vibrations of the drum and to reduce noises.

Figure 2.1 Asko washing machine components: drum, motor and dumpers

- Drain pump: The pump removes the water from the bottom of the tube and lifts it out to the drain. Figure 2.2 shows how a typical drain pump looks like.

- Fill valve: it is about the size of a coffee cup. It controls the entry of hot and cold water into the machine. The valve has three major components: a hot-water solenoid, a cold-water solenoid and a mixing valve body. The inlet valve has three hoses connected to it, for : the hot water from the house, the cold water from the house and the water directed into the washing machine's inner tub (either hot or cold, or both) to fill it with water. When electricity flows to one or both solenoids, water flows through the valve into the washing machine's inner tub. When the electricity stops, the water also stops.

Figure 2.2 Drain pump

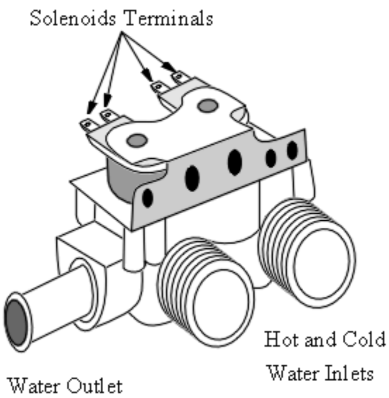

Figure 2.3 Typical fill valve

2.2 Operation of a washing machine

A washing machine is an appliance which operation is based on the rotational movement of the drum, which turns clockwise and counter clockwise in order to mix clothes with water and detergent, and also to dry them during spinning with help of centrifugal force. The centrifugal force can be calculated as function of spinning internal parameters:

$$F_c = m \cdot a_n \tag{2.1}$$

Where: $$a_n = \frac{V_t^2}{R} \tag{2.2}$$

and $$V_t = \omega \cdot R \tag{2.3}$$

Thus, Equation (2.1) can be expressed as function of the rotational speed:

$$F_c = m \cdot \omega^2 \cdot R \tag{2.4}$$

where m is the mass turning around with the drum, a_n is the normal component of acceleration, V_t is the tangential velocity, R is the radius of the drum and ω is the angular speed [radians/s].

Modern washing machines are available in two configurations: horizontal axis and vertical axis, where horizontal axis washing machines are front loading designs. This design is the most popular in Europe and is the one used in the experiments. Front loading washing machines mount the inner basket and outer tub horizontally and loading is through a door at the front of the machine. The door often but not always contains a window. Agitation is supplied by the back-and-forth rotation of the cylinder and by gravity. The clothes are lifted up by paddles on the inside wall of the drum and then dropped. This motion flexes the weave of the fabric and forces water and detergent solution through the clothes load. Because the wash action does not require the clothing be freely suspended in water, only enough water is needed to moisten the fabric. Because of it, front-loaders typically use less soap, and the aggressive dropping and folding action of the tumbling can easily produce large amounts of foam.

Figure 2.4 shows a standard efficiency label, where the spin drying performance (as well as other characteristics) is represented with a letter from A to G, being A the higher quality of drying.

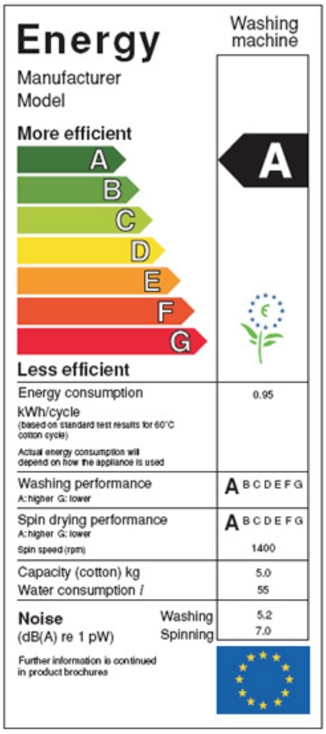

Figure 2.4 Efficiency label

2.3 Overview of similar processes

The dehydration process of a washing machine is a field in which there are not many previous written studies or at least not external publications, but there are several applications of the centrifugal force that could help to understand this process. In addition it is advisable to review novel patents on washing machines (see e.g. [1]).

The utilization of the centrifugal force to separate different substances in commercial use is quite common. This phenomenon is seen in spinning to extract water from wet clothes in washing machines, but it’s also used for water-oil separation or in different liquid-solid separation processes.

Liquid-solid separation is the most similar process to the water extraction in washing machines. This application of the centrifugal force is used in two different ways: centrifugal separation and centrifugal filtration. The former uses a solid bowl. Liquid removal is accomplished using a skimmer or by overflowing the bowl rim. During centrifugal decantation, centrifugal force is used to accelerate the gravity sedimentation process in which the solid particles move radially through the liquid and accumulate on the walls of the solid bowl.

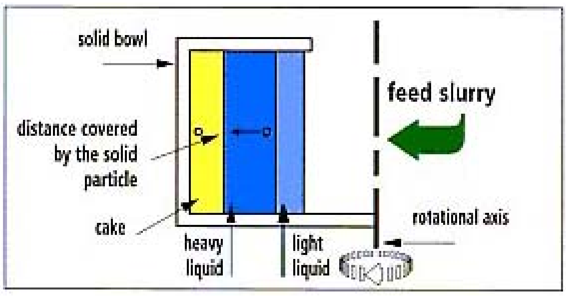

Figure 2.5 Solid-liquid centrifugal separation

Centrifugal solid-liquid separation is similar to spinning because it uses a perforated basket to make the liquid come out through the holes. The basket is equipped with a filter cloth or removable filter bag. During centrifugal filtration, centrifugal force produces pressure that forces the liquid through cake, filter cloth, backing screen, and finally out the basket perforations. The filter cloth retains the solid particles within the basket. The cake is the solid phase retained around the filter cloth.

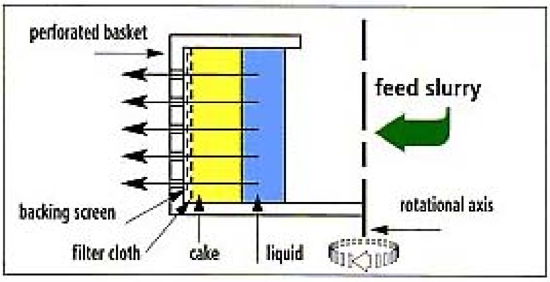

Figure 2.6 Solid-liquid centrifugal filtration

This technique is applied in many industries as for instance: chemical, pharmaceutical, food, textile, metal working and environmental.

3 Test Rig

For carrying out the experiments a test rig was constructed from components already available in the laboratory, and using some others provided by Asko Appliances AB. This test rig consists of a set of non-sophisticated components, which produces fairly accurate results.

It mainly consists on a washing machine, a jerry can where the extracted water is stored in order to be measured with a load cell, a steel structure to hang the load cell and the jerry can and the required electronic equipment to process data and control the both the spin speed sent to the motor and the drain pump of the washing machine.

A sketch of the test rig is displayed in Figure 3.1:

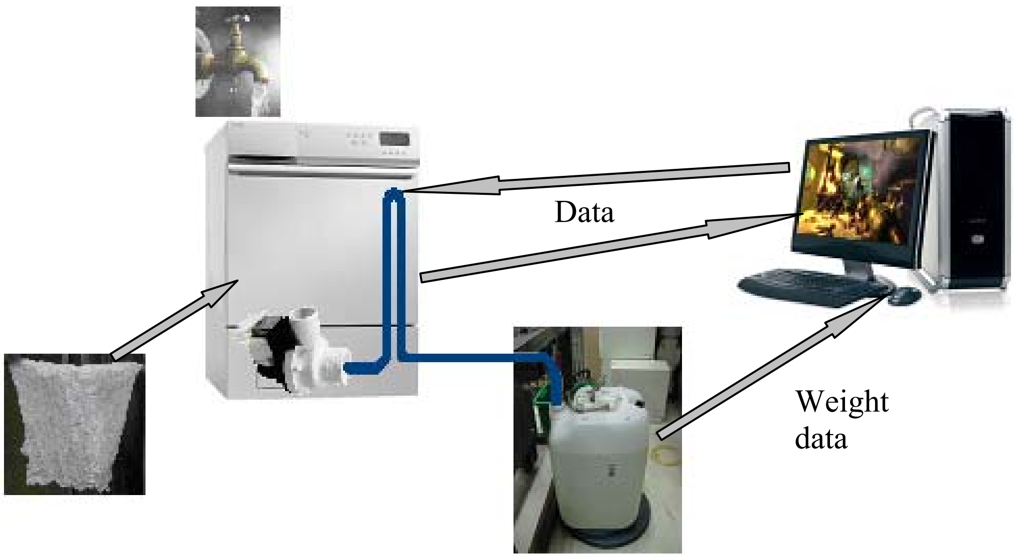

Figure 3.1 Sketch of the test rig

A brief explanation of the components and some pictures taken at the laboratory are shown below.

3.1 Components

Washing machine

This element is undoubtedly the most important one. It consists on a standard Asko appliance, model W6761W supplied by that company for previous experiments done in the department of Applied Mechanics. Some of the most important parameters of the washing machine are collected in the following table:

Table 3.1 Parameters of the washing machine

Parameter	Value
Load capacity	7 kg
Max. spin speed	1600 rpm
Energy consumption (normal program)	0.9 kWh/cycle
Water consumption (normal program)	35.2 l/cycle
Diameter of the drum	450 mm
Shipping weight	78.9 kg

Figure 3.2 Asko W6761W washing machine

Electronic devises

The control for the motor of the washing machine is mainly composed by a computer and some electronic devises. A brief explanation of the most important components of the control system is shown bellow:

- *Virtual instrument (VI):* In order to carry out the experiments in the most automatic way as possible, a computational model for the motor control was developed in LabVIEW®. This tool allows the following characteristics:

    - To send the spin speed sequence to the motor, by first introducing them into LabVIEW® in text format. Those text files containing the spin sequence for each experiment are easily created in Matlab.

- In its internal structure the different parameters involved in the process can be controlled, as for instance the maximum gradient or the spin speed. The introduced values can be compared to them in order not to be exceeded.

- It also allows watching live results (see Figure 3.3): in the upper plot of the front panel of the VI live values for the extracted water are represented during the experimentation and in the lower plot, both the desired spin speed sequence and the real one followed by the drum, are plotted together.

- About the resulting data, the VI creates text files with the data containing, both the extracted water along time and the profile of the spin speed followed by the drum. This data is later imported to Matlab in order to compare and analyze the results.

- Finally it is also possible to control some more parameters, as for instance: control the initial period to moisten clothes properly with the introduced amount of water, add comments to the file that contains the results and even there is a section on the right side where the errors occurred are reported to the user.

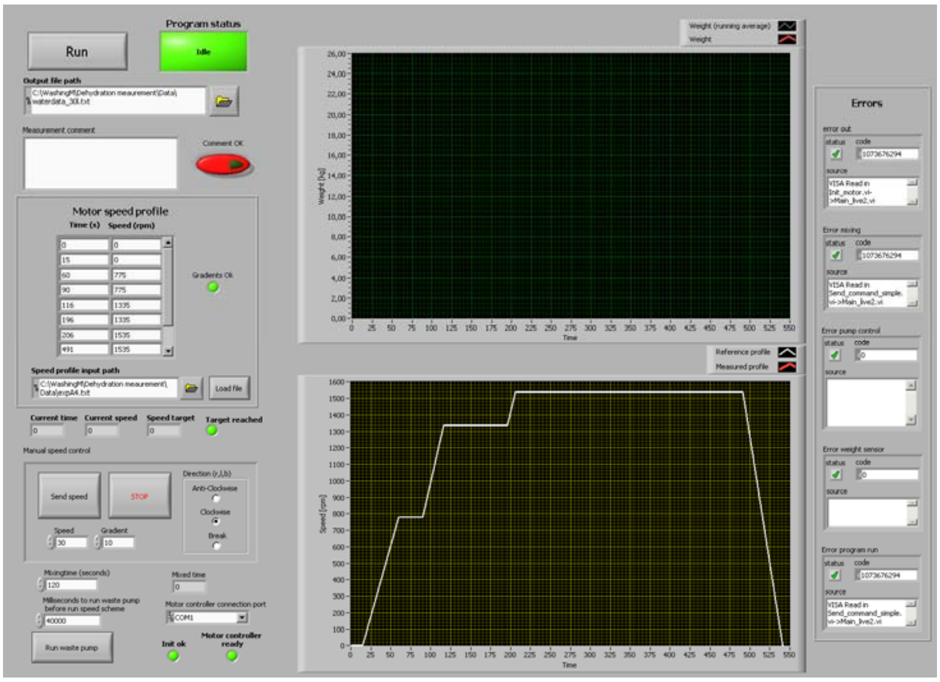

Figure 3.3 Front panel of the virtual instrument

- *Voltage transformer*: as it can be seen in Figure 3.4 it is a home made voltage transformer, needed to convert the low voltage provided by the computer into high voltage required to run the drain pump of the washing machine.

Figure 3.4   Voltage transformer

Measurement system

This part of the test rig is where the amount of water being extracted is measured in real-time. The results are measured and imported to the computer. The measurement system consists of four components which are: the jerry can, the load cell, the computer and the structure to hang the load cell and the jerry can. Next these components are explained:

- Water jerry can: it's a simple jerry can with a handle and capacity for 30 litres, where the water being extracted is stored. The jerry can is hanged with a rope to the load cell.

Figure 3.5   Water jerry can

- Load cell: it is the device that measures the weight of the extracted water at each instant of time. For the experiments 1 kg/l is taken as the value for the density of water at atmospheric conditions of pressure and temperature, so the dehydration process can be expressed either in kilos or in litres. Some of the characteristics of the load cell are shown in the table below:

Table 3.2 Characteristics of the load cell

Parameter	Value
Nominal load capacity	25 kg
Nominal output sensitivity (N.O.)	2,0+/-0,1% mV/V
Overload allowed	150% of N.O.
Breaking load	> 400% of N.O.
Weight	0.3 kg

Figure 3.6 shows two pictures of the load cell. The picture on the left shows how it looks like and the picture on the right shows how the water jerry can is hanging from the load cell with a piece of rope. On the right picture it can be seen that the load cell is screwed to the structure built to support the jerry can.

