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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

БАЯНДАМАЛАРЫ

ДОКЛАДЫ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

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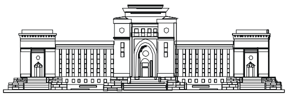

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PROBLEM OF AUTOMATIC CONTROL AND NUMERICAL MODELING OF THE SPEED OF OPTICAL FIBER EXTRACT IN THE PROCESS OF ITS MANUFACTURE

Abstract. This paper describes the basic design of the drum for pulling optical fiber. This is a key element that affects the speed and tension of the optical fiber, and ultimately its main geometrical parameters, such as the diameter and shape of the cross section, whose stability determines the performance characteristics of the finished optical fiber. Also, the work is devoted to the development of a mathematical model of the drum (coil), taking into account the dynamic equation of motion, inertia and speed changes. An open loop transfer function is obtained for a belt pulley, a motor and a speed controller with feedback control in proportion to an integral controller. A transient process was obtained through the channel "drawing speed - diameter" for various types of exhaust drums.

Keywords: optical fiber hood, optical fiber exhaust drum, pulley, pulley diameter, optical fiber diameter, PI - regulator, drawing speed.

I. INTRODUCTION

A critical point in the production of optical fiber is the constancy of the diameter of the fiberglass and its light-guide core. The diameter of the optical fiber must remain constant in order to create a product capable of transmitting broadband optical data. The design for pulling the optical fiber has a significant impact on the quality of the fiber produced. As well as the manufacture and use of Bragg fiber-optic gratings is not possible without measuring their characteristics at each stage of manufacturing the gratings themselves [1], it is necessary to control the drawing process of the optical fiber, since it is at the production stage that its performance characteristics are laid.Since the exhaust speed is used to control the fiber diameter, the ability of the exhaust device to follow speed control commands directly affects the resulting fiber diameter [2 –5].

II. RESEARCH MODEL

The basic design of the fiber pulling drum is a flexible strap, partially wound on a flat pulley, which moves / pulls the continuous optical fiber all the way from the heated billet. The tests confirmed the connection between the fiber diameter and the line speed around the operating point. The basis of the relationship is a constant volumetric flow rate of glass.

Changes in fiber diameter often occur due to technological failures such as unevenness of the diameter of the workpiece, inconsistency between the volume flow rate of the feed of the workpiece relative to the hood and the temperature shift of the furnace / glass. Thus, a speed regulator must be included in the design of the spindle to prevent unacceptable changes in fiber diameter from technological disturbances [6].

The target dimensions of the fiberglass are the outer diameter of 125 microns and the inner diameter of the core is 9 microns. Product specifications provide tolerances for an outer diameter of ± 1 μm. To achieve this specification, the permissible diameter error must be aimed at a smaller size. As a rule, the allowable deviation of the calculated diameter is ± 0.1 μm. Mechanical, electrical and control structures of the exhaust drum synergistically affect the ability to achieve this tolerance on the fiber diameter.

With specified tolerances, the next step will be to understand how the selected design parameters of the drum affect the final product. Although many decisions must be made in any project, there are usually a limited number of critical parameters that have a significant impact on performance. These options include:

- Diameter and tolerances for connecting rod pulley;
- limits of inertia;
- Belts, contact length and bearings;
- Torques and speeds of engines;
- Gain control;
- Maximum limits of current and amplifier power.

In this system, the mechanical design and the control design affect the overall performance of the system. The main mechanical design solution is the pulley diameter. The required line speed and machining tolerances are the basis of the design. When there is no interference, they determine the maximum possible changes in diameter.

In a typical cable drive, belt tension, damping and bearing loads are present. The tension of the belt is much higher than the slight tension of the fiber, necessary for its tension (usually from 50 to 100 grams). The dynamic effects of the belt and bearings can be perceived as viscous damping and additional inertia.

The material of the belt, the contact length and the belt tension must be selected appropriately to ensure that the belt slides with respect to the belt pulley. Belt / drum friction and the prevention of damage to the fiber coating are other key factors.

