Intellectual parachute monitoring system based on twisted fiber optic sensors

Oleg G. Morozov, Gennady A. Morozov, Mikhail Yu. Zastela

Abstract— **For any parachute system, it is important to predict the opening forces it will experience in order to make a safe and economic choice of materials to be used. Pre-design researches on creation of the built-in parachute parameters monitoring system that can be used both at a stage of its tests, and at stage of its control for the purpose of its characteristics management are resulted. Fiber optic sensor based on two twisted fibers with the locked ends offered by us for this purpose does not demand lamination, is indifferent to a temperature field, and provides a wide dynamic range of measurement as pressure and tension of parachute elements. Developed fiber optic sensors have variable twisting step and have been used for creation of intellectual knots of perspective vehicles, in particular, parachute canopies and slings. We decided to change our measuring procedure from checking of transmitted power or its Rayleigh scattering in different ends of twisted fibers onto Brillouin scattering characterization. For this situation, we offered the kind of frequency variation method to get the information about the frequency shift and *Q*-factor of the Brillouin scattering in each sensor.**

Index Terms— **parachute system, embedded fiber optic sensors on two twisted fibers with the locked ends, Brillouin scattering, signal processing, frequency shift, *Q*-factor, two-frequency probing signals.**

I. Introduction

For any parachute system, it is important to predict the opening forces it will experience in order to make a safe and economic choice of materials to be used. Only limited data for these decisions is available and any numerical model sought to be used is also limited by the lack of data to use and to verify the model. Novel techniques are therefore needed to determine the structural behavior of a parachute during inflation. A different method for experimental measurement of parachute behavior during opening is also needed. There are other fabrics and textiles that are subjected to stress, such as, for example, balloons and the like [1].

A parachute comprises two main parts: the canopy and the slings. A parachute drop generally consists of three principal stages: deployment, inflation, and descent. The deployment phase begins with the ejection of the payload from the aircraft, rocket or the like, and ends when the slings and folded canopy have been fully extracted from the deployment bag. The full extension of the parachute system is marked by the "snatch" force impulse, an acquisition event that occurs when the falling payload accelerates the parachute mass up to its own velocity [2]. In most military airdrops, the deployment bag is attached to the aircraft by a static tether; hence, the time lag between payload ejection and the snatch point is usually small. In free-fall personnel drops and sport parachute jumps, the time delay is usually longer. In either case, the parachute shape at the end of the deployment phase is essentially that of an elongated but deflated tube. During the subsequent inflation phase, the elongated parachute transforms from a closed tube to an open canopy, ultimately increasing the aerodynamic drag and decelerating the payload. Eventually, a steady-state condition or descent is reached where the aerodynamic drag balances gravity and the payload drifts to earth at a relatively constant velocity.

In the design of parachute systems, therefore, it is very important to use structural properties that have been developed under the representative force rates expected in flights. Without such data, the designer is potentially forced to incorporate unrealistic safety margins, resulting in a parachute that is heavier and costlier than necessary. Laboratory test data has generally been limited to that which can be acquired at quasi-steady strain rates. Past work has suggested that the properties of textile materials obtained through the typical quasi-static testing process are inapplicable to dynamic strain conditions [1].

Researchers in parachute technology recognize the need for small, accurate differential and absolute pressure sensors, temperature sensors, flow sensors, fabric stress monitors and strain sensors that can be used in small and large-scale test systems. These systems need to be able to accommodate rapid turnaround and a large number of sensor nodes without excessive setup and calibration requirements [3]-[6].

Currently, no sensor systems for low-pressure parachute measurements are available to accurately measure the low differential pressures across the parachute fabric during airdrop missions. While conventional technologies such as capacitance-based industrial pressure transmitters can provide the desired pressure range and resolution [3], [4], these units are generally bulky, heavy and power-consumptive. Micromachined capacitive pressure sensors with integrated electronics offer an improved solution, although they typically fail to reach the low operating range requirements of 100 Pa (0.015 psi) or less and are not available in differential or gage pressure configurations. Low cost piezo resistive pressure sensors, which comprise the majority of pressure sensors sold today, have limited signal-to-noise ratios that prevent them from giving accurate measurements of differential pressure at low operating ranges and have relatively high power consumption. Recent innovations by other researchers of integrated capacitive pressure sensors for tire pressure sensors have produced smaller devices that are typically configured as absolute pressure sensors and as such, do not have the capability of measuring small differential pressures that are of particular interest in parachute monitoring. Accommodations for wireless data communications, local data storage, batteries and an antenna add size and weight to

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the sensor node, which can alter the flow field and distort the structural response of the parachute. Still another advantage would be to use fiber optics technology to determine the stress/strain relation of flexible devices such as parachutes during deployment and inflation. Fiber optic sensors (FOS) with different principles of operating [5], [6] are more accurate and available for system integration.