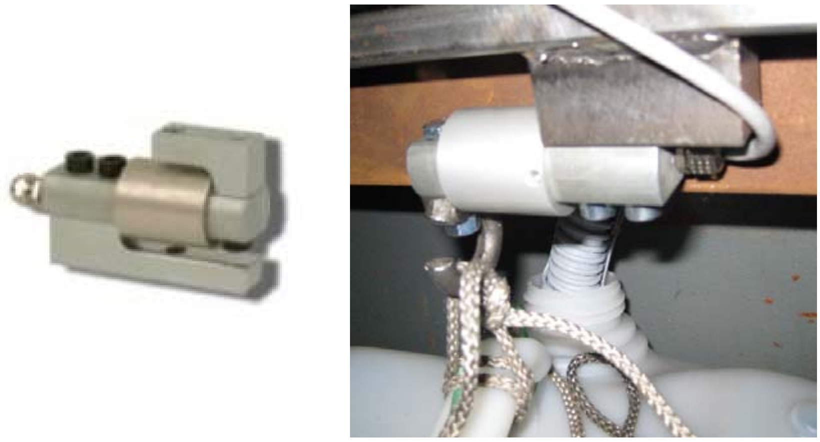

Figure 3.6 Load cell

- Structure to hang the load cell and the jerry can: as it's been described before, the jerry can where the extracted water is stored is hanging from the load cell where its weight is measured. Therefore, the load cell must be hanging somewhere, so in order to obtain accurate results it's necessary to hang it on a rigid structure, isolating the load cell as much as possible from vibrations transmitted from the jerry can or from the floor because of the vibration of the washing machine.

In Figure 3.7 the following elements can be seen: the back of the washing machine with the water path, the jerry can, the outlet pipe and the structure in which the jerry can is hanged.

Figure 3.7 Water path

Figure 3.8 Drain pump and water outlet pipe

- Ni CompactDAQ: this component is a USB data logger designed to bring a true plug-and-play experience to a variety of measurements. With the included software, National Instruments LabVIEW SignalExpress LE, it’s possible to acquire and log data to a file in a few clicks. It consists of a Ni CompactDAQ chassis with different modules inside. It is mainly required because is not possible to send the signal directly from the computer to the motor.

Figure 3.9 Ni CompactDAQ chassis 9172

4 Experiments

In this chapter different relevant aspects for carrying out the experiments are described, as for instance: how the input profiles look like, the procedure followed to accomplish all the tasks required and all the parameters and decisions taken in order to accomplish the objectives involved in the experiments as well as the results provided by the experiments run in the laboratory.

4.1 Design of experiments

Experiments represent the most important part of the thesis because they are the source to acquire the data necessary to accomplish the aims of the project. Taking into account the importance of the experiments it's necessary to pay special attention to the parameters involved in the process, in order to control those, design right experiments and obtain interesting data.

The experiments consist on recreate different spinning processes and collect data of the water extraction; therefore the parameters to control are those that take part in the dehydration process and that can be controlled somehow. In consequence, these parameters are: material and weight of clothes for spinning, the introduced amount of water to moisten the clothes, the rotational speed of the drum at each instant of time, their gradients during the process and the maximum spin speed of the drum allowed by the motor. Some other parameters as for instance the number, disposition and shape of the holes in the drum are given by the characteristics of the washing machine provided by Asko.

When running the experiments it's important to do it under the same or controlled conditions, in order to be able to compare their results, thus it's desirable to use the same quantity of clothes and water in each experiment. The decisions about the laundry material, the weight of clothes and the litres of water to be used in the experiments were imposed by Asko. These parameters are 7 kg of cotton for the laundry and 19.1 litres of water, which correspond to the maximum weight of clothes admissible by the washing machine and its corresponding water quantity required in a normal washing program to produce foam and moisten clothes properly producing a good wash. Figure 4.1 shows one of the sixty-nine cotton cloths used in the experiments.

Figure 4.1 Cloth used in the experiments

Another important parameter is spinning time; as it is logical, during the dehydration, if the process is long enough there is an instant of time where saturation appears so the amount of extracted water does not increase anymore. Therefore, the duration for the process must be long enough to extract as much water as possible. But it's also necessary to take into consideration if it's worth or not such a long period according to the energy consumption and the final amount of extracted water. Nevertheless this is not going to be evaluated in this thesis. A period of 490 seconds was set as spinning time, according to the common value used by Asko.

In a normal washing program, after the rinse the drum contains some water which was not completely absorbed by the laundry. This amount of water can be easily extracted from the drum because it's not necessary to remove it from the clothes, so it's very advisable to open the water outlet and run the pump some time before the spinning starts for beginning the water extraction. After some experiments for calibrating this kind of parameters, a period of 40 seconds was set for extracting that unabsorbed amount of water. It is necessary that this period is long enough for being able to remove it all; otherwise the water extraction would be worse at the beginning.

Finally, last parameters to be set and possibly ones of the most important are the maximum spin speed reachable by the drum and its maximum gradient. These parameters are limited by the characteristics of the motor and the drums structural strength, in order to not reach values that could damage its operation. For the motor supplied with the washing machine the maximum value for the spin speed is 1600 rpm due to the lack of unbalance control. Following again the values used by Asko, a top speed of 1535 rpm is going to be used in order to compare easily the results from the experiments with some data provided by Asko. However, the durability of the motor is very high and it usually lasts much longer that the other parts inside the machine. On the other hand, the maximum speed gradient depends on which speed it's being accelerated from, and the unbalance, but normally with 80 rpm/s there's no problem (motor maximum rating is 200 rpm/s).

Next, some of the spin speed profiles designed for the experiments are going to be described, with a description of the procedure to carry out each experiment and the expected results from each of them. The total number of experiments used for the study is 19. Some of them are repetition of another experiment in order to evaluate the disagreement between the results, and others have just modifications from a previous one.

At first, some experiments were run for calibrating the whole system and evaluating if everything worked properly. The following plot corresponds to the first experiment run and it consists on recreate the same spin profile used in experiments performed by Asko in order to compare results and verify the perfect working of the developed test rig.

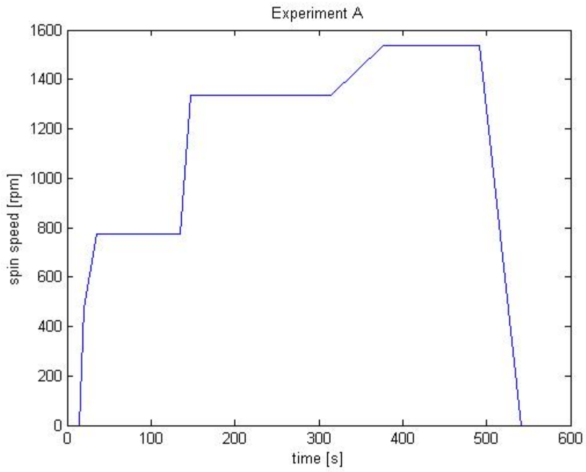

Figure 4.2 Experiment A

Next experiment could be expected to be the most efficient one, because velocity reaches its maximum value quickly, what means that it will be working longer at maximum centrifugal force. However, according to the initial information supplied by Asko, if the spinning process starts with a high speed gradient that increases the speed from zero to a high value the consequences are negative for the water extraction due to it causes the clogging of the outlet of water. The purpose of experiment B is to contrast whether this information is true or not.

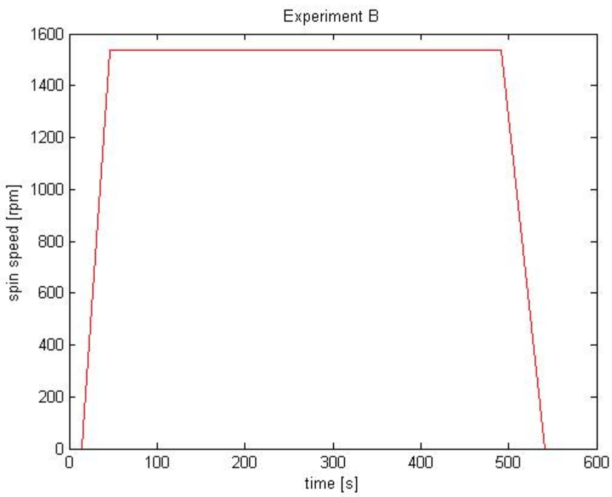

Figure 4.3 Experiment B

Assuming that the clogging should appear (in the experiments occurs another different anomaly that is commented on the results chapter) next step should try to determine when does it appear and try to prevent it by introducing some periods with constant speed or lowering the gradient. That's the reason why the following experiments were performed.

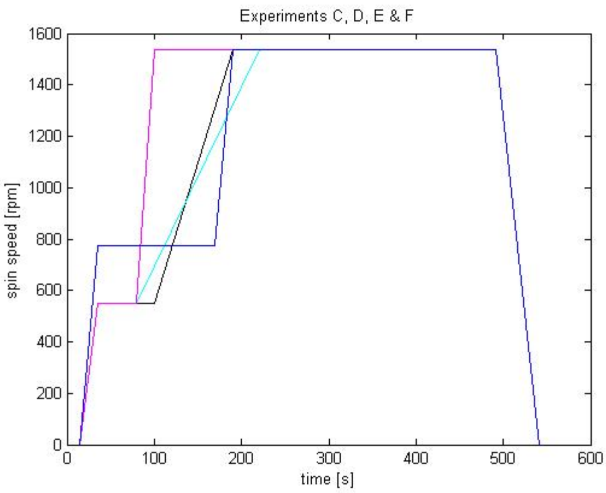

Figure 4.4 Experiments C, D, E and F

Since the speed gradient is a fundamental parameter in the experiments, it is of great importance to analyze the results obtained when varying the input speed gradient. Figure 4.5 shows different initial gradients that were tested.

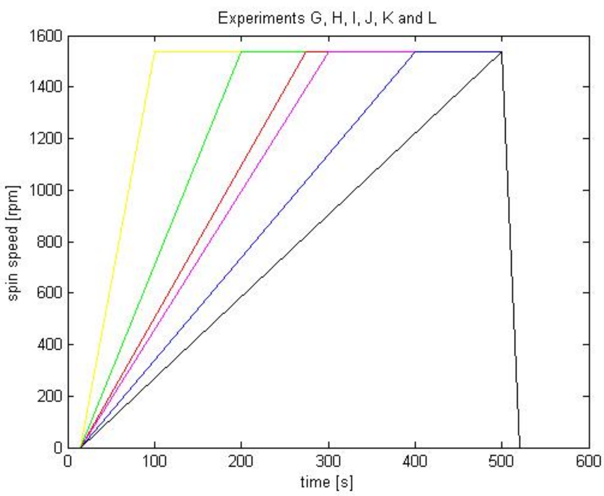

Figure 4.5 Experiments G, H, I, J, K and L

Taking the results from the previous experiments into consideration, as for instance the problems with the motor controller that as said are going to be described in Chapter 5, some new experiments are designed to overcome those problems including intermediate steps and varying the gradients.

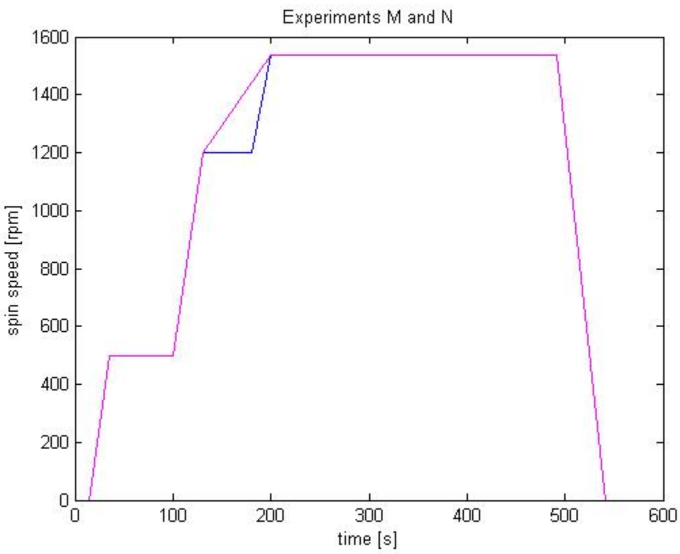

Figure 4.6 Experiments M and N

In experiment O the maximum speed was tried to be reached as soon as possible by including a low gradient instead of several intermediate steps with constant speed.

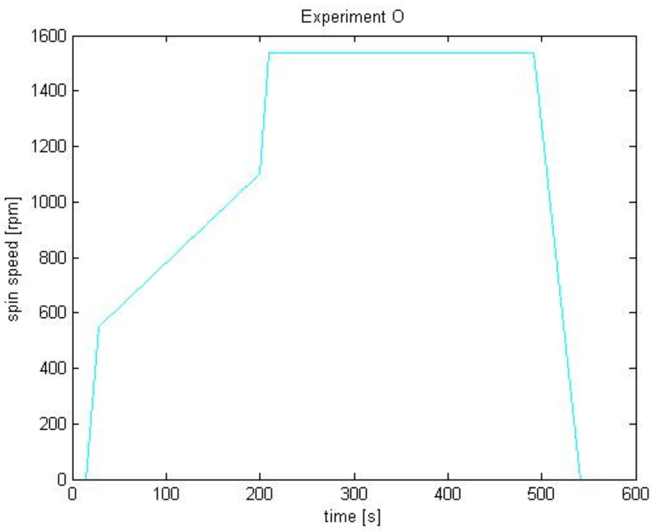

Figure 4.7 Experiment O

In the experiments P and Q instead of having high gradients at the beginning and later reduced to avoid that control problem the other way around was tried, starting with a low gradient and increasing it progressively.

