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NON–PARAMETRIC IDENTIFICATION OF THE GLASS FIBER DRAWING PROCESS

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Abstract. Optical fibres, together with light sources and detectors, play a key role in telecommunication systems. One of the factors affecting the transmission losses of the fibre and its tensile strength, is the diameter uniformity which is directly related to the drawing process. A high degree of diameter uniformity in the fiber drawing process is achieved by an appropriate construction of the drawing machine and by applying an optimal system for the control of the diameter. Optimization of such a control requires prior structural identification of the drawing process and its parameters. In this work, a nonparametric identification of the drawing process has been done. The cross-correlation method has been used, with a random noise as the input signal. The obtained transfer function is a second-order one with real poles, which accords well with the theoretical assumptions. Identification of the drawing mechanism and fibre diameter measurement system, which contains a significant dead time, has also been done. The results obtained can be used for the synthesis of the optimal control function.

1. Introduction

Optical fibre drawing is a well–established technological process, thoroughly covered in the literature [1]. In short, optical fibers are produced by heating one end of a cylindrical glass rod (preform), followed by drawing of the melted part which is, at first rapidly and then more slowly, narrowed during cooling. Temperature changes are in the range of hundreds of degrees along the distance of only a few millimeters.

The main elements of the drawing process control system are: a sensor for measuring fibre diameter, located at a certain distance from the drawing zone, the appropriate electronic system and the electromechanical system of the drawing mechanism. The remaining elements of the system, like the

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preform feeding mechanism or the temperature of the heater, are rarely included in the control process because of their long time constants.

Drawing of optical fibres is a process that can be easily described qualitatively. However, it is a very complex problem of fluid dynamics, which includes an enormous change in viscosity. As a result, the process is susceptible to disturbances, especially at higher drawing velocities, which leads to its instability. Stability of the process has been studied from three aspects: 1) stability at sudden disturbances, when a fibre rupture can occur, 2) stability related to the drawing conditions and examining the resonant effects and 3) dynamic behavior at small input signals, aimed at finding an optimal solution for the process control.

In a limited sense, process identification requires knowledge of its model's structure. A mathematical model is often based on the equations derived from the fundamental laws of physics. For the optical fiber drawing process, these are the Navier–Stokes and the heat transfer equations [2]. Since these equations are non–linear, most authors linearized them using the perturbation analysis. Thus, various drawing conditions have been examined, mainly by numerical solving of the equations of linearized models.

Many authors studied the stability in the process of nonisothermal drawing [3]. Their work is characterized by the simplified energy equations. The more complete analysis, which took into account all modes of heat transfer, was done by Paek and Runk [4] and Geyling and Homsy [5]. The heat transfer, and mathematical and numerical models of temperature profiles were studied by Dianov *et al.* [2]. They also analyzed the stability of drawing in time domain, by solving the Navier–Stokes equations numerically. As the boundary conditions, they were using the disturbances which correspond to the changes in temperature, drawing velocity etc. In this way, by using the numerical simulation, they obtained the impulse responses and transfer functions of fiber diameter, related to the various input parameters. Myers [6] developed the mathematical model of the drawing process even further, by using the radiation model of heat transfer. By solving the perturbation equations numerically, Myers obtained the frequency response for the fiber diameter as a function of the change in drawing velocity. In addition, he tested the system excited with a sine wave perturbation at three different frequencies.

Purely experimental identification was done by Smithgall [7], who used the Fourier filtering technique for determination of amplitude and phase responses of the process. Although the process is highly non–linear, these techniques are used primarily to obtain linear model for control purpose.

This work contains a theoretical background and an experimental verification of a method for the identification of the fiber drawing process, a method which can be applied without halting or even disturbing the process.

2. Selection of the test signal and identification method

The chosen method was an identification of continuous–time model via non–parametric form. This is an indirect approach in which linear dynamical system is first modelled in terms of non–parametric descriptions such as impulse response, step response, and frequency response functions. Continuous-time parametric model could be then fitted to the non–parametric form. Several methods are available for identification of non–parametric models. Deterministic test signals such as step, saturated ramp, block pulse, etc. give rise to time–domain methods of estimation of impulse response function, step response function, etc. Use of random noise signals in the framework of correlation methods meets stochastic situations. The deterministic time–domain methods are based on deconvolution. The frequency domain methods also have their deterministic and stochastic versions. The frequency and time domain methods are recognized to be complementary rather than rivalling. Nonparametric models from one domain can be transformed into the other with the help of certain inter–domain transformation formulae [8].

