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SPECIFIC FEATURES OF OPTICAL FIBER CABLE OPERATION DURING TENSION AND CHANGE OF AMBIENT TEMPERATURE

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SPECIFIC FEATURES OF OPTICAL FIBER CABLE OPERATION DURING TENSION AND CHANGE OF AMBIENT TEMPERATURE

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Abstract. This article examines the effect of longitudinal and thermoelastic deformation of an optical module on the technological reserve of an optical fiber. Analytical expressions are given for determining the lower limit of the technological margin of an optical fiber for various types of fiber-optic cable section along the axis.

Keywords: optical fiber, fiber, optical module, fiber-optic cable, temperature, deformation

Introduction

At present, fiber-optic cables (FOC) are widely used to transmit information at high speed. Fiber-optic communication lines (FOCL) have a number of advantages [1, 2, 8, 14]:

- extremely low transmission losses;
- absence of any influence of electromagnetic fields and even lightning strikes;
- the ability, thanks to sealing, to transmit several times more information than through a metal conductor - practically unlimited broadband.

For optical cables, which are used in networks and information transmission systems, and are operated outdoors, in addition to the requirements for resistance to external mechanical influences, reliability, requirements are also imposed on the stability of operation at various ambient temperatures [3, 6, 20].

Figure 1 shows a generalized block diagram of a fiber optic cable. A modern fiber optic cable is a structure consisting of n layers containing, among other things, an optical fiber (or an optical module), a sheath, filaments, etc. Filaments are a reinforcing layer consisting of reinforcing elements, conductive veins, etc. [2, 9].

Fiber optic cable layers are made of various materials. For the manufacture of optical modules (optical fiber), polybutylene terephthalate, polycarbonate, and polyamide are used. In fillers, hydrophobic compounds, powders, water-blocking threads and tapes are used to protect the optical cable from moisture. The elements of the core of the optical cable are fastened using polyethylene terephthalate tapes, the cordels are made on the basis of polyethylene compositions, fiberglass rods, aramid threads, and steel wire are used in the power elements. For the manufacture of outer shells, polyethylene compositions, PVC compounds, polyurethanes, and polyamides are used. In the case of combined sheaths of an optical cable, aluminum and steel tapes are used [2, 18].

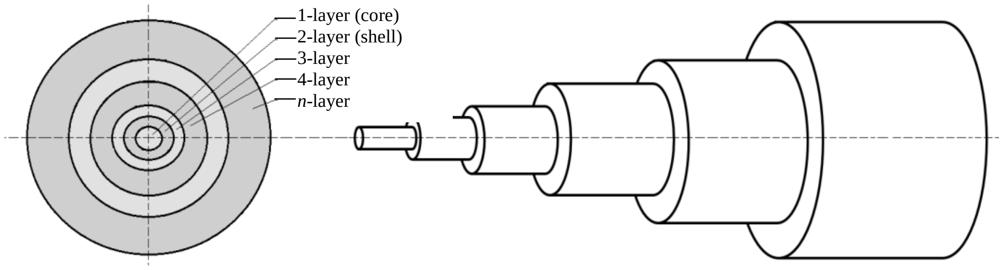

Figure 1. Generalized block diagram of a fiber-optic cable

Main part

The materials used in optical fiber have a temperature coefficient of linear expansion (TCLE), which is different from each other. The temperature coefficient of linear expansion expresses the relative change in body length when its temperature changes by one degree [3, 6]:

$$\alpha = \frac{1}{l_i} \cdot \frac{\Delta l}{\Delta T}, \left[\frac{1}{\deg}\right], \qquad (1)$$

where l_i - the initial length of the sample in the measured direction;

Δl – change in the length of the sample in the measured direction;

ΔT – change in sample temperature.

Table 1 shows the values of the thermal coefficient of linear expansion for some materials used in the production of fiber-optic cables [6, 17, 18].