Developed by us FOS based on two twisted fibers with the locked ends (TFL) and variable twisting step [7]-[10] have been used for creation of intellectual knots of perspective vehicles, in particular, parachute canopies and slings from Capron and SVM. To show possibilities of application of the given type of FOS in practice, the mechanical pressure put to the gauge which has been twisted in various sling types of cargo parachute systems has been measured. The stand for rupture tests with slings of LTK- and SKP-type according to twisted in their structure TFL FOS was shown [8]. It is a little exemplary FOS with various twisting step were made for experiment, the various efforts of a tension intended for measurement. In each gauge were used single mode optical fibers with step change of refraction index.

Further, the paper is structured as following. The second part is devoted to the structure of TFL FOS, third – for new sensor data acquisition method based on Brillouin contour characterization, fourth – for system integration questions, and fifth – to the results of measuring.

I. THEORETICAL BASICS OF TFL FOS

Past reported work presents the use of electronic strain gauge equipment for measuring stresses under various loading conditions. Testing materials at representative high strain rates of dynamic forces requires much more sophisticated equipment than found in a typical material testing laboratory. It would be a great advantage in the art to have an improved methodology and apparatus, which takes advantage improved data acquisition techniques, such as that of advances in fiber optic sensors for fabrics, textiles and other flexible structures [11]. Heretofore, conventional methods of measuring stress or strain in fabrics have proved ineffective and/or cumbersome [1].

All of the methods using extensometers or other transducers to measure strains in the flexible sheet require knowledge of the material properties in order to compute the stresses. Often the biaxial stress-strain properties are not known well enough, or are not constant from one sample to another, to permit accurate computation of the stresses from the measured strains. In yet another arrangement, a transducer for load measurement uses a strain gage on a flat link which is secured at each end to a yarn. This arrangement can only be used to measure the load in one direction at a point. Typical disclosures of the prior art arrangements may be found in U.S. Patents [12]-[13].

Results of our colleagues described in [1] and connected with FOS based on modal power distribution (MPD) technique and fiber bragg gratings (FBG). The MPD technique is used with multimode optical fibers for real-time characterization of the textile structures. In order to monitor the state of the material, the variation of the modal power within multimode optical fibers in response to external loads is used. The light in multimode optical fibers propagates in a finite number of guided modes forming set modal patterns. In the presence of an external load applied to a multimode optical fiber, the boundary conditions at the core-cladding interface will change. Changing the boundary conditions will lead to a redistribution of the modal power. This redistribution will be detected at the fiber output. The modal power redistribution (MPR) measurements will lead to the information on the external disturbance applied to the embedded fiber. By scanning the far-field pattern at the fiber end using a CCD camera or array of photo-detectors, the measurements of the distribution and subsequent redistribution of the modal power can be continuously recorded and used as an indication of the applied loads. In the experiments with FBG, a canopy fabric was tested. The grating region of the optical Bragg grating fiber was bonded on the surface of the canopy textile material sample and located at its central part. This sample integrating the optical Bragg grating fiber was placed in the biaxial tensile tester. As has been mentioned before, this machine is equipped with electro-mechanical force and displacement measurements. Therefore, when the sample is subjected to an amount of load and displacement, it can easily be calibrated.

Developed TFL FOS on two twisted fibers with the locked ends and variable twisting step have been used for creation of intellectual knots of perspective vehicles, in particular, parachute canopies and slings from Capron and SVM. As we show in [13] it is athermal sensor because of it symmetrical structure. The sensor is obtained by twisting two fibers, as shown on fig.1

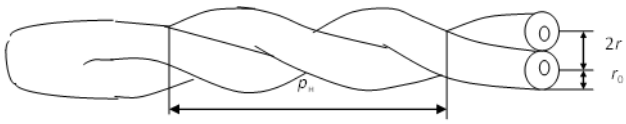

Figure1. The structure of single-mode FOS with two twisted fibers:
r_0 – radius of the fiber shell, $2r$ – the distance between the fiber core centers,
$p_н$ – permanent step of the twist

Fibers remain permanently bent along its length after twisting. When the axial mechanical impact (e.g., stretching) applies, the level of losses in the sensor becomes lower, as the curvature decreases. The relationship between optical loss and mechanical stress was obtained theoretically in the form shown below.