Non-standard drives with smaller diameters are preferred. In addition to less mass inertia and faster dynamic response with less control effort, they have less material and lower processing costs. The diameter of the driving pulley is limited at the lower end by the mechanical strength of the fiber under tension and bending. Experiments have shown that the smallest permissible diameter is 75 mm. The diameter selection must also take into account machining tolerances and maximum engine speeds. Half of the design error (0.05%) is embedded in the mechanical tolerances, and the other half is assigned to the control circuit. Potential processing tolerances of ± 0.05 mm in diameter indicate that a diameter of 100 mm or more should be used to achieve the maximum design error.

The moment of inertia of the mass of the spindle roller is a parabolic function of the diameter. The lower the inertia of the pulley, the less effort and power control is required. As such, smaller diameter pulleys are more desirable, given the effects of control and inertia.

Another important factor in the design of the exhaust drum is the maximum engine speed. In order to control the diameter at a normal drawing line speed of 50 m / s, the maximum line speed must be higher. Based on the requirements for speed, there are two possible diameters. For an engine with a limit of 4000 rpm, a pulley diameter of approximately 300 mm (or more) is required. A pulley diameter of about 200 mm is the minimum required diameter for a limit of 6000 rpm. With previously established design preferences for pulleys of smaller diameter, a pulley with a diameter of 200 mm is a logical choice if there is an engine with a maximum speed of 6000 rpm or more that meets electrical requirements.

The motor can be selected for each of the two possible diameters (200 mm and 300 mm) of the drive pulley. The choice of motor depends on several factors, including maximum speed, torque, inertia, current and power limits. The motor must be able to withstand the power limits of the controller amplifier 800 watts per axis continuous and 1600 watts peak. The rated current of the motor must be greater than the maximum amplifier current of 10A to prevent overheating.

For a pulley with a diameter of 300 mm, an engine rated for 4000 rpm or more is required. The preferred design is a retainer with a smaller pulley (diameter 200 mm).

III. CONSTRUCTION OF THE MATHEMATICAL MODEL

Dynamic equations of motion for the belt pulley system are developed using the listed parameters:

$$J\,\dot{\omega} = -B\,\omega + T_{engine} \tag{1}$$

where J - is the moment of inertia; B - rotational damping; ω - engine rotation speed; T_{engine} - engine torque.

The motor torque T_{engine} is a function of the applied current $i(t)$ and the integral gain Ki:

$$T_{engine} = K_i i(t) \tag{2}$$

Substituting equation (2) into equation (1) gives the equation:

$$J_{common}\,\dot{\omega} = -B\,\omega + K_i\,i(t) \tag{3}$$

The moment of inertia relative to the center of rotation of the drum is the sum of the inertia of the rotor, pulley, belt and motor rollers:

$$J_{common} = J_{engine} + J_{pulley} + J_{belt} + J_{motorrol} \tag{4}$$

The spindle pulley can be modeled as a rim and flange (μ the thickness of the drive pulley rim):

$$J_{pulley} = M_{rim}r^2 + \frac{1}{2}M_{flange}(r-2\mu)^2 \tag{5}$$

The moment of mass inertia for the belt and three rollers is expressed in the formula:

$$J_{belt} + J_{roller} = M_{belt}r^2 + 3\left(\frac{1}{2}M_{roller}r_{roller}^2\right) \tag{6}$$

The effective damping of the system is the sum of the damping from the bearings and the belt:

$$B_{common} = B_{belt} + B_{bearing} \tag{7}$$

To estimate the damping, we transform equation (3):

$$\dot{\omega} + \frac{B_{com}}{J_{com}}\omega = \frac{K_i}{J_{com}}\,i(t) \tag{8}$$

Applying the Laplace transform, we get:

$$s\Omega(s) + \frac{B_{com}}{J_{com}}\Omega(s) = \frac{K_i}{J_{com}}I(s) \tag{9}$$

From equation (9), the transfer function between speed and current can be obtained:

$$G_M(s) = \frac{\Omega(s)}{I(s)} = \frac{\frac{K_i}{J_{com}}}{s + \frac{B_{com}}{J_{com}}} \tag{10}$$

Using formula (10), the total damping (7) can be estimated from the current input step and velocity data. The root of the first-order system of equation (10) is real and negative. Since the damping values are usually small, the response of the engine can be relatively slow, so control is needed to effectively reduce noise [7].