Transfer function can be obtained from non–parametric models in a number of ways. There is a class of methods in which certain salient features in the step response function such as flexion tangents, times to reach certain percentage values of the steady–state value, overshoot, etc., are directly related to the parameters of transfer function in some standard form [9]. Fitting parametric data to measured frequency response is another viable approach that has received considerable attention in the past.

The choice of a method of experimentation, the domain in which the signals and models are to be handled, and the method to yield desired results are often governed by the ultimate objectives and the conditions existing in a situation.

The identification methods in time domain applied in the theoretical analyses, cannot be used in the case of fibre drawing process because of the following:

- The step excitation function is not applicable because the process is not linear, i.e., it would yield to exiting from the range of optimal stationary conditions.
- Process in which no regulation is applied, is "weakly" oscillatory with a very large oscillation period. Hence, it is difficult to determine the new stationary state after the step function has been applied.

- In frequency domain, assuming that we are dealing with small signals, i.e., that the process is in the linear range, the application of a sinusoidal excitation signal would still not give the satisfactory results. There are at least two reasons for this. The first is the existence of physical modal frequencies which, after being provoked, produce resonant effects, thus giving the false picture of the transfer function. The second reason is the duration of measurement. Practically, the complete preform would be used in order to measure only a few frequencies, because of the long period of integration for frequencies of the order of 10^{-2} Hz.

The inevitable dead time of the diameter measurement system presents a big problem in the determination of the phase characteristics of the fiber drawing process. Potential solution for sinusoidal excitation is simultaneous application of multiple sine waves, given as an ensemble.

Another class of test signals, known as binary noises, are excellent test signals when applied to a suitable point of entry of an industrial process, providing necessary plant excitation for process identification. From an operational point of view, binary noise is much more acceptable than a test signal having non–constant amplitude such as an ensemble of sine wave signals. Moreover, since in the binary noise case the energy applied is more or less evenly distributed over the frequency range of interest, the average amplitude can be considerably smaller than when energy is concentrated in a small number of frequencies associated with the ensemble. From a theoretical point of view such a multisine wave is attractive, since it is shown to be optimal test (input) signal, when suitably chosen, for identification of linear processes [10]. This approach calls for detailed *a priori* knowledge of process dynamics, as a number of test frequencies and associated amplitude levels must be chosen properly. This obviously contradicts the essence of experiment design, where *a priori* knowledge about the plant is very limited.

There is another practical disadvantage: as already mentioned before, the optimal multisine wave signals concentrate their test frequencies at, or in neighborhood of, natural frequencies since this is most informative. However, plant operational staff would not easily accept such a concentration of energy being applied at such "critical" frequencies. In fact, in the process industry it is preferred that control engineers apply binary noise excitation, i.e. the test signal that should not affect the process itself. The best choice for the test signal is white noise, because its power–density spectrum is constant.

Of course, any noise whose power–density spectrum is constant in a frequency range that is much wider than the process bandwidth, may be considered as a physically realizable white noise.

The proposed process identification technique has at least three advantages over conventional methods:

- Test can be performed during the normal operation of the system. It is not necessary to stop the process or make some sort of special connection to it. This is possible because the energy of the noise is distributed in a wide frequency range, so its amplitude at specified frequencies is very small.
- The measurement is insusceptible to the influence of an external unwanted noise, providing that the test signal is not correlated with it [11].
- The presence of the inherent process energy does not affect the measurement.