The optical fiber radius of curvature R after two optical fibers twisting [6] is given by

$$R = L_p / (2\pi)^2 r \quad (1)$$

and

$$L_p = \sqrt{p_Н^2 + (2\pi r)^2}\ , \quad (2)$$

where $p_н$ – the twist step, r – half the distance between the centers of two fibers, as shown in fig.1, and L_P – the length of the fiber attributable to step twist. When mechanical stress is applied uniformly over the entire length of the sensor, step twist changes and takes the value

$$p = p_н(1+\xi)\,. \quad (3)$$

On the other hand, the distance r decreases as stretching optical fibers compressed, and their main shell deformed. The value of r for a certain amount of mechanical stress ξ is determined when all of the potential energy of the system is minimal in relation to this stress. The potential energy of U per unit length is defined as

$$U = k(r - r_0)^2 + S_f \xi_f^2 + EIR^{-2} + GJ\theta^2 , \quad (4)$$

and

$$\xi_f = (L_p - L_0)/L_0 , \quad (5)$$

where k – the transverse stiffness of the main shell by a statement of proportionality between changes in r and repulsive force per unit length, S_f – the resistance of the fiber to stretch, E – Young's modulus, G – shear modulus, I – moment of inertia, J – polar inertia moment, r_0 – radius of the shell of the optical fiber at rest, ξ_f – the value of applied to the fiber forth, L_0 – the length of the fiber in the free state, and θ – the angle of twist per unit length.

Each term in the expression corresponds to the energy of deformation, responsible for the compression of the main shell, elongation of the optical fiber, its bending and twisting. In the case of our sensor by a rough assessment of it can be neglected the third and fourth term because they are two orders of magnitude smaller than the first and second.

The relationship between r and ξ is determined from the expression

$$dU/dr = 2k(r - r_0) + 4\pi S_f r(1/l_0 - 1/l_0)/l_0 = 0 . \quad (6)$$

Because $(2\pi r/p)^2 << 1$, then the length of the fiber L, attributable to step twist, is approximately equal to p_H, and (6) can be rewritten in the form

$$2k(r - r_0) + 4\pi S_f r(1/L_0 - 1/p)/L_0 = 0 . \quad (7)$$

From (7) and (3) we obtain the distance r as a function of ξ:

$$r(\xi) = r_i/(1 + A\xi), \quad (8)$$

where

$$A = \frac{\pi S_f}{kp_i^2}\frac{r_i}{r_0}\left[1 + \left(1 + 2\frac{kp_i^2}{\pi S_f}\frac{r_0 - r_i}{r_i}\right)^{1/2}\right] = \frac{S_f}{4\pi kR_i}\frac{1}{r_0}\left[1 + \left(1 + 2\frac{4\pi kR_i}{S_f}(r_0 - r_i)\right)^{1/2}\right]. \quad (9)$$

Here, we believe that the value of ξ is sufficiently small that all its values with orders higher than the second, i.e. ξ^2, and use the initial conditions, where r corresponds to the initial distance r_i, when ξ=0.

Substituting (3) and (8) in (1), we obtain the relationship between the radius of curvature R and mechanical stress ξ:

$$R(\xi) = p^2/(2\pi)^2 r = R_i(1 + A\xi)(1 + \xi)^2 , \quad (10)$$

where R_i – initial radius of curvature $R_i = p_i^2/(2\pi)^2 r_i$.

This report presents a sensor of the two twisted fibers with closed ends. Cross-elasticity k takes a value of 0.15 kg/mm^2 (main shell is made of silicon) or 38 kg/mm^2 (shell from ultraviolet cured rubber). The value of step twist lies in the range of 5 to 25 mm, to obtain normal losses allowed by the system. If the tension ξ little (~ 1%), it is possible (10) can be written

$$R(\xi) = R_i(1 + \Delta_R \xi) , \quad (11)$$

where $\Delta_R = A + 2$.

On the other hand, for single-mode optical fiber with a step change in the refractive index of bending loss α is not unit length expressed as a function of the radius of curvature:

$$\alpha(R) = \frac{\sqrt{\pi}\kappa^2 \exp\left[-2/3(\gamma^3/\beta^2)R\right]}{2\gamma^{2/3}V^2\sqrt{R}K_{n-1}(\gamma a)K_{n=1}(\gamma a)}, \quad (12)$$

where β, γ and κ – coefficients of distribution, a – radius of the core, $K_n(z)$ – n-th modified Bessel function and V – normalized frequency.

Substituting (11) in (12) we obtain the relationship between α and ξ:

$$\alpha(\xi) = \alpha_i \frac{\exp\left[-2/3(\gamma^3/\beta^2)R_i\Delta_R\xi\right]}{\sqrt{1 + \Delta_R\xi}}, \quad (13)$$

where R_i – initial radius of curvature, $\alpha_i = \alpha(R_i)$.