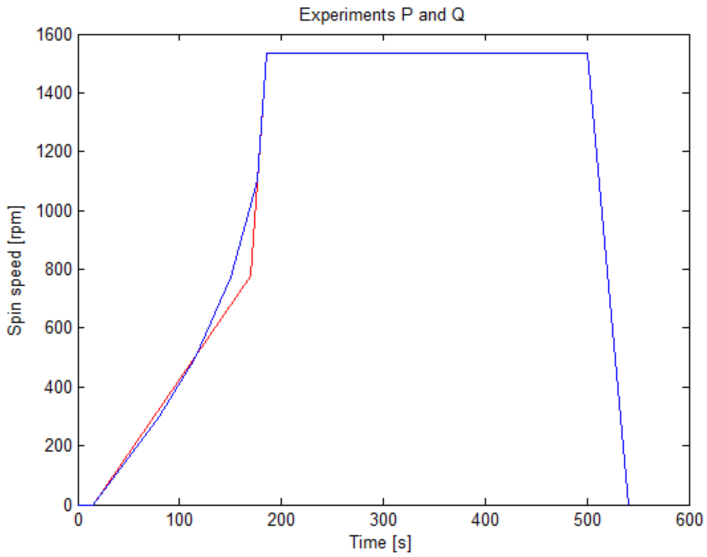

Figure 4.8 Experiments P and Q

In experiment R a different profile combining low gradients and intermediate steps was tested.

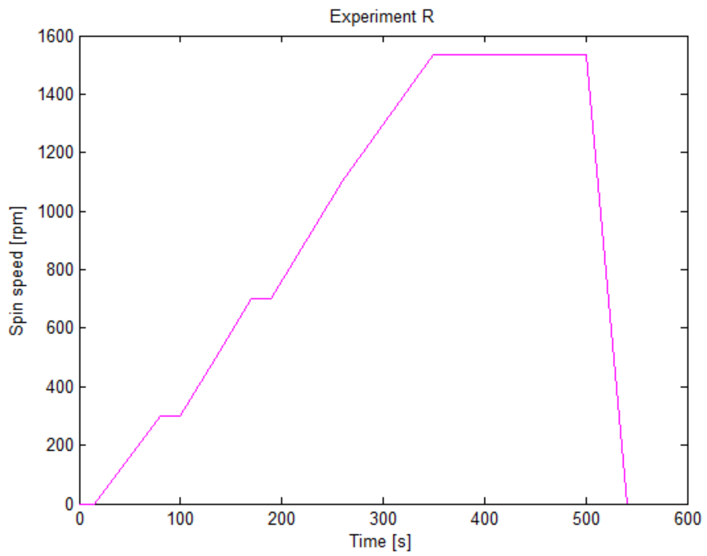

Figure 4.9 Experiment R

In order to analyse the internal parameters of the process, in the following experiment it was desired to prove the effect of the maximum spin speed by reaching it at almost the end of the process. Some evident conclusions are shown in Chapter 5.

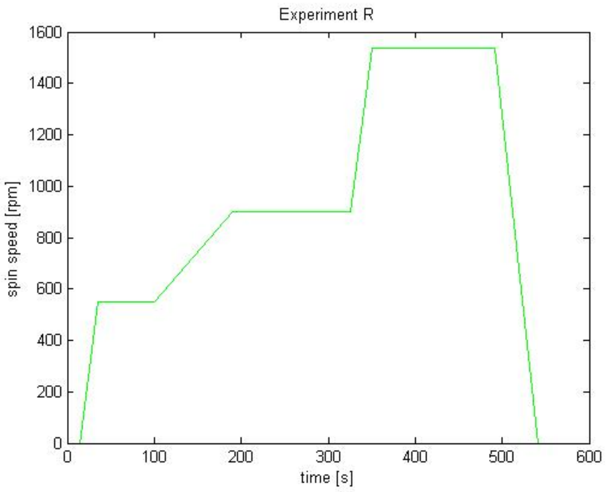

Figure 4.10 Experiment R

In the last two experiments some intermediate steps were introduced in order to balance the load and obtain better spin speed control.

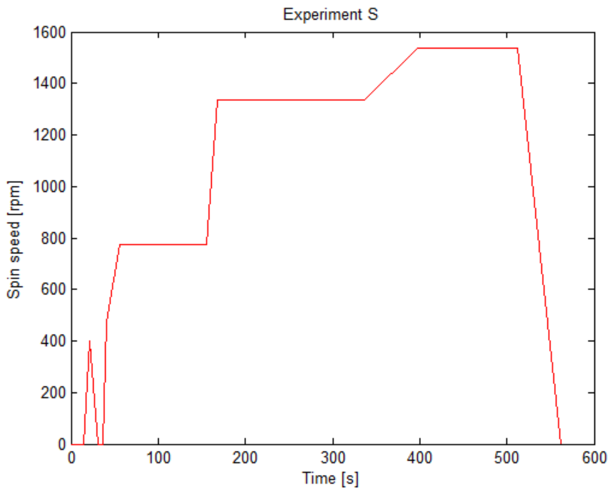

Figure 4.11 Experiment S

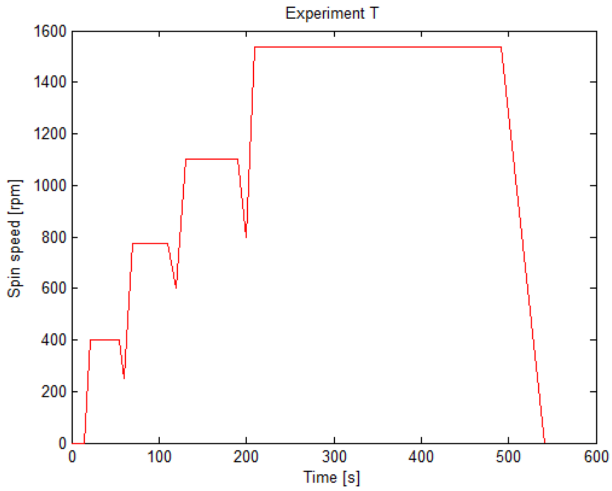

Figure 4.12 Experiment T

4.2 Execution of experiments

Before running the experiments in order to collect data efficiently it is necessary to have previously designed both the experiments and the test rig. Next step is to decide how to execute the different experiments. For that purpose, a few things were already decided: the amount of clothes (7 kg of cotton cloths) the amount of water (19.1 litres) and the spin speed profile for each experiment, but there are still many other decisions to take, as for instance how to mix water and clothes before running each experiment.

Before running any experiment, the system of measurement must be calibrated to avoid errors. In the current setup, it's just necessary to calibrate the load cell, which consists of fitting the relationship between the amount of kilograms measured by the load cell and the value in volts of the electric signal that it provides to the system. The relationship between kilos and volts is as the following:

$$W = a \cdot V + b \tag{4.1}$$

where a and b are constants. To determine these constants is necessary to measure the output signal in volts provided by the electronic load cell for two already known loads and work out the value of the constants. This way the weight of the jerry can and its rope is cancelled beforehand.

After calibrating the system the experiments can be run. In the first experiment, initial conditions are not the same because the clothes are dry and water is not yet inside the washing machine. What must be done first is to put the laundry inside the appliance and then introduce the water in the circuit. Later it is necessary to run the drum in order to moisten well the cloths and obtain accurate results. To accomplish this task the motor was programmed to follow a specific pre-spinning program. In order to design this program the drum was run for a long time at medium speed, but examining the clothes after that period it was evident that the clothes located in the middle of the drum don't get damp unless the process was lengthen too much, what is bad for experimentation because experiments would take too long time if simulating a washing process. So the decision was to increase the amount of water inside the drum from 19.1 to 30 litres. This decision will only modify the results in the sense that the amount of extracted water at the beginning of spinning is going to be greater, but after short time, the profile of the water extraction, which corresponds to the extraction of the water bound to the fabric, is going to be the same. Finally the pre-spinning program consists on running the drum at 30 rpm for 120 seconds with an initial speed gradient of 10 rpm/s, to help the laundry getting damp, with a clockwise rotational movement in order to distribute the water well around the drum and therefore obtain more realistic results.

Another way to acquired data is measuring the moisten clothes after each experiment in a scales. This way is possible to determine the real moisture in clothes after spinning, what helps also to know the real weight (clothes and water) that is introduced in the following experiment adding this value and the extracted water to the jerry can at the end of the experiment.

$$W_i = L_w + W_e = \left(L_d + M\right) + W_e \tag{4.2}$$

where W_i is the introduced weight (cloths and water) in the experiment, L_w is the weight of the wet cloths after the experiment, W_e is the amount of water in the jerry can at the end of the experiment, L_d is the weight of dry clothes, which is always 7 kg, and M is the remaining moisture inside the cloths at the end of the experiment.

Although the test rig has been designed so that water is in closed circuit, some water can leak while filling up the drum before each experiment, given that this filling up process consists on pouring the extracted water into the washing machine. But since the introduced amount of water in each experiment is known this phenomenon is not important while the leaked water is not too large.

After taking out the clothes for measuring the remaining moisture they have to be placed back into the washing machine for running next experiments.

5 Results from Experiments

In this chapter, the data collected during the experiments, is presented, accompanied by comments explaining and justifying it. Two different kinds of data can be differentiated, on one hand the data which is directly obtained from the experiments and on the other hand the data which is obtained after processing the directly-obtained data.

The data which is directly obtained from the experiments is read in LabVIEW® and stored as a text file in the computer for being later analyzed in Matlab. Those files contain information of the water extraction profile (which is one of the aims of the project) and also information of the spin speed profile followed by the drum. The latter data, is supposed to be an input data for the experiments (which were designed in Section 4.1) but the fact is that the motor in some cases is incapable of following the desired profile accurately, so this is why it's necessary to measure this data as well. Probable reasons for this problem are later explained.

5.1 Pre-processing data

When acquiring the data from the experiments, the signals (spin speed and extracted water) are not syncronized, due to the difference between the start times for their respective sensors. But this delay is easily removed by calculating the difference between both start times and adding it to the time vector of the variable which is measured the latest (it can vary in each experiment).

Another inconvenience is that the number of data points for each one of both signals (spin speed and extracted water) is not the same, and therefore it is not possible to plot relation between them directly. In order to solve this problem it's necessary to interpolate the spin speed data points. Since the data for the extraction of water is measured every $62 \cdot 10^{-3}$ s, it can be done easily. To do so it is necessary to load the data for the spin speed and its time vector for each experiment separately, adjust this data with an *interpolant* function (obtaining a perfect fit for the experimental data) and finally evaluate each of those functions for the same time vectors measured during experimentation for the extracted water in each experiment again. This method of fitting does not provide the explicit function for each curve but it doesn't matter because the only purpose of that fitting is to adjust the data for the extracted water and the spin speed of the drum for the same time vector.

5.2 Acquired data

The data collected from the experiments was properly adjusted in order to be easily processed for obtaining the mathematical model. Here it is presented. Figure 5.1 and Figure5.2 show the data from the experiments for the spin speed. In the figures the curves for the desired spin speed and the real speed followed by the drum due to problem in the motor control are represented together.