Being a broad–band (white) signal, with the following power density

$$\Phi_{xx}(\omega) = 2\pi\sigma^2 \tag{1}$$

and with autocorrelation function:

$$\phi_{xx}(\tau) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \Phi_{xx}(\omega)e^{j\omega\tau}d\omega = \sigma^2\delta(\tau) \tag{2}$$

this type of signal can be used for easy identification of process transfer function, $G(j\omega)$, according to very well known formula [12]:

$$G(j\omega) = \frac{\Phi_{xy}(j\omega)}{\Phi_{xx}(j\omega)} = \frac{\Phi_{xy}(j\omega)}{2\pi\sigma^2} \tag{3}$$

where $\Phi_{xy}(j\omega)$ denotes cross–spectral power density between the output and input of the system.

The main drawback of this method is the physical realizability, since very short and very intensive peaks could be contained in the signal. This drawback can be overcome by using a so–called pseudorandom noise which has a limited amplitude, which prevents the disturbance of the process or entering into a non-linear mode of operation. It has similar autocorrelation function as the white noise (Dirac impulse), but periodic, with a period T. Therefore, the autocorrelation function of the pseudorandom noise has a value $\neq 0$ at times $\tau = 0, T, 2T, 3T$, whereas for all other values of τ it is equal to zero.

When using this type of test signal, the cross-correlation function will be [8]:

$$\begin{aligned}\phi_{xy}(\tau) = &\int_0^T g(s)\phi_{xx}(\tau - s)ds + \int_T^{2T} g(s)\phi_{xx}(\tau - s)ds \\ &+ \int_{2T}^{3T} g(s)\phi_{xx}(\tau - s)ds + \cdots\end{aligned} \tag{4}$$

i.e.:

$$\phi_{xy} = \sigma^2[g(\tau) + g(T+\tau) + g(2T+\tau) + \cdots] \quad (5)$$

where $g(t)$ is impulse response of the system with transfer function (3). If T is chosen so that the impulse response drops to zero during the period shorter than T, the equation (5) becomes:

$$\phi_{xy}(\tau) = \sigma^2 g(\tau) \quad (6)$$

Naturally, the pseudorandom white noise is a pure mathematical fiction. Therefore, its approximations are used instead. One of them is a pseudorandom binary sequence (PRBS). Practically, it is a sequence of binary signals with discrete amplitude which changes stochastically between its two possible states (logical 0 and logical 1). PRBS has the following properties:

- The signal has two levels ($\pm V$) and may switch from one level to the other at certain intervals of time $t = 0, \lambda, 2\lambda \ldots$
- Whether or not the signal changes level at any particular interval is predetermined. The PRBS is thus deterministic and experiments are repeatable.
- The PRBS is periodic with period $T = N\lambda$, where N is an odd integer.
- In any one period, there are $1/2(N+1)$ intervals at one level and $1/2(N-1)$ intervals at the other level.

It is well known that the frequency spectrum of such a "conventional" PRBS is almost white in the frequency band of interest. It is, therefore, generally regarded as an optimal test signal, since all relevant process frequencies are tested with about equal power.

Consequently, in this way fast process characteristics are usually well identified, in contrast to the middle and the lower frequency characteristics of the process involved (slower transients and stationary gain). Of course, binary noise can be manipulated in such way that more energy is placed at middle and lower frequencies. An obvious way to realize this [13] follows from the choice of enlarged basic switching time $T_E = MT$, which is a multiple $M(M = 2, 3, \ldots)$ of the standard basic switching (sampling) time interval T. Although test signal energy is shifted towards the lower frequencies as M increases, an important drawback is hidden behind this short-cut approach.

Since we are interested in frequencies over the whole range $[0, \pi/T]$ it is not possible to excite frequencies greater than $\omega = 2\pi/(MT)$ because the basic switching time is $T_E = MT$.

However, if we change the switching probability of binary noise (instead of being 0.5) to the smaller values (e.g. 0.2), then we can obtain smoother spectrum with enough energy at the lower and middle parts.

3. Experimental results

3.1 Process identification system

From system theory it is known that the linear system is completely characterized by its impulse response. The Laplace transform of the impulse response function is called transfer function of the system. Since there exists a unique relation between both the time– and frequency–domain representation, the impulse response can be obtained from measurements in both domains.

