Methods for acoustic desensitization of fiber optic interferometer

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Abstract. Methods for acoustic desensitization of fiber optic interferometer were studied as applied to the compensation interferometer (CIF) of a fiber optic phase sensor system. Materials with high mechanical loss factor were used for the fiber optic interferometer rack case. Also case acoustic conditioning measures and vibration isolation system based on steel springs were developed. Different types of fiber coating for acoustic desensitization were investigated. The best implementation provided up to 30 times (-29.8 dB) suppression of CIF undesirable acoustic sensitivity level.

1. Introduction

At present, fiber optic interferometric sensors are becoming increasingly widespread as sensitive elements (SE) of various measuring systems (fiber optic gyroscopes, current and voltage sensors, seismic streamers and many others) [1-9]. The following advantages are common such sensors: low overall dimensions of the sensitive element, extremely high sensitivity, explosion and fire safety (the optic fiber is a dielectric material), absolute insensitivity of the sensitive element to the external electromagnetic field (extremely high noise immunity), the possibility of placing the sensitive element in harsh environments (temperature effects, chemical activity, etc.), the possibility of multiplexing a large number of sensors on single fiber (spatial measurement arrays).

One of the most important components of the measuring systems based on the fiber optic phase interferometric sensors is a fiber optic interferometer, or compensation interferometer (CIF), in which the combination of the measuring and reference optical signals is carried out to obtain an interference pattern received by a photodetector device.

The CIF principle of operation is as follows: at the input, one optical pulse is divided into two pulses, which propagate along its two fiber optic arms (short and long), the lengths difference between which coincide with the optical path inside the sensitive element. One of the fiber optic arms comprises an integrated electro-optic phase modulator [10-12], which is used to well-known signal detection algorithm [13,14]. With the addition of the corresponding measuring and reference pulses on the photodetector, the resulting interference pulse arises, the magnitude of the optical power span of which, in accordance with the curves of visibility and sensitivity of the sensitive element, it becomes possible to make a conclusion about the magnitude of the measured effect on the sensitive element.

When operating under real conditions, the effects of environmental noise and vibrations are observed, which leads to a variation of the lengths of the interferometer arms [15] and, consequently, undesirable modulation of the optical path length. The result of such effects is the noise of the interference pattern on the photodetector, and, as a consequence, the reduction of the accuracy
parameters of the measuring system and its sensitivity. The main problem is the fact that, in view of
the design of the measuring system based on fiber optic phase interferometric sensors, the arms of the
interferometer have a sensitivity level similar to one of the sensitive element and, respectively, the
overall sensitivity of measuring system is distributed between CIF and SE, and therefore the effect of
noise and vibrations on the CIF significantly limits the accuracy characteristics and dynamic range of
the system.

2. Experimental method
The effect of environmental noise on fiber optic devices includes addition extra phase difference
according to the following analytic expression [15]:

\[ \Delta \phi_f = \frac{2\pi n}{\lambda} P L \left( \left[ \frac{(1 - 2\mu)}{E} \right] + \frac{n^2}{2E} (1 - 2\mu)(2p_{12} + p_{11}) \right), \] (1)

\( \lambda \) – wavelength (m), \( n \) – optical fiber effective refractive index, \( L \) – optical fiber length (m), \( P \) –
aoustic pressure level (Pa), \( \mu \) – optic fiber Poisson’s coefficient, \( E \) – optic fiber Young’s modulus, \( p_{12} \)
and \( p_{11} \) – elements of the strain-optic tensor for a homogeneous isotropic material.

In case of the use of protective coatings for optic fiber this additional phase difference can be
described using following formula [16]:

\[ \Delta \phi_c = \frac{2\pi n}{\lambda} P L \left( \left[ 1 - \frac{n^2}{2} \left( p_{12} - p_{11}\mu - p_{12}\mu \right) \right] \left[ R^2 (1 - 2\mu') + 2r^2 (\mu' - \mu) \right] \right. \\
\left. - \left[ \frac{n^2}{2} \left( p_{11} + p_{12} \right) \frac{1 - \mu - 2\mu'}{E} \right] \right), \] (2)

\( R \) and \( r \) – outer and inner radii of the coating material (m), \( E' \), \( \mu' \) – Young’s modulus and Poisson’s
coefficient of the coating material respectively.

During the review of the scientific and technical literature, the main directions of solving this
problem were discovered - the use of protective coatings of optic fiber [15-17], as well as the
protection of sensitive elements using vibration isolation devices [17].

The main purpose of this work is to research into CIF environmental noise protection methods,
which, in turns, will result in increasing the sensitivity and accuracy of fiber optic measurement
systems.

The investigation of efficiency of CIF rack case acoustic and vibration isolation methods (see
figure 1) was carried out in this research.

