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TOPICAL REVIEW

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Topical Review

A century on diameter measurement techniques in cylindrical structures

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Abstract

This work addresses the historical development of techniques and methodologies oriented to the measurement of the internal diameter of transparent tubes since the original contributions of Anderson and Barr published in 1923 in the first issue of Measurement Science and Technology. The progresses on this field are summarized and highlighted the emergence and significance of the measurement approaches supported by the optical fiber.

Keywords: century, diameters, measurements, cylindrical structure, optical instrumentation, optical fiber sensors

1. Introduction

The precise determination of the internal diameter of tubes continues to be a significant undertaking in numerous scientific and industrial contexts, persisting as a relevant task a century following the introduction of Anderson and Barr's methodologies [1]. Precise determination of the internal diameter of tubes is a critical undertaking in numerous scientific and industrial contexts, for example during a catastrophic incident at a nuclear power station, the temperature and pressure within the containment structure will increase fast [2, 3]. Nevertheless, the execution of this task may present challenges owing to the composition of the tubes and the inherent complexities associated with accessing their internal components. Anderson and Barr have put forth a pair of novel methodologies for quantifying the internal dimensions of glass tubes and other types of tubes. Furthermore, the significance and practicality of these methods have been extended beyond their initial expectations.

In contemporary times, the precise assessment of the internal dimensions of cylindrical structures holds significant importance across various domains, particularly in the realm of medicine. This pertains to the utilization of glass tubes within a diverse range of medical apparatus, encompassing laboratory test tubes as well as tubes employed in invasive

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medical interventions. Precise measurement of these tubes is crucial in order to guarantee the safety and efficacy of these procedures.

Glass tubes are commonly employed in manufacturing processes within the semiconductor industry [4, 5]. The precise measurement of the inner diameter of these tubes has a direct impact on the quality and efficiency of the manufacturing process.

Another illustration can be found in the realm of fiber optic technology, where the significance of precise measurement of the diameter of tubes has been further amplified [6]. Optical fibers can be described as slender glass tubes, wherein the precision of their internal dimensions plays a crucial role in determining the effectiveness and caliber of data transmission.

Furthermore, as research has progressed and incorporated the realm of fiber optic technology, optical sensors based on fiber optics have been devised to quantify changes in diameter within cylindrical structures [7–10].

Although Anderson and Barr's methods were originally developed in a distinct historical context, they remain highly pertinent and applicable in contemporary settings. Moreover, their methodologies have served as catalysts for numerous practical implementations. Undoubtedly, as society progresses toward a future that heavily relies on glass and other transparent materials with a relevant fraction assembled along cylindrical geometries, the significance of precise measurement techniques for these structure will inevitably grow.

In this way, this work presents a century evolution on diameter measurement techniques in cylindrical structures. This paper is organized as follows: the second section introduces the historical context about techniques for measuring the internal diameter of transparent tubes. The third section contains an overview about the Anderson and Barr's methods for quantifying the internal diameters of transparent tubes, including glass tubes. The fourth section presents the impact of Anderson and Barr's work after publication. The fifth section shows the advancement of optical techniques for measuring the diameter of glass tubes and other cylindrical constructions that have progressed independently from the methods described by Anderson and Barr, along with their subsequent improvements. The sixth section presents modern fiber optic-based methods. The research conducted by Anderson and Barr served as a catalyst for subsequent investigations that produced novel optical techniques for measuring the diameters of cylindrical objects, ranging from clear tubes to bigger entities such as pipes or trees. Finally, the conclusions expose that the work of Anderson and Barr continues to be pertinent and significant in the field of measuring the diameter of transparent tubes and other cylindrical constructions.

2. Historical context

The article authored by Anderson and Barr was published in 1923 [1], a time characterized by significant transformations and progress in the fields of science and technology. The era was characterized by a surge in innovative ideas and exploratory endeavors, leading to the emergence of novel theories and technologies across diverse disciplines.

During that period, the precise determination of the internal diameter of tubes posed a considerable obstacle. The significance of this task extends to a wide range of applications, encompassing industrial manufacturing as well as scientific research efforts. Nevertheless, the tubes within this particular framework. The techniques employed by the researchers, which incorporate the utilization of immersion liquids and x-ray technology, introduced a novel and pioneering approach to address the issue at hand.

Despite the limitations associated with these methods, they offered a more precise and dependable means of measuring the internal diameter of transparent tubes compared to numerous contemporary techniques.

3. Anderson and Barr's methods

Anderson and Barr, introduced two novel techniques for quantifying the internal diameters of transparent tubes, including glass tubes.

The initial technique, referred to as the 'Immersion Method,' involves submerging the tube under test in an appropriate liquid and adjusting the wavelength of the illuminating beam until achieving a state of refractive index equivalence. As the system achieves homogeneity, the direct measurement of the diameter becomes feasible. The document presents a comprehensive overview of the optimal liquids to utilize and incorporates a variety of practical recommendations that enhances the ease of conducting the test.

The second approach involves capturing a radiographic image of the tube's shadow through x-ray imaging and subsequently determining the dimensions of the resulting image.

The utilization of either method enables the precise determination of the internal diameter of nearly all transparent tubes, irrespective of their external configuration, whether they are sealed or open.

Theoretical discussions are presented regarding the accuracy of these techniques, highlighting the potential to achieve a refractive index measurement with a precision of 0.001 or even greater.

Theoretical discussions are presented regarding the accuracy of these methods, highlighting the potential to achieve a refractive index equality with a precision in the refractive index of 0001 or even greater. Consequently, this particular source of error may be inadvertently disregarded.

The methods exhibit flexibility in their applicability to various types of tubes. Transparent pipes, whether sealed or open, of any external shape can be accurately measured for their inner diameter using these techniques.