As seen from this expression, the losses decrease with increasing ξ. Formula is simple enough to calculate the characteristics of changes in losses in the sensor.

II. Characterization of Brillouin Scattering Using a Two-Frequency Radiation

We used amplitude measuring process to get information from sensors in [7]-[9]. We decide to change our measuring procedure from measuring of transmitted power or its Raleigh scattering in different ends of twisted fibers onto Brillouin scattering (BS). The twisted fibers with locked distal ends are more suitable for Brillouin measurements than any other [14].

The BS separation $\Delta\nu$ of the fibers must be designed taking account of the temperature-induced fluctuation in the BS, and strain dependent changes that occur in an outside environment. BS can be described as

$$\Delta\nu \geq w + \Delta S \cdot C_S + \Delta T \cdot C_T, \quad (14)$$

where w, ΔS, ΔT, C_S and C_T are the full width at half-maximum (FWHM) of the Brillouin gain spectrum, the fluctuation of strain and temperature, and their BS coefficients, respectively. The Brillouin frequency shift depends on temperature and tension, and the values are 1.08 MHz/°C and 500 MHz/1% strain at 1650 nm, respectively [15].

The use of stimulated Brillouin scattering (SBS) for distributed measurement of temperature and strain was already demonstrated 20 years ago [15]. The SBS is the most dominant nonlinear effect in single-mode silica fibers and can be described as a three-wave-interaction of two contra-propagating light waves and an acoustic wave in the fiber. Because of the strain and temperature dependence of the Brillouin frequency shift of the scattered light, sensor systems based on this effect can be used for distributed strain and temperature measurements.

The first distributed Brillouin sensing systems named Brillouin optical-fiber time-domain analysis (BOTDA) operated in a time-domain, which means that a short pulse is sent along the fiber and the backscattered light is recorded over time and contains information about the strain or temperature along the fiber. During the last two decades the performance of BOTDA sensor systems has improved steadily. The operating range of these sensors is typically in the order of 20-30 km for 2-3 m spatial resolution. Today, several devises based on this technique are commercially available.

In 1996 an alternative approach named Brillouin optical-fiber frequency-domain analysis (BOFDA) was introduced. The BOFDA operates with sinusoidal amplitude-modulated light and is based on the measurement of a baseband transfer function in frequency domain by a network analyzer (NWA). A signal processor calculates the inverse fast Fourier transform (IFFT) of the baseband transfer function. In a linear system this IFFT is a good approximation of the pulse response of the sensor and resembles the strain and temperature distribution along the fiber. The frequency-domain method offers some advantages compared to the BOTDA concept. One important aspect is the possibility of a narrow-band-width operation in the case of BOFDA. In a BOTDA system broadband measurements are necessary to record very short pulses, but in a BOFDA system the baseband transfer function is determined point-wise for each modulation frequency, so only one frequency component has to be measured by NWA with a narrow resolution bandwidth. The use of a narrow bandwidth operation (detectors) improves the signal-to-noise ratio and the dynamic range compared to those of a BOTDA sensor without increasing the measurement time. Another important advantage of a BOFDA sensor is that no fast sampling and data acquisition techniques are used. This reduces costs. Particularly, the low-cost-potential of BOFDA sensors is very attractive for industrial applications.

As already pointed out, distributed Brillouin sensors are well qualified for the distributed monitoring of mechanical deformation (strain) of extended geotechnical structures like dikes, dams and highways of lengths of some hundred meters up to some kilometers and no alternative sensor techniques for such monitoring purposes exist so far. To push the development of such sensor systems in connection with innovative monitoring solutions based on smart technical textiles, several research projects have been running in Germany and Europe [5], [15].

For conversion of the complex BS from optical to the electrical field the optical single-sideband modulation with scanning of frequency of a sideband component can be used, including the information about the frequency shift and *Q*-factor of the BS. The measurement method offered by us is based on the two-frequency probing radiation of BS without single-sideband modulation [16]-[17].

Thus, single-band double-frequency radiation with components $f_1 = f_{rf} - \Delta f$, $f_2 = f_{rf} + \Delta f$ probes the BS and the frequency $\nu_0 - f_{rf}$ tuned to the center of the gain spectrum conforms to its central frequency ν_{MB}, detuning Δf – half of its half-width $\Delta\nu_{MB}$, and the carrier frequency ν_0 – pump frequency $\nu_P = c/\lambda_P$. Double-frequency radiation, passed through the sensor under test (SUT), is received by photo detector.