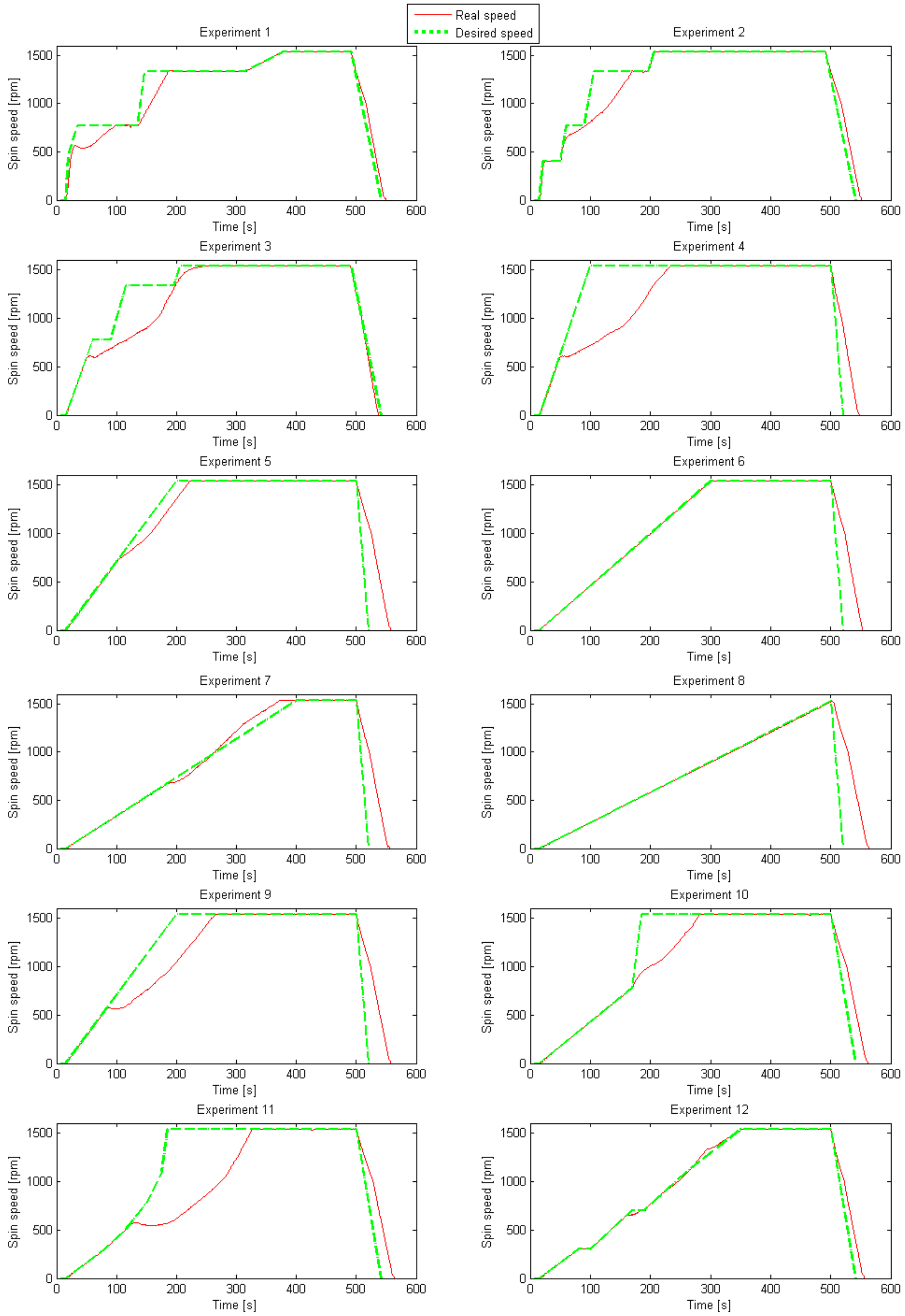

Figure 5.1 Spin speed vs. time: experiments 1-12

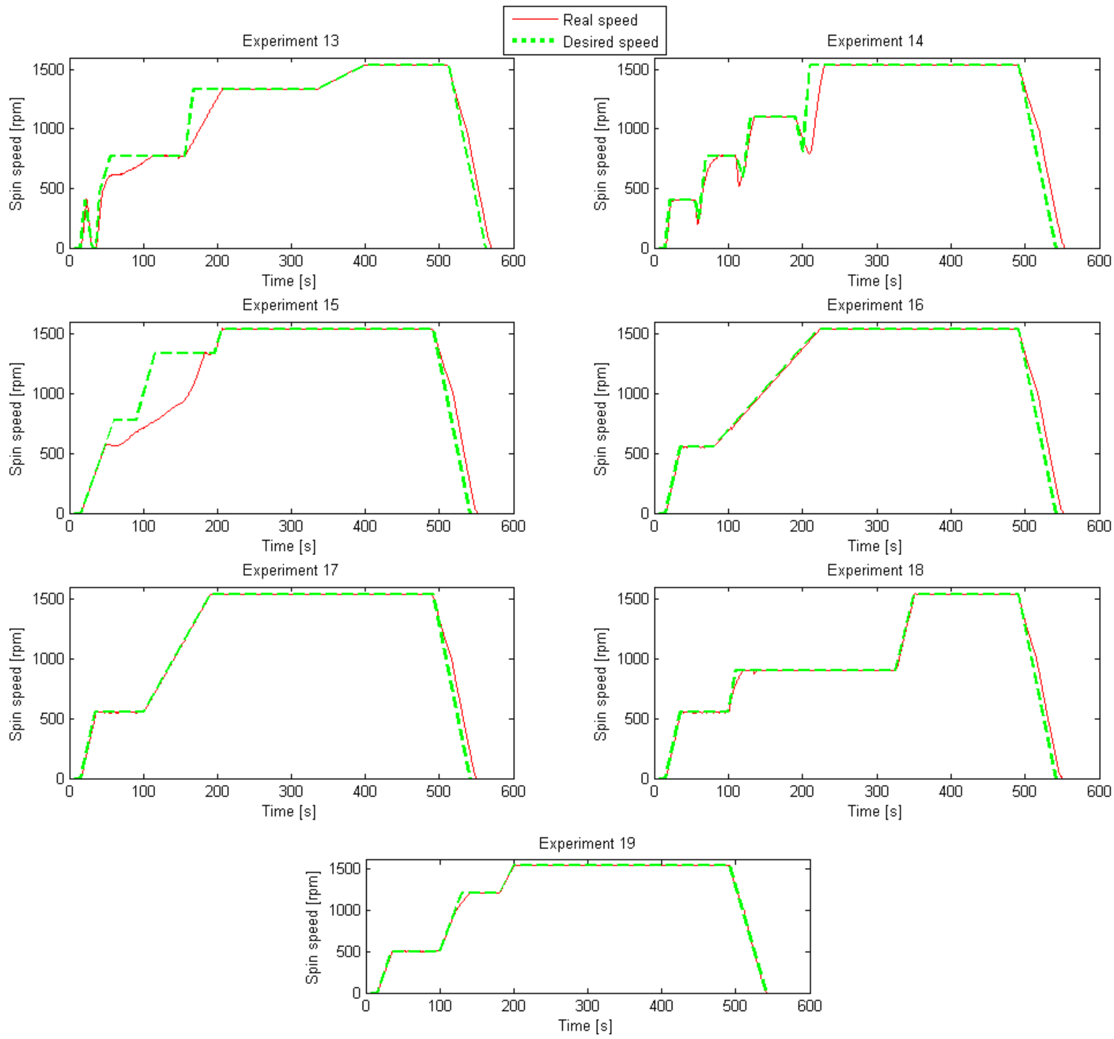

Figure 5.2 Spin speed vs. time: experiments 13-19

As it has been commented before, in the previous figures a discrepancy can be noticed between the desired spin speed and the real speed followed by the drum. These problems in some cases are negligible but in others are really significant, making the real profile seem very different to the expected profile. At first that reasons were supposed to be caused by a wrong motor controller, but after replacing it by a new one, the problems were still the same. Having a look into the results it can be seen that the greatest errors appear almost always when increasing the spin speed at the beginning with a high gradient (approximately from 30 rpm/s), so it was thought that the system couldn't use so high gradients, but having a deeper look into the results it can be noticed that this phenomenon is also dependent on the final speed value after a high gradient, because, as it can be seen in many experiments, as for instance in experiments 16, 17 and 18 (see Figure 5.3), if after a high gradient there is a period with constant spin speed, the real profile is almost as the desired one, what means that the problem is avoided. This phenomenon can be justified as a result of the imbalance caused by load and water inside the drum.

Figure 5.3 and Figure 5.4 show the profile of the remaining weight inside the drum (clothes plus water) for each one of the experiments run in the lab. The collected data during experimentation corresponds to the amount of extracted water along the duration of each experiment. However, according to industry standard performance measures it is more relevant to show the total remaining weight inside the drum, which can be estimated as the weight of the laundry plus the quantity of water still bound to it.

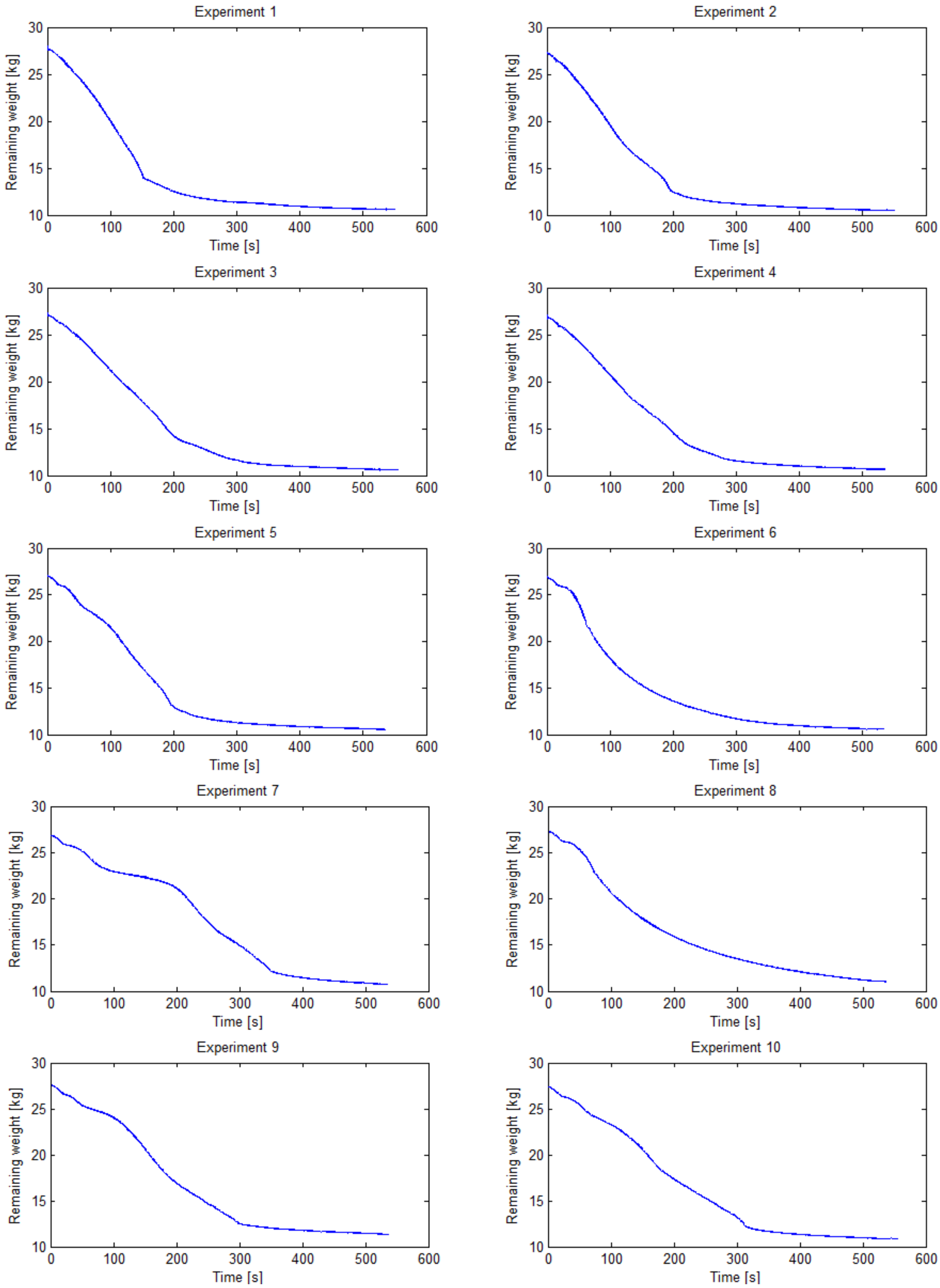

Figure 5.3 Remaining weight inside the drum vs. time: experiments 1-10

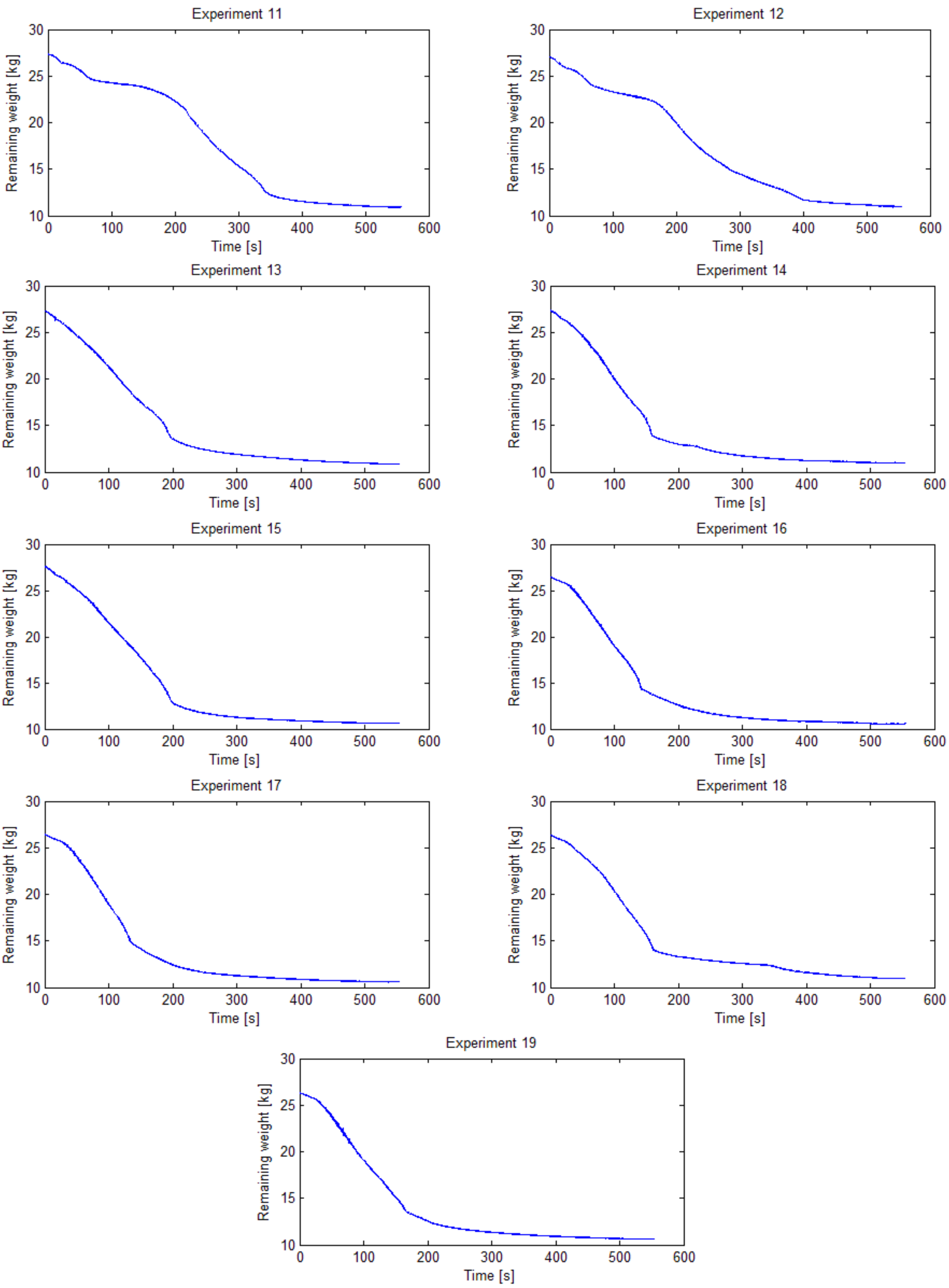

Figure 5.4 Remaining weight in the drum vs. time: experiments 11-19

In the previous figures the process of extracting water from drum and clothes as a function of time it can be seen. During the experimentation not all the experiments start with the same amount of water because it depends on the amount of water that remains in the circuit inside the washing machine, which is not a constant value. This phenomenon is due to the geometry of the washing machine outlet circuit. This circuit, as it can be seen in Figure 3.6 and Figure 3.7, consists on a pipe for extracting water from the bottom of the washing machine just under the drum. Water is elevated for about 1 metre driven by the drain pump, and then goes down again to the water jerry can, which top is about at the same level as the bottom of the washing machine. As a consequence of the difference in elevation, the pump is not able to drain all the water from the circuit.

5.3 Processing data

In order to make the resulting data from the experiments more clear and make their analysis easier, the remaining water inside the clothes is going to be expressed as a fraction of unity. Hence it is going to be easier to analyze the goodness of the results (comparing it with data supplied by Asko) and be able to decide which of the spin profiles generates the best dehydration process.