Furthermore, they possess the benefit of yielding a lasting documentation of the measurements pertaining to a cylindrical structure. Multiple tubes have the potential to be captured in a single photographic plate. Although the first method

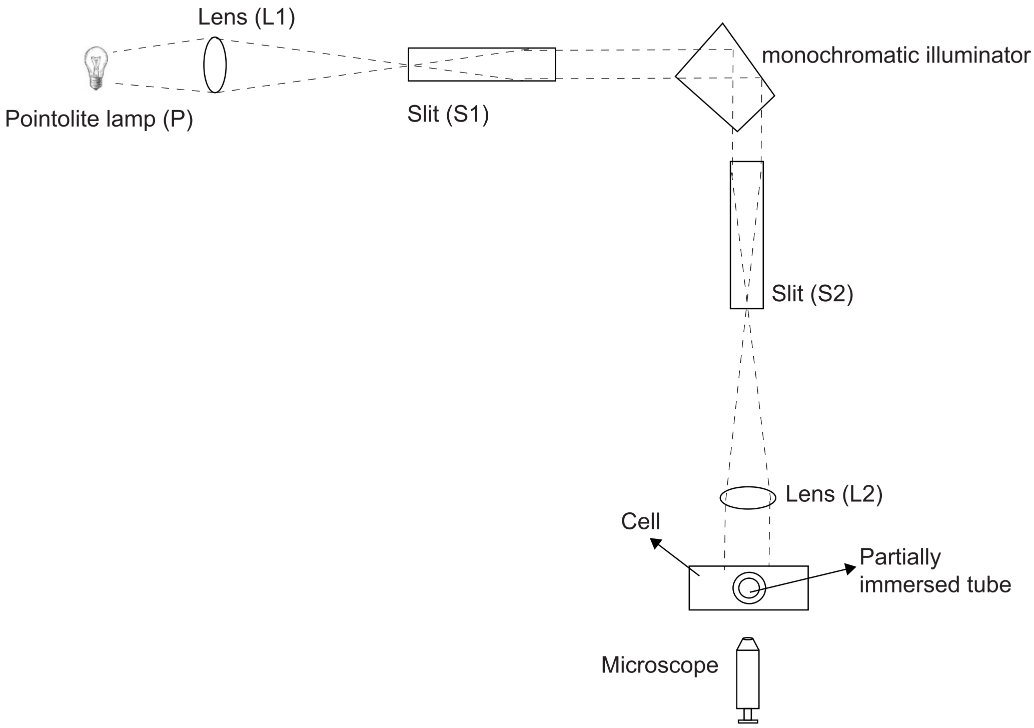

Figure 1. Schematic of the proposed method. Reproduced from [1].

is generally considered the most convenient option, the second one can serve as a viable alternative in certain situations. For instance, it may be particularly useful when measuring the internal diameter of large pipes that are permanently installed. The accuracy of the x-ray method is independent of the level of homogeneity exhibited by the material composing the pipe.

It is important to acknowledge the limitations associated with the methods discussed in the article by Anderson and Barr for measuring the inner diameter of transparent tubes. In what concerns the first method (figure 1), the utilization of a high-intensity light source, such as an arc lamp, is necessary as the intensity of the illumination experiences a significant decrease upon traversing the monochromatic illuminator. Furthermore, it is imperative to ensure that the immersion liquid does not infiltrate the tube during the measurement of open tubes.

The effectiveness of this approach is constrained by the uniformity of the glass within the tube. If the glass lacks strict homogeneity, the interference fringe system may exhibit a diminished level of definition. The selection of the immersion liquid is a crucial determinant. Certain liquids, such as mercury and potassium iodide, require continuous agitation to prevent the disruption of homogeneity caused by the gravitational settling of denser liquid droplets due to surface evaporation.

Concerning the second technique, its effectiveness is constrained by the level of granularity of the grain and the absence of 'scattering' on the photographic plate employed. Achieving measurements with a precision greater than approximately five thousandths of a millimeter is not feasible. The experimental procedure necessitates the positioning of the tube in close proximity to a photographic plate, while maintaining a certain distance, such as 2 m, from an x-ray lamp. To achieve optimal outcomes, it is recommended that the tube be filled with a substance that possesses opacity, such as mercury. Nevertheless, it is feasible to achieve adequate contrast with an empty tube by carefully selecting an appropriate x-ray wavelength.

Both methods, although valuable, possess inherent limitations, and the selection of the appropriate method will be contingent upon the particular circumstances and level of precision desired. It is imperative to bear in mind that despite the limitations associated with these techniques, they continue to offer a valuable means of quantifying the internal diameter of transparent tubes. This measurement is of utmost significance in numerous scientific and industrial environments.

4. Impact of Anderson and Barr's work

The techniques developed by Anderson and Barr in 1923 for quantifying the internal dimensions of translucent tubes were pioneering and influential in the field of optical metrology. At that time, they presented a solution to the prevalent difficulty of accurately and dependably measuring the internal diameter of transparent tubes.

Throughout the past century, these methods have been implemented and modified in diverse contexts. An article with title 'A method for measuring the internal diameters of transparent tubes' authored by F H Rolt, R M Wilmotte and J S McPetrie was published in the *Journal of Scientific Instruments* in 1929 [11]. This article describes a technique for quantifying the internal diameters of transparent tubes through the utilization of two spherical objects. It enables the measurement of the diameter at any axial plane and at any position along the tube, facilitating the detection and quantification of elasticity and variations in the cross-sectional shape.

The investigation carried out by these authors makes mention of the influential research conducted by Anderson and Barr. Although does not directly build upon their studies, it is evident the impact of the 1923's paper in the approaches and methodologies followed.

Near 20 years after the Anderson and Barr's seminal paper a subsequent study surfaced which introduced important advances in the field. It is due to D J Behrens, published in 1941 in *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, entitled 'A Method for Measuring the Internal Area of Sections of a Glass Tube' [12]. In particular, a new optical technique was presented that addressed the challenges identified in the methodologies proposed by Anderson and Barr. In addition, the technique allows the determination of the refractive index of a tube's material when the end of the tube is readily accessible. The article concludes by examining the potential application of the method to opaque tubes, wherein a mechanical technique is employed to ascertain the separation distance between the two spheres.

Furthermore, the methodologies proposed by Anderson and Barr have been modified and adjusted to incorporate emerging technologies. For instance, the introduction of fiber optic technology has led to the development of techniques for measuring the dimensions of structures using sensors based on optical fibers.

Nevertheless, despite the extensive acceptance of Anderson and Barr's approaches, it is important to acknowledge that that some of the constraints already identified remained in the upgrades that appeared along the years, particularly and in what concerns the immersion technique the need of a compatible immersion fluid, while for the x-ray method the limitations were associated with the need to use a x-ray source as well as high quality photographic plates.

5. Evolution of optical measurement methods

This section addresses the evolution of optical methods to determine the diameter of both glass tubes and other cylindrical structures not directly connected with the approaches proposed by Anderson and Barr and associated upgrades. Besides being supported in novel concepts, they also benefit from the technology progress, most remarkably the availability of more flexible and high performance optical sources and the outcome of optical fibers.