Probing process is schematically shown in fig. 2.

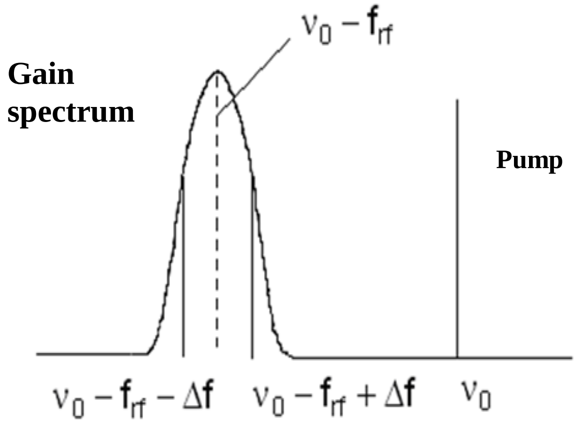

Figure 2. Probing of the gain spectrum by double-frequency signal

Radiation at the output of the optical MZM modulator is given by

$$E_{in}(t) = +A_1 \exp[\, j2\pi(\nu_0 - f_{rf} - \Delta f)t] + A_2 \exp[\, j2\pi(\nu_0 - f_{rf} + \Delta f)t] , \quad (15)$$

where $A_1 = |A_1|\exp(j\phi_1)$, $A_2 = |A_2|\exp(j\phi_2)$ – complex amplitudes of the optical carrier and the double-frequency signal. This optical signal propagates through the SUT, which has an optical transfer function $H(\nu)$ characterizing the BS spectrum; therefore, the optical field at the output of the fiber is given by

$$\begin{aligned} E_{out}(t) = A_1 |H(\nu_0 - f_{rf} - \Delta f)| \times \\ \times \exp[\, j \arg H(\nu_0 - f_{rf} - \Delta f)] \times \\ \times \exp[\, j\, 2\pi(\nu_0 - f_{rf} - \Delta f)t] + \\ + A_2 |H(\nu_0 - f_{rf} + \Delta f)| \times \\ \times \exp[\, j \arg H(\nu_0 - f_{rf} + \Delta f)] \times \\ \times \exp[\, j\, 2\pi(\nu_0 - f_{rf} + \Delta f)t]. \end{aligned} \quad (16)$$

The output current on the beat frequency of the two probing components $2\Delta f$ is proportional to

$$\begin{aligned} |i_{out}(t)| \propto |A_1||A_2||H(\nu_0 - f_{rf} - \Delta f)| \times \\ \times |H(\nu_0 - f_{rf} + \Delta f)| \times \\ \times \cos[4\pi t\Delta f + \phi_1 - \phi_2 + \\ + \arg H(\nu_0 - f_{rf} - \Delta f) - \arg H(\nu_0 - f_{rf} + \Delta f)]. \end{aligned} \quad (17)$$

Analysis of (17) shows that, from the electrical output signal of the photo detector we can get the image of the optical transfer function at the frequencies of the two probing signals.

The optical transfer function of the SUT is equivalent to concatenation of the fiber linear transfer function and the BS.

It is significant that at the moment when center frequency of a double-frequency signal $\nu_0 - f_{rf}$ gets to the resonance frequency of a BS spectrum ν_B, the envelope of the output signal is matched in phase with the envelope of the double-frequency signal at the SUT's input, and the modulation index of the output double-frequency signal's envelope is maximum and equal to 1.

The measurement fractional inaccuracy of the central frequency can be 0,1% and determined by bandwidth of the laser radiation (in our case 0,1 MHz), and also by accuracy of keeping the difference frequency $2\Delta f$. Some part of the inaccuracy can be added by the appearance of not completely suppressed upper sideband of the double-frequency radiation in the spectrum. Among methods of its decreasing we can offer the usage of a chirp fiber Bragg grating, tuned on the suppression in the bandwidth of possible position change at scanning.

We think that such solution is more effective, than offered in [9], as by efficiency of suppression, and also by ability to control the distortions, caused by chromatic dispersion.

Defining $\nu_0 - f_{rf} = \nu_{MB}$, we can find *Q*-factor of the BS. It is necessary because FOS TFL sensors in system have different initial step twist and different initial ν_{MB} for each with different *Q*-factors.