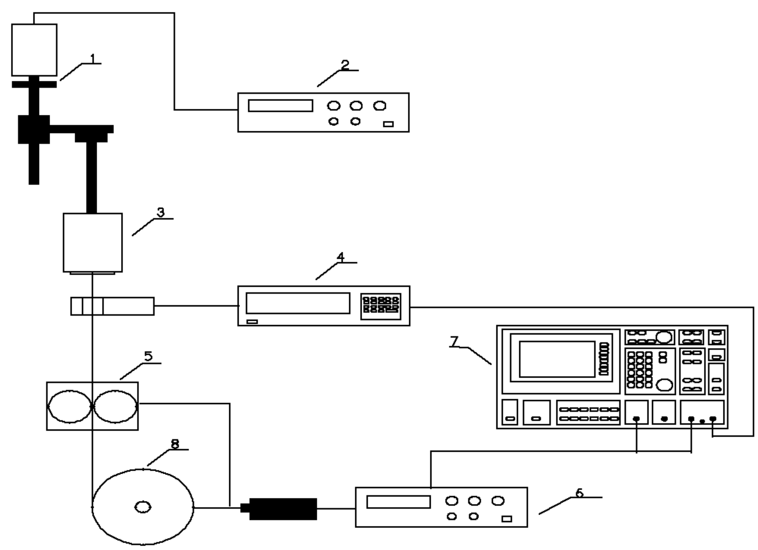

Figure 1. Fiber drawing mechanism and measurement system:
1. Preform feeding mechanism; 2. Preform lowering speed controller;
3. Furnace; 4. Laser diameter measuring system; 5. Capstan drive;
6. Drawing speed controller; 7. Signal analyzer; 8. Winding drum.

The Fourier transform of the impulse response function is called the frequency response. In practice, most instruments use frequency domain approach because this results in a higher signal–to–noise ratio. In the beginning, these measurements were made frequency–by–frequency, but in the late seventies, fast Fourier transform (FFT) analyzers appeared on the market making it possible to measure the frequency response at a large number of frequencies at once.

One of such an instruments is Hewlett Packard HP3562A dynamic analyzer. It contains high-speed Fourier transform processors, realized in hardware, providing a capability for correlation function calculations. The programming feature of the analyzer allows the creation and running of so–called "waveform math sequences", enabling very comprehensive calculations. Another advantage is the built–in source of continuous Gaussian noise, which may be considered as white noise in the frequency band up to 100 kHz. In contrast to high sample–rate PRBS, continuous noise has an adequate amplitude to excite the drawing process, and therefore does not need to have the lower part of its spectrum emphasized.

Figure 1. shows the measuring system for identification of the parameters of the drawing process and determination of the drawing mechanism transfer function. Electromotor/tachometer was used as a driving system both for the preform feed mechanism and the fiber drawing mechanism. For the velocity control, two classical analog controllers were made and additionally stabilized with a tachometer feedback loop. At the output of each controller, there is a power amplifier with a built–in electronic brake, which enables the accuracy of the velocity control to be better than 1% in the whole measuring range. Both controllers contain inputs for remote adjustment of the set point.

3.2 Transfer function of the motor and the drawing mechanism

The drawing mechanism can be a tractor (two pinched disks, one of which is connected to the motor), or a drum on which the fiber is automatically wound. The motor was connected to the tractor by an 1:60 reductor, and the diameter of the tractor disk was 19 cm. Due to the high degree of reduction, it can be considered that the motor is operating virtually with no load.

Figure 2. illustrates the frequency response of the described mechanism with the regulated velocity. By using the fitting algorithm from the analyzer, the monotonous, second–order function with the separated real poles was obtained:

$$G_t(s) = \frac{3}{(s+6.3)(s+19.58)} \tag{7}$$

If it is necessary to use the drawing mechanism with a drum (which is usually the case when drawing and spinning a number of fibres simultaneously), the dynamics is somewhat different.