5.1. A method of completely filling capillary with mercury for diameter determination

This study, which was published in the *Journal of Scientific Instruments* in 1958 [13], introduces a novel methodology for the measurement of tube diameters, thereby providing a significant advance in the field. The methodology employed in this research entails the utilization of a specific type of viscometer equipped with a collection of stainless steel capillaries possessing diameters reaching up to 0.48 mm and exhibiting a length-to-diameter ratio of 40 to 1. The procedure commences with the closure of one end of the capillary using a glass disc. The introduction of mercury into the capillary is facilitated by employing a glass tube with an extremely narrow diameter. Ensuring the prevention of air entrapment during the filling process is of utmost importance. This can be achieved by inserting the end of the tube to the bottom of the capillary and subsequently withdrawing it gradually as the mercury enters. Ultimately, a small surplus of mercury is introduced in order to cause the meniscus to extend beyond the upper end prior to sealing the capillary.

The method was tested with a set of four capillaries with diameters in the range, 1.14–0.48 mm. For each of them the average of few measurements resulted in an accuracy of 0.5 μm. For individual measurements it was obtained an estimated accuracy of 1 μm. The findings of this study suggest that the devised method is a viable approach to address the issue of achieving full mercury filling in capillary tubes for the purpose of determining their diameter.

5.2. Method of non contact optical measurement of the diameter of transparent tubes

The method for determining mercury content, which was frequently employed during the 1950s, presents challenges in its application due to the intricate process of achieving full hole saturation with mercury [14]. Therefore, an evolution of the methods for determining the diameter of tubes was necessary.

This research introduces a novel approach that utilizes the shadow image generated by illuminating a transparent tube with a scattered light source featuring a rectangular aperture. The edges of this aperture are aligned parallel to the axis of the tube. The purpose of this method is to accurately measure the inner diameter of such transparent tubes.

The methodology presented relies on the analysis of the shape and positioning of shadow band fronts. Specifically, it introduces an operational model for a non-contact optical device designed to measure the inner diameter of transparent tubes. The model encompasses several components, namely a microcomputer, a two-coordinate sliding device, a light source, an objective, and an RCC camera. The quartz tube that has been measured is positioned in proximity to a light source comprising an incandescent lamp featuring an elongated luminescent element and frosted glass equipped with a rectangular aperture. The positioning of these maxima is independent of the correlation between the dimensions of the measured tube and the illuminator, as well as the distance between them. This property can be utilized to directly determine the inner diameter of a transparent tube. A distance of 45 mm is chosen for the separation between the edges of the diaphragm. The primary objective of the Zh-53 type (lens) is to project a magnified image of the measured tube onto the RCC camera, effectively doubling its size. The block diagram can be observed in figure 2.

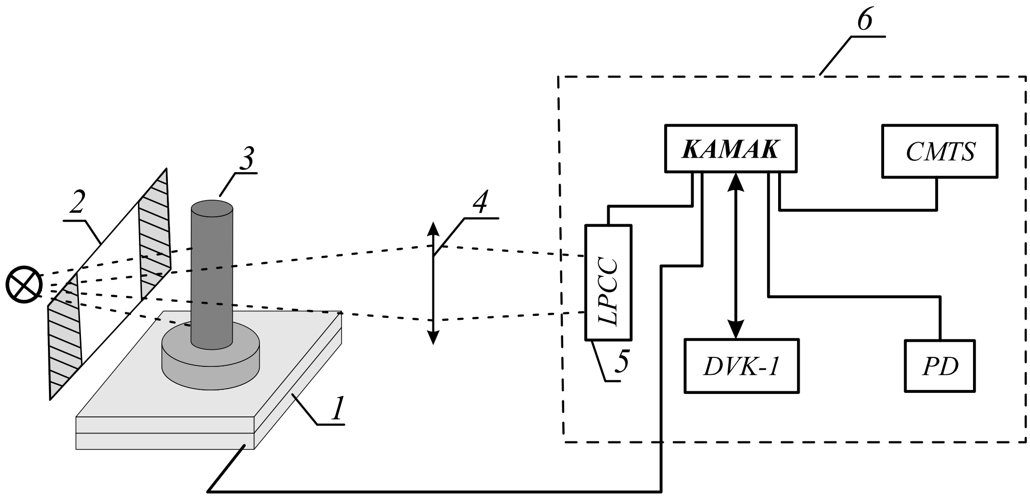

Figure 2. Block diagram of the proposed method. Adapted from [14], with permission from Springer Nature.

The algorithm for processing the tube image includes several cycles of *linear photoelectric receiver with charge coupling* (LPCC) interrogation and averaging. The value data are processed by median and moving average filtering subprograms to eliminate overshoots caused by faulty LPCC elements and to smooth the illumination intensity distribution curve of the image.

Subsequently, the image fronts are identified and local maxima are determined by locating the maximum of the second derivative. The inner diameter can be calculated by measuring the distance between the centers of the front sections, which are limited above bu the local maximum. This calculation takes into consideration the magnification of the optical circuit during the linear extrapolation of the indicated sections.

The authors findings demonstrate the feasibility of developing precise gauges for measuring inner diameter through the utilization of the proposed methodology.

5.3. A new comparator for measurement of diameter and form of cylinders, spheres and cubes under clean-room conditions

The aforementioned study was conducted by M Neugebauer *et al* and was published in 1997 in *Journal Measurement Science and Technology* [15]. The objective of this study was to enhance the precision of an instrument used for calibrating the diameter of cylindrical, spherical, and cubical structures within a single sample configuration. This was achieved by employing a contact probe technique. The measurement of diameters is conducted utilizing an optical comparator. This device exhibits a notable capability in accurately determining the diameter of an object. The measurement procedure is executed in the following manner:

- The item to be measured is positioned within the comparator.
- The object is illuminated by a beam of light, and the resulting shadow is cast onto a screen.
- The diameter of the object is subsequently determined by measuring the projected shadow.

This technique is especially advantageous in the assessment of the dimensions of diminutive and fragile entities, such as spheres and cylinders, as alternative measurement approaches may cause harm or impairment to these objects. The objective of this study was to decrease the existing uncertainties in straightness and parallelism calibrations, which currently ranged from 0.03 to 0.05 µm, to a more precise value of 0.01 µm. Additionally, the aim was to reduce the uncertainties in diameter calibrations to 0.01 µm for the outer diameter and 0.015 µm for the inner diameter per 100 mm of measurement length. This was to be achieved while simultaneously minimizing the required measurement time.

