FIZOPTIKA FIBER OPTIC ROTATION SENSORS
RELIABILITY ESTIMATION

The method for calculation of reliability parameters of fiber optic rotation sensors is presented. It was used to estimate lifetime and mean time to failure (MTTF) for Fizoptika sensors.

1. MAIN RELIABILITY PARAMETERS

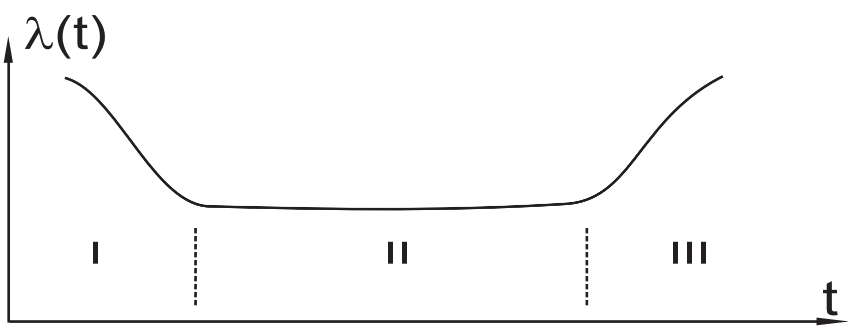
Reliability is a composite index which includes operability, life time etc.
Main reliability (operability) parameters for non-repairable units (which can not be recovered after failure - e.g. microcircuits, connectors etc.) are listed below:

- probability of no-failure operation during ***t*** period: ***P(t)***;
- probability of failure during ***t*** period: ***Q(t)= 1 - P(t)***;
- failure rate λ***(t)*** the frequency with which a sensor fails, expressed in failures per hour;
- mean operating time to failure ***T***.

Axioms:

- ***P(0)=1*** (only operating units are considered);
- $\lim_{t\to\infty} P(t)=0$ (operability can not be kept for infinitely long period);
- $dP(t)/dt \le 0$ (a unit can not be repaired after failure).

Typical dependence $\lambda(t)$ during operation life is presented below:



I initial run-in stage $d\lambda(t)/dt<0$
II normal use stage $\lambda(t)$***-const***
III ageing stage $d\lambda(t)/dt>0$

Reliability parameters interrelation:

$$P(t) = \exp\left(-\int_0^t \lambda(t)dt\right) \text{ for stage II } \quad P(t)=\exp(-\lambda t)$$

$$T = \int_0^\infty P(t)dt \text{ for stage II } \quad P(t)=\exp(-t/T), \text{ где } T=1/\lambda$$

Reliability of non-repairable units will be characterized by mean operating time to failure ***T***

2. RELIABILITY CALCULATION METHOD

Calculation background:

- calculation is performed for normal use stage - λ***(t)-const*;**
- unit reliability diagram should be designed;
- failure of unit is caused by a failure of any component (group of components) which is included in reliability diagram;
- each component (included in reliability diagram) is characterized by failure rate λ_i and probability of no-failure operation $P_i(t)$;
- the failures of components are mutually independent (at least to first approximation).

So, for probability of unit no-failure operation $P_{unit}(t)$ we have:

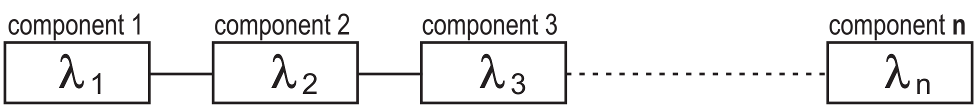
$$P_{unit.}(t)=P_1(t) * P_2(t) * \ldots * P_n(t)= \prod_{i=1}^{n} P_i(t);$$

for failure rate of unit λ_{unit} we have:

$\lambda_{unit} = \lambda_1 + \lambda_2 + \ldots + \lambda_n = \sum_{i=1}^{n} \lambda_i$ (exponent indexes should be summarized in expression $P=exp(-\lambda t)$),

and, finally, mean operating time to failure $T_{unit} = 1/\lambda_{unit}$.