The procedure to obtain the remaining water in clothes as a function of unity uses the following equations:

$$W_r(t) = W_i - W_j(t) - \alpha \tag{5.1}$$

$$\alpha = W_e - L_w \tag{5.2}$$

$$w(t) = \frac{M}{L_d} = \frac{L_w - L_d}{L_d} = \frac{L_w}{L_d} - 1 \tag{5.3}$$

where W_r is the remaining water inside the clothes at each instant of time , W_i is the weight introduced in the experiment (cloths and water), W_j is the weight in the jerry can at each instant of time, α is a correction term for the remaining water inside the outlet circuit, W_e is the amount of water in the jerry can at the end of the experiment, L_w is the weight of the wet cloths after spinning, w is the remaining moisture inside the clothes at each instant of time as a fraction of unity, *M* is the remaining water in cloths at the end of each experiment and L_d is the weight of the dry cloths, which was always 7 kg during the experiments.

After obtaining the remaining water inside the cloths as a fraction of unity, it is easy to decide which of the experiments produces the best spinning process with a graphical study, with just plotting all the results together in the same plot and see in which of them the lowest final value for the remaining water is obtained. Figure 5.5 shows those results, where the most efficient experiments are highlighted in green. Those ones are experiment 2, experiment 5 and experiment 16, obtaining rates of 50.80 %, 50.83 % and 50.86 % respectively. Also experiment 1, similar to the profile used by Asko is highlighted in red.

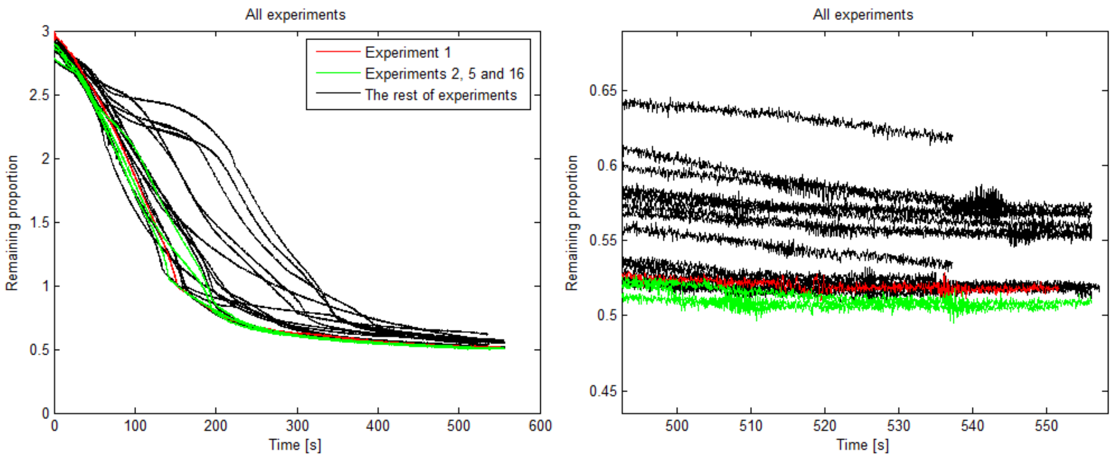

Figure 5.5 Remaining moisture in clothes as a fraction of unity for all the experiments

Table 5.1 reflects the percentage of remaining water inside the laundry for all the experiments, allowing proving numerically which of the experiments is the best regarding to the dehydration process.

Table 5.1 Percentage of remaining moisture in clothes and other measurements

No. of Exp.	Water Introduced [g]	Weight Introduced [g]	Wet Clothes [g]	Moisture [g]	Final water in can [g]	Remaining moisture [%]
1	28691	35691	10629	3629	25062	51.84
2	28691	35691	10556	3556	25327	50.80
3	28883	35883	10648	3648	25093	52.11
4	28741	35741	10671	3671	25058	52.44
5	28729	35729	10558	3558	24953	50.83
6	28511	35511	10596	3596	24800	51.37
7	28396	35396	10710	3710	24606	53.00
8	28316	35316	11040	4040	24288	57.71
9	28328	35328	11330	4330	24306	61.86
10	28636	35636	10870	3870	24493	55.29
11	28363	35363	10918	3918	24086	55.97
12	28004	35004	11002	4002	23740	57.17

No. of Exp.	Water Introduced [g]	Weight Introduced [g]	Wet Clothes [g]	Moisture [g]	Final water in can [g]	Remaining moisture [%]
13	27742	34742	10894	3894	24055	55.63
14	27949	34949	10984	3984	23657	56.91
15	27641	34641	10612	3612	24542	51.60
16	28154	35154	10560	3560	24286	50.86
17	27846	34846	10620	3620	24471	51.71
18	28091	35091	10962	3962	24010	56.60
19	27972	34972	10627	3627	24280	51.81

In accordance with one of the aims of the thesis, now the results can be compared more accurately. As it was predicted graphically the experiments which provide better dehydration are experiments 2, 5 and 16, with a percentage of remaining moisture in clothes after spinning of 50.80 %, 50.83 % and 50.86 % respectively. From these results it can be assured that at least there are three different spin speed profiles that provide better spinning than experiment 1 (similar to the profile used in Asko washing machines). These new profiles provide improvements in spinning of 1 %. The only objection to this statement is that while running the experiments there were problems in the control of the velocity of the drum (see Section 5.2), because those discrepancies between the desired spin speed and the real one, appear in experiment 2 and 5, but also in experiment 1 (not in experiment 17). However, it must be said that the discrepancy real and desired data in experiments 2 and 5, doesn't matter even if real profiles do not much with the desired ones. This is because what really matters in order to compare the results is to have the real spin speed data corresponding to each water extraction process. In experiment 1 the discrepancy between both curves is not too big, but due to this discrepancy it can't be said that its profile corresponds to the one used by Asko, what impedes comparing the results.

Attending to the real profiles of experiments 2, 5 and 16, they are very similar, so this shape seems to provide good results. In general terms they have a high speed gradient at the beginning (of about 27.5 rpm/s), then a short period with constant spin speed at about 500 rpm to avoid control problems (in experiment 5 there is not this step), after it there's a speed gradient again, but lower this time (about 10,9 rpm/s), and finally the maximum spin speed (1535 rpm) is reached.

After analyzing the results from the experiments, it's time to compare them with some results provided by Asko from their own experiments, which are shown in Table 5.2.

Table 5.2 Percentage of remaining moisture in clothes from experiments run by Asko

Dry clothes (g)	Wet clothes (g)	Remaining moisture
6849	9998	46.00 %
6849	9996	45.90 %
6849	10025	46.40 %
6849	10124	47.80 %
6849	10154	48.30 %

Having a look at the data supplied by Asko it is proved that the profiles tested at the laboratory didn't obtain better rates of remaining moisture in cloths after spinning because in Asko they are able to reach values between 45.90 % and 48.30 % while in the experiments run in this thesis only the 50.80 % is reached. In the experiment run at the lab using a similar profile to that used in Asko (experiment 1), the obtained result is 51.84 %, which is a little bit higher than theirs, but this difference can be justified because of the problems occurred in the spin speed control. This fact suggests that the rate obtained throughout the experimentation (50.80 %) could also be improved with a better spin speed control.

5.4 General conclusions from the experiments

The experiments have provided the information showed in the previous sections of this chapter, so now it's time to make a comparison between expected results and outcomes. In the first place, as it is commented in Section 4.1, the water outlet was expected to clog up when starting spinning with a high gradient, but having a look at the results, it can be easily appreciated that in the experiments, independently of the initial spin speed gradient, that phenomenon does not appear. Instead, there are the problems already mentioned with the drum speed control.

Another conclusion which can be drawn easily is that in the dehydration process there is a fast and huge extraction during the first part of the spinning (until $t = 150\ s$ or $t = 350\ s$ depending on the spin speed profile), and then, water is removed more slowly, e.g. in experiments 1, 10, 14, 15 or 18 (Figures 5.3 and 5.4) where this change on the water extraction gradient is more obvious. The explanation for the easiness to remove water at the beginning of spinning lies in two aspects: the first one is that there is a certain unabsorbed amount of water that can easily be removed; and secondly because clothes are too moisten so it's also easy to remove water from them with a low centrifugal force, it means, with a low spin speed. Since then, the curve for the remaining weight (clothes and water) can be estimated as the weight of the clothes and the water still bound to them, because the only water remaining in the drum is contained inside the clothes. After the fast initial water extraction, the gradient of extracted water becomes lower, and this is because it gets harder to remove water from clothes. Finally the process enters in a kind of saturation, where even if lengthening the duration of the process, almost no more water is removed from clothes unless the rotational speed is increased, but in the experiments the maximum spin is reached and can't be increased because this value is imposed by characteristics of the components of the washing machine.

Having a look at the curves obtained for the remaining weight inside the drum for all the experiments together, shown in Figure 5.6, it can be noticed that the process and the final value vary from one experiment to another. Thus it's obvious that there is a direct relationship between the spin speed sequence and the dehydration process.

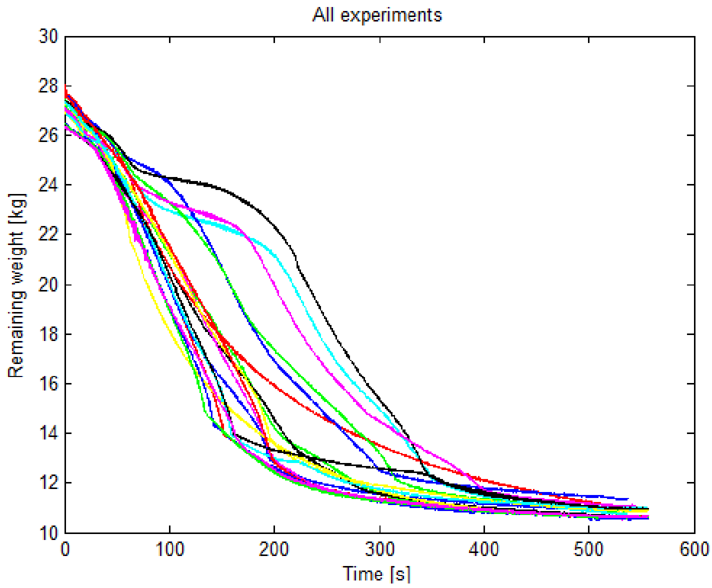

Figure 5.6   Remaining weight inside the drum vs. time, for all the experiments

From the experience acquired during the experimentation together with an analysis of the experiments one by one and comparing how the variations on the spin sequence affect the water extraction, the following conclusions were inferred:

- In order to avoid problems controlling the spin speed, it is necessary to use not so high gradients (bigger than 30 rpm/s); otherwise the drum won't be able to follow the desired profile by the reasons described in Section 5.2. In case of using high speed gradients it's not possible to accomplish a big speed change without having that kind of problems, as it can be seen in experiments 4, 5, 9 or 11 (see Figure 5.1). A way of working around this problem is to introduce some intermediate period with constant spin speed, as it was done in experiments 16, 17 or 18 (see Figure 5.2).

- The higher the maximum spin speed the better drying, it means, lower remaining moisture in the laundry at the end of spinning. This statement can be noticed in experiment 1 or experiment 18 (see Figure 5.3 and Figure 5.4 respectively). For instance in experiment 18, after spinning for a long time at 900 rpm (see Figure 5.2 for spin speed profile) it seems as if the remaining moisture inside the cloths couldn't be decreased anymore, but from instant $t = 350\ s$ where there is a spin speed change from 900 to 1535 rpm, the remaining moisture is clearly reduced.

- Another characteristic related to the remaining moisture are speed gradients which affect directly to the gradients of the dehydration process. For instance, in experiments 8 and 12 where speed gradients are 3.16 and 4.58 rpm/s respectively, the velocity of removing water from the drum is very slow (see Figure 5.3 and Figure 5.4), as the most part of the extracted water is not removed until $t = 400$ s or even later. On the other hand, for instance in experiments 1, 2, 15 or 17 where the gradients are bigger, the great majority of the final extracted water is removed before $t = 200$ s or even earlier.

- Same desired profile obtains different real ones. Since Experiments 5 and 9 (see Figure 5.1) have the same desired profile for the spin speed, but they have different real profiles, there is a clear evidence that there are more factors than those taken into account that affect spinning, as for example the unbalance of the load. As it can be seen in those experiments, they have similar real profiles but not the same. In experiment 5 the deviation from the theoretical spin speed appears at 712 rpm with a small deviation, while in experiment 9 it appears at 571 rpm and the deviation is much larger, it even suffers a drop on the rotational speed. Undoubtedly the differences between both experiments are caused by a random phenomenon as it is the distribution of the load inside the drum, which generates unbalances.

6 Mathematical Model

As it was explained at the beginning, spinning is a mechanical process that depends on several parameters. In the experimentation done in the lab, the controlled variables in each experiment where time, spin speed, amount of water and amount of cloths in order to obtain the data of the remaining water inside the clothes. Since one of the aims of the thesis is to create a mathematical model of the entire spinning processes, the acquired data throughout the experimentation is going to be used for building it.

6.1 Building the model

The data used for building the model consists of three parameters: time, spin speed and remaining weight inside the system. The later consists of the remaining weight expressed as a fraction of unity, as the data used to analyze the experiments in Section 5.3.

The methodology used to build the model consists of evaluating different polynomials by the least square method. This method is used to approximately solve systems of equations in which there are more equations than unknowns. Least squares method is often applied in statistical contexts, particularly regression analysis and it can even be interpreted as a method of fitting data. This is why it is used in this thesis, to fit the data acquired throughout experimentation with a suitable mathematical expression. The best fit in the least-squares sense is that instance of the model for which the sum of squared residuals has its least value, a residual being the difference between an observed value and the value given by the model. The least squares method is available in most statistical software packages, as for example in Matlab, which is the software used in this project to fit the experimental data. The main functions to accomplish this kind of fitting in Matlab are: *lsqnonlin* or *lsqcurvefit* when approximating with nonlinear expressions (see e.g. [5]).

Mathematically, the process of building the model consists of three main steps:

1. At first it's needed to suppose a mathematical expression as the first guess to approximate the experimental data. Since the remaining water in the system as a fraction of unity (w) depends on two variables which are: the spin speed (ω) and time (t), the model is represented as follows:

$$w = f(t, \omega) \tag{6.1}$$

For the initial guess a linear polynomial is used in order to start the approximation with simple expressions. This initial expression is:

$$w = a + b \cdot t + c \cdot \omega \tag{6.2}$$

where a, b and c are the unknown coefficients and (t, ω, w) correspond to the experimental data: time, spin speed and the remaining water in the system as a fraction of unity.