For this situation we offer the kind of variation of frequency method [17], [18], which based on the dependence

$$Q_{1,2} = \frac{\nu_0 - f_{rf}}{f_1 - f_2}\sqrt{\frac{i_{\text{out}(\nu_0 - f_{rf})}}{i_{\text{out}1,2}} - 1}\,, \qquad (18)$$

where $i_{\text{out}(\nu_0 - f_{rf})}$ and $i_{\text{out}1,2}$ – amplitudes at center frequency and at components of the double-frequency signal at the output of the photo detector when center frequency of the probing components at frequencies $f_1 = f_{rf} - \Delta f$ and $f_2 = f_{rf} + \Delta f$ is tuned on the center of gain spectrum. The value of $i_{\text{out}1,2}$ is determined by output signal of the photodetector, and the value $i_{\text{out}(\nu_0 - f_{rf})}$ is unknown.

If we change the Δf by a certain value $\Delta f'$, not changing the tuning on the center of gain spectrum, then we will get the new value of frequencies $f_3 = f_{rf} - \Delta f - \Delta f'$ and $f_4 = f_{rf} + \Delta f + \Delta f'$. For frequencies f_3 and f_4 we can rewrite the (18) as

$$Q_{3,4} = \frac{\nu_0 - f_{rf}}{f_3 - f_4}\sqrt{\frac{i_{\nu_0 - f_{rf}}}{i_{3,4}} - 1}\,. \qquad (19)$$

Since $Q_{1,2} = Q_{3,4}$, from the combined solution of the equations (18) and (19) we get $i_{\text{out}(\nu_0 - f_{rf})}$ and then, inserting this value in one of the equations we find the *Q*-factor of the MBGS and half-width $\Delta\nu_{MB}$.

The advantage of the offered method is that in the measuring process the information signal is influenced by noises only of a bandwidth of the gain spectrum (20-100 MHz), not noises of all bandwidth from BS to the pump (10-20 GHz). Therefore, signal/noise ratio of the measurements in this case is 10^2 - 10^3 greater than similar ratio in previously offered methods.

III. System Integration Questions

During the filling, the area of parachute canopy and its factor of resistance change both. The knowledge of laws of change above the listed parameters would allow simplifying essentially the decision of problems connected with parachute filling. At drawing up of the equations of movement of system "cargo-parachute" assume, that at decrease in system an axis of the parachute which is passing through sling thimble and top of a canopy, a tangent to a trajectory of cargo movement, and the parachute is flowed round by a stream which speed on infinity is equal to speed of movement of cargo and coincides in a direction with a parachute axis. The weight of cargo is much more then parachute weight. Neglect the indignations brought in a stream by presence of cargo. Neglect also the centrifugal forces operating on a parachute at movement of system on a curvilinear trajectory. A material of a canopy and a sling we will consider not extensible, and air – incompressible. On fig. 3 [16] experimental and theoretical dependences of parachute system (PS) inflation speed change on time are given.

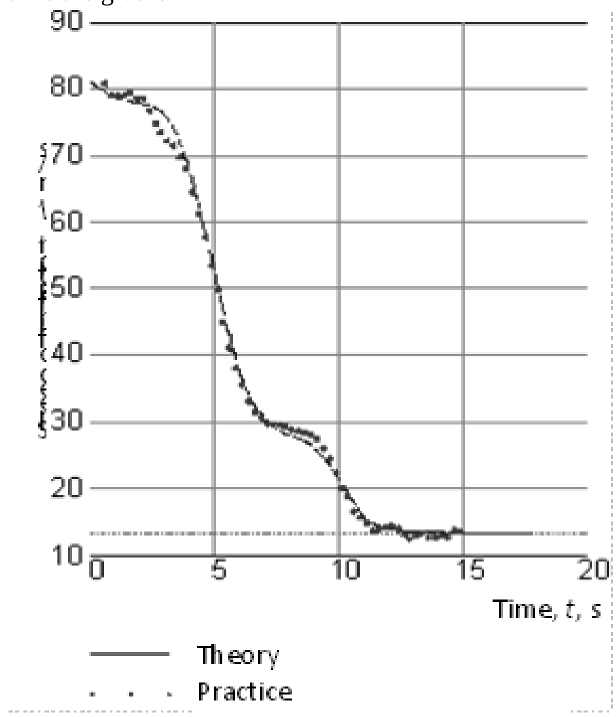

Figure 3. Speed of inflation vs time

In summary it is necessary to notice, that the found dependence of change of the effective area of resistance of a parachute on time of its filling will allow simplifying essentially the decision of problems of dynamics of movement of system "cargo-parachute", receiving thus authentic results. The force on the payload, with the exception of the snatch impulse is small during the initial stages of inflation. As the inflation continues, the opening force exerted by the continually filling canopy increases to a peak, then decreases over time.