The comparator that has been developed possesses a measuring volume with dimensions of 160 mm × 100 mm × 120 mm. It has been strategically placed in the cleanroom center of the Laboratory for Dimensional Standards at the Physikalisch-Technische Bundesanstalt (PTB), Germany. This placement aimed to minimize any potential disruptions caused by dust particles on the contact probe technique. The length measurement system comprises an air bearing system positioned beneath the vertical carriage, facilitating movement along the *X*-axis. The two carriages are driven independently by inchworm-type piezo motors. The bearing systems, carriages, and drives are constructed using alumina ceramics, which effectively guarantee the necessary stability of the carriage positions when in a compressed state.

The measurement of diameters in this study is conducted utilizing two probing systems in accordance with the Abbe principle. During the measurement process, the contact balls of the two probing systems establish contact with the specimen by touching its opposite sides. This contact is started with an initial displacement of approximately 0.5 µm, thereby ensuring a well-defined and controlled contact. The displacement is augmented to approximately 10 µm through incremental movement of the X-carriage. The measurement of these movements is conducted using a laser interferometer and a plane

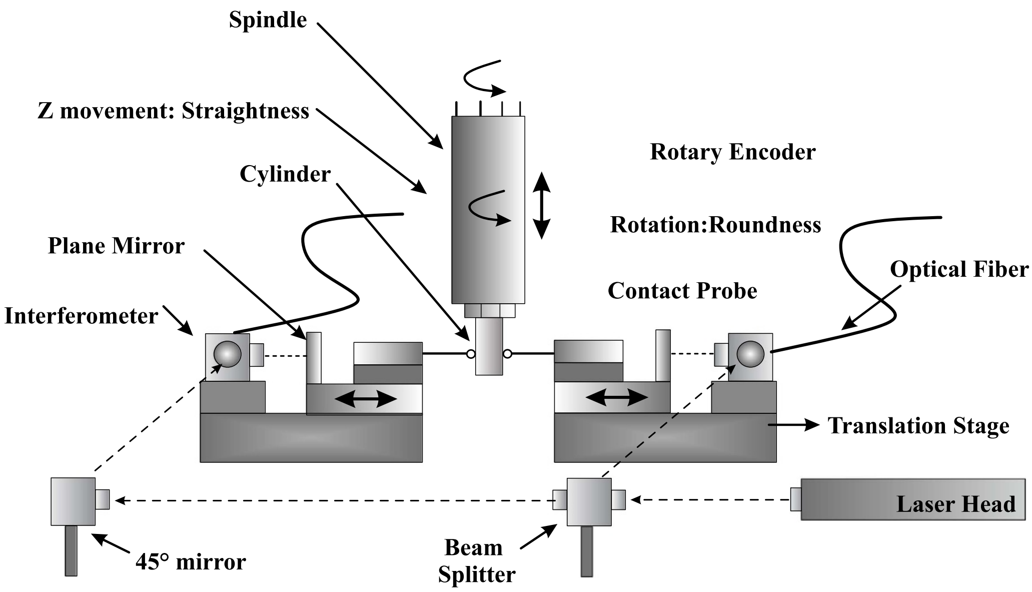

Figure 3. General layout of new instrument. Reproduced with permission from [16]. © (2001) COPYRIGHT Society of Photo-Optical Instrumentation Engineers (SPIE).

mirror, while considering the impact of the refractive index of the surrounding air.

The results from the external length measurements conducted on three of PTB's standard length comparators and the newly introduced comparator demonstrate a level of agreement within a range of ±20 nm. The measured length values provided for the new comparator are derived from the average of two measurement series, each consisting of six and two measurements respectively. These series collectively encompass over 300 measurements conducted over a period of three weeks. The calculated standard deviation for the eight series is 7 nm. The measured length values fall within the uncertainty range of the comparators and exhibit a comparability within a narrower range of less than 20 nm. The method's operational dimensions span 160 mm in length, 100 mm in width, and 120 mm in height. The desired level of uncertainty for calibrations involving outside diameter, shape, and parallelism is 0.01 µm per 100 mm length.

5.4. New instrument for the measurement of diameter and form of cylinders

This research authored by John Miles of the Australia National Measurement Laboratory was published with the title 'Recent Developments in Traceable Dimensional Measurements' in volume 4401 of *Proceedings of SPIE* related to the conference '*Lasers in Metrology and Art Conservation*', held in Munich, Germany, in 2001 [16].

This study details the creation of a novel apparatus capable of conducting precise measurements of cylinder shape and diameter. The precision and sensitivity of the instrument are demonstrated by the nanometer-level accuracy of these measurements.

The necessity to develop such an apparatus emerged due to the requirement for a device capable of examining the geometric properties of pistons utilized in the fabrication of high-pressure standards. Nevertheless, the utilization of the instrument is not restricted solely to this particular application. The aforementioned tool exhibits the capacity to be advantageous in diverse scenarios that necessitate precise measurements of cylinders.

The functioning of the instrument relies on the ongoing, position-agnostic observation of two opposing contact probes. These probes are affixed to a pair of translation stages, as depicted in figure 3. The location of these probes is monitored using a pair of laser interferometers capable of conducting displacement measurements at a sub-nanometer level.

A prototype of the instrument was developed, encompassing several of the characteristics that were intended for its ultimate iteration. The development of the clamping and measuring structures played a crucial role in this study, as it was imperative to establish and sustain the mutual alignment and linearity of the systems movement, as well as the optical alignment of the interferometers.

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5.5. Measurement of diameter of metal cylinders using a sinusoidally vibrating interference pattern

This work published in 2006 in *Optics Communications* introduces a novel technique for quantifying the dimensions of metallic cylinders by utilizing a sinusoidal vibrating interference pattern [17]. The method being proposed relies upon the phenomenon of interference between two light waves that undergo reflection from a metallic cylinder. The superposition of these waves gives rise to an interference pattern which can

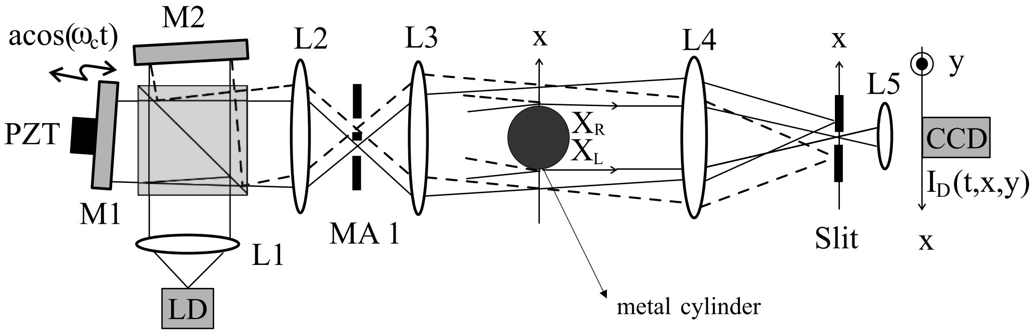


Figure 4. Configuration of an instrument for measuring eternal diameter of metal cylinder. Reprinted from [17], Copyright (2006), with permission from Elsevier.

be utilized for the purpose of ascertaining the diameter of the cylinder. Its layout can be observed in figure 4.

