Nonlinear Modeling of Optical Fibre Drawing with OFC 20

Abstract

Several researchers have modeled various aspects of the fibre drawing process in many different ways. There is also a lot of information on the chemistry of fibres. However, for industrial control purposes, a complete picture of the whole process, also taking into account the fibre characteristics, is desirable. In other words, it is not sufficient to accurately control fibre diameter neglecting the strength and attenuation characteristics. Most of the models reported in literature so far are physical models based on first principles, with several simplifications and assumptions. Empirical approaches have also been considered in some papers. The empirical models usually resemble reality more closely than the physical models, and such models can be used for control purposes. Figure 1 shows the ideal situation where one or several separate empirical models for several variables would also take into account natural laws like conservation of mass, heat and momentum as far as possible.

While dynamic models are useful in the ramp up stages, steady state models are sufficient for control of fibre characteristics during normal production runs where short term dynamics do not play a significant role. This paper reports only a small subset of the desired set of models as depicted in Figure 1. Two such component models, which are steady state models, and software incorporating the models is reported in this work. The software has features for efficient use of the models and for determining optimal process conditions. In future, the software will also be able to learn these and other component models on its own from production or experimental data.

Keywords

Fibre drawing, nonlinear modeling, neural networks, fibre diameter, fibre characteristics

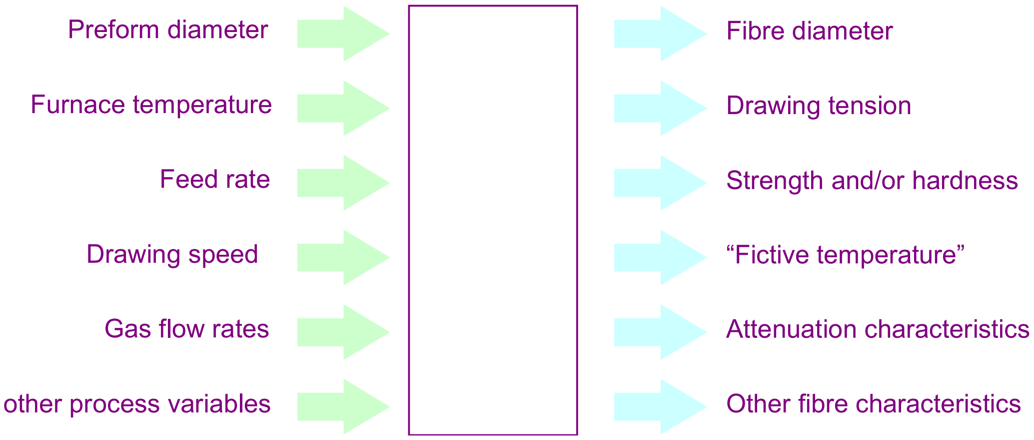

Figure 1. Empirical models of this kind are desirable for industrial control purposes

1. Introduction

New techniques of nonlinear modeling have come up in the last ten twelve years, and have been successfully use for a variety of purposes, particularly for prediction and control of material properties of various kinds of materials [1-4]. A separate section describes the basics of nonlinear modeling and neural networks.

Several researchers have modeled various aspects of the fibre drawing process in many different ways. Imoto et al. [5] describe the effects of furnace temperature, line speed and fibre diameter on drawing tension.

Even neural network modeling has been attempted in fibre drawing. Shi et al. [6] describe the use of neural networks for identifying furnace decay from patterns of process variables, specifically the normalised tension, standard deviation of drawing speed, standard deviation of furnace power, and frequency of speed fluctuations. Drawing tension is also shown to increase as the furnace decays.

Mulpur and Thompson reported the nonlinear aspects of the process dynamics of fibre drawing. Under certain conditions, the dynamics degenerates into a limit cycle, as is illustrated by simulation. The simulation model is then used to test model reference control and quasi-nonlinear control, and the authors conclude that the second approach is simpler and effective. They also show the closed loop stability of the scheme.

Kim et al. focus on material properties of the fibres through their relations with the fictive temperature. They report valuable observations from experiments carried out under different process conditions. The paper describes even the smaller details of the measurement procedures they followed. The relation of fictive temperature with fibre diameter, drawing tension and aluminium content is given in the paper as a linear equation. Fictive temperature is also quadratically correlated with the dynamic stress corrosion susceptibility.