The integration of a number of sensors from each type forms the sensory components of the system of this invention. The orientation of these fiber sensors is designed to match with the line and direction of forces in both the canopy fabric and the suspension lines. However, other orientation directions may be considered. In this way, the stress/strain field can be detected and continuously measured everywhere in the textile structure. As a result, the stress/ strain field in the structure can be monitored in real-time. Dynamic forces can be continuously measured in-situ in real-time.

Data acquisition, signal processing and RF modulation will be performed to enhance the signal to noise ratio and signal preparation for wireless transmission. The signal can be recorded or read-out before modulation. The wireless transmission is developed for real-time measurements of dynamic forces during airdrop. A wireless RF transmitter is used to transmit the information to the ground receiver. The received signal will be demodulated and signal processing will be performed to enhance the output signal before read-out or recording**.** Samples of the sensory system components were integrated into a parachute canopy fabrics and suspension lines for testing and proving the invention concept. Successful results were obtained from static and dynamic testing.

Experimental setup for measurements is shown on fig. 4

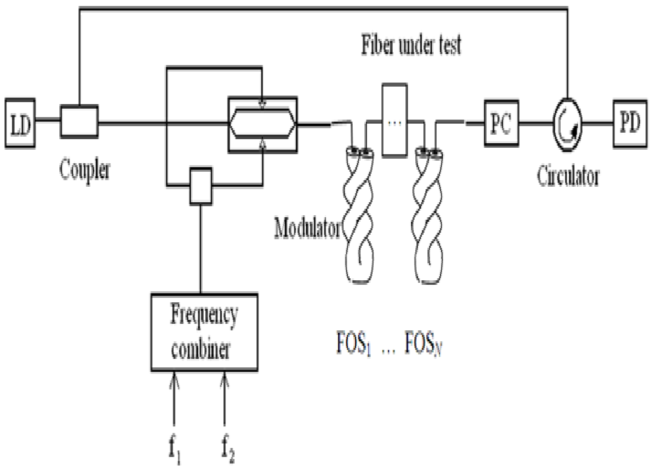

Figure 4. Experimental setup: LD – laser diode; PC – polarization controller; PD– photodetector

The optical signal from a 1550-nm laser diode with a bandwidth about 100 kHz is divided into two paths by a fiber-optic coupler. In the first path signal is modulated by an optical MZM modulator in zero point. Signal from the frequency combiner is applied to one of the modulator's inputs. The MZM modulator is based on a dual-drive Mach-Zehnder modulator design [19]. The modulated signal is applied to the Fiber under test (FUT), two twisted fibers with locked ends, where the optical radiation passed through the second path counter propagates. That un-modulated radiation is the BS pump radiation in FUT.

To show possibilities of application of the given type of FOS in practice, the mechanical pressure put to the gauge which has been twisted in various sling types of cargo parachute systems has been measured. On fig. 5, *a-b* the stand for rupture tests with slings of LTK-type and SKP-type according to twisted in their structure TFL FOS (fig. 1) is shown.

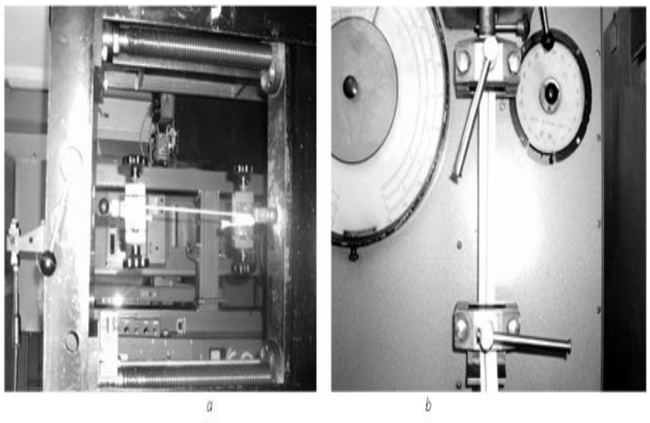

Figure 5. Stand for rupture sling tests

For experiment have been made it is a little exemplary FOS with various twisting step, the various efforts of a tension intended for measurement. In each gauge were used single mode optical fibers with step change of refraction index.

IV. Measuring Results

Measurements of losses have been spent with use of the laser diode with λ=1,5 microns and a measuring instrument of capacity of optical radiation. Initial losses were measured by a method of an increment of attenuation at influence of external factors. The given method is usually applied in scientific researches by manufacture fiber, FOS or in case of occurrence of failures at installation or system operation. Mechanical influence was put in regular intervals by means of the stand for tests parachute a sling on rupture.