Figure 3. shows the recorded frequency response of the drawing mechanism using a plastic drum with diameter of 15 cm and weighing 430 g. By fitting the transfer function we obtain:

$$G_{dp}(s) = \frac{s+208}{(s+146)(s+417)} \tag{8}$$

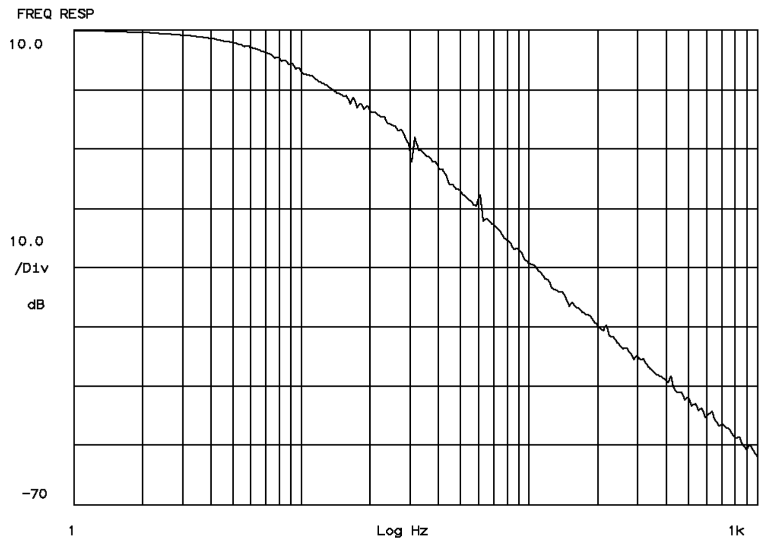

Figure 2. *Frequency response of the drawing mechanism with tractor.*

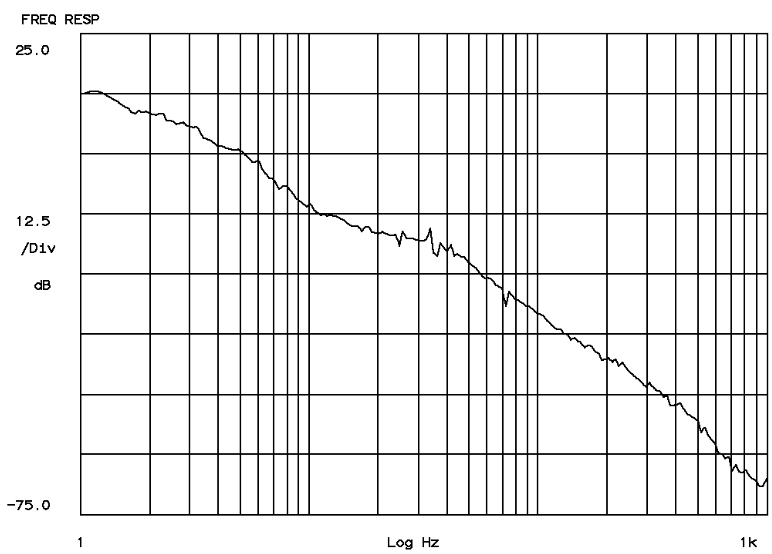

Figure 3. *Frequency response of the drawing mechanism with a plastic drum.*

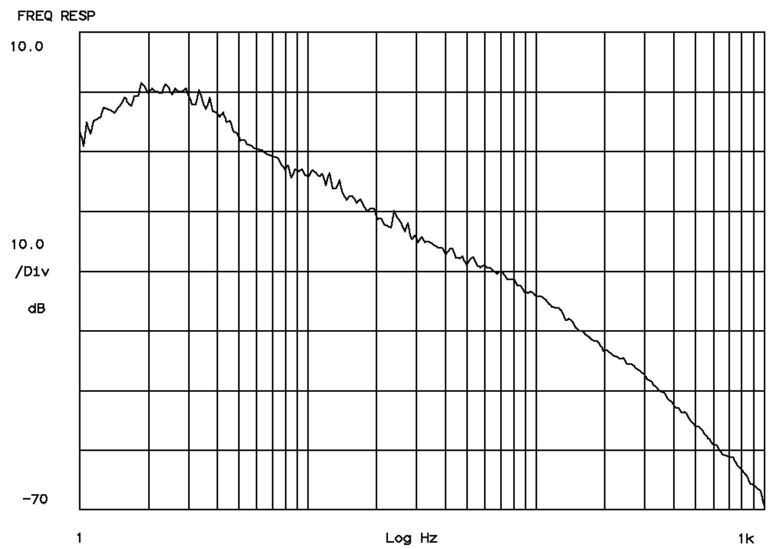

Figure 4. Frequency response of the drawing mechanism with a metal drum.