2. The fibre drawing tower, OFC 20

The fibre drawing tower OFC 20 (Figure 2) is designed for high quality fiber production from a wide range of preforms. The tower modules and the selection of components enable a flexible and upgradable layout for all specific needs.

The produced fiber is of high strength. Its optical and geometrical properties meet all prevailing standards and recommendations.

The optical fiber drawing tower OFC 20 suits a wide range of preform types. Mechanical integrity and solid construction, high quality components like the advanced drawing furnace and coating system, and an advanced control system NOMOS® result in strong fibre and high yield. The drawing tower also suits the most advanced research applications.

The drawing tower has a frame with a height of upto 30 metres, with alternative component layouts. Several drawing furnace systems are available; several fibre coating systems are possible. The standard measurements include fibre diameters, tensions, flows and temperatures. A process control system with data logging is also included. The experimental and training tower in Vantaa allows experimentation, research and training in a realistic environment.

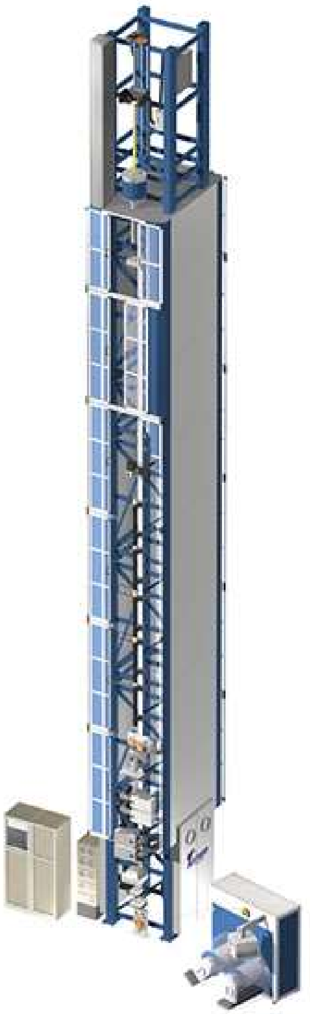

Figure 2. The fibre drawing tower, OFC 20

3. Nonlinear modeling

New techniques of nonlinear modeling have come up in the last ten twelve years, which have made it possible to develop more complicated nonlinear empirical models which take into account the nonlinearities more efficiently. Artificial neural networks are inspired by the biological neural networks, but have very little in common from our perspective. A large number of different kinds of artificial neural networks are reported in literature, of which, about four or five find real world applications. In process engineering, artificial neural networks are more or less synonymous with feed-forward neural networks shown in Figure 3. These networks are said to have universal approximation capability. In other words, they are capable of approximating any continuous, first-order differentiable function to any desired degree of accuracy with a single layer of neurons with sigmoidal activation functions. There is plenty of literature on neural networks. At least one book on neural networks is designed for chemical engineers [1] which describes several aspects of process modeling and process control.

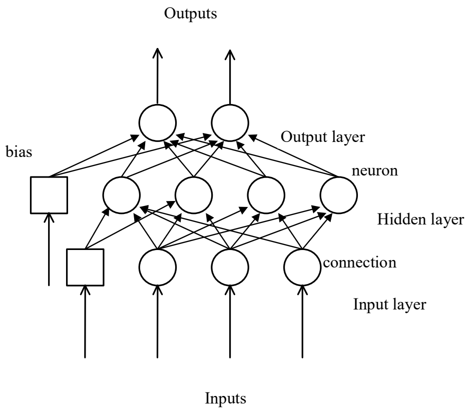

Figure 3. A feed-forward neural network

Nonlinear models are used for various purposes in process industries. In particular, prediction and control of product properties of various kinds of materials can be performed better with neural networks than with the conventional, linear statistical techniques like linear regression. Mechanical properties of rolled and drawn steel products like wire rods [2], paperboard [3], plastics, concrete [4], etc. have been modeled successfully with artificial neural networks. This kind of models are used for various purposes including process control (determining process variables), for optimizing plant operation, for quality control and reduction of rejects, for estimating variables which are difficult to measure, for product design, for fault detection, etc.

4. Results

Two main components of the relations shown in Figure 1 are fibre diameter and drawing tension. Winding tension is related to drawing tension, and in this case, a nonlinear model of winding tension is reported.

