AN INSTRUMENT FOR CHARACTERIZING STIFFNESS OF PROTRUDING OPTICAL FIBERS

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Abstract

This paper presents the design of an instrument intended for measuring the stiffness of optical fibers terminated in MT ferrules. This paper describes the concept, detailed design of the instrument, details of major component analysis, and operation of the instrument. The instrument described in this paper will allow the operator to measure the stiffness of each optical fiber in the array of fibers in a ferrule.

Keywords: optical fiber, MT ferrule, fiber stiffness, protrusion length, flexure

Introduction

Optical fiber connectors consist of an array of optical fibers terminated within a ferrule that precisely aligns the fibers. Example types of ferrules include single-fiber ceramic, multi-fiber polymer, and multi-fiber silicon vee-grooves. Fig 1 illustrates a conventional MT ferrule and ribbon cable. Twelve single-mode optical fibers are terminated so that their ends protrude from the face of the ferrule (~1 µm). The termination process includes stripping away the cable cladding, bonding the fibers within the ferrule, and polishing the ferrule face. To minimize the signal loss within a connection, two ferrules are mated so that protruding fibers contact.

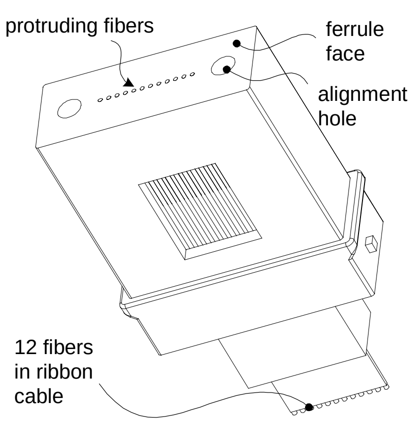

Fig 1: MT Ferrule and Terminated Fiber Array

Ensuring that mechanical contact exists between each fiber in the ferrule is crucial to effective fiber connections. Achieving mechanical contact depends upon the stiffness and amount of protrusion associated with each fiber. Fig 2 illustrates a set of hypothetical force-displacement relations for fibers terminated in a single ferrule. Each fiber has a unique curve resulting from variability in the adhesive joint, material properties, and compliance of the ferrule.

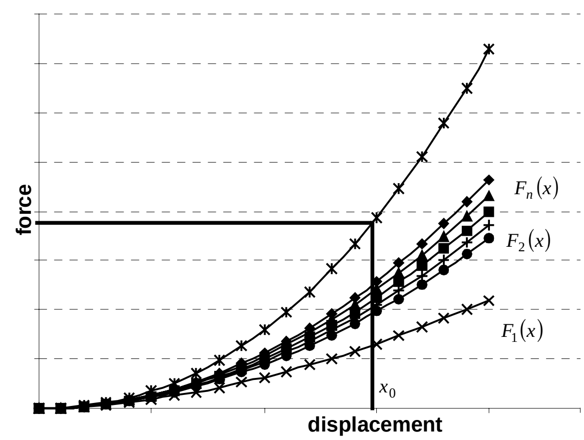

Fig 2: Force-Displacement Curves for Fibers Terminated in a Ferrule

Variability in the force-displacement curves requires that a sufficient preload force be established between two mating ferrules to ensure mechanical contact. The total force, F_{tot}, for compressing the

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fibers a distance, x_o, when mating a ferrule is then approximated with Eq (1).

$$F_{tot} \propto \sum_{i=1}^{n} F_i(x_0) \qquad (1)$$

The amount of force for mechanical contact depends upon a wide range of material and process variables that are difficult to predict and should therefore be characterized experimentally. This paper describes a new instrument, illustrated in Fig 3, for measuring the force-displacement relations fibers terminated in ferrules. The stiffness of each fiber, *k(x)*, can be determined by differentiating the force, *F(x)*, as shown in Eq (2). These relations can subsequently be used to assess the quality of the termination process.