If a metal drum with the diameter of 31.8 cm and weighing 5.3 kg is used, the rise of frequency response in the vicinity of 2 Hz is observed (Figure 4.); it is attributed to the lower efficiency of the electronic brake in the regulator, due to the relatively heavy drum. In this case, the transfer function is:

$$G_{dm} = \frac{(s+0.7)(s+17)}{(s+8.3)(s+128)(s+729)} \tag{9}$$

3.3 Transport delay of the diameter measuring system

Identification in the presence of unknown time–delays is generally agreed to be a difficult problem. There are different methods for accomplishing this goal [14]. Here, two of them are exploited, and both are non-parametric, cross–correlation based techniques.

PRBS excitation

Consider a glass fiber drawing process described by the discrete model:

$$A(q^{-1})r(k) = q^{-d}B(q^{-1})u(k) + \nu(k) \tag{10}$$

where

$$A(q^{-1}) = 1 + a_1 q^{-1} + \cdots + a_n q^{-n} \tag{11}$$

$$B(q-1) = b_0 + b_1 q^{-1} + \cdots + b_m q^{-m} \tag{12}$$

and where $u(k)$ is the deviation of the drawing velocity, $r(k)$ the deviation of the fiber radius, $\nu(k)$ the random disturbance signal, and q^{-i} the delay operator of i sampling periods. Let $b_0 \neq 0$ and let an unknown transport delay, $d \geq 0$, be an integer multiple of the sampling period. $u(k)$ and $\nu(k)$ are stationary, ergodic random processes with the mean value of zero. By multiplying equation (10) with $u(k-t)$, where $k, t \in \mathcal{Z}$, and by finding the mathematical expectation, the following function is obtained:

$$\phi_{ru} = \sum_{i=1}^{n} a_i \phi_{ru}(t-i) + \sum_{i=0}^{m} b_i \phi_{uu}(t-d-i) + \phi_{\nu u}(t) \tag{13}$$

where the autocorrelation function $\phi_{uu}(t)$ and the cross-correlation functions $\phi_{ru}(t)$ and $\phi_{\nu u}(t)$ are defined as:

$$\begin{aligned} \phi_{uu}(t) &= E\{u(k)u(k-t)\} \\ \phi_{ru}(t) &= E\{r(k)u(k-t)\} \\ \phi_{\nu u}(t) &= E\{\nu(k)u(k-t)\}. \end{aligned} \tag{14}$$

Let the deviation of the fiber drawing velocity be a discrete white noise with the variance σ_u^2, which is uncorrelated with the disturbance signal, i.e. $\phi_{\nu u}(t) = 0$. Its autocorrelation function is:

$$\phi_{uu}(t) = \begin{cases} \sigma_u^2 & t = 0 \\ 0 & t \neq 0 \end{cases} \tag{15}$$

By substituting (15) in equation (13) it is directly obtained that:

$$\begin{aligned} \phi_{ru}(t) &= 0, \quad t < d \\ \phi_{ru}(t) &= b_0 \sigma_u^2 \neq 0, t = d \end{aligned} \tag{16}$$

This means that the cross-correlation function $\phi_{ru}(t)$ positively equals zero in the range from $t = 0$ to $t = d - 1$. Let $\hat{d}$ be an estimate of the delay d $(d, \hat{d} \in \mathcal{Z})$. It will be assumed that

$$\begin{aligned} \phi_{ru}(t) &= 0, \quad t < \hat{d} \\ \phi_{ru}(t) &\neq 0, \quad t = \hat{d}. \end{aligned} \tag{17}$$

According to [15], from the equation (17) the transport delay can be found by evaluating the cross–correlation function on the basis of the N recorded data:

$$\hat{\phi}_{ru}(t) = \frac{1}{N}\sum_{k=1}^{N} r(k)u(k-t), \quad t = 0 \ldots d_{max} \tag{18}$$

where d_{max} is the maximal expected value of the transport delay. Consequently, the following criterion is applied:

$$|\hat{\phi}_{ru}(t)| < \varepsilon \qquad t < \hat{d} \tag{19}$$

or equivalently:

$$|\hat{\phi}_{ru}(\hat{d})| >> max\{|\hat{\phi}_{ru}(t)|, \quad t = 0, \ldots \hat{d} - 1\} \tag{20}$$

where ε is an arbitrary small positive number. The moment when the cross-correlation function starts to increase steeply over the noise level marks the pure transport delay of the system, τ. It is calculated as $\tau = d \times T$, where d is an unnamed integer obtained from equation (15), and T is the sampling period in seconds.