IV. OPTICAL FIBER EXTRACT VOLTAGE CONTROL

The diameter error is used to change the setpoint of the speed of the tensioning mechanism, based on a constant volume flow. The volumetric flow rate is the square of the fiber diameter multiplied by the spindle pull rate and π / 4. Positive diameter error requires a positive increase in speed to reduce the diameter. The change in motor speed from the change in diameter is relatively small.

The speed change is added to the original speed setpoint. Thus, the control of the fiber diameter is the exact setting of the speed setpoint [8].

The transfer function of the drum speed without feedback, $G_M(s)$ is a first-order system and gives an exponential function of time for an abrupt change in current.

$$(t) = \Delta I \left(\frac{K_i}{J_{com}}\right)\left[1 - \exp - \left(\frac{B_{com}}{J_{com}}\right) t\right] \omega \tag{11}$$

Although high-gain proportional control can reduce error, a steady-state error can be eliminated with a compensator with proportional and integral (PI) control:

$$C(s) = K_p \left(s + \frac{K_i}{K_p}\right) \tag{12}$$

When creating a fiber, the main prerequisite for drum operation and speed control is a constant volume flow of glass *Q*. The control logic is to increase the specified nominal speed of the drum if the fiber diameter is too thick, or reduce it if it is too small. Thisisexpressedinformula (12) andtheequation:

$$Q = \frac{\pi}{4} r \omega_d d_{act}^2 = \frac{\pi}{4} r \omega_{nom} d_{nom}^2 \tag{13}$$

$$\omega_d = \omega_{\text{ном}} \left(\frac{d_{\text{пот}}}{d_{\text{акт}}}\right)^2 \tag{14}$$

Typical changes in the diameter of the glass preform can be approximated as a 2% change per 10 mm of the preform length. The ratio of the preform diameter to the fiber diameter is approximately 700: 1. Squaring gives a volume ratio of 490,000: 1. Thus, a drawing time of 10 mm of the workpiece (or 4900 m of fiber) will be approximately 100 s (the speed of the fiber line is 50 m / s). Squaring the diameter error gives a 4% change in volume per 10 mm length of the workpiece. This volume error will be taken into account in the control project by changing the setpoint for the drawing rate. Assuming a linear function of linear variation for the working diameter (input), the linear velocity of the fiber will require a speed change of 0.04% per second to keep the fiber diameter constant. In addition, this corresponds to 1.25 s for uncontrolled fiber diameter in order to deviate to half the tolerance (deviation 0.05%). Thus, it is desirable to maintain a settling time of less than one second for the internal speed loop in order to reduce the dynamic effects on the external control loop.

The open loop transfer function for the belt pulley, engine, and speed controller is shown in equation 15. The speed controller *C(s)* was designed with PI feedback control.

$$C(s) G_M(s) = \frac{\Omega}{\Omega_d} = \frac{K_p \left(\frac{K_m}{J_{com}}\right)\left(s + \frac{K_i}{K_p}\right)}{s^2 + \left(\frac{B_{com}}{J_{com}}\right) s} \tag{15}$$

Integral and proportional gains, *Ki* and *Kp*, were determined using root loci and modeling methods. Responding to speed fluctuations with insufficient damping, which can cause a significant speed error, should be avoided, so all the roots were intended for a negative real axis. From the point of view of the frequency domain, it was desirable to have a high ratio of integral to proportional gain (Figure 1).