2. Later what must be done is to evaluate the suggested model with the experimental data in order to obtain the optimum coefficients a, b and c, according to the least sum of squared errors (SSE) for the whole experiments (see equation (6.3)).

3. Finally it is necessary to check the results to see how reliable the fitting is. In case of having a great discrepancy between the experimental data and the data given by the model it is advisable to evaluate a new fitting with a more complex model, until the SSE is admissible. One way to evaluate how representative the SSE is, is to calculate the percentage of the average deviation for all the experiments, with equation (6.4).

$$SSE = \sum_{j=1}^{p}\sum_{i=1}^{n}(w_i - w_i^m)_j^2 \ , \qquad j \in [1, p] \ , \quad i \in [1, n] \tag{6.3}$$

$$\bar{\varepsilon} = \frac{\sum_{j}^{p} \frac{\sum_{i}^{n}\left(\frac{w - w^m}{w}\right)_i}{n}}{p} \cdot 100 = \frac{100}{p \cdot n}\sum_{j}^{p}\sum_{i}^{n}\left(\frac{w - w^m}{w}\right)_i \tag{6.4}$$

$$j \in [1, p] \ , \quad i \in [1, n]$$

Where SSE is the sum of squared errors, w and w^m are the experimental and the modelled remaining water inside the cloths as a fraction of unity respectively, p is the number of experiments (19), n the number of data points in the whole experiments (168254) and $\bar{\varepsilon}$ is the percentage of the average deviation for all the experiments,

Another way to evaluate the model is calculating the error for different points along the curves of the experiments. Both ways of estimating the accuracy of the model are going to be evaluated in Section 6.2.

Table 6.1 shows some tested models, as well as their more characteristic parameters: optimum coefficients, SSE and the percentage of the average deviation of the remaining moisture inside the drum for the most accurate model. For more information about other models that were tested see Appendix A.

Table 6.1 Some of the models with best fitting

Expression	Parameters	SSE	Average deviation
$w = a + b \cdot t + c \cdot \omega$	$a = 7.68 \cdot 10^{-1}, b = -7.36 \cdot 10^{-4}$	$3.11 \cdot 10^{2}$	
$w = a + b \cdot t + c \cdot t \cdot \omega$	$a = 7.10 \cdot 10^{-1}, b = -5.47 \cdot 10^{-4}$, $c = -1.88 \cdot 10^{-7}$	$4.42 \cdot 10^{2}$	
$w = a + b \cdot t + c \cdot \omega + d \cdot t^4 \cdot \omega^2$	$a = 7.93 \cdot 10^{-1}, b = -7.31 \cdot 10^{-4}$, $c = -1.12 \cdot 10^{-4}, d = 7.58 \cdot 10^{-19}$	$2.53 \cdot 10^{2}$	6.23 %
$w = a + b \cdot t + c \cdot \omega + d \cdot t^2$ $+ e \cdot \omega^2 + f \cdot t^3 + g \cdot \omega^3$ $+ h \cdot t^4$	$a = 7.37, b = 9.99 \cdot 10^{-2}$, $c = -1.06 \cdot 10^{-2}, d = -9.31 \cdot 10^{-4}$, $e = -2.49 \cdot 10^{-6}, f = 2.77 \cdot 10^{-6}$, $g = 4.04 \cdot 10^{-9}, h = -2.60 \cdot 10^{-9}$	$1.48 \cdot 10^{6}$	
$w = a + b \cdot t + c \cdot \omega + d \cdot t^2$ $+ e \cdot t^4 \cdot \omega^2$	$a = 8.68 \cdot 10^{-1}, b = -2.80 \cdot 10^{-2}$, $c = 2.81 \cdot 10^{-3}, d = 4.82 \cdot 10^{-5}$, $e = -2.09 \cdot 10^{-17}$	$4.98 \cdot 10^{4}$	

Having a look at Table 6.1, it's obvious that the best fitting is obtained with model: $w = a + b \cdot t + c \cdot \omega + d \cdot t^4 \cdot \omega^2$, given that it has the lowest SSE ($2.53 \cdot 10^2$), with an average deviation of 6.23 %. Other models where studied generating worse results.

6.2 Validation of the model

After testing different models and obtaining one whose solutions seem to be reasonable it's time to study the accuracy of the model in other to validate it if the results are satisfactory. As it was said in the previous section the model that better fits to experiments is: $w = a + b \cdot t + c \cdot \omega + d \cdot t^4 \cdot \omega^2$.

Next, the results for each one of the experiments are going to be plotted together with the results given by the model, in order to make easier to estimate for which experiments the model fits to the experimental data properly and for which ones the model is not adequate. The experiments are grouped in groups of six.

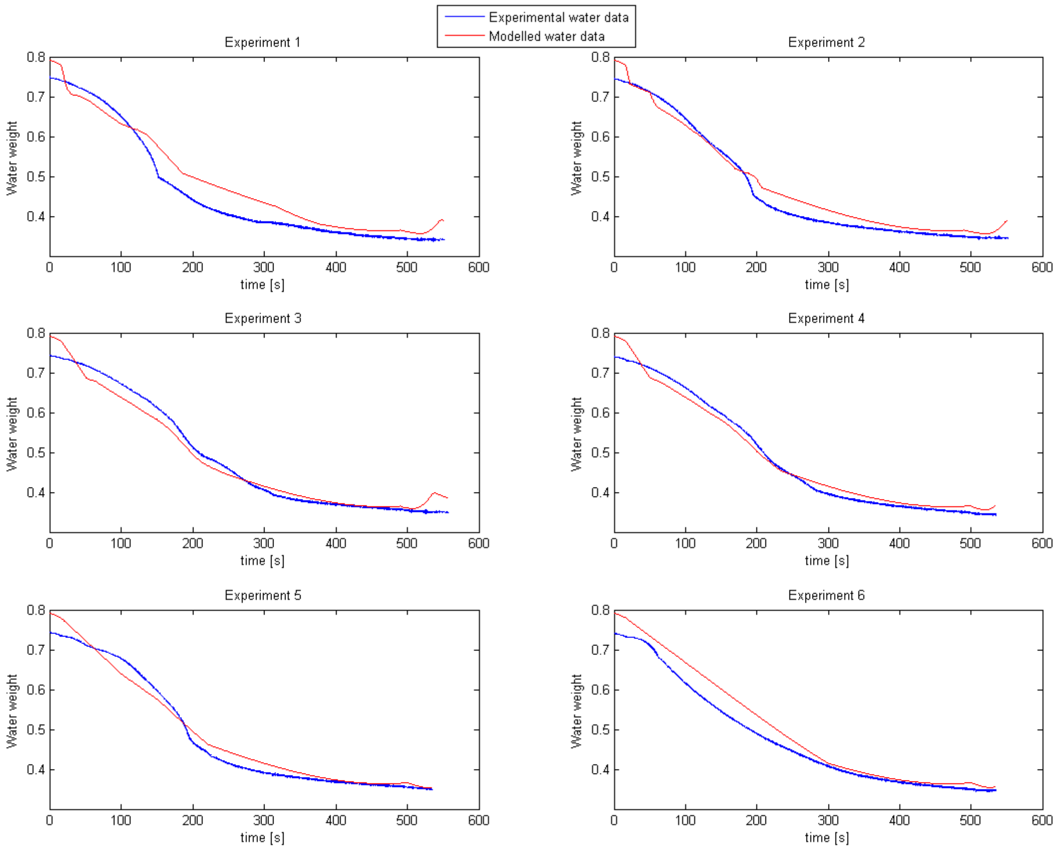

Figure 6.1 Modelled and experimental remaining water given as a fraction of unity: experiments 1-6

For the first six experiments the experimental data is properly fitted by the model, except for experiment 1 (see Figure 6.1), where there is a bigger discrepancy between both curves in the period from $t = 100\ s$ to $t = 350\ s$, with a maximum deviation of 14%. In Figure 6.2 this discrepancy can be checked, where the percentage error along time for each one of the first six experiments is presented. In the other five experiments in some cases the error can reach values around 8 %, but this deviation is almost instantaneous. An important lack of fitting appears just at the end of the experiment, where the model changes its value rapidly. This is an important problem if the model is used to get the final value of the remaining water inside the clothes. But since at the end of the dehydration process there is a kind of saturation, if when calculating the final remaining water it is noticed that this value differs too much from the previous ones, it must be disregarded. In order to get a reliable value it is advisable to get a previous value for which the remaining water inside the clothes at instants of time before and after it don't differ too much.

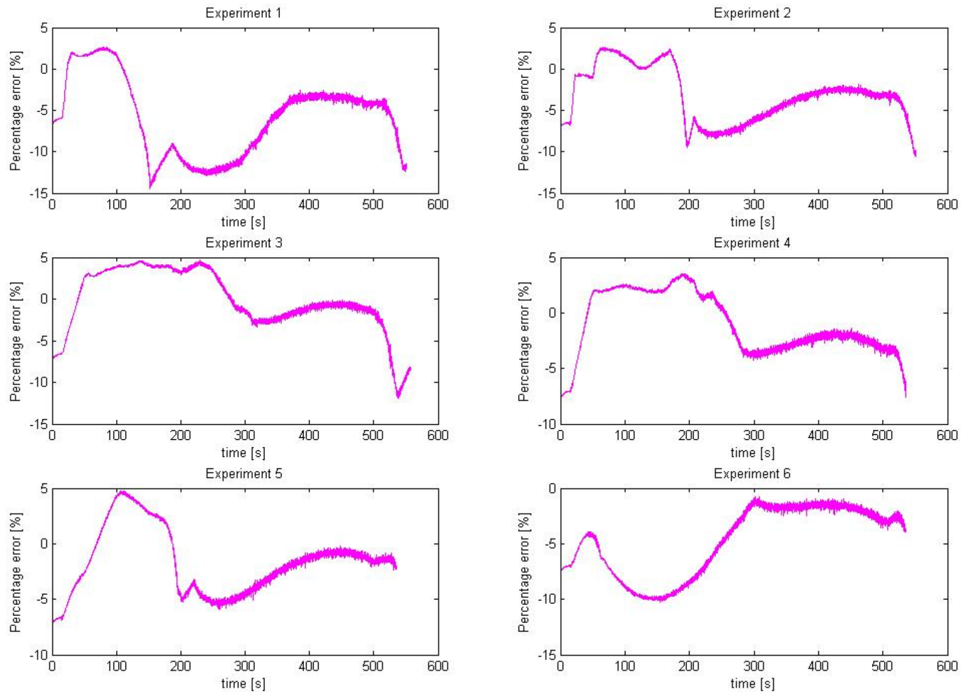

Figure 6.2 Percentage errors for the remaining water inside the system: experiments 1-6

Figure 6.3 and Figure 6.4 shows the results for experiments from 7 to 12.

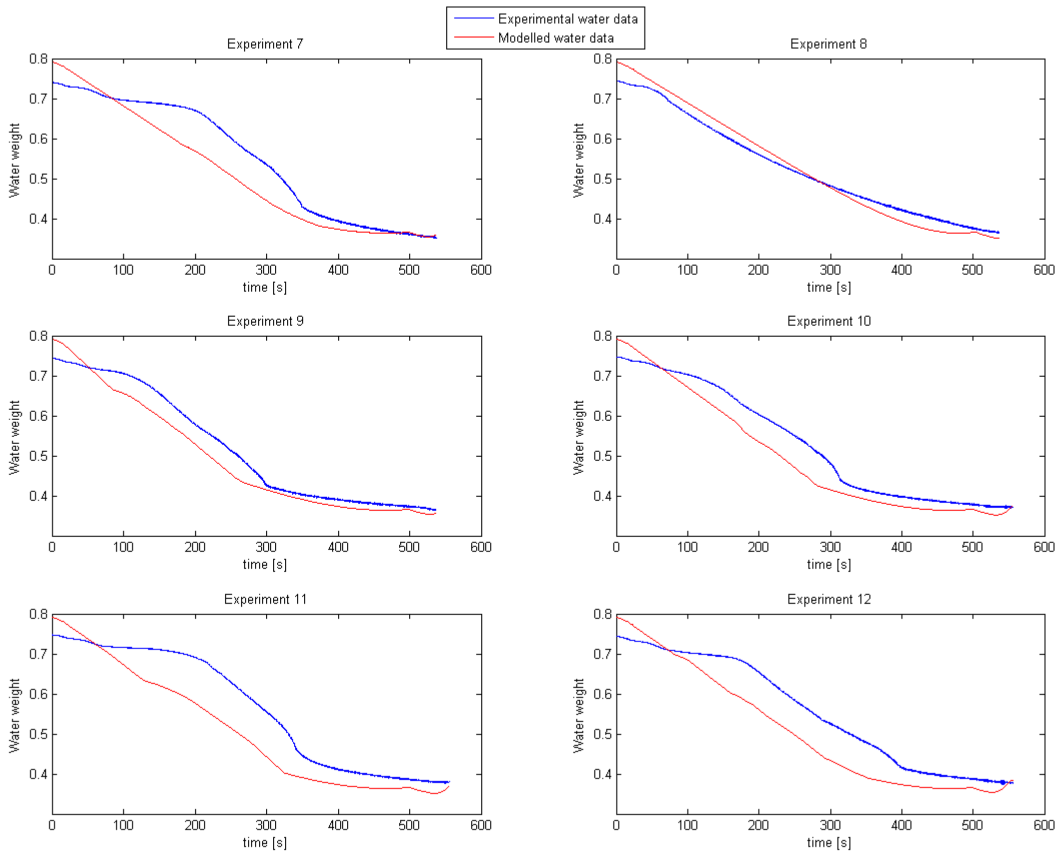

Figure 6.3 Modelled and experimental remaining water given as a fraction of unity: experiments 7-12