The authors start by providing an introductory overview of the issue pertaining to the measurement of metallic cylinder diameters, highlighting the necessity for a more precise methodology. Subsequently, they detail the intricacies of the proposed technique, encompassing an elucidation of the underlying principles of light interference and its application in the measurement of the cylinder diameter.

Subsequently, a series of experiments are described in order to evaluate the efficacy of the proposed methodology. A steel cylinder of a predetermined diameter was employed to conduct a comparative analysis between the outcomes obtained through the approach proposed and those achieved along conventional techniques. The findings indicate that the method exhibits greater accuracy and reliability, pointing out it shows an effective potential for application in various industrial sectors that necessitate precise measurement of metal cylinder diameters.

5.6. Cylinder gauge measurement using a position sensitive detector

The study titled 'Utilization of a Position Sensitive Detector for Cylinder Gauge Measurement' examines the application of a position sensitive detector (PSD) for the purpose of measuring the diameter of cylinder pins. It was authored by W Doyle St. John and published in 2007 in *Applied Optics* [18].

The findings of the study provide confirmation that the PSD exhibits a response that is influenced by the centroid of the light beam. In addition, this result remains valid even when considering asymmetric beams. Furthermore, it has been verified that the accurate prediction of the shift in beam centroid caused by the partial obstruction of a cylindrical object does not require the consideration of pin thickness or diffraction. Hence, the determination of cylinder diameters can be achieved by measuring the maximum alteration in centroid utilizing a one-dimensional PSD.

The experiment was conducted utilizing a laser light source of argon, characterized by a Gaussian and axially symmetric beam with wavelength 532 nm. The beam, oriented toward the central region of the PSD, exhibited a lack of focus and possessed a waist diameter of 0.92 mm.

The theoretical framework, which at first does not account for diffraction, admits that the laser beam possesses ideal collimation properties. Additionally, the gauge pin is assumed to have negligible thickness, infinite extension in the vertical dimension, and complete opacity. Moreover, it is postulated that the spatial distribution of the laser beam, when obstructed, follows a Gaussian intensity profile with the obstructed portion subtracted as observed in the plane of the PSD.

The expression for the intensity of a TEM_{00} Gaussian laser mode in one dimension with waist w can be represented as:

$$I(x) = I_o e^{\left(-2x^2/w^2\right)} \tag{1}$$

where, I_o is the on-axis intensity and w is the waist size. The theoretical centroid of the beam can be determined by calculating the position-weighted intensity, denoted as $\chi_{c,\mathrm{thry}}$. This quantity is defined as the integral of the product of position (x) and intensity ($I(x)$) divided by the integral of intensity.

By employing a rectangular obstruction with width d that is centered at X_p, pin position, and substituting the intensity equation into the centroid equation, it comes out an equation that represents the theoretical beam centroid as a function of the position of the pin and the diameter of the pin.

It is also delivered a more exact model that incorporates the effects of diffraction, starting by acknowledging the existing body of literature on the topic of diffraction caused by cylindrical obstructions. The proposed theoretical framework employs the Babinet principle in conjunction with the Fresnel–Kirchhoff diffraction integral. The assumption is made that the laser beam exhibits perfect collimation, the gauge pin possesses negligible thickness, extends infinitely in the vertical dimension, and exhibits complete opacity.

Initially, it is determined the electric field amplitude at the PSD which is located at a distance of 76 mm from the central point of the pin. The intensity can be ascertained from the given information and, subsequently, the centroid of the diffracted beam can be obtained. A set of mathematical equations is given that elucidates the characteristics of the electric field at the observation plane, as well as the normalized intensity.

The results obtained showed an average percentage difference between the theoretically value and the known value for the pin diameter amounting to 1.73% when the model does not incorporate diffraction effects, which decreases slightly to 1.59% when they are taken into account.

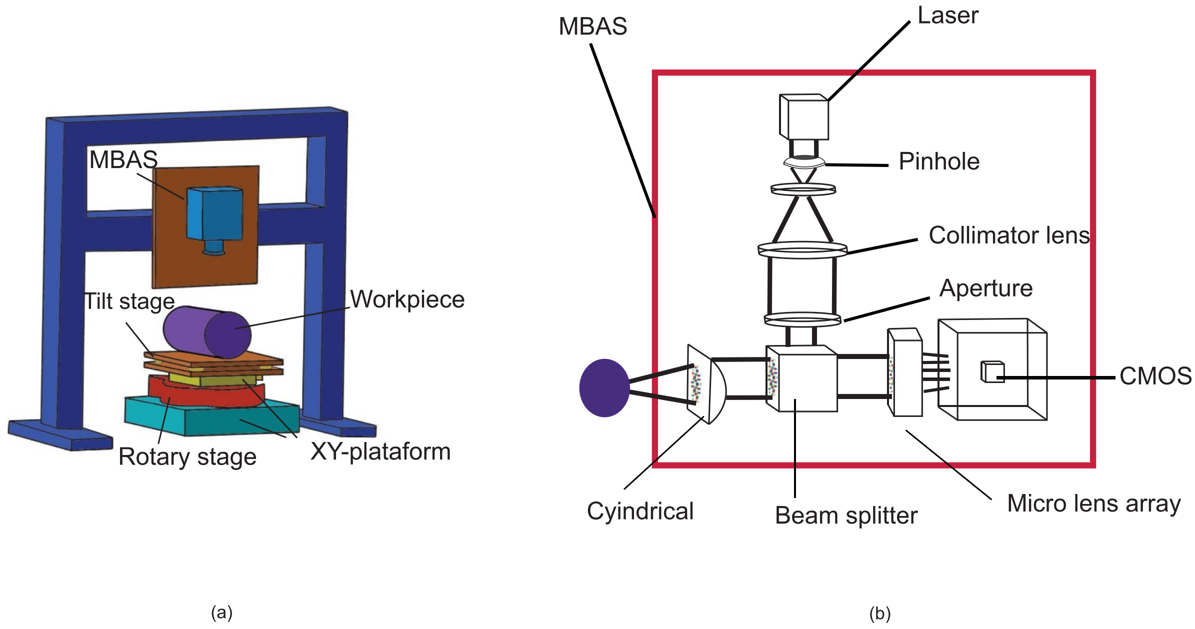


Figure 5. Configuration of an instrument for measuring cylindrical surface. Reproduced from [19]. CC BY 4.0.