V. THE NUMERICAL EXPERIMENTS RESULTS

Experimental studies were carried out, which allowed to obtain a transient process on the channel "drawing speed - diameter" for various types of exhaust drums. Thus, Figure 2 shows the frequency response of the mechanism with adjustable speed, which has two pinched disks, one of which is connected to the engine or a drum, onto which the tire is automatically wound. The engine was connected by a 1:60 gearbox, and the diameter of the disk was 19 cm. Due to the high degree of reduction, we can assume that the engine runs almost without load. This process corresponds to a monotonic function of the second order separated by real poles:

$$G_1(s) = \frac{3}{(s + 6,3)\,(s + 19{,}58)} \tag{16}$$

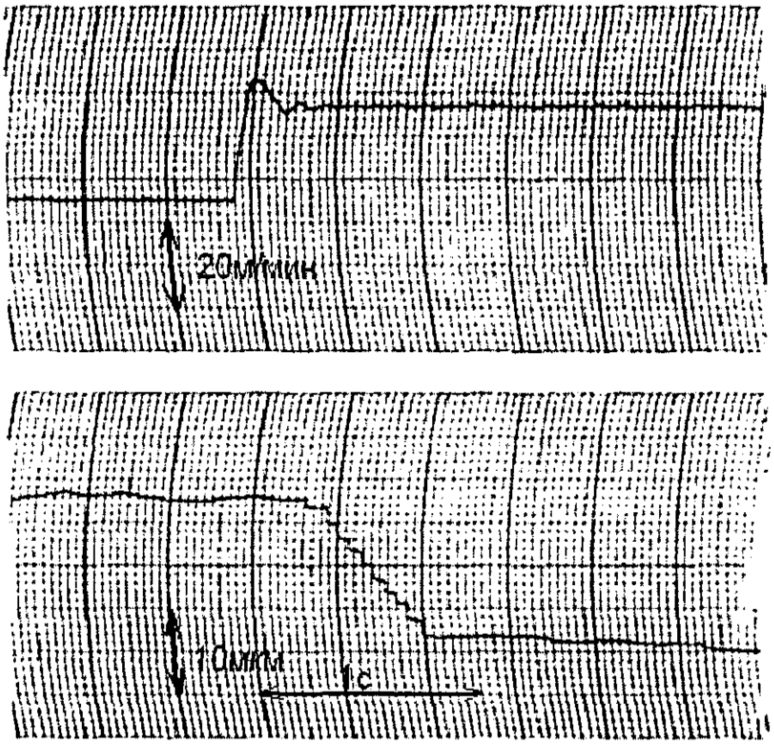

Figure 1 - Transition on the channel "drawing speed - diameter"

If it is necessary to use a pulling mechanism with a drum (which usually occurs when several fibers are simultaneously pulled and rotated), the dynamics are somewhat different.

Figure 3 shows the recorded frequency response of the exhaust mechanism using a plastic drum 15 cm in diameter. Weobtainthetransferfunction:

$$G_2(s) = \frac{s + 208}{(s + 1463)\,(s + 417)} \tag{17}$$

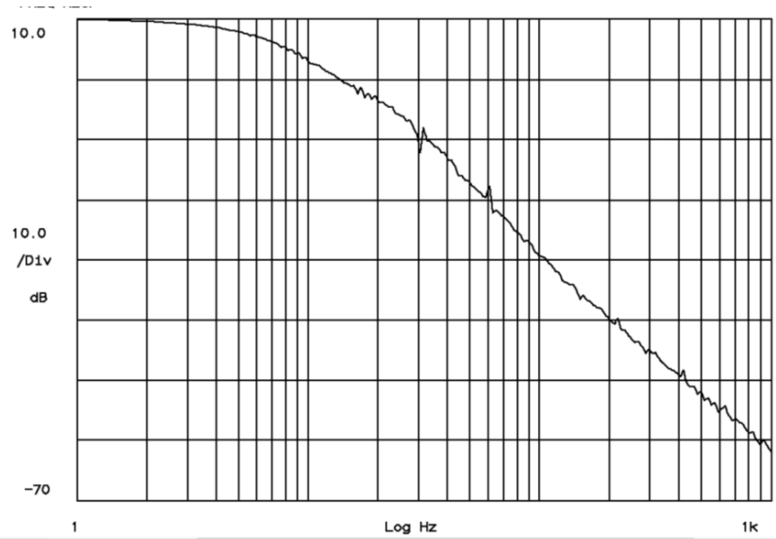

Figure 3 - Transient for a variable speed exhaust mechanism (disc diameter 19 cm)