The variables which affect the fibre diameter are shown in Figure 1. The variations in preform diameter and gas flow rates were not considered for the results reported here. That leaves three input variables, furnace temperature, preform feed rate and drawing speed. Figure 4 shows schematically the structure of the nonlinear model for fibre diameter. The same variables determine drawing tension and the winding tension.

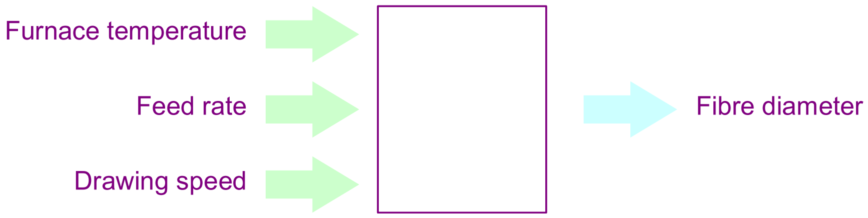

Figure 4. Prediction model for fibre diameter with three inputs

Artificial neural network models of various configurations were developed and tested for prediction of fibre diameter from limited experimental data. Needless to say, the nonlinear models perform much better than the linear regression models in terms of accuracy. However, they can also be made more reliable, and thus suitable for process control. This exercise was carried out only for illustration purposes, and the actual models for industrial use anyway cannot be reported for reasons of confidentiality.

The rms errors of prediction of fibre diameter with a nonlinear model were 6.74 µm on the training set and 5.92 µm on the test set. The corresponding rms errors from a linear model were 8.19 µm and 8.87 µm respectively.

The results of prediction of winding tension with a preliminary model look even better. They would further improve when the process variables of coating are taken into account. The rms errors of prediction of winding tension with a nonlinear model were 2.60 g on the training set and 2.13 g on the test set. The corresponding rms errors of a linear regression model were 5.74 g and 4.67 g respectively. Figure 6 shows the measures of the errors on training set and test set in different colours for linear and nonlinear models.

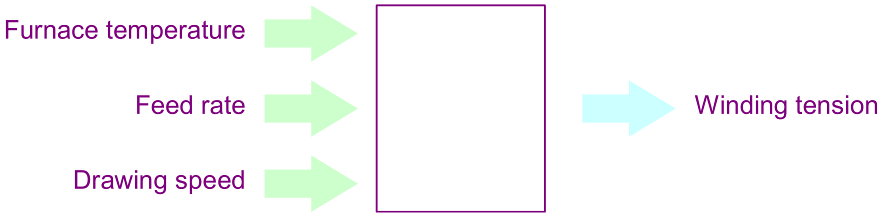

Figure 5. Prediction model for winding tension with the same three inputs

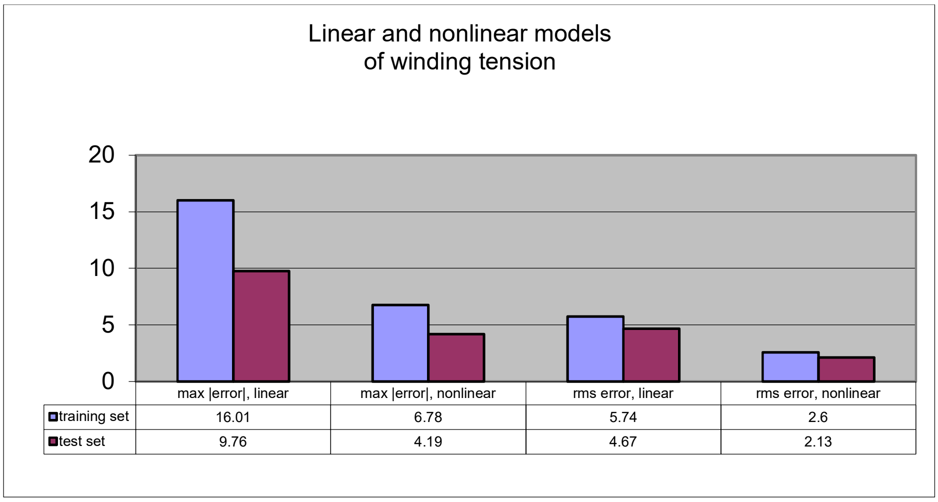

Figure 6. Comparison of linear and nonlinear models for winding tension

Figure 7 shows the results of prediction compared with the measured values of winding tension. The data was taken from an experiment where dynamics was simultaneously being studied. As a result, the actual winding tension varies even when the three input variables are constant, and that is visible in Figure 7.