![Figure 1. CIF rack case acoustic conditioning (desensitization).](image-url)
The measurement technique included the exposure to acoustic white noise signal of examined CIF compared with samples without any desensitization measures in order to estimate the efficiency of taken measures. The demodulation of phase signal was held using homodyne demodulation algorithm in the frequency range of 1-500 Hz [18-21]. The scheme of experimental setup is shown in figure 2 (L is fiber interferometer unbalance length).

3. Results and discussion

The research consisted of several stages of CIF rack case acoustic conditioning (desensitization) with estimation of CIF relative acoustic sensitivity on each stage (see figure 3).

The first part of this research consisted of several stages of CIF case acoustic conditioning (desensitization) with estimation of CIF relative acoustic sensitivity on each stage (figure 3). On the first stage (line 1 on figure 3) CIF eigen acoustic sensitivity level was measured. Then (line 2 on figure 3) CIF was placed into standard steel 19” rack case. It resulted in decrease of sensitivity by from 1.04 to 4.64 times (-0.36 to -13.33 dB) in comparison to the CIF without outer case.

After that, 19” rack case was customized by sealing with polymer compound and adding a layer of synthetic rubber, a layer of 500 µm galvanized metal sheet and a layer of polyurethane foam material on its inner surface. It provided all-range decrease of CIF acoustic sensitivity (line 3 on figure 3) from 1.43 to 6.7 times (-3.13 to -16.53 dB) compared with a CIF without outer case. This effect can be explained by the fact, that case material, synthetic rubber and galvanized metal sheet together form a resonator with high mechanical loss factor, which efficiently absorbs the energy of external noise impact.
The final stage of CIF case sound conditioning included the development and implementation of a suspension vibration isolation system based on steel springs. This implementation provided the best all-range decrease of CIF acoustic sensitivity (line 4 on figure 3) from 2.49 to 13.14 times (-7.93 to -22.37 dB) compared with a CIF without outer case.

![Image](image.png)

**Figure 3.** 1 – CIF without outer case (for reference); 2 – CIF, installed into standard 19” rack case; 3 – CIF, installed into sealed custom acoustically desensitized 19” rack case; 4 – CIF with spring vibration isolation suspension system, installed into sealed custom acoustically desensitized 19” rack case.

The second part of the research includes the study acoustic isolation properties of different optical fiber coatings. The samples under test included optical fiber, coated with copper tube (with the air gap between copper and fiber to achieve the maximum level of acoustic isolation), stranded steel rope reinforced fiber optical cable (with hydrophobic compound), optical fiber with aramid coating and standard optical fiber without coatings for reference (figure 4). Copper tube coated fiber (with air gap) demonstrated from 1.01 to 2.83 (-0.16 to -9.03 dB) decrease in undesirable acoustic sensitivity of optical fiber (line 1 on figure 4). This relatively poor result could be explained by the fact, that optical fiber partially touched the inner walls of the copper tube, and, consequently, the energy transfer of oscillatory processes took place. From the point of acoustical isolation, the most efficient coating is stranded steel rope (line 2 on figure 4), decrease of undesirable acoustic sensitivity is from 1.66 to 2.35 times (-4.38 to -7.43 dB) compared to the level of bare optical fiber acoustic sensitivity. This effect can be explained by the fact, that this cable is a composite system, the high rigidity of which is due to the material of the cable ropes (steel), and the aggregate elastic properties are distributed between the polymer sheath, the hydrophobic filler and the twisted metal ropes. This complex structure represents a high-efficiency damping system, which can dissipate sound pressure energy with low transition ratio to the core of optical fiber. The implementation of aramid coating for optical fiber (line 3 on figure 4) leads to the increase of acoustic sensitivity from 1.27 to 2.08 times (+2.05 to +6.38 dB) related to bare optical fiber (line 4 on figure 4), which can also be useful in some applications [21].
The resonant peaks and flatness of experimental curves could be explained by longitudinal and transverse resonances of experimental samples structures and also by the influence of acoustic room modes on acoustical pressure level at the point of measurement [22].

4. Conclusions

As a result, the combination of case acoustic conditioning measures with sealing with polymer compound and covering its inner surface with a layer of synthetic rubber, a layer of 500 μm galvanized metal sheet and a layer of polyurethane foam material, use of spring-based vibration isolation system and the use of stranded steel rope reinforced coating for CIF arm fiber leads up to 31 times (~29.8 dB) undesirable acoustic sensitivity level suppression in certain frequency range. The results of this work are important and applicable in different spheres of modern fiber-optical instrumentation for environmental noise protection of fiber lasers, fiber sensors and fiber-optical interferometers in order to significantly increase their operating parameters.

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