Small-sized multichannel optical rotary joint for optical sensors
based on rotating objects

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ABSTRACT
We advance an original construction of a small-sized optical rotary joint with fiber optic ring converters made in a single monolithic fiber optic unit. It is intended for transmission of optical signals from optical sensors based on rotating objects (rate of rotation of up to several thousands rpm). We developed a mathematical model and performed computer simulation of the construction, depending on the geometry and optical properties of its elements, with allowance made for radial and end beats of the rotary joint rotor section. On the basis of the calculations made, we fabricated a prototype of rotary joint (for five optical transmission channels) for telemetry of equipment with rate of rotation of up to 1000 rpm and studied its characteristics experimentally. This model is adaptable to manufacturing and comparatively low-cost.

Keywords: fiber optics, fiber optic rotary joint (FORJ), optical rotary connector

1. INTRODUCTION
Up to now, various contact, capacitance or induction rotary current collectors have been used in different areas of science and engineering to transmit signals from rotary objects to stationary ones. The contact current collectors are applied most often because they are the simplest ones. However, despite the fact that rotary contact systems (RCS) are relatively simple, their further application in novel devices becomes problematic, or even impossible in principle.
One of the reasons is as follows. Due to narrow pass band of electric transmission channels, the modern all-round looking radars require RCS for several hundreds of such channels to transmit packages of information signals from the electronic devices located on the complex column (rotated by the antenna) to the stationary devices. At that the RCS are heavy (300−400 kg) and bulky (over 1.5 m in length). Contact slip rings for several thousands (rather than hundreds) of electrical channels will be required for usage in new radar complexes with phased arrays which are currently constructed. So, this class of slip rings, being supersaturated with numerous electrical channels, will become all the more complicated.
Such factors as high noise level (resulting from friction and instability of contact resistance) and presence of parasitic thermo-emf in channels for data transmission, along with crosstalk between electrical channels and high sensitivity of contact slip rings to the electromagnetic barrier, also cause serious problems when using the equipment where strong electromagnetic fields are present. These problems generate a need to preamplify weak electrical signals in a lead-in of a slip ring and to install special electromagnetic screens between channels. Besides, both sparking and a possibility of self-ignition of contacts lead to unsafe conditions for use of slip rings in equipment where explosion hazard exists.
Due to recent advances in optoelectronics, one can find another solution to the above problem. To transmit telemetric information, signals and control commands from rotary objects to stationary ones and vice versa, a principally novel class of devices, namely, optical rotary joints, are being developed at present. The electric signals are converted into optical ones. The latter are compressed and transmitted from rotary objects to stationary ones using multichannel fiber-optic rotary joints (FORJs).
Being insensitive to electromagnetic interferences, FORJ has a number of advantages over its electric analogs. Among them are the following ones: (i) Its passband is broader (by a factor of several hundreds) than that of an electric channel; (ii) there are no reactances in optical communication channels; (iii) information can be transmitted concurrently in two opposite directions at different wavelengths; (iv) small masses and sizes (to illustrate, the mass of a 8-channel FORJ which can functionally replace RCS for 800 electric channels does not exceed 2 kg); (v) long service time, no need to fulfill regulative works during long-term (years) service, they all meet just the space technique requirement.
The development of FORJs has received much attention in such developed countries as USA, Canada, Japan, Germany, and United Kingdom. In USA, the problem of development of FORJs for instrumentation engineering is in the foreground. However, despite the considerable attention to the problem of FORJ development, the essential success in the device quality has been achieved only for single- and dual-channel FORJs made by leading companies, such as Focal Technologies Inc. (Canada), Oil Electronic Company (Japan), Schleifring und Apparatebau GmbH (Germany), etc.
Some significant results in the development and introduction into practice of multipass FORJs for four optical fibers (with a possibility to enlarge the number of channels up to ten) have been made by the Canadian company Focal Technologies Inc. The models have appropriate optical characteristics. However, the weight and sizes of the multipass FORJs are far from perfect. As an example, the weight of a FORJ for eight fibers amounts to 10 kg, while its length exceeds 0.5 m. The size dependence of the number of physical channels is also the drawback of the multipass FORJ. When a demand arises to replace one FORJ for another (with bigger number of fibers), then increase of space for the new FORJ installation is required. Obviously, it is not always realizable.