As a first step of calculation the most critical components (group of components) should be determined and reliability diagram of the following structure should be composed.



A failure of any critical component results in a failure of unit. Summarized failure rate of unit is calculated in accordance with reliability diagram.

3. CALCULATION RESULTS

3.1. CALCULATION BACKGROUND

Fizoptika fiber optic rotation sensor (FORS) comprises two main modules which are built in common housing: optical module and electronics module.

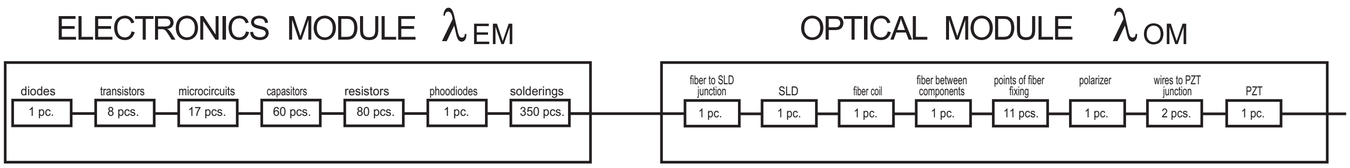
Reliability estimation was based on MIL-HDBK-217F and on the data from united handbooks “Reliability of products of electronic engineering and quantum electronics” (issued by SRI “Electrostandard”).

The failure rate values for main components of optical module were based on relevant information from manufacturers of optical components. Humidity factor was not involved into consideration.

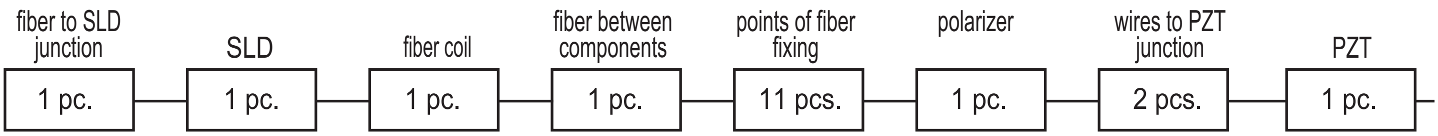
Summarized failure rate for sensor was estimated for Ground Fixed Operation (GF) environment and for ambient temperature +25°C. The failure rate for the “low noise” sensors (with increased operating current) was estimated from the results for (GF, +25°C) environment by using 2-times increased failure rate value for SLD.

3.2. RELIABILITY DIAGRAMS

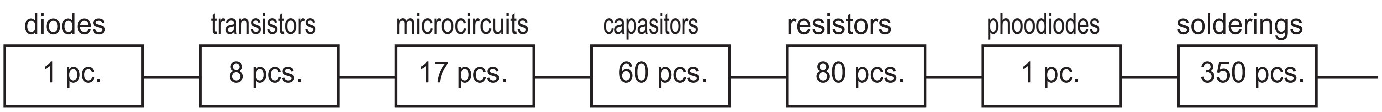
Reliability diagram of fiber optic rotation sensor and its modules are presented below:



Reliability diagram of optical module:



Reliability diagram of electronics module:



Electronics module OE141FOS-3: failure rate of components

Component type	Number of components	Number of failures for 1 million hours [10^{-6}/h]
Diode	1	0.006
Transistor	8	0.08
Microcircuit chip	17	0.016
Capacitor	60	0.016
Resistor	80	0.005
Semiconductor photodiode	1	0.02
Points of soldering	350	0.0004

Optical module: failure rate of components

Component type	Number of components	Number of failures for 1 million hours [10^{-6}/h]
Fiber to SLD junction	1	0.4
SLD (option - increased operating current)	1	6.0 (12.0)
Fiber coil	1	0.3
Fiber between components	1	0.12
Points of fiber fixing	11	0.01
Polarizer	1	0.95
Wires to PZT junction	2	0.12
PZT	1	0.02

3.3. MTTF ESTIMATION

From the above failure rate data we have the following estimation:

- for optical module:

$\lambda_{OM} = 1 \cdot 0.4 + 1 \cdot 6.0 + 1 \cdot 0.3 + 1 \cdot 0.12 + 11 \cdot 0.01 + 1 \cdot 0.95 + 2 \cdot 0.12 + 1 \cdot 0.02 =$ **8.25 [10^{-6}/h]**;

- for optical module of the sensors with increased operating current:

$\lambda_{OM} = 1 \cdot 0.4 + 1 \cdot 12.0 + 1 \cdot 0.3 + 1 \cdot 0.12 + 11 \cdot 0.01 + 1 \cdot 0.95 + 2 \cdot 0.12 + 1 \cdot 0.02 =$ **14.25 [10^{-6}/h]**;

- for electronics module:

$\lambda_{EM} = 1 \cdot 0.006 + 8 \cdot 0.06 + 17 \cdot 0.016 + 60 \cdot 0.016 + 80 \cdot 0.005 + 1 \cdot 0.02 + 350 \cdot 0.0004 =$ **2.44 [10^{-6}/ч]**

Taking into account the values of failure rates ($\lambda_{OM}, \lambda_{EM}$) calculated above, mean operating time to failure ***T*** for fiber optic rotation sensors can be estimated as follows:

$$T = 10^6 / (\lambda_{OM} + \lambda_{EM}) = 10^6 / (8.25 + 2.44) = 93545 \text{ hours}$$

For the “low noise” sensors (with increased operating current) we have:

$$T = 10^6 / (14.25 + 2.44) = 59916 \text{ hours}$$

4. LIFE TIME PREDICTION

Optical fiber is a most critical component, which determines life time of fiber optic rotation sensors, so far as long length of fiber (~100m) is placed into sensor' housing in a stressed state. That can result in growth of microcracks and eventually - in break of fiber (so called - “glass static fatigue”).

Estimation of life time of optical fiber can be based on the following expression:

$$\mathbf{t = t_o(\varepsilon_n/\varepsilon)^n},$$

where **n** $\approx$ **20** - fiber static fatigue parameter, ε_r - fiber specific elongation at its rewinding under tension, ε - fiber specific elongation in use, $\mathbf{t_o}$ - time parameter.

From above expression it is clear, that life time will be equal $\mathbf{t_o}$ if the fiber will be elongated in use up to $\boldsymbol{\varepsilon = \varepsilon_r}$. Typical values of $\mathbf{t_o}$ parameter for fiber section of **100m** length can be characterized by 1 sec magnitude ($\mathbf{t_o} \approx$ **1 sec**).

If specific elongation of fiber in use ε equals to $\mathbf{0.3}\varepsilon_r$, life time of optical fiber is estimated as tens of years due to big value of fiber static fatigue parameter (**n**). If specific elongation of fiber in use ε is close to **0** the fiber life time tends to infinity. So, if for fiber in use we have $\varepsilon < \mathbf{0.3}\varepsilon_r$, calculation of fiber life time gives big value (tens of years) and from practical point of view more detail estimation is not needed.

Fiber deformations are generated in manufacturing process of fiber optic rotation sensor (winding of sensing coil, fiber placing etc.). Fiber deformations remain constant during all stages of life cycle (storage, use, testing). Fiber stress arises due to fiber bend at coil winding which results in different length of internal and external sides of wound fiber.

Fiber specific elongation ε can be calculated from the following below expression on conditions that diameter of winding is much more than diameter of fiber in plastic cladding: $\boldsymbol{\varepsilon = d/D}$, where **d** diameter of quartz part of the fiber, **D** - diameter of winding.

Optical fiber for Fizoptika sensors is rewound on transportation bobbin in production process under tension of **40 g**, that corresponds to fiber specific elongation ε_r **= 0.5%**. In order to reach fiber life time of 15 years fiber specific elongation should be less than **0.15%** (as follows from above stated consideration). If diameter of fiber quartz part equals to 0.04 mm, from above expression we have estimation for minimal allowable value of diameter of winding **D=2.5см**. This value is a typical parameter for small fiber optic rotation sensors produced by Fizoptika and we can predict their life time of more than 15 years.