5.7. A high-precision multi-beam optical measurement method for cylindrical surface profile

This work published in 2023 in *Micromachines* proposed a high-precision multi-beam optical detection method to cylindrical workpiece. The article introduces a novel technique for quantifying the profiles of cylindrical surfaces. The suggested technology employs numerous beams of light to capture the surface, enabling enhanced precision and efficiency compared to conventional techniques [19]. The proposed configurations are depicted in figure 5.

The paper commences by addressing the difficulties associated with conventional methods of measuring profiles of cylindrical surfaces. Typically, these methods employ a solitary laser beam to illuminate the surface, resulting in measurement inaccuracies caused by light reflection and diffraction. Moreover, these methods can exhibit sluggishness and inefficiency, particularly when dealing with expansive areas.

The approach presented in the article addresses these difficulties by employing numerous laser beams to illuminate the surface. The beams are intentionally arranged to overlap on the surface, so minimizing measuring errors caused by reflection and diffraction. Furthermore, the technique is integrated into an automated measurement system, resulting in enhanced speed and efficiency. The proposed methodology comprises three primary stages:

- Illumination: the surface is lighted by a multitude of light beams. The beams are engineered to possess a consistent intensity distribution and to intersect on the surface.
- Detection: a sensor detects the light that is reflected by the surface.
- Analysis: the collected data is analyzed in order to create the surface profile.

The experimental results confirm the precision and effectiveness of the suggested approach. A technique was employed to quantify the shape of a cylindrical surface characterized by a roughness value (*Ra*) of 0.2 µm. The results demonstrated that the method possesses the ability to measure the profile with a precision of 0.05 µm.

The proposed method represents a substantial advancement in the field of measuring profiles of cylindrical surfaces. The technology exhibits superior accuracy and efficiency compared to conventional procedures, rendering it well-suited for a diverse array of applications.

6. Modern fiber optic-based methods

The research undertaken by Anderson and Barr was a trigger for studies that generated new optical methods for measuring diameters of cylindrical structures, from transparent tubes to larger structures like pipes or trees. These developments had impact in topics not directly linked to diameter measurement but which need the assessment of this parameter. A classic example is the monitoring of pipes subjected to a wide pressure range that will induce changes in their diameters, which may be within certain limits [20–23]. Among a relatively large number of optical techniques devised to perform such measurement the ones based in optical fibers are particularly appellative due to the favorable characteristics of these structures, well known in the context of optical fiber sensing [24–29]. In the following some examples are presented from several fields in which diameter related measurements are achieved supported by the utilization of the optical fiber.

6.1. Respiration monitoring

The respiratory process involves the cyclic expansion and contraction of the abdominal region, resembling the

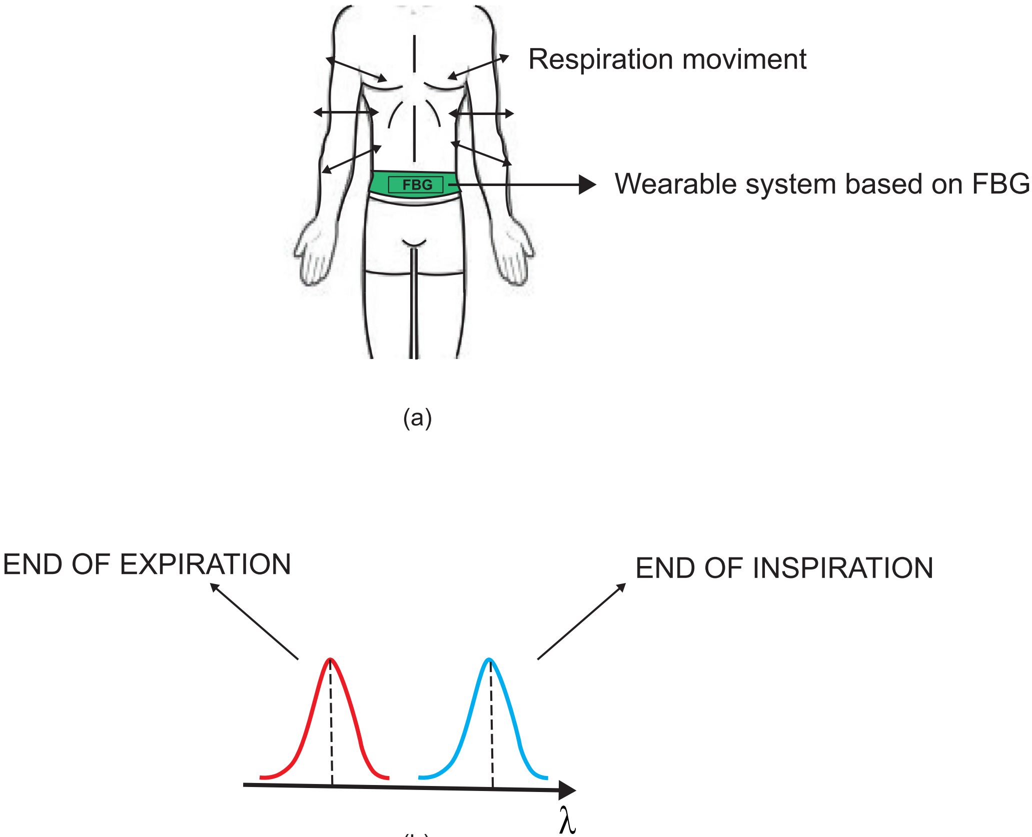


Figure 6. Schematic of the wearable system based on FBG to respiration monitoring. © 2019 IEEE. Reprinted, with permission, from [32].

movement of a cylindrical structure [30]. These movements can be readily detected through optical fiber sensing structures embedded into wearable. This feature, combined with the trend towards healthcare delivery beyond traditional hospital settings, turned out quite attractive the fiber sensing approach [31].