Table 1

Characteristics of the materials used in the production of FOC

Materials	Young's modulus, [N/mm^2]	TCLE, [1/deg]
Quartz glass	72500	$5{,}5 \cdot 10^{-7}$
Polybutylene terephthalate	1600	$1{,}5 \cdot 10^{-4}$
Polyamide	1700	$7{,}8 \cdot 10^{-5}$
Polycarbonate	2300	$6{,}5 \cdot 10^{-5}$
Aramid fiber	100000	$-2 \cdot 10^{-6}$
Fiberglass	5000... 6000	$6{,}6 \cdot 10^{-6}$
Steel	200 000	$1{,}3 \cdot 10^{-5}$

Low density polyethylene	200... 300	$(1...2,5)\cdot 10^{-4}$
Medium Density Polyethylene	400... 700	$(1...2,5)\ 10^{-4}$
High density polyethylene	1000	$(1...2,5)\cdot 10^{-4}$
Polyvinyl chloride compound	60	$1,5\cdot 10^{-4}$

Therefore, the issues of optimizing the FOC design become relevant and it is proposed to use the following implementation of the algorithm for assessing the FOC performance at different ambient temperatures (Fig. 2) [3, 4, 6].

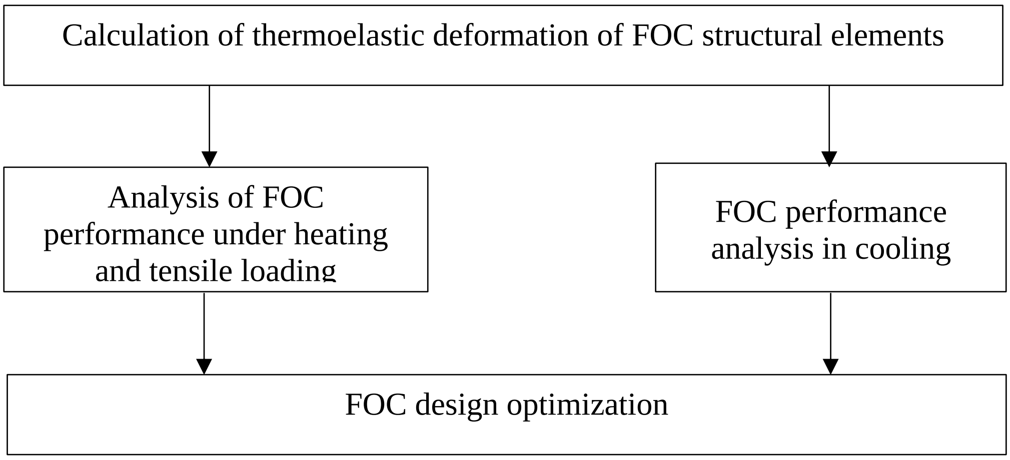

Figure 2. Algorithm for assessing the performance of FOC

Analysis of literature [1, 3-5, 20] sources showed that there are two main types of deformation in a fiber-optic cable: longitudinal deformation of the optical module under the action of a tensile load on the cable and thermoelastic deformation of the optical module along its axis.

The thermoelasticity equation for longitudinal deformation of FOC elements in the absence of slippage between layers is described as follows [3, 5, 20]:

$$\left.\begin{aligned} &\varepsilon_1 = \alpha_1 \Delta T + \frac{Q_{21}}{k_1};\\ &\varepsilon_i = \alpha_i \Delta T + \frac{Q_{i+1;i} + Q_{i-1;i}}{k_i},\\ &i = 2,...,n-1;\\ &\varepsilon_n = \alpha_n \Delta T + \frac{Q_{n-1;n}}{k_n}; \end{aligned}\right\} \quad (2)$$

$$\varepsilon_1 = \varepsilon_i = \varepsilon_n = \varepsilon_T.$$

where ε_T – longitudinal thermoelastic deformation of FOC layers along the axis;

ΔT – temperature difference;

$Q_{i;j}$ – contact force acting from the *i*-layer on the *j*-layer along the FOC axis;

α_i – temperature coefficient of linear expansion of FOC layers;

k_i – longitudinal stiffness of layers FOC;

n – number of FOC layers.

Due to the fact that there are different designs of FOC, it can be represented as a rectilinear element with a constant cross-section along the length, in the form of spiral elements (reinforcing elements, optical module, etc.), with a variable cross-section along the length.

Figure 3 shows the FOC view, which can be represented as a straight-line element with a constant cross-section along the length.

For the case of FOC, which is a rectilinear element with a constant cross-section along the length, the longitudinal stiffness of the layers [2, 3, 5, 20]:

$$k_i = E_i F_i, \qquad (3)$$

where E_i – modulus of elasticity of the material of the i-layer under tension-compression along the cable axis;

F_i – sectional area of the i-layer.