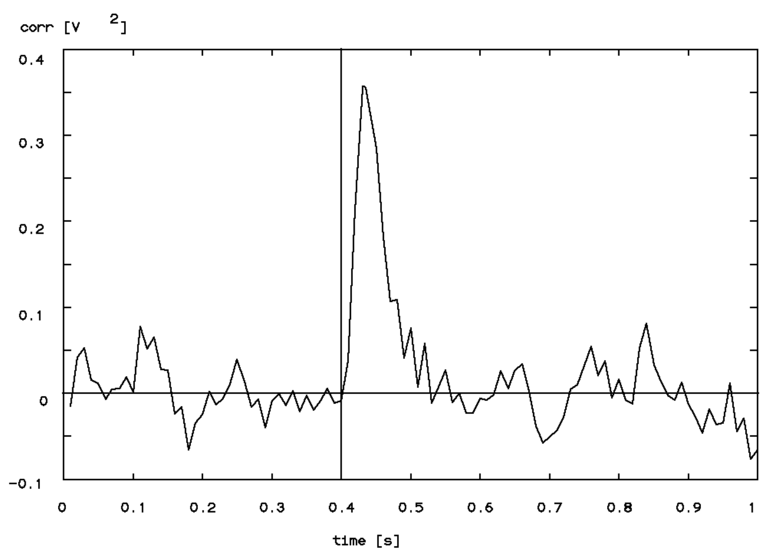

Figure 5. Experimental cross–correlation function with PRBS excitation.

Obtained cross–correlation function is shown in Figure 5. The delay can be estimated directly by observing the diagram, at the crossing of the two dashed lines. However, obtaining this result by using the equations (19) and (20) is not so easy, because the function is very "noisy". Such a high amplitude of the cross-correlation function, in the region where it should be zero, is due to the significant low-frequency content of the applied PRBS. From Figure 5., it can be seen that the delay is 400 ms.

Continous noise excitation

In the second type of experiment, again an advantage was taken of HP 3562A dynamic analyzer. Random noise was superimposed on the DC signal, and an experiment was carried out in an equivalent way to that in the case of PRBS. The cross-correlation function (Figure 6) was obtained by taking 256 linear averages over a 2.048– second time interval. The presence of noise was mainly due the quantization effect of the laser measuring device. This noise could be reduced by increasing the variance of the excitation signal, or by using of an appropriate filtering technique.

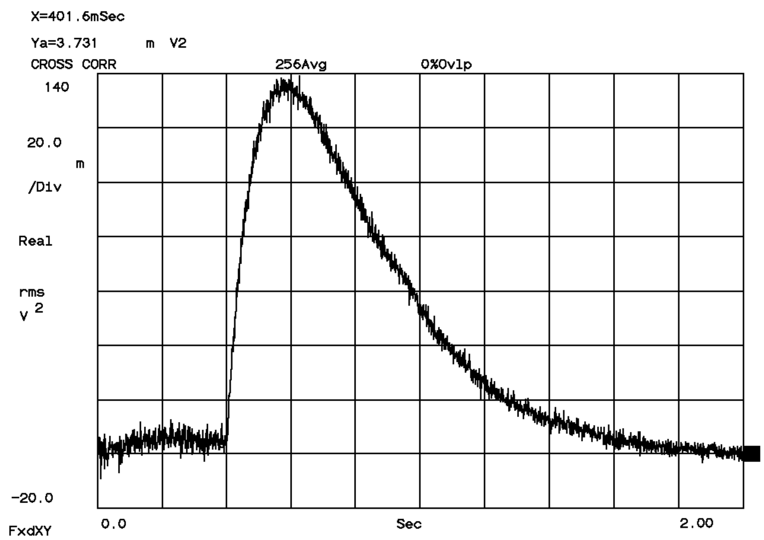

Figure 6. Experimental cross–correlation function with continuous noise excitation.