2. METHODOLOGY

In one-channel FORJs, optical connection between the transmission and reception components of the optical communication channel can be rather easily realized through optical transmitter location in line with the optical receiver rotation axis [1]. Organization of optical transmission channels in multichannel FORJs makes a more complicated problem. Contrary to one-channel FORJs, the multichannel FORJs involve an additional optical connection unit. It is a focusing [2], mirror-deflecting [3], light-guide [4-6, 22] or compensating for light beam rotation optical system [7-17]. The optical characteristics of multichannel FORJ depend, to a large extent, on the optical connection unit placed between the transmission and reception components of multichannel FORJ.

Our scientific analysis of the technical solutions for multichannel FORJs (known from the scientific-technical and patent sources) showed that the biggest number of optical transmission channels can be obtained in the compensatory-type devices. They enable one to realize facilities with tens of optical channels having high optical parameters. At the same time, the compensatory-type FORJs have rather big mass and dimensions. Besides, they are intended for low rates of rotation because use a kinematic transmission mechanism. That is why we advanced a novel technique for compensation of light beams motion [18, 19] that enables one to make direct-drive multichannel compensatory-type FORJs. However, up to now the devices based on the above principle have not been realized. The reason is lack of efficient manufacturing technology for compensators.

In this work we chose fabrication of light-guide FORJs on the basis of fiber-optic ring converters (FORCs). They can be used for production of small-sized FORJs (with a small number of optical channels) that may be applied in rotating objects (rate of rotation of up to several thousands rpm), say, to monitor helicopter propeller blades in the course of flight.

2.1 The multichannel FORJs with light-guide principle of operation.

Generally speaking, optical model of arrangement of emitter and receiver elements in multichannel FORJs may be arbitrary. In practice, however, reasoning from construction manufacturability, the following two main arrangements of emitters and receivers relative to the axis of rotation are preferred: coaxial [4,5,21] and radial [22].

In the coaxial construction, the emitter and receiver elements are arranged in such a way as to provide beam propagation from the transmitter section of the optical channel to the receiver section in parallel to the rotation axis. In the radial construction, radiation propagates between the transmitter and receiver sections perpendicularly to the rotation axis.

The coaxial and radial constructions operate on the principle of formation of a light flux source at the transmitter part of the FORJ optical channel. This source is made as a ring whose axis coincides with that of rotation. The light flux is transmitted to the receiver part of the FORJ optical channel along either the axis or the radius. The optical pupil of the FORJ receiver part is ring-like as a rule. In some constructions (given in the patent descriptions) point receivers are used. This makes construction simpler, but, on the other hand, leads to big undesirable optical losses.

To form ring light source and optical receiver, FORCs of the light flux form are used. These FORCs are made either as a multifiber bunch of light-guides (with some ends uniformly distributed over the ring and other joined in a bunch of circular cross-section), or as single light-guides twisted in rings that radiate (and, correspondingly, receive) light through the side surface at the ring section of single light-guides.

2.1.1 The light-guide FORJs with coaxial FORCs of light beam form.

At the moment the following FORJ constructions with FORCs are known:

- that with one-row distribution of light-guides over the FORC ring [5,21];
- that with multi-row distribution of light guides over the FORC ring, that use in multichannel FORJ constructions corresponding numbers of discrete FORCs joined in a single ring fiber optic collector with cylindrical bushes (which serve as both fastening and optical isolators between the neighboring channels, see Fig.1) [4];
• that with multi-row distribution of light guides over the FORC ring, but with ring optical channels integrated inside a monolithic fiber optic unit (advanced and designed by us, see Fig.2).

The constructions with one-row distribution of light-guides over the FORC ring suffer from an essential drawback: amplitude modulation factor for optical signal in them is 20% and even more. In constructions with multi-row distribution of light-guides over the FORC ring, the amplitude modulation factor is reduced down to 1% due to broad light-guide rings. In this case, however, the FORJ carrying capacity (number of optical channels) decreases, while the total optical losses grow. These losses are due to mismatch between the diameters of receiving fiber optic cable (0.05–0.2 mm) and multifiber light-guide bunch of FORC (2–5 mm).

The reason is that, as the number of physical channels grows, the diameters of peripheral FORC ring channels also grow. Along with this, the areas occupied with the light-guide ends in these channels (the ring channel width being constant) increase. And the diameters of ring ends of the FORC light-guide bunches (which serve as an optical interface for radiation input-output from FORJ) increase correspondingly.

It is easy to verify that, when all the ring channels of FORC are of the same width \( S \), the bunch diameter \( d_n \) for the \( n \)-th optical channel of FORJ is proportional to the ring channel width \( S \) and the square root of \( (n - 1) \):

\[
d_n = 2S\sqrt{2(n-1)} ,
\]

where \( n \) numbers the ring light-guide channel (counted from the central one). According to Eq. (1), for five-channel FORJ with ring channel width of 0.4 mm and the same width of the walls of cylindrical bushes, the diameter \( d_n \) of FORC ring end in the fifth channel is 3.3 mm. If no optical matching units are used, then the input-output optical losses between FORC and a fiber cable are 24 (36.4) dB for a cable whose core diameter is 0.2 (0.05) mm.

The severity of the problem of radiation output from FORJ is aggravated by the fact that a light beam at the FORC output never is either parallel or homo-centric, even if at the FORC input an ideal radiator is used that is emitting strictly parallel (or strictly homo-centric) beam. Misalignment of light beam at the FORC output is due to beam symmetrization in light-guides and energy redistribution (from lower-order modes to higher-order ones). Within the context of this work, we investigated the indicatrix of light scattering at the output of a bended light-guide bunch of O-TX-1-type. Our aim was to obtain some data required for calculation of FORJ construction. It was found that, when the light-guide end is exposed to a parallel bunch normal to it, then most beams at the bunch output are concentrated not along the axis (as
would be expected in the case of no energy redistribution between modes) but within a light cone whose apex angle is about 10°. It is known from the laws of geometrical optics that “compression” of light beams to smaller diameter results in proportional increase of the beam aperture. So the above fact means that there is no reason to “compress” light beam at the FORJ output more than down to a certain diameter (for which the beam aperture at the focusing facility output becomes over that of the fiber cable). Further decrease of the light beam diameter at the FORC output does not provide reduction of optical losses at cable input. The reason lies in proportional increase of the optical loss component stemming from mismatch of light beam apertures and that of cable.

Therefore, from the point of view of optical losses, the width of the FORC ring channel is one of the crucial parameters of FORJ construction. Bearing in mind this factor, as well as manufacturability considerations and search for maximal number of physical channels, one can conclude that of most practical interest among the light-guide-type constructions with ring converters is that with FORCs integrated inside a single fiber optic unit (designed by us). Integration of ring channels in a single unit makes it possible to substantially improve the accuracy of ring channel fabrication. As a result, the ring channel width can be reduced down to several tens of microns. Besides, such technical solution makes it possible to arrange ring channels in close neighborhood to one another. This means that multichannel FORC can be made without centering cylindrical bushes. This factor alone enables one to double the number of optical channels (as compared to the known analogs), to say the least, while making both optical losses and amplitude modulation factor for signal several times lower.

2.1.2 The light-guide FORJs with radial FORCs of light beam form.

A FORJ construction of radial type with FORCs of the light beam form may be exemplified by that described in the UK patent [18]. It is rather similar to the construction presented in Fig. 1. The distinction is that the light-guide ends located on circles are oriented at a normal to the axis rather than along it; they form radial (rather than axial) ring channels (fig. 2). Obviously, in this case the drawbacks which took place in axial FORJs remain. Besides, the radial FORJs are more complicated from the technological point of view, since conical light-guides are required to provide very close packing of them on a circle. Otherwise the optical losses and modulation percentage for optical signals will be higher than in the axial constructions.

The highest possible number of optical channels in a FORJ of this type is restricted by the number of interfacial fiber optic bundles from the radial FORCs that go through the ring hole of FORC. The limiting number of optical channels is a ratio between the areas of the ring hole of FORC and fiber optic bundle of FORC:

\[ N_{\text{max}} = \frac{1 + r}{2h}, \]  

where \( r \) is the radius of the ring hole of FORC and \( h \) is the ring height.

Taking into account that the light-guides are not placed very close in the FORC hole, one concludes that the factual number of optical channels is below the above value. In practice the factor of FORC hole filling with light-guides (at manual packing) is 0.8. So the maximal number of channels is approximately

\[ N_{\text{max}} \approx \frac{r}{3.6 \cdot h}. \]  

It is easy to show that in this case the diameters of the ends of ring bundles in FORJ are related to the number of channels in the following way:

\[ d = 5.36 \cdot h \sqrt{N}. \]  

According to the above expression, in a ten-channel FORJ with FORC rings height of 0.2 mm the diameters of circular ends of converters will be no less than 3.3 mm. Obviously, such big bundle diameter is not acceptable, because it is practically impossible to lead radiation out of a fiber optic bundle 3.6 mm in diameter and put in into a fiber optic cable (whose typical diameter is 0.05–0.2 mm) without considerable optical losses. Therefore one has to reduce either the number of optical channels or the ring height. To illustrate, at ring height \( h = 0.06 \) mm the bundle diameter will be 1 mm. However, production of radial FORCs with light-guide ring height of 0.06 mm makes a complicated technological problem. Besides, in this case amplitude distortions of signals will occur, and requirements for accuracy of optical and mechanical sections production will become too severe. So the only sound decision is reduction of the number of optical channels in the device.

When comparing Eqs. (1) and (4), one can see easily that, at the same numbers of optical channels in the axial and radial constructions and the same values of the ring channel width in the axial construction and the ring channel height in the radial construction, the diameters of the fiber optic bundles of converters differ by a factor of 1.5–2. At that the optical losses in axial FORJs are less (by a factor of 2–4) than in the radial ones.
Thus the FORJ construction with FORCs of radial type ranks below that of axial type in both manufacturability and optical characteristics (optical losses and modulation distortions). At the same time, the radial constructions (at small number of optical channels) are protected better against the crosstalk signals between the optical channels. In such constructions these crosstalk signals can be removed easily using additional optical screens between the channels, while in the axial constructions it is difficult to realize such procedure.

3. COMPUTER SIMULATION AND OPTIMIZATION OF THE GEOMETRY OF FORC RING CHANNELS

The drawback of the advanced construction is presence of a slight cross interference between the neighboring channels due to interface scattering of some portion of light beams. If, however, these interfaces are made polished, then the contribution from the above does not exceed 0.16%. Incorrect choice of geometry of transmitter and receiver FORC channels may result in a considerable cross interference between the neighboring optical channels due to direct penetration of light beams into the neighboring channels (see Fig.1). To prevent this, (i) diameter of the receiver channel in the central channel should be over that of the transmitter channel, and (ii) outer diameters of the receiver channels in the ring channels should be over (and inside diameters below) the corresponding diameters of the transmitter ring channels by

$$\Delta D \geq 2d \cdot \tan \alpha \quad (5)$$

Here \(d\) is the gap between the FORC ends; \(\alpha\) is the maximal angle of beam departure from the FORC end surface relative to the normal to this surface.

To exclude the cross interference component stemming from inaccuracy of geometry of FORC channels, as well as from FORJ mechanism faults (radial and end beating of the transmitter ring channels relative to the receiver ones), the difference of the diameters of receiver and transmitter channels should be somewhat over the value required by the inequality (5). One can show that in this case the following relations are to be fulfilled:

$$D_{\text{2out}} \geq D_{\text{1out}} + \Delta_{\text{out}} + 2\delta_{\text{rad}} + 2d \cdot \tan(\alpha) \cdot \cos(\beta_1) + 2d \cdot \sin(\beta_1) \cdot \tan(\alpha) + \Delta_{\text{2out}} + 2\delta_{\text{rec}} \quad (6)$$

$$D_{\text{2in}} \leq D_{\text{1in}} - \Delta_{\text{in}} - 2\delta_{\text{rad}} - 2d \cdot \tan(\alpha) \cdot \cos(\beta_1) - 2d \cdot \sin(\beta_1) - \Delta_{\text{2in}} - 2\delta_{\text{rec}} \quad (7)$$

Here \(D_{\text{1in}}\) (\(D_{\text{1out}}\)) are the inside (outer) diameters of the receiver ring channel; \(D_{\text{2in}}\) (\(D_{\text{2out}}\)) are the inside (outer) diameters of the transmitter ring channel; \(\alpha\) is the aperture angle for radiation at the transmitter ring channel output; \(\beta_1\) (\(\beta_2\)) is the angle between the plane of transmitter (receiver) FOC end surface and the plane normal to the rotation axis; \(\Delta_{\text{out}}\) (\(\Delta_{\text{2out}}\)) is the tolerance for FORC transmitter (receiver) ring channel outer diameter drift; \(\Delta_{\text{in}}\) (\(\Delta_{\text{2in}}\)) is the tolerance for FORC (transmitter) receiver ring channel inside diameter drift; \(\delta_{\text{out}}\) (\(\delta_{\text{in}}\)) is the radial displacement of transmitter ( receiver) FORC channel center relative to the common rotation axis. (These displacements are due to departure of ring channels from concentricity, displacements of their centers relative to the rotation axis, and radial beating of bearings used for FORCs mounting in the FORJ case.)

Eqs. (6) and (7) were obtained for the case when the FORC end surfaces deviate from each other in the opposite directions (Fig. 3). Just in this case the effect of the end beats on the size of the inside and outside diameters of the receiver channel is maximal, provided that \(\alpha \geq \beta_1\) and \(\alpha \geq \beta_2\). If \(\alpha \leq \beta_1\) and \(\beta_1 = \beta_2\), then this effect for the inside diameters of ring channels will be maximal when the end surfaces of both FORCs deviate from the horizontal plane in the same direction. The equation derived for this case differs from Eq. (6). In practice, however, the first case takes place in actual constructions. It should be noted that, when considering revolution of the rotary section of FORJ, the sign of angles ("plus" or "minus") is of no importance; only the magnitude of end beats is significant. That is why the absolute values of angles \(\beta_1\) and \(\beta_2\) are present in Eqs. (6) and (7).

Shown in Fig. 4 is a set of dependences of outer and inside diameters of the receiver FORC ring channels on the gap \(d\) between the FORC end surfaces. These dependences were calculated from Eqs. (6) and (7).

The width of ring channels is one of the crucial geometrical parameters affecting the FORJ optical characteristics. That is why it is of importance to determine the degree of ring channel width dependence on other FORJ construction...
parameters. First, this would determine (at preset FORJ characteristics) the admissible departures of the actual construction elements from the calculated ones, bring them to the same tolerance range and thus optimize the construction for manufacturability from the accuracy figure. Second, this would enable one to determine the expected FORJ optical characteristics at a preset number of optical channels.

To this end, we have developed the technique for calculation of FORC channel geometry. This technique is based on the graphic-analytical analysis of the following dependences:

\[
\Delta D_2 = D_{2\text{in}} - D_{2\text{out}} = f(\alpha)\beta_1 d D_{2\text{out}} \\
\Delta D_1 = D_{1\text{in}} - D_{1\text{out}} = f(\alpha)\beta_2 d D_{1\text{out}}.
\]

Eqs. (8) and (9) were derived from (6) and (7) on the understanding that \(\beta = \beta_1 = \beta_2\), and both tolerances for ring channel size (\(\Delta_{1\text{out}}\), \(\Delta_{2\text{out}}\), \(\Delta_{1\text{in}}\), and \(\Delta_{2\text{in}}\)) drifts and radial displacements of the ring channel centers from the rotation axis (\(\delta_{\text{rec}}\) and \(\delta_{\text{rad}}\)) are zero. We propose to make allowance for their effect on the receiver ring channel diameters after determination of \(\Delta D_{\text{out}}\) and \(\Delta D_{\text{in}}\) from the above expressions, by summing them algebraically with the result obtained.

A computer program in MATLAB system has been developed for computer simulation of construction. Shown in Figs. 5 and 6 are the sets of characteristics [calculated from Eqs. (8) and (9)] for construction parameters taken as indicative. One can easily see that the most impact on \(\Delta D\) value is made by (i) the aperture angle \(\alpha\) at which light beams depart the FORC end surface, and (ii) the gap \(d\) between the FORC end surfaces. At the same time the \(\Delta D\) dependence on the end beating angles is much weaker. Therefore, when producing high-quality multichannel FORJ with FORCs, one should use light-guides with small energy redistribution between the lower-order and higher-order modes, as well as precision mechanics should be used to provide width of the gap between the FOC end surfaces no more than 20–40 \(\mu\)m.
4. EXPERIMENTAL RESULTS OF FORJ PROTOTYPE INVESTIGATION AND DISCUSSION

Using the results of our calculations, we fabricated an operating FORJ prototype for five optical transmission channels (of which three transmit in one direction and two in the opposite direction). The FORC receiver (transmitter) ring channel width is 200 (100) microns. The prototype mass is 350 g, and its length (diameter) is no more than 10 cm (5 cm).

The bearings used in the prototype provide its operation at low temperatures and in space vacuum. No optical matching facilities were used at the optical inputs and outputs of the FORJ prototype, so we studied its optical characteristics (optical losses, crosstalk between channels and the amplitude modulation factor) as a part of electrical connection lines, with pin photodiodes as light receivers.

The following optical characteristics of the prototype were obtained: the amplitude modulation factor for each channel no more than 0.5%; the optical losses in the central channel 4.6 dB; those in the ring channel no more than 6.2 dB. The crosstalk between channels did not exceed −30 dB. When short (15 ns) rectangular optical pulses passed through the prototype and were registered with a stroboscopic oscillograph (time resolution of 1 ns), no pulse front distortions have been detected.

A low crosstalk value in the prototype was achieved due to a small (about 15 microns) gap between the FORC interfacial ends and high quality of polishing of FORC ends, as well as precise mechanics and considerable difference $\Delta D$ between the widths of the receiver and transmitter ring channels ($\Delta D = 100$ microns). At that light (that was scattered at the end surface of the FORC receiver channel) experienced at least three reflections from the polished FORC end surfaces before coming to the next receiver channel, and so its intensity could not exceed $(0.4)^3\% = 0.064\%$ the initial value.

An increased loss values and their distinction for the central and ring channels result from loose packing of light-guides at the input FORC ring ends. Looser packing of light-guides in ring channels as compared to that in the central one is due to the applied FORC manufacturing technology.

5. CONCLUSION

1. Our theoretical studies of the design principles for multichannel optical rotary joints showed that the compensatory joints are most promising from the viewpoint of obtaining considerable number of transmission channels. Their carrying capacity is tens of optical channels, with complete optical isolation between channels. The drawback of such constructions is presence of a geared mechanism in optical rotary joint; it reduces rate of rotation of the FORJ rotating section down to several hundredths rpm.
2. For the objects whose rate of rotation is up to several thousands rpm, the promising constructions are those made on the basis of FORCs integrated in a single fiber optic unit. In practice the number of optical channels in such constructions is no more than 6-7. However, they are small-sized and highly reliable, as well as more manufacturable and of lower cost.

3. Our experimental studies of the FORJ prototype with fiber optic ring collectors demonstrated good optical characteristics and possibility to use it for transmission of both analog and digital information. The information carrying capacity of the FORJ prototype is over several hundreds Mb/s; its carrying capacity is 7–8 channels (the optimal number of channels is 3–5). Optical losses in this prototype (with allowance made for the FORJ input-output losses) depend on the number of physical channels and are, on the average, 6 dB per channel. The signal amplitude modulation factor is no more than 1 dB, while the crosstalk value does not exceed –30 dB.

The results obtained make it possible to perform experimental design of the operating prototypes of multichannel optical rotary joints intended for transmission of analog and digital measurement information from rotating objects to stationary ones using optoelectronic techniques.

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