Measurements were spent in the following sequence:

1. Output optical radiation of FOS was registered at the maximum external load.
2. Discretely, with necessary step of change, external load was reduced and exit optical radiation of FOS was fixed.
3. On each step of change FOS was maintained under the influence of the external factor during time necessary for an establishment of rest mode, then change of exit optical radiation was defined.
4. External influence was interrupted and values of exit optical radiation directly after its influence and also through set time were defined.

The output of these optical sensors will be collected in a central unit and transferred to electronic signals. The enclosed mechanical pressure also was estimated under indications of the bench indicator which was used for comparison. Comparison results between the mechanical pressure measured by the gauge and the mechanical pressure measured by the stand are resulted in [8]. Sensitivity of the gauge and linearity of its characteristics are closely connected with structure and parameters of fiber. Sensitivity is mainly defined by cross-section elasticity of fiber cladding. Linearity of characteristics also depends on cross-section elasticity of fiber cladding, radius of core and a difference of their refraction index.

Measurements results with BS acquisition are shown on fig. 6-7. We show difference between Rayleigh and Brillouin components (fig. 6) and Brillouin components from sensors with different step of twisting (fig. 7). Difference in sensor losses caused by changing in twisting step under load was compensated and measured in input power values P_{IN} for BS analysis [20].

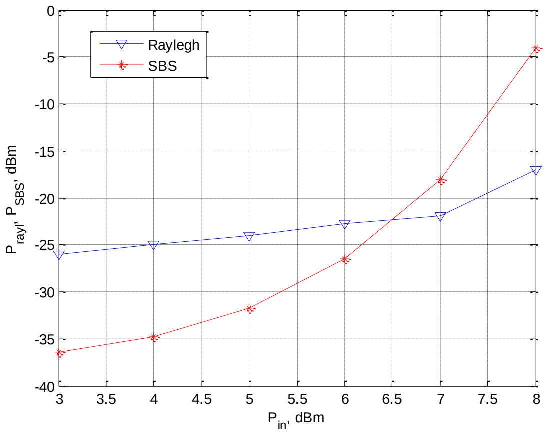

Figure 6. Rayleigh and Brillouin components vs P_{IN}

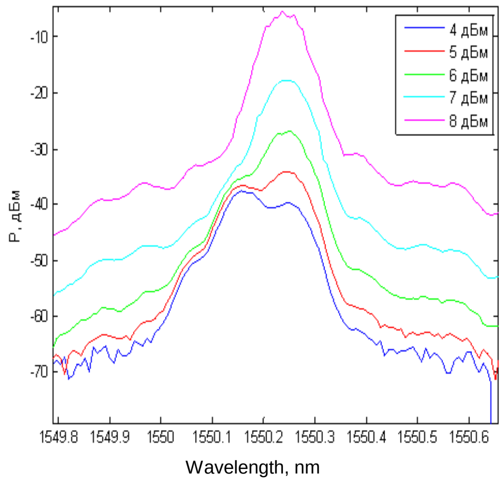

Figure 7. BS components from sensors with different step of twisting caused by change of load (losses were compensated and measured in input power values P_{IN} 4-8 dBm (дБм))

V. Conclusion

As can be seen, the purpose of this paper, to develop the methodology required for stress/strain measurements of a parachute canopy and slings under deployment and inflation dynamics in-situ and in real-time, has been accomplished. Discrete point sensing as well as distributed sensing methods were used. Sensor embeddment into parachute canopy fabrics as well as in slings were investigated, ultimately culminating in the integration of the fiber sensors into textile fabrics and fiber architecture. New type of fiber optic sensor on the basis of two twisted fibers with the locked ends and variable twisting step offered by us for this purpose. It does not demand lamination, indifferent to a thermal (temperature) field, provides a wide dynamic range of measurement as pressure and tension of parachute elements.

Developed fiber optic sensors on two twisted fibers with the locked ends and variable twisting step have been used for creation of intellectual knots of perspective vehicles, in particular, parachute canopies and slings. We changed our measuring procedure from measuring of transmitted power or its Rayleigh scattering in different ends of twisted fibers onto Brillouin scattering characterization. For this situation we offered the kind of method of frequency variation to get the information about the frequency shift and *Q*-factor of the Brillouin scattering in each sensor.

Prospects for the application of the sensor in the fiber-optic data-measuring systems for monitoring the parachute emphasizes are its indifference to the temperature field, provision of wide dynamic range of measuring parameters such as pressure and stress on the surface of the parachute. Multiplexing of sensors provides information on the structure and deformation in a single point of canopy or slings.

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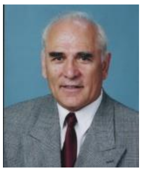

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