The model shows an increasing effect of preform feed rate as well as furnace temperature on fibre diameter, which can also be seen from Figure 8. This kind of curves are also reported by Imoto et al. [5].

5. The software system

The nonlinear models developed for fibre drawing can be complicated for a normal user in the industry. Engineers cannot be expected to be familiar with nonlinear modeling. They cannot be expected to use the raw equations of the models for carrying out predictions or process optimization. However, if the models are available to the engineers in an easily usable form, it could benefit a large number of companies. Therefore, in line with Nextrom’s policy of providing a support service, a software system has been developed to be a part of their process knowledge package, which will be available in near future, not only to its own customers but also to other companies with optical fibre production.

Engineers in industries today are overwhelmed by the amount of software that they can use. Almost all of them require some amount of learning to use, and the software can be used efficiently only after some amount of experience with it.

We did not want to add to that load, so this software system is designed to be very simple to learn to use. A user without any user training would still be able to use this software conveniently.

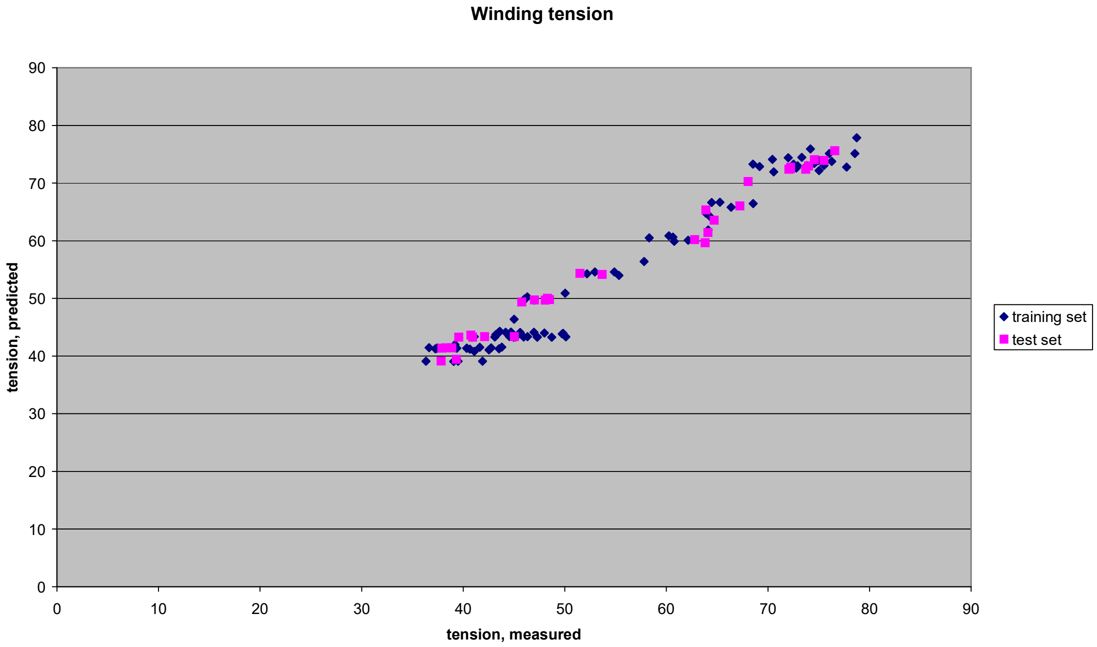

Figure 7. Predicted and measured values of winding tension on training and test sets

The software is highly modular, and each model can be stored in a separate file which the software system reads and uses. The input as well as output variables can be different for different models. The values of input variables can be fed in manually, or can be picked up from a file. One click of the mouse predicts the output variables. Various features allow the user to see the effects of each input variable on each output variable. Another facility allows the user to determine suitable process conditions such that the output variables stay within desired limits.

Maintenance and recalibration of models is usually necessary. The software also includes algorithms for updating models. This, however, needs some familiarity with nonlinear modeling and requires user training, though the software tries to guide the user with simple messages.

6. Conclusions

This paper illustrates with an example that for industrial control purposes, nonlinear empirical modeling is a practical approach, which does not require assumptions, and is entirely based on observed behavior of the process and the materials.