Figure 3. Example of FOC with constant cross-section along the length

Figure 4 a view of FOC with spiral elements is shown, in Fig. 5 - FOC with a section variable along the length (for example, with a corrugated shell).

Figure 4. Example FOC with spiral elements

Figure 5. Example of a FOC with a variable length section

For the case of FOC, which is spiral elements, the longitudinal stiffness of the layers [2, 3, 5, 20]:

$$k_i = L_i, \qquad (4)$$

where L_i – spiral stiffness of the *i*-layer.

Contact force Q_{ij} and thermoelastic deformation of elements ε_T are unknown variables in the system of equations (2). If we take into account that $Q_{ij} = Q_{ji}$ and exclude ε_T from (2), then after the transformation we get a system of (*n-1*) linear algebraic equations with (*n-1*) unknowns [3, 20]:

$$
\left.
\begin{aligned}
&Q_{21}\frac{k_1+k_2}{k_1k_2}-\frac{Q_{32}}{k_2}=(\alpha_2-\alpha_1)\Delta T;\\
&-\frac{Q_{i;i-1}}{k_i}+Q_{i+1;i}\frac{k_i+k_{i+1}}{k_ik_{i+1}}-\frac{Q_{i+2;i+1}}{k_{i+1}}=(\alpha_{i+1}-\alpha_i)\Delta T,\\
&i=2,\ldots,n-2;\\
&-\frac{Q_{n-1;n-2}}{k_{n-1}}+Q_{n;n-1}\frac{k_{n-1}+k_n}{k_{n-1}k_n}=(\alpha_n-\alpha_{n-1})\Delta T.
\end{aligned}
\right\} \quad (5)
$$

When solving the system of equations (5), we use the Gauss method, the essence of which is that, through successive elimination of unknowns, the given system turns into a stepwise (in particular, triangular) system, which is equivalent to the given one.

Since the thermoelastic deformation ε_T is the same for all layers of a generalized structure, it is sufficient to know only one value of the contact force, for example, between the first and second layers Q_{21} of the structure, to determine it. As applied to Q_{21}, the solution to the system of equations (5) has the following form [3, 20]:

$$
Q_{21}=\frac{\sum_{i=1}^{n-1}k_{i+1}(\alpha_{i+1}-\alpha_1)}{\sum_{i=1}^{n}k_i}k_1\Delta T. \quad (6)
$$

After substituting (6) into the first equation of the system of equations (2), an expression is obtained for determining the thermoelastic deformation ε_T for all layers of the generalized structure of an optical cable along the FOC axis [2, 3, 20, 24]:

$$
\varepsilon_T=\left(\alpha_1+\frac{\sum_{i=1}^{n-1}k_{i+1}(\alpha_{i+1}-\alpha_1)}{\sum_{i=1}^{n}k_i}\right)\Delta T. \quad (7)
$$

The lower limit of the technological margin ε_e of the optical fiber, which is in the FOC (optical module), is determined by the relation [3, 20]:

$$
\varepsilon_e>\varepsilon_Q^{OM}+\varepsilon_T^{OM}, \quad (8)
$$

where ε_Q^{OM} – ongitudinal deformation of the optical module under the action of a tensile load Q on the cable;

ε_T^{OM} - thermoelastic deformation of an optical module along its axis.

When conditions (8) are fulfilled, the requirements for the FOC operability are implemented with the simultaneous action of a tensile load and heating of the cable.

For the case of a straight-line arrangement of the optical module in FOC (Figure 6), the thermoelastic deformation of the optical module along its axis is equal to $\varepsilon_T^{OM} = \varepsilon_T$ [3] and can be determined from relations (7) [20]:

$$\varepsilon_T^{OM} = \left(\alpha_1 + \frac{\sum_{i=1}^{n-1} k_{i+1}(\alpha_{i+1} - \alpha_1)}{\sum_{i=1}^{n} k_i} \right) \Delta T.$$

For the case when the optical module is located in a spiral (Fig. 7), the deformation ε_S along the axis of the optical module is associated with the deformation ε_C along the cable axis by the relation [3, 20-25]:

$$\varepsilon_S \approx \sqrt{1 + \frac{\varepsilon_C(\varepsilon_C + 2)}{1 + \frac{\pi^2 (D_C + D_{OM})^2}{H_{OM}^2}}} - 1, \quad (9)$$

where D_C - central element diameter;

D_{OM}- optical module diameter;

H_{OM}- fiber module twisting pitch.