$$k(x) = \frac{d}{dx} F(x) \qquad (2)$$

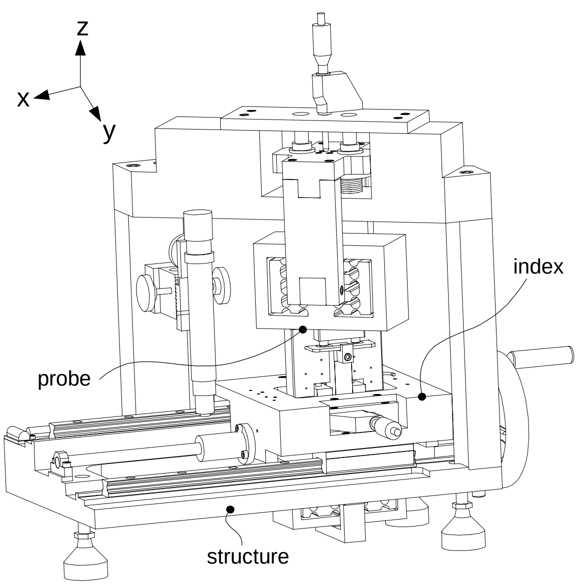

Fig 3: Instrument for Measuring Force-Displacement Relations for Optical Fibers

Conceptual Design of the Instrument

Fig 4 illustrates the conceptual principle of the instrument. A jewel probe with a flat face is displaced a distance, x_p, so that it pushes against the end of a single fiber. The fiber compresses a distance, δ_f, and the force is transmitted through the epoxy and ferrule to the ferrule base. The ferrule base floats on a compliant spring, so that the applied force can be inferred by measuring the compression within the spring. The compression of the fiber should be measured with respect to the face of the ferrule.

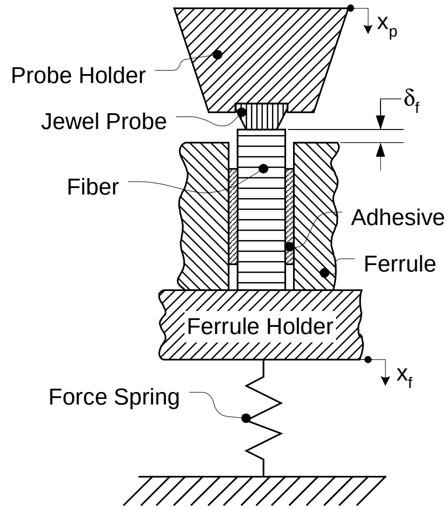

Fig 4: Concept for Measuring Fiber Stiffness

Since the displacements and compression of the fiber are only a few microns, flexural bearings [1] are used for the force spring and guide the probe holder. Fig 5 illustrates two double compound flexures that guide the probe and hold the ferrule. Flexural bearings provide maintenance-free, dirt-insensitive limited motion with very high stability and repeatability [2]. The displacement of the probe is controlled using a low-voltage PZT that actuates against flexure 1. The deformation in the fiber and the deflection of flexure 2 (force measurement) can be measured with capacitance displacement gages.

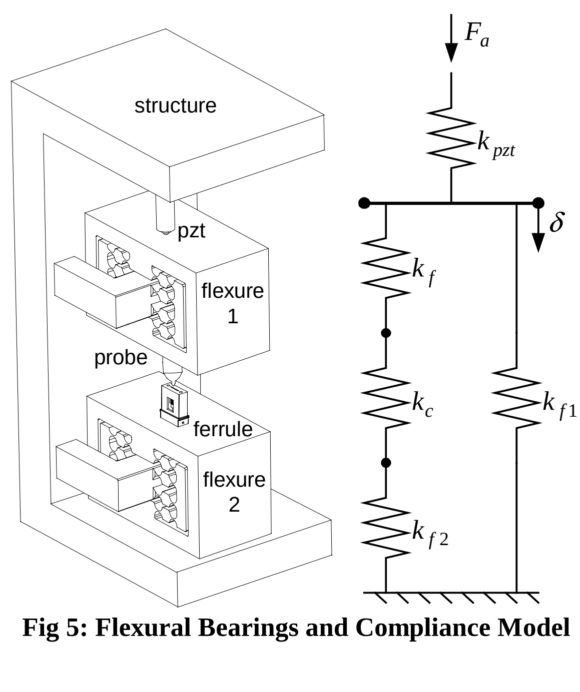

Fig 5: Flexural Bearings and Compliance Model

Detailed Design of the Stiffness Tester

Separate metrology loops limit the number of error sources, including structural deflections, thermal expansion, and alignment errors, near the ferrule face are illustrated in Fig 6. In order to measure the displacement of the fiber tip relative to the ferrule face, datum bars are implemented on either side of the optical fiber being analyzed.

The two independent datum bars have the same mass and center of gravity, which is coincident with the axis of the fiber being measured. Each datum bar contacts the ferrule face by way of a contact pin. The pin has a cylindrical surface, resulting in line contact in the vicinity of the fiber, preventing rotational errors and form errors from producing errors in the displacement measurement.