Conventional linear statistical techniques of empirical modeling are not suitable because the process is clearly nonlinear. Nonlinear models, perhaps even plain neural network models, or better still, their combination with other models or constraints, can be expected to perform better than the conventional linear techniques, or physical models. The approach has been utilised successfully for a wide range of processes and materials.

The technology has been incorporated in a software system for facile use by OFC producers.

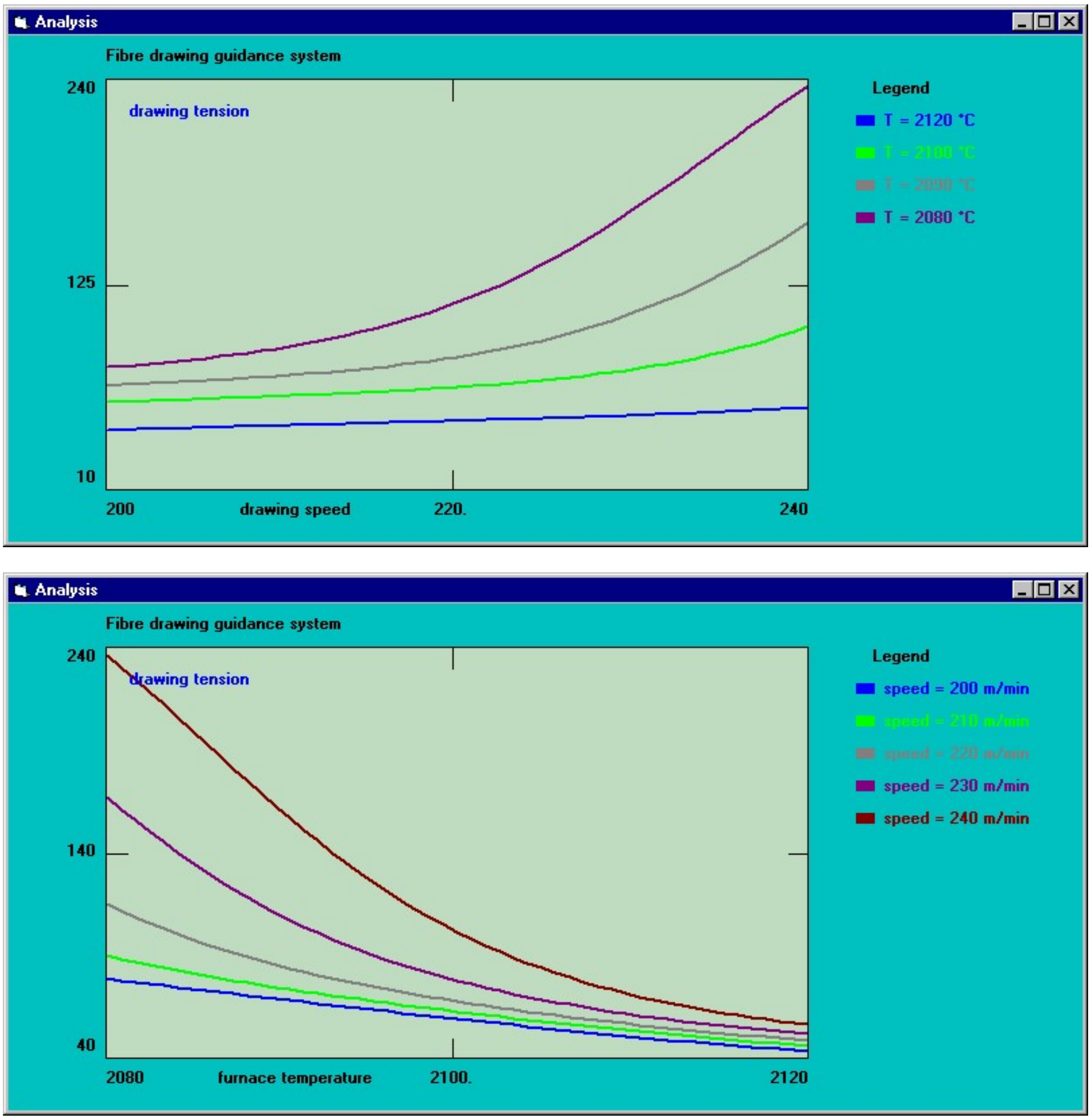

Figure 8. The fibre drawing guidance system also shows the effects of process variables on fibre diameter or other output variables