3.4 Transfer function of the drawing process

Figure 7. shows the frequency response of the drawing process obtained by using the described measurement method, on the apparatus shown in

Figure 1. With the obtained data, the synthesis of the transfer function related to the drawing process and diameter measurement system was done. Then, transfer function is:

$$G_p(s) = \frac{0.01e^{-0.4s}}{s^2 + 0.816s + 0.118} \tag{21}$$

The transfer function (21) can be written in a more general form as:

$$G_p(s) = \frac{Ke^{-\tau s}}{(T_1 s + 1)(T_2 s + 1)} \tag{22}$$

where v_f is the drawing velocity, L is the furnace length and the time constant $T_1 \sim L/v_f$, i.e., it is proportional to the hydrodynamic properties of the system. The second time constant is proportional to the thermal properties of the system, i.e., $T_2 \sim mC_p/k$, where m is a mass of the molten glass, C_p - specific heat and k - heat transfer coefficient [16]. The obtained frequency response shown in Figure 7, looks very much like the theoretical curve which Myers [6] obtained by simulation.

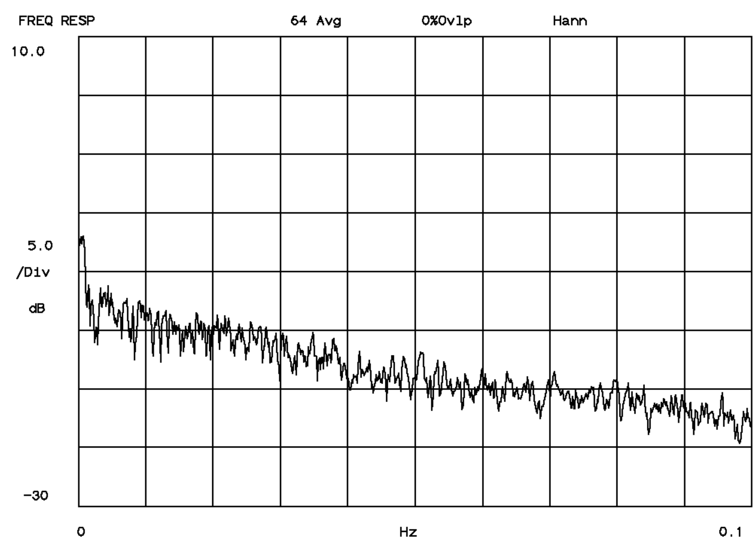

Figure 7. The measured frequency response of the drawing process.

4. Conclusion

Drawing of glass fibers is a complex process with the distributed parameters. Therefore, theoretical analyses usually start with developing the adequate models and their subsequent simplification and linearization. If rapid acquisition of system parameters is needed, instead of detailed system analysis, the system could be experimentally identified. In case of the fiber drawing process, conventional methods are unsuitable for such an identification: step function, because of the nonlinearity of the process, and swept or multiple sine method, because of the resonant effects. Hence, the cross-correlation method was used, enabling the undisturbed operation during process identification. It is the best suited method since it is not restricted to model assumptions and therefore it is easy to compute. Further advantage is low sensitivity to uncorrelated disturbance noise, allowing higher sampling rate, providing higher resolution of the estimate. The cross–correlation method was also used for the evaluation of the dead time, i.e., the time between freezing of the fibre and measurement of its diameter. Knowledge of the dead time is important for the synthesis of a stable control system in a closed loop. The transfer function describing the relation between fiber diameter and drawing velocity was obtained. It is a second–order function with two real poles and a transport delay caused by the measuring instrument. Which of these poles is predominant, depends on the physical parameters of the drawing process. In one case, the prevailing phenomenon is the heat transfer and in the other, the fluid dynamics. The proposed identification method can be applied directly in the plant by using commercially available device (such is HP 3562A) for very fast changes of operating conditions - depending on glass material, drawn-down ratio and required final fibre diameter.

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