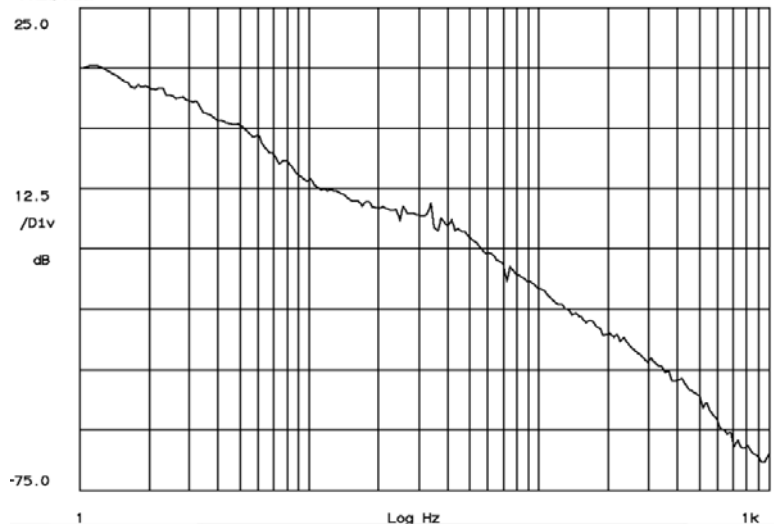

Figure 4 - Transient for exhaust mechanism with a plastic drum with
a diameter of 15 cm for the extraction of several threads

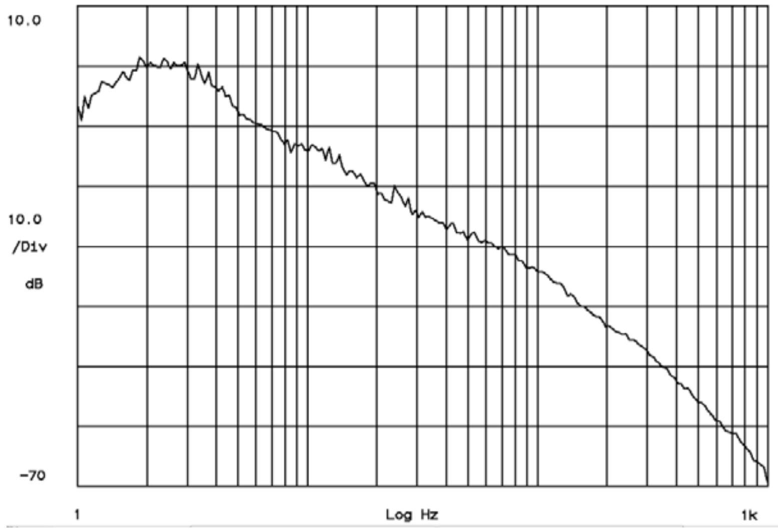

Figure 5 - Transient for exhaust mechanism with a metal drum

If a metal drum with a diameter of 31.8 cm and a weight of 5.3 kg is used, an increase in the frequency response is observed in the region of 2 Hz (Figure 5). This is due to the lower efficiency of the electronic brake in the regulator due to the relatively heavy drum. In this case, the transfer function:

$$G_3(s) = \frac{(s+0.7)(s+17)}{(s+8.3)(s+128)(s+729)} \tag{18}$$

The transport delay of the diameter measurement system was determined to be 0.4 s.