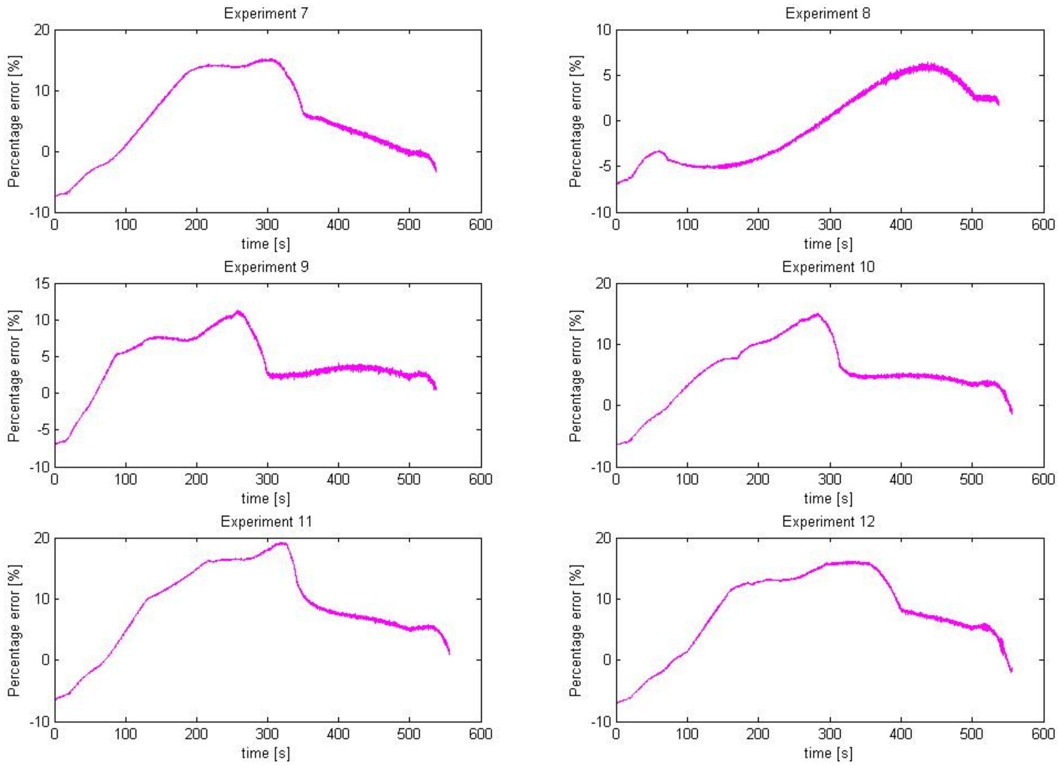

Figure 6.4 Percentage errors for the remaining water inside the system: experiments 7-12

Experiments from 7 to 12 are not as well fitted as the first six experiments are. The values given by the model for experiment 8 are really accurate, especially at the end of the experiment. For the other experiments they are not so reliable, at least from approximately $t = 0\ s$ to $t = 310\ s$, instead most of them have a good fitting from $t = 350\ s$ to the end of the experiments. The problem in those experiments is that their spin speed profile is very simple, in most of them it consists on a constant gradient and then speed stays at 1535 rpm. This simplicity of the spin speed profile makes the fitting to be worst because it is difficult to fit experimental curves when the internal parameters don't vary too much.

Figure 6.5 and Figure 6.6 show the results for experiments from 13 to 19.

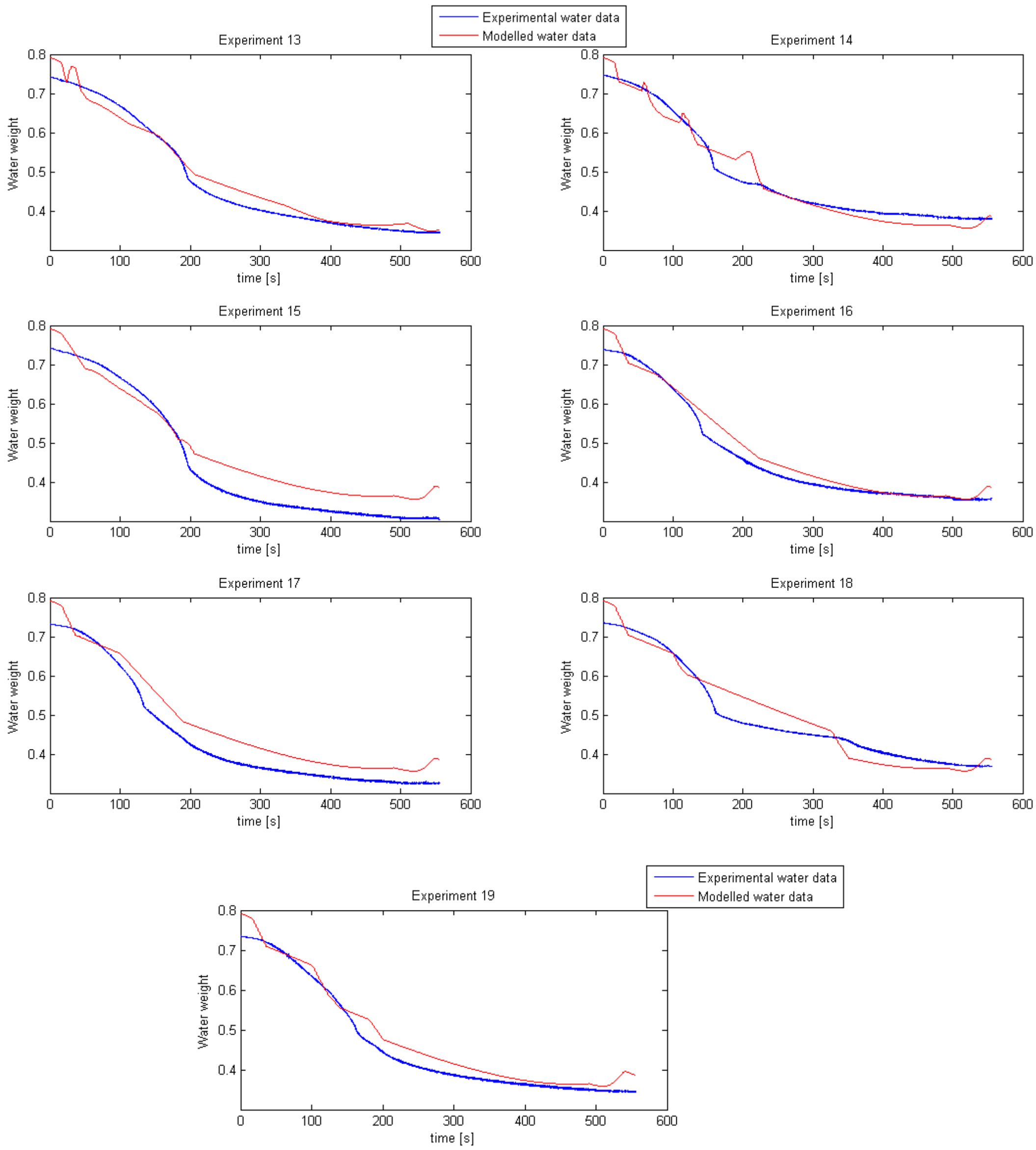

Figure 6.5 Modelled and experimental remaining water given as a fraction of unity: experiments 13-19

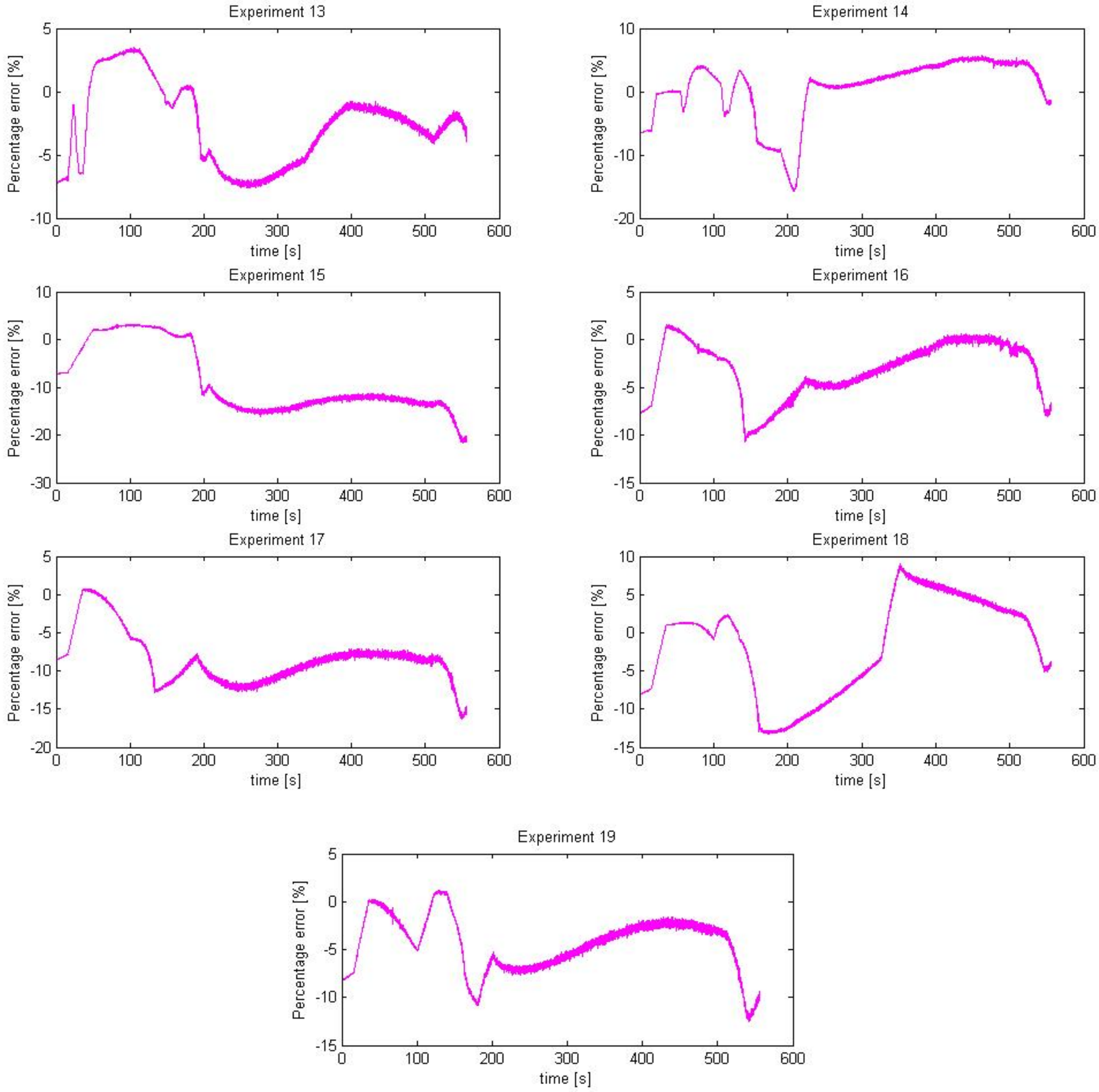

Figure 6.6 Percentage errors for the remaining water inside the system: experiments 13-19

For experiments 13-19 the results given by the model are a little more accurate than the six previous ones, especially in experiments 13 and 16. In experiment 14 the modelled data has an strange profile at the beginning of the extraction process because of the estrange profile of the spin speed, because it goes up and down, which doesn't seem to be good for water extraction because its rate of final remaining water is not very low. In experiment 2 the model does not provide a good fitting, and since it is the most successful experiment in remaining water terms, it is advisable to optimize a new model just for it for further studies searching for improvements in drying rates. The structure used for that mathematical model is the same as for the entire experiments, but now the optimum parameter $(a, b, c \text{ and } d)$ might be different. Table 6.2 shows the parameters for this new optimization:

Table 6.2 Parameters of the model for experiment 2

Expression	Parameters	SSE	Average Error
$w = a + b \cdot t + c \cdot \omega + d \cdot t^4 \cdot \omega^2$	$a = 8.10 \cdot 10^{-1}$, $b = -8.10 \cdot 10^{-4}$, $c = -1.27 \cdot 10^{-4}$, $d = 1.05 \cdot 10^{-18}$	2.67	1.73 %

In Figure 6.7 the results given by the models as well as the experimental data for the remaining water inside the clothes are plotted together:

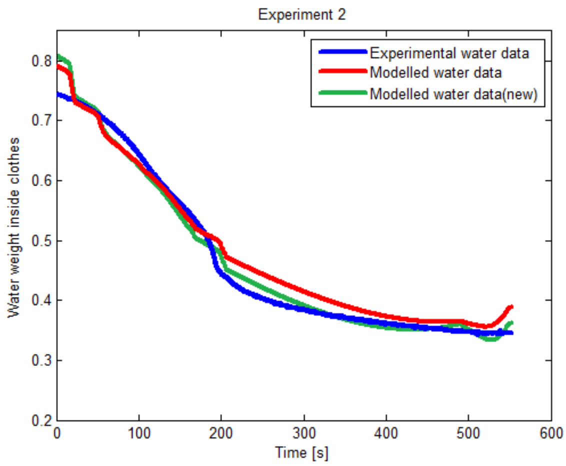

Figure 6.7 Modelled and experimental remaining water inside the system as a fraction of unity: experiment 2

This time the results given by the model for experiment 2 are more accurate and they can be really trusted. Improvements are located from $t = 200\ s$, mainly at the end of spinning, what is really important when trying to estimate final drying. Having a look at Figure 6.8, an obvious decrease in the percentage error can be noticed. With the general mathematical model for the whole experiments errors of 11 % were reached in experiment 2 whereas with the model for just experiment 2 it is reduced to an average deviation of 1.73 %, having a maximum deviation of 7.5 %, disregarding initial values that are not relevant.