Fiber sensors based on fiber Bragg gratings (FBGs) have been widely targeted to address the field of respiration monitoring. For example, in the work described in [32] an FBG sensor is integrated within a wearable garment. The whole system is designed to monitor respiratory rate in a non-invasive and comfortable way. It is accomplished by measuring the changes in body shape caused by breathing, which are detected by the FBG sensing head in view of its intrinsic sensitivity to strain (figure 6). The system underwent testing across different scenarios, encompassing periods of rest, exercise, and sleep. The findings of the study indicate that the system demonstrates a high level of accuracy in monitoring both respiratory and heart rate across all of these conditions. Furthermore, it was demonstrated the capability to identify sleep apnea, thereby establishing its potential as a diagnostic and monitoring tool for this particular medical condition. The strain sensitivity of this FBG sensing system was $\pm 1.12\,\mu\varepsilon^{-1}$, indicating its ability to accurately perceive minute variations in strain induced by the breathing dynamics.

Another fiber optic sensing approach for these applications relies on Mach–Zehnder interferometry (MZI). The research reported in [33] entitled 'Wearable respiration monitoring using an in-line few-mode fiber Mach–Zehnder interferometric sensor' follows this line and was the first to incorporate MZI technology into a wearable design for monitoring respiration rate and volume.

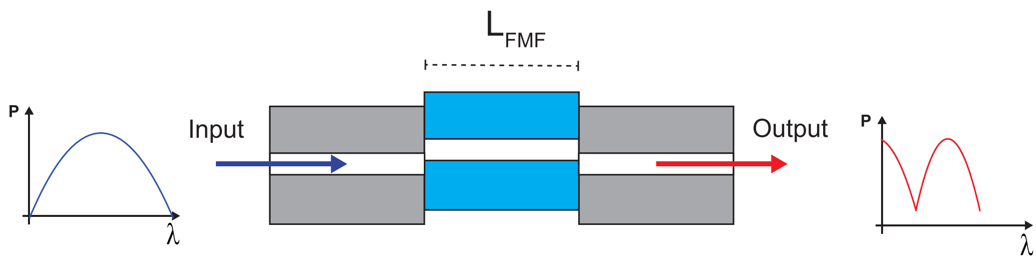
The sensor includes a length of a few-mode fiber (FMF) that is positioned between two single-mode fibers (SMFs), like a sandwich. The schematic of the proposed sensor can be observed in figure 7(a). When light emitted from a broadband source is introduced into the sensor region of an FMF via an input SMF two modes of the FMF become excited. Upon traversing this fiber length interference appears at the boundary separating the FMF and the output SMF with characteristics that are dependent on the strain applied to the FMF induced by the breathing movements.

This system has the ability to monitor relevant respiratory parameters such as respiration rate, tidal volume and minute ventilation via a wearable device (figure 7(b)).

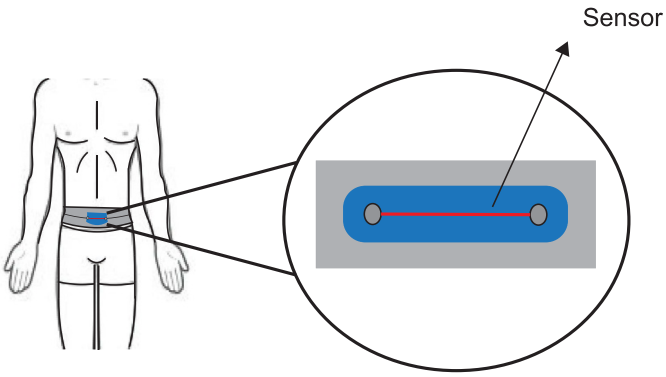
These studies provide evidence that splice-based fiber optic sensors, particularly those utilizing FBGs and Mach–Zehnder interferometers, exhibit high potential for breath monitoring in a variety of situations.

6.2. Pipeline monitoring

The approach pointed out in the context of determining respiratory movements can be used to assess the conditions to which



(a)



(b)

Figure 7. (a) Schematic the FMF–MZI sensor. (b) Wearable design to respiration monitoring. Reproduced with permission from [33].

pipelines operate, that is, by monitoring their diameter through real-time recording of the circumferential strain applied to an optical fiber attached to the pipeline which incorporates a sensing element. Particularly suited to these applications are the FBGs mostly because the strain signal is encoded into an absolute parameter, the resonant optical wavelength of these devices (figure 8).

Introducing some background, pipelines are a crucial infrastructure for transporting oil and gas across long distances, often traversing populated areas or regions with harsh conditions [34, 35]. A significant number of pipelines have been in operation for an extended period and are currently experiencing a state of deterioration. Consequently, the occurrence of pipeline breaks resulting from third-party intrusion, geohazards, and material degradation becomes increasingly challenging to prevent. Leakages in pipelines are particularly dangerous as they can lead to significant environmental pollution and even severe safety accidents, with factors such as corrosion, vibration, and external impacts often being the cause. The detection of defects in pipelines primarily relies on periodic inspections carried out by dedicated inspection robots [36–38].

Nevertheless, the current practice of conducting periodic inspections does not offer the advantage of real-time monitoring. Consequently, there exists a possibility that a leak may go undetected, resulting in significant economic ramifications and environmental contamination. Therefore, the maintenance of these systems, including water supply systems, is a strategic task that requires significant investment. A number of technologies and methods have been developed for monitoring pipeline leakage using various sensors, including piezoceramic and acoustic emission transducers [39, 40]. However, some of the traditional sensing techniques are inappropriate for pipeline monitoring due to limitations like larger loss in the process of electrical signal transmission and the risk of causing fire and explosion accidents. Naturally emerges the conclusion that optical fiber sensing technology is particularly well suited for these applications.

