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

D.A. Davronbekov, Z.T. Khakimov

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](image)

**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]:

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

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

$\Delta l$ – change in the length of the sample in the measured direction;

$\Delta T$ – 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>
<thead>
<tr>
<th>Materials</th>
<th>Young's modulus, [N/mm²]</th>
<th>TCLE, [1/deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz glass</td>
<td>72500</td>
<td>5,5·10⁻⁷</td>
</tr>
<tr>
<td>Polybutylene terephthalate</td>
<td>1600</td>
<td>1,5·10⁻⁴</td>
</tr>
<tr>
<td>Polyamide</td>
<td>1700</td>
<td>7,8·10⁻⁵</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>2300</td>
<td>6,5·10⁻⁵</td>
</tr>
<tr>
<td>Aramid fiber</td>
<td>100000</td>
<td>-2·10⁻⁶</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>5000... 6000</td>
<td>6,6·10⁻⁶</td>
</tr>
<tr>
<td>Steel</td>
<td>200 000</td>
<td>1,3·10⁻⁵</td>
</tr>
<tr>
<td>Material</td>
<td>Density Range</td>
<td>Thermal Expansion Coefficient</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Low density polyethylene</td>
<td>200... 300</td>
<td>(1...2,5)·10^4</td>
</tr>
<tr>
<td>Medium density polyethylene</td>
<td>400... 700</td>
<td>(1...2,5)·10^4</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>1000</td>
<td>(1...2,5)·10^4</td>
</tr>
<tr>
<td>Polyvinyl chloride compound</td>
<td>60</td>
<td>1,5·10^4</td>
</tr>
</tbody>
</table>

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].

**Calculation of thermoelastic deformation of FOC structural elements**

- Analysis of FOC performance under heating and tensile loading
- FOC performance analysis in cooling

**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]:

\[
\varepsilon_i = \alpha_i \Delta T + \frac{Q_{ij}}{k_i} + \frac{Q_{-ij}}{k_i},
\]

\[
i = 2, \ldots, n-1;
\]

\[
\varepsilon_n = \alpha_n \Delta T + \frac{Q_{n+1,0}}{k_n};
\]

\[
\varepsilon_1 = \varepsilon_i = \varepsilon_n = \varepsilon_T.
\]

where \( \varepsilon_T \) – longitudinal thermoelastic deformation of FOC layers along the axis;

\( \Delta T \) – temperature difference;
$Q_{ij}$ – contact force acting from the $i$-layer on the $j$-layer along the FOC axis;

$\alpha_i$ – 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]:

$$k_i = E_i F_i,$$  \hspace{1cm} (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 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]:

$$k_i = L_i,$$ \hspace{1cm} (4)

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

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

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).
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 \( \varepsilon_T \) 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 \([3, 20]\):

\[
Q_{21} = \frac{Q_{22}}{k_2} - \frac{Q_{22}}{k_1} k_2 = (\alpha_2 - \alpha_1) \Delta T; \\
\frac{Q_{i-1}}{k_i} + \frac{Q_{i+1}}{k_{i+1}} k_{i+1} - \frac{Q_{i+2}}{k_{i+1}} = (\alpha_{i+1} - \alpha_i) \Delta T, \\
i = 2, ..., n-2; \\
\frac{Q_{n-1}}{k_{n-1}} + \frac{Q_{n+1}}{k_n} k_n = (\alpha_n - \alpha_{n-1}) \Delta T. \\
\]

(5)

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

\[
\varepsilon_e = \alpha_i + \sum_{i=1}^{n} \frac{k_{i+1}(\alpha_{i+1} - \alpha_i)}{\sum_{i=1}^{n} k_i} \Delta T. \\
\]

(7)

where \( \varepsilon_Q^{OM} \) – longitudinal deformation of the optical module under the action of a tensile load \( Q \) on the cable;

\( \varepsilon_T^{OM} \) – 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]:

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

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

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

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 \( \varepsilon_Q^{OM} \) of the rectilinear optical module is equal to the longitudinal optical deformation \( \varepsilon_C \) FOC:

\[
\varepsilon_Q^{OM} = \varepsilon_C. \tag{10}
\]

Longitudinal deformation \( \varepsilon_C \) FOC with a rectilinear optical module is determined from the relation [3, 20]:

\[
\varepsilon_C = \frac{Q}{\sum_{i=1}^{n} k_i}. \tag{11}
\]

In the case of spiral optical modules, the deformation \( \varepsilon_Q^{OM} \) 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 $\varepsilon_{Q}^{OM}$ under the action of a tensile load in (8) can be disregarded.

![Figure 8. Microcable type](image)

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>
<thead>
<tr>
<th>N</th>
<th>FOC section views along axis</th>
<th>Longitudinal deformation of the optical module under the action of a tensile load on the cable, $\varepsilon_{Q}^{OM}$</th>
<th>Thermoelastic deformation of an optical module along its axis, $\varepsilon_{T}^{OM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rectilinear</td>
<td>$Q = \sum_{i=1}^{n} k_{i}$</td>
<td>$\left[\sum_{i=1}^{n} k_{i} \left(\alpha_{i+1} - \alpha_{i}\right)\right] \Delta T$</td>
</tr>
<tr>
<td>2</td>
<td>Spiral</td>
<td>$1 + \frac{e_{c}(e_{c} + 2)}{1 + \pi^{2} (D_{c} + D_{OM})^{2}} - 1$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Microcable</td>
<td>disregarded</td>
<td></td>
</tr>
</tbody>
</table>

**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.

REFERENCES


[18] www.ruscable.ru