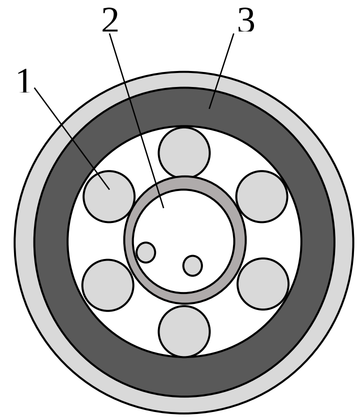

Figure 6. Example of a straight-line arrangement of the optical module in the FOC: 1-reinforcing elements; 2-optical module; 3-shell FOC

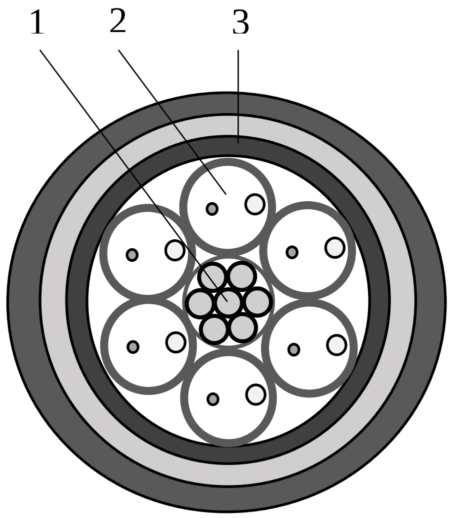

Figure 7. Example of a spiral arrangement of an optical module in FOC: 1-reinforcing elements; 2-optical module; 3-shell FOC

Under the action of a tensile force Q on FOC, the deformation ε_Q^{OM} of the rectilinear optical module is equal to the longitudinal deformation ε_C FOC:

$$\varepsilon_Q^{OM} = \varepsilon_C . \quad (10)$$

Longitudinal deformation ε_C FOC with a rectilinear optical module is determined from the relation [3, 20]:

$$\varepsilon_C = \frac{Q}{\sum_{i=1}^{n} k_i} . \quad (11)$$

In the case of spiral optical modules, the deformation ε_Q^{OM} can be determined from relation (9).

In practice, FOCs, the so-called microcables, are also widely used (Figure 8). For example, such fiber-optic microcables are used by Internet service providers when laying FOCs in the house, in interconnect and inter-node communication lines of mobile communication systems, etc. [1, 2, 19, 21]. These fiber optic microcables operate under low tensile loads. In them, optical fibers play the role of reinforcing elements and an elongation of FOC of up to 0,25% is allowed without significantly affecting its service life [3, 6]. For such FOCs, the component of the longitudinal deformation of the optical module ε_Q^{OM} under the action of a tensile load in (8) can be disregarded.

Figure 8. Microcable type

Table 2 summarizes the analytical expressions for determining the lower limit of the technological margin of an optical fiber for various types of FOC sections along the axis [3, 6, 20].

Table 2

Longitudinal and thermoelastic deformations of the optical module for different types of FOC cross-sections

N	FOC section views along axis	Longitudinal deformation of the optical module under the action of a tensile load on the cable, ε_Q^{OM}	Thermoelastic deformation of an optical module along its axis, ε_T^{OM}
1	Rectilinear	$\frac{Q}{\sum_{i=1}^{n} k_i}$	$\left(\alpha_1 + \frac{\sum_{i=1}^{n-1} k_{i+1}(\alpha_{i+1} - \alpha_1)}{\sum_{i=1}^{n} k_i}\right)\Delta T$
2	Spiral	$\sqrt{1 + \frac{\varepsilon_C(\varepsilon_C + 2)}{1 + \frac{\pi^2 (D_C + D_{OM})^2}{H_{OM}^2}}} - 1$	
3	Microcable	disregarded	

Conclusion

The analysis of the results obtained allows us to conclude that under the influence of the external environment, in particular, temperature and stretching, processes occur in the FOC that can lead to a change in the physical dimensions of the components that make up the FOC [10-16]. Due to the fact that the composition of the FOC components is heterogeneous and made of different materials, situations are possible when the deformation of the FOC can exceed the limit of the technological deformation margin, which, in turn, can lead to an increase in signal losses in FOC, deterioration of the FOC quality, decrease in reliability, and etc.

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