Example of this approach is the research performed by Jiang *et al* published as 'Application of FBG Based Sensor in Pipeline Safety Monitoring' (*Applied Sciences Journal*, 2017, [41]) and 'Experimental Investigation of Fiber Bragg Grating Hoop Strain Sensor–based Method for Sudden Leakage Monitoring of Gas Pipeline' (*Structural Health Monitoring Journal*, 2020, [42]). As illustrated in figure 9, it is used an FBG hoop strain sensor for real-time monitoring of gas pipeline leakage, being observed it is accurately sensitive to variations in internal pressure. These studies also found that

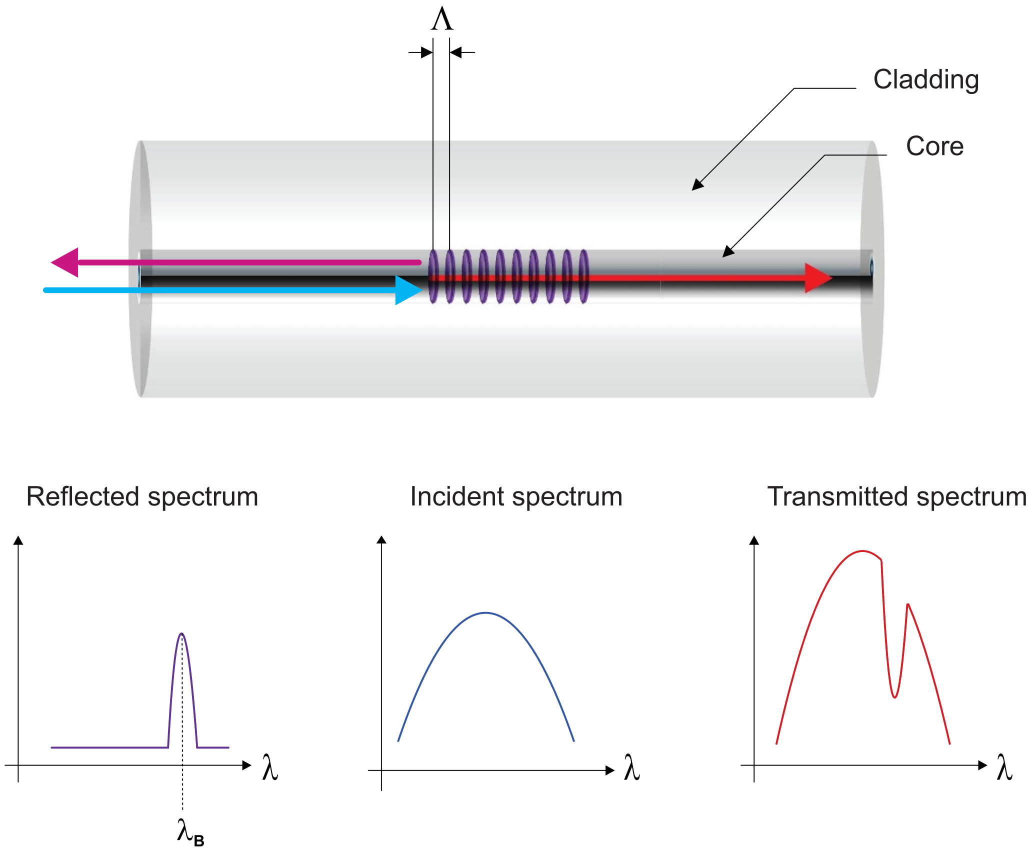


Figure 8. Principle of operation of the fiber Bragg grating sensor.

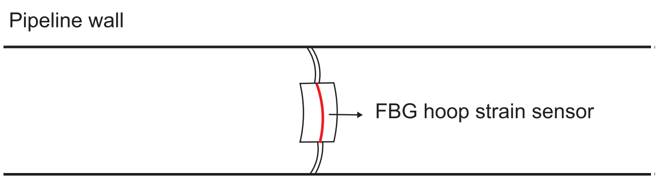


Figure 9. The proposed experimental setup of fiber Bragg grating hoop strain sensor—based method for sudden leakage monitoring of gas pipeline. (Adapted from [41, 42]).

circumferential strain measured by the sensor decreases linearly for a period after a negative pressure wave arrival, which is a characteristic of a leakage event [43, 44].

6.3. Diameter measurement combined with additive manufacturing

Additive manufacturing (AM), commonly referred to as three-dimensional (3D) printing, is a manufacturing technique utilized to fabricate 3D objects based on a digital model. The implementation of this technology has brought about a significant transformation in the manufacturing sector, enabling the fabrication of intricate components that would pose challenges or be unfeasible to produce using conventional methodologies [45]. AM operates by incrementally depositing material in successive layers, thereby justifying its designation as an 'additive' process. This stands in contrast to subtract manufacturing techniques, such as machining, which involve the removal of material from a solid block. AM offers a significant level of customization and design flexibility, rendering it highly suitable for rapid prototyping, production of custom parts, and manufacturing of intricate components [46].

There exist various AM techniques, namely fused deposition modeling, stereolithography, selective laser sintering, and metal 3D printing, each possessing distinct merits and demerits [47]. The selection of a particular technique is contingent upon various factors, encompassing the nature of the material, the intricacy of the design, the intended surface texture, and the associated expenses.

AM has a wide range of applications in various industries. In the aerospace industry, for example, AM is used to manufacture lightweight, high-strength components for aircraft and rockets [48]. In the medical industry, AM is used to create customized implants, prostheses and even bioprint tissues and organs [49]. This technology offers several advantages, such as waste reduction, design versatility, automation possibilities, development of lighter and more robust products, as well as hardness, chemical and impact resistance, transparency and ductility. In addition, it allows the use of biodegradable and biocompatible materials.

AM is a dynamic field that is continuously advancing through ongoing research efforts aimed at the development of novel materials and printing techniques, enhancement of production quality and efficiency, and broadening the scope of applications for this technology [50]. In recent times, the

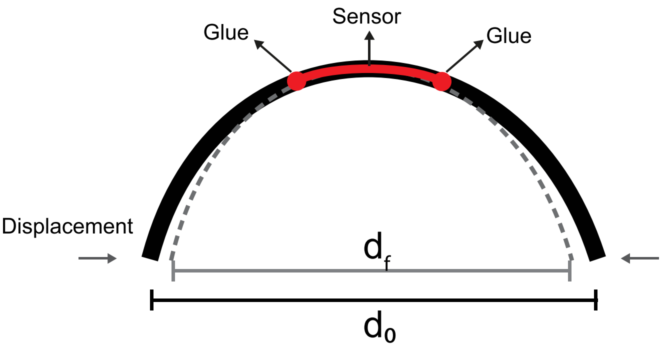


Figure 10. Schematic of the sensor embedded in 3D piece. Reproduced from [60]. CC BY 4.0.

utilization of AM has been observed in conjunction with fiber optic sensors for the purpose of enhancing measurement optimization [51–53]. For example, Yu *et al* successfully devised and manufactured an acoustic sensor based on an FBG combined with a 3D printing technique and employed polylactic acid (PLA) material as its substrate [54]. In general, the integration of fiber