Based on the data obtained, a synthesis was performed of the transfer function associated with the drawing process and the transport delay of the diameter measurement system:

$$G_p(s) = \frac{0{,}01e^{-0.4s}}{s^2+0{,}816s+0{,}118)} \tag{19}$$

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

$$G(s) = \frac{K\,e^{-\tau s}}{(T_1 s+1)\,(T_2 s+1)} \tag{20}$$

where $T_1 \sim L\ /\ vf$, that is, it is proportional to the hydrodynamic properties of the system (*vf* - is the extraction rate, *L* - is the length of the furnace), that is, it is proportional to the hydrodynamic properties of the system. The second time constant T_2 is proportional to the thermal properties of the system, i.e. *T2 ~mCp / k*, where *m* - is the mass of molten glass, *Cp* - is the specific heat capacity, and *k* - is the heat transfer coefficient.

VI. CONCLUSION

There has been presented the basic design of the drum for pulling fiber. Critical parameters, drum operation, which have a significant impact on the performance of optical fiber, have been determined. The maximum engine speed in relation to the pulley diameter has been determined. A mathematical model has been developed for the operation of a drum (coil), taking into account the dynamic equation of motion, inertia, change of speed, and using proportionally an integral controller. An open loop transfer function is obtained for a belt pulley, a motor and a speed controller with feedback control in proportion to an integral controller. A transient process was obtained through the channel “drawing speed - diameter” for various types of exhaust drums.

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ОПТИКАЛЫҚ ТАЛШЫҚТЫ СОЗУ ПРОЦЕСІН ДАЙЫНДАУ КЕЗІНДЕГІ ОНЫҢ ЖЫЛДАМДЫҒЫН САНДЫҚ МОДЕЛДЕУІ МЕН АВТОМАТТЫ БАСҚАРУЫНЫҢ МАҚСАТЫ

Аннотация. Оптикалық талшықты созу үшін барабанның базалық құрамы сипатталған. Бұл оптикалық талшықты созу мен жылдамдығына әсер ететін басты элемент, нәтиженің соңында оның көлденең қимасының пішіні мен диаметріне, яғни негізгі геометриялық парамерлеріне әсер етеді. Оның орнықтылығы дайын оптикалық талшықтардың пайдалану сипаттамаларын анықтайды. Сонымен қатар қозғалыстың динамикалық теңдеуін, жылдамдықтың өзгерісі мен инерциясын ескере отырып, бұл жұмыс барабан (орауыш) жұмысының математикалық моделін өңдеуге арналған. Ременді шкивтің, қозғалтқыштың және кері байланысы пропорционалды-интегралдық жылдамдық реттегішімен бақыланатын ажыратылған контурдың беріліс функциясы алынған. «Созу жылдамдығы - диаметр» каналы бойынша әртүрлі типті созу барабандары үшін өтпелі процесі алынған.

Түйін сөздер: оптикалық талшықты созу, оптикалық талшықтың созу барабаны, шкив, шкив диаметрі, оптикалық талшықтың диаметрі, реттеуш, соу жылдамдығы.

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ЗАДАЧА АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ И ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ СКОРОСТИ ВЫТЯЖКИ ОПТИЧЕСКОГО ВОЛОКНА В ПРОЦЕССЕ ЕГО ИЗГОТОВЛЕНИЯ

Аннотация. В работе дано описание базовой конструкция барабана для вытягивания оптического волокна. Это ключевой элемент, который влияет на скорость и натяжение оптического волокна, а в конечном итоге на его основные геометрические параметры, такие как диаметр и форма поперечного сечения, стабильность которых определяют эксплуатационные характеристики готового оптического волокна. Также работа посвящена разработке математической модели работы барабана (катушки) с учетом динамического уравнения движения, инерции и изменения скорости. Получена передаточная функция разомкнутого контура для ременного шкива, двигателя и регулятора скорости с контролем обратной связи пропорционально – интегральным регулятором. Получен переходной процесс по каналу «скорость вытяжки - диаметр» для различных типов вытяжных барабанов.

Ключевые слова: вытяжка оптического волокна, вытяжной барабан оптического волокна, шкив, диаметр шкива, диаметр оптического волокна, ПИ - регулятор, скорость вытяжки.

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