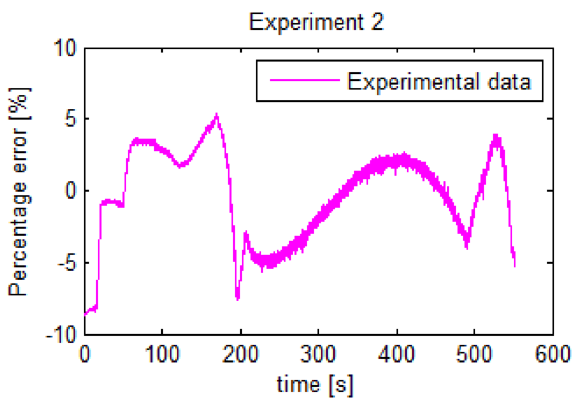

Figure 6.8 Percentage deviation for the remaining water inside the system: experiments 2

7 Conclusions and Recommendations

Throughout this thesis, the spinning process in washing machines was studied in order to acquire more information about its dynamics and if possible to come up with some improvements of the dehydration process with the purpose of making these appliances more efficient. The results from the most successful experiments show a final remaining amount of water in laundry after spinning of 50.8 % while the figures reached by the company interested in this study are between 45.9 % and 48.3 %. Due to some problems with the spin speed control in the experiments run at the lab, when using a similar profile to that used in Asko, the obtained results are a little worse than the figures they obtain, so this could suggest that the 50.8 % could also be improved with a better spin speed control. Those problems with the control are justified as a consequence of the unbalance caused by load and water inside the drum, probably due to the out-of-balance control system, provided nowadays with all commercial washing machines. However, they can be solved using small speed gradients or having some intermediate steps with constant spin speed. Another reason to think that the results could also be improved is that the amount of water used in the experiments is higher than that required in a normal washing program to moisten clothes properly producing a good wash, because since the washing process is not run before the experiments with just 19.1 litres is not enough to moisten them properly.

In the experimentation many different spin profiles were tested in order to analyze similarities and differences between all of them in order to know more about the process, so some conclusions were extracted. At first it can be assured that the results for the remaining water inside the cloths after spinning are really dependent on the spin sequence, and mainly it depends on the maximum spin speed reached, the higher the maximum spin speed the better drying. Also speed gradients have relevance on how fast the remaining water is reduced.

Another line of research was the creation of a mathematical model that can predict outcomes for the remaining water inside the system. This model could be helpful to test new spinning profiles without the necessity of running the experiments. Analyzing the results given by the model it can be said that the fitting between the modelled data and the experimental data is not too bad; an average for the whole experiments of 6.23 % is obtained.

The lack of available time for testing similar profiles to the most successful one made the results poorer. Also the lack of time for mathematical model update in order to adjust it to the real moisture in clothes instead of in the system made the results less interesting from client’s point of view.

In order to obtain better results in future studies, the following recommendations should be taken into account:

- It is advisable to remove water from the outlet circuit after running each experiment; otherwise every experiment will start with an unknown amount of water in the circuit. It is possible to drain it because there is an opening at the bottom of the washing machine.

- Include some kind of pre-spinning period in order to make the laundry load and the water inside the drum more evenly distributed, so the real profile of the drum might fit better to the desired profile.

- Since the imbalance generated by the load inside the drum affects spinning, a deep research about the distribution of the load could provide some new parameters to include in the mathematical model, and therefore, make it more accurate.

8 References

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[3] Rosenblatt, F., *Principles of Neurodynamics*, Washington D.C., Spartan Press, 1961 [Rose61].

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[5] *Optimization Toolbox^{TM} 4 User's Guide*, March 2009

Appendix A: Results from other mathematical models

Expression	Parameters	SSE
$w = a + b \cdot \frac{(c+t)}{(d+w)}$	$a = -3.11 \cdot 10^{-1}, b = -5.00,$ $c = -1.64 \cdot 10^{3}, d = 7.47 \cdot 10^{3}$	$3.02 \cdot 10^{2}$
$w = a + b \cdot \frac{\cos t}{\cos \omega}$	$a = 4.95 \cdot 10^{-1}, b = 1.51 \cdot 10^{-6}$	$3.28 \cdot 10^{3}$
$w = a + b \cdot t$	$a = 7.20 \cdot 10^{-1}, b = -7.36 \cdot 10^{-4}$	$5.05 \cdot 10^{2}$
$w = a + b \cdot \omega$	$a = 7.28 \cdot 10^{-1}, b = -2.18 \cdot 10^{-4}$	$1.23 \cdot 10^{3}$
$w = a + b \cdot t \cdot \omega$	$a = 6.60 \cdot 10^{-1}, b = -4.82 \cdot 10^{-7}$	$8.37 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot \omega$	$a = 7.68 \cdot 10^{-1}, b = -5.96 \cdot 10^{-4},$ $c = -1.02 \cdot 10^{-4}$	$3.11 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot t \cdot \omega$	$a = 7.10 \cdot 10^{-1}, b = -5.47 \cdot 10^{-4},$ $c = -1.88 \cdot 10^{-7}$	$4.82 \cdot 10^{2}$
$w = a + b \cdot \omega + c \cdot t \cdot \omega$	$a = 6.82 \cdot 10^{-1}, b = -4.58 \cdot 10^{-5},$ $c = -4.02 \cdot 10^{-7}$	$8.14 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot \omega + d \cdot t \cdot \omega$	$a = 8.01 \cdot 10^{-1}, b = -7.53 \cdot 10^{-4},$ $c = -1.56 \cdot 10^{-4}, d = 1.97 \cdot 10^{-7}$	$2.75 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^{2}$ $+ e \cdot t \cdot \omega$	$a = 8.36 \cdot 10^{-1}, b = -9.21 \cdot 10^{-4},$ $c = -1.75 \cdot 10^{-4}, d = 1.55 \cdot 10^{-7},$ $e = 2.56 \cdot 10^{-7}$	$2.97 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^{2}$ $+ e \cdot \omega^{2} + f \cdot t \cdot \omega$	$a = 8.31 \cdot 10^{-1}, b = -9.23 \cdot 10^{-4},$ $c = -1.27 \cdot 10^{-4}, d = -3.19 \cdot 10^{-9},$ $e = -5.77 \cdot 10^{-8}, f = 4.05 \cdot 10^{-7}$	$2.67 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^{2} \cdot \omega$	$a = 7.99 \cdot 10^{-1}, b = -7.74 \cdot 10^{-4},$ $c = -1.26 \cdot 10^{-4}, d = 3.36 \cdot 10^{-10}$	$2.61 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot \omega + d \cdot t \cdot \omega^{2}$	$a = 7.99 \cdot 10^{-1}, b = -6.78 \cdot 10^{-4},$ $c = -1.46 \cdot 10^{-4}, d = 8.15 \cdot 10^{-11}$	$2.93 \cdot 10^{2}$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^{2} \cdot \omega^{2}$	$a = 7.97 \cdot 10^{-1}, b = -7.12 \cdot 10^{-4},$ $c = -1.30 \cdot 10^{-4}, d = 1.82 \cdot 10^{-13}$	$2.67 \cdot 10^{2}$

Expression	Parameters	SSE
$w = a + b \cdot t + c \cdot \omega + d \cdot t^3 \cdot \omega$	$a = 8.02 \cdot 10^{-1}, b = -7.42 \cdot 10^{-4}$, $c = -1.23 \cdot 10^{-4}, d = 5.78 \cdot 10^{-13}$	$2.62 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^4 \cdot \omega$	$a = 7.60 \cdot 10^{-1}, b = -7.81 \cdot 10^{-4}$, $c = -1.05 \cdot 10^{-4}, d = 1.21 \cdot 10^{-15}$	$2.59 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^3 \cdot \omega^2$	$a = 7.95 \cdot 10^{-1}, b = -7.28 \cdot 10^{-4}$, $c = -1.20 \cdot 10^{-4}, d = 3.79 \cdot 10^{-16}$	$2.56 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^4 \cdot \omega^3$	$a = 7.93 \cdot 10^{-1}, b = -7.19 \cdot 10^{-4}$, $c = -1.14 \cdot 10^{-4}, d = 4.83 \cdot 10^{-22}$	$2.56 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^5 \cdot \omega^2$	$a = 7.92 \cdot 10^{-1}, b = -7.33 \cdot 10^{-4}$, $c = -1.09 \cdot 10^{-4}, d = 1.52 \cdot 10^{-21}$	$2.55 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^3 \cdot \omega^3$	$a = 7.94 \cdot 10^{-1}, b = -7.01 \cdot 10^{-4}$, $c = -1.22 \cdot 10^{-4}, d = 2.26 \cdot 10^{-19}$	$2.61 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^3 \cdot \omega^2$	$a = 8.02 \cdot 10^{-1}, b = -6.84 \cdot 10^{-4}$, $c = -1.15 \cdot 10^{-4}, d = 7.79 \cdot 10^{-16}$, $e = -3.79 \cdot 10^{-10}$	$2.67 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^2$ $+ e \cdot \omega^2 + f \cdot t^3 \cdot \omega^2 + g \cdot t^2 \cdot \omega$	$a = 8.02 \cdot 10^{-1}, b = -5.30 \cdot 10^{-4}$, $c = -1.25 \cdot 10^{-4}, d = -9.62 \cdot 10^{-6}$, $e = 1.73 \cdot 10^{-6}, f = 2.58 \cdot 10^{-14}$, $g = 2.41 \cdot 10^{-8}$	$3.35 \cdot 10^5$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^2$ $+ e \cdot t^3 \cdot \omega^2 + f \cdot t^2 \cdot \omega$	$a = 8.02 \cdot 10^{-1}, b = -5.62 \cdot 10^{-4}$, $c = -2.29 \cdot 10^{-4}, d = -9.07 \cdot 10^{-7}$, $e = -1.69 \cdot 10^{-15}, f = 2.29 \cdot 10^{-9}$	$4.36 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^3 \cdot \omega^2$ $+ e \cdot t^2 \cdot \omega + f \cdot t \cdot \omega$	$a = 8.02 \cdot 10^{-1}, b = -6.91 \cdot 10^{-4}$, $c = -9.78 \cdot 10^{-5}, d = 5.01 \cdot 10^{-16}$, $e = 1.61 \cdot 10^{-10}, f = -1.93 \cdot 10^{-7}$	$2.63 \cdot 10^2$
$w = a + b \cdot \omega + c \cdot t + d \cdot t^2$ $+ e \cdot t^3 + f \cdot t^4$	$a = 8.02 \cdot 10^{-1}, b = -1.36 \cdot 10^{-4}$, $c = -9.67 \cdot 10^{-5}, d = -7.41 \cdot 10^{-6}$, $e = 2.81 \cdot 10^{-8}, f = -3.03 \cdot 10^{-11}$	$2.87 \cdot 10^2$

Expression	Parameters	SSE
$w = a + b \cdot \omega^2 + c \cdot t + d \cdot t^2$ $+ e \cdot t^3 + f \cdot t^4$	$a = 8.02 \cdot 10^{-1}, b = -1.69 \cdot 10^{-7}$, $c = -4.83 \cdot 10^{-5}, d = 2.94 \cdot 10^{-6}$, $e = -1.06 \cdot 10^{-8}, f = 6.83 \cdot 10^{-12}$	$1.39 \cdot 10^3$
$w = a + b \cdot \omega^3 + c \cdot t + d \cdot t^2$ $+ e \cdot t^3 + f \cdot t^4$	$a = 8.02 \cdot 10^{-1}, b = -6.45 \cdot 10^{-11}$, $c = -6.76 \cdot 10^{-5}, d = -8.63 \cdot 10^{-7}$, $e = -3.36 \cdot 10^{-9}, f = 5.79 \cdot 10^{-12}$	$1.29 \cdot 10^3$
$w = a + b \cdot \omega^4 + c \cdot t + d \cdot t^2$ $+ e \cdot t^3 + f \cdot t^4$	$a = 8.02 \cdot 10^{-1}, b = -2.62 \cdot 10^{-14}$, $c = -8.30 \cdot 10^{-5}, d = -3.91 \cdot 10^{-6}$, $e = 5.78 \cdot 10^{-9}, f = -1.06 \cdot 10^{-12}$	$9.89 \cdot 10^2$
$w = a + b \cdot \omega^5 + c \cdot t + d \cdot t^2$ $+ e \cdot t^3 + f \cdot t^4$	$a = 8.02 \cdot 10^{-1}, b = -2.74 \cdot 10^{-17}$, $c = -8.39 \cdot 10^{-5}, d = -4.46 \cdot 10^{-6}$, $e = 1.55 \cdot 10^{-8}, f = -1.75 \cdot 10^{-11}$	$1.15 \cdot 10^3$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^2$ $+ e \cdot t^2 \cdot \omega$	$a = 8.36 \cdot 10^{-1}, b = -9.06 \cdot 10^{-4}$, $c = -1.44 \cdot 10^{-4}, d = 5.48 \cdot 10^{-8}$, $e = 4.77 \cdot 10^{-10}$	$2.91 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^2$ $+ e \cdot \omega^2 + f \cdot t^4 \cdot \omega^2$	$a = -1.53 \cdot 10^{-1}, b = -1.64$, $c = -3.67 \cdot 10^{-1}, d = 3.04$, $e = -7.55 \cdot 10^{-2}, f = -5.16 \cdot 10^{-12}$	$5.56 \cdot 10^{15}$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^4 \cdot \omega^2$ $+ e \cdot \sin(t) + f \cdot \cos(\omega)$	$a = 7.92 \cdot 10^{-1}, b = -7.61 \cdot 10^{-4}$, $c = -9.66 \cdot 10^{-5}, d = 8.79 \cdot 10^{-19}$, $e = 7.40 \cdot 10^{-4}, f = 3.37 \cdot 10^{-2}$	$3.19 \cdot 10^2$
$w = a + b \cdot t + c \cdot t^4 \cdot \omega^2$ $+ d \cdot \sin(t) + e \cdot \cos(\omega)$	$a = 7.40 \cdot 10^{-1}, b = -9.25 \cdot 10^{-4}$, $c = 6.28 \cdot 10^{-19}, d = 1.30 \cdot 10^{-4}$, $e = 2.65 \cdot 10^{-2}$	$5.22 \cdot 10^2$
$w = a + b \cdot t + c \cdot \omega + d \cdot t^2$ $+ e \cdot \omega^2 + f \cdot t^3 + g \cdot t \cdot \omega$	$a = 8.36 \cdot 10^{-1}, b = -9.01 \cdot 10^{-4}$, $c = -1.28 \cdot 10^{-4}, d = -2.30 \cdot 10^{-8}$, $e = 6.42 \cdot 10^{-8}, f = -8.05 \cdot 10^{-11}$, $g = 4.22 \cdot 10^{-7}$	$2.75 \cdot 10^2$