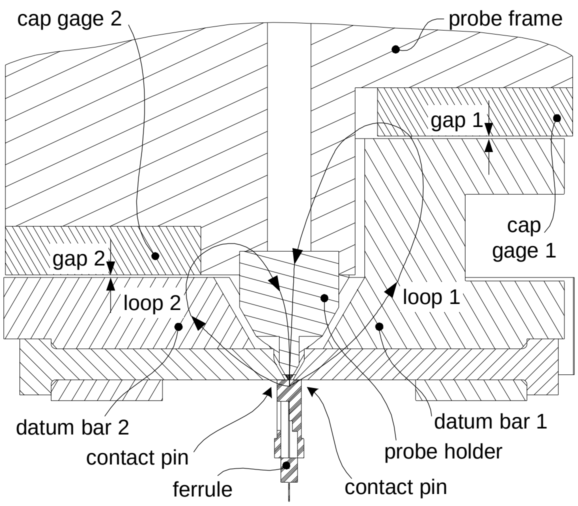

Fig 6: Ferrule Contact Region

The cap gages, mounted to the probe frame, measure the displacement of the datum bars relative to the cap gage surface. As the probe frame approaches the surface of the ferrule, the datum bars rest at a constant distance from the cap gage surface. When the datum bars touch the ferrule surface, the distance between the datum bars and the cap gages is reduced. In turn, the cap gages output a voltage that is proportional to displacement.

The probe frame, illustrated in Fig 7, functions as a housing for the air bushings, cap gages, and probe holder. The probe frame, mounted to flexure 1, travels vertically to allow the probe tip to push the tip of the optical fiber. Air bushings provide accurate linear motion without stiction. The air bushings are inserted into the probe frame and epoxy is forced into the space between the bushing o-rings and the frame to prevent movement. Bushing pins are pressed into the datum bars and translate vertically through the air bushings, allowing the datum bars to travel independently. Slots are ground into the bushing pins and the pin hard stop is inserted into the slots through the probe frame to control the total amount of displacement and prevent the datum bars from making contact with the cap gage surfaces.

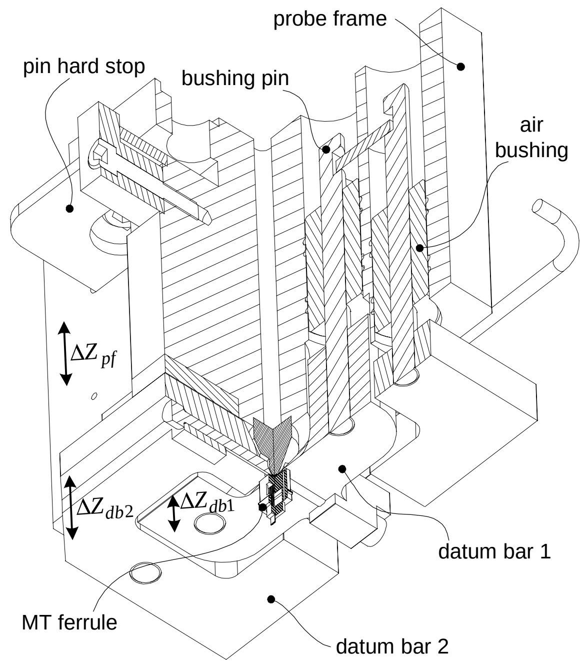

Fig 7: Probe Frame, Datum Bars, & MT Ferrule

The displacement for the loading of the optical fiber is provided by a PZT in conjunction with flexure 1. Together, they provide accurate linear motion with high resolution. The requirements for translation in the x direction led to the development of a z stage on the probe assembly, illustrated in Fig 8, where the micrometer head translates the components of the ferrule contacting region in the –z direction. The probe assembly is mounted to a gantry structure that is oriented at an angle to the x-axis.

The index assembly, illustrated in Fig 9, is comprised of components that enable translation in the x and y directions. The x-stage is mounted to a pair of recirculating linear ball bearings. These bearing rails provide accurate linear translation while withstanding a sufficient load. The rails are staggered to eliminate the effect of Abbe offsets in both the x and y stages. The x-stage is driven by a leadscrew and handwheel. The leadscrew provides repeatable positioning capabilities with no backdrive. One revolution of the handwheel translates the nut 1.58 mm. The y-stage rests upon a pair of crossed roller bearings and is driven by an absolute digital micrometer.

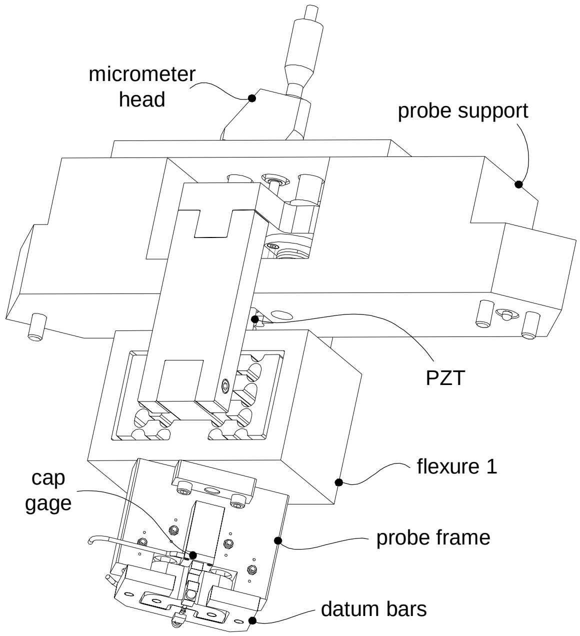

Fig 8: Probe Assembly

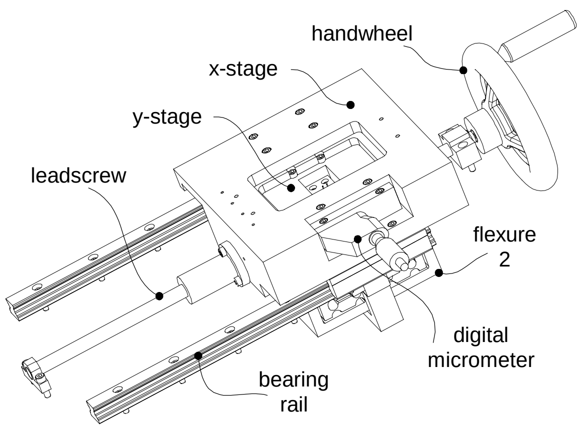

Fig 9: Index Assembly

Analysis of Flexures

The first step in the design of the flexures is to determine the force and displacement range expected in the fiber tip. A force of approximately 5 lb is required to properly mate two MT ferrules. The expected displacement for the fiber tip will be within the range of 0μm – 10 μm. Using Eq (2), the expected optical fiber stiffness, k_f, can be calculated.

The stiffness of the ferrule connector, k_c, is determined by finite element analysis. Using the known force and material properties, FEA gives an estimate for the displacement, from which the stiffness can be calculated using Eq (2).

The stiffness of flexure 2, k_{f2}, is governed by the capacitance gage that measures the force propagated between the connector and structure. The cap gage selected has a sensing range of 20 – 30 μm. This sensing range is the effective displacement range of flexure 2. The force through flexure 2 is the same as the fiber and ferrule connector. Therefore, k_{f2} is known by applying Eq (2).

The next step in the design is to select the PZT. Illustrated in Fig 5, both flexures as well as the PZT are attached to the structure. In the spring system diagram, the force from the PZT is equivalent to the combination of the forces from other components. The force balance equation for the spring system is given in Eq (3) where F_a is the effective PZT force, F_{f1} is the force from flexure 1, and F_s is the force that propagates through the fiber (F_f), ferrule connector (F_c), and flexure 2 (F_{f2}).

$$F_a = F_{f1} + F_s \tag{3}$$

The equivalent stiffness for the lower half of the spring system, k_s, is given in Eq (4) as a combination of springs in series and in parallel.

$$k_s = \left[\frac{1}{1/k_f + 1/k_c + 1/k_{f_2}} + k_{f_1} \right] \tag{4}$$

The PZT is selected by choosing the desired maximum displacement of the PZT without external loading, ΔL_o, and the stiffness of the PZT, k_{pzt}. The equivalent spring stiffness may then be related to the effective PZT force by using Eq (5) [3].

$$F_a \approx k_{pzt} * \Delta L_o \left(1 - \frac{k_{pzt}}{k_s + k_{pzt}} \right) \tag{5}$$

The stiffness of flexure 1 can be calculated by substituting Eq (4)-(5) into Eq (3) and using the relation $F_{f1} = k_{f1}*\delta$. Geometry for flexure 1 is designed around its stiffness and displacement, δ. The flexure geometry also depends upon other variables such as material properties and PZT positional errors. The parameters of the flexure geometry, illustrated in Fig 10, can be modeled with Eq (6)-(8) [4]. Θ is the hinge rotation, δ is the displacement, L is the length between hinges, E is the modulus of elasticity, b is the flexure depth, t is the hinge section thickness, R is the hinge section radius, and σ_{max} is the maximum allowable stress.

$$\Theta = \delta / 2L \tag{6}$$

$$\Theta_{max} = \frac{4\left[.365\, t/R + .166\right] R \sigma_{max}}{\left[\frac{2.7t + 5.4R}{8R + E} + .325\right] Et} \tag{7}$$

$$k_{f1} = \left(\frac{4}{9\pi}\right)\left(\frac{Ebt^{5/2}}{L^2 R^{1/2}}\right) \tag{8}$$

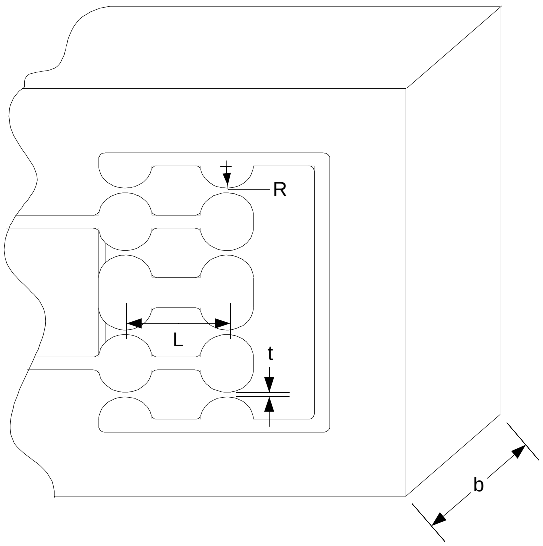

Fig 10: Flexure Dimensions

Operation of the Instrument

The stiffness tester will perform the task of measuring the stiffness of terminated optical fibers by following the procedure below. Fig 11 models the coordinates and vectors used in the procedure.

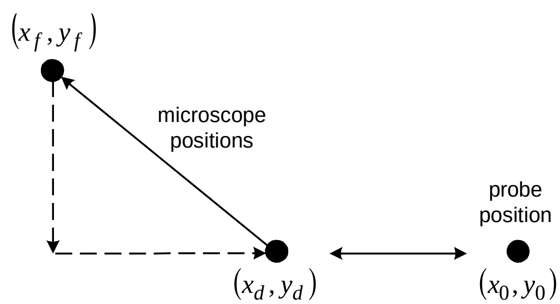

Fig 11: Positioning Vector Diagram

1. Align MT ferrule onto the ferrule mount by inserting the ferrule onto the alignment pins.

2. Translate the index assembly with the handwheel and position it under the probe assembly.

3. While monitoring the force from the resulting displacement in the flexure 2 cap gage, translate the probe assembly in the –z direction using the micrometer head until a force indicates that contact has been made. Null out the force by retracting the micrometer head. Actuate the PZT over the predefined range until a dimple is made at a random location on the ferrule surface. Record the x and y location of the index assembly (x_0,y_0) from the linear encoder and digital micrometer.

4. Translate the probe assembly in the +z direction to clear the index assembly. Translate index assembly along the x-axis with the handwheel and position it under the microscope.

5. Using the microscope, translate index assembly with handwheel and digital micrometer to locate the dimple and position it directly under the microscope reticle. Record the x and y dimple location (x_d,y_d).

6. Using the microscope, translate as in step 5 to locate the fiber to be analyzed and position it under the reticle. Record the x and y fiber location (x_f,y_f).

7. Translate index assembly to position (x_0,y_0). Position fiber under the probe by translating index assembly in y direction by the amount $y_f - y_d$ and in the x direction by the amount $x_f - x_d$.

8. One now knows that the fiber is positioned under the probe. Repeat the procedure in step 3 to apply a load to the optical fiber tip. Record the displacement of the datum bar cap gages, which is the displacement of the fiber. Using Eq (2), calculate the stiffness of the terminated optical fiber, δ_f.

Conclusions and Future Work

Currently, there is no instrument to experimentally determine the stiffness of optical fibers terminated in MT ferrules. This paper describes a concept, detailed design of the instrument, component designs, and operation of the fiber stiffness tester. Future work will include implementing control data acquisition systems. After assembly, experiments will be conducted to determine the stiffness of optical fibers terminated in MT ferrules. This design will benefit optical fiber connector manufacturers that are interested in fiber stiffness as a parameter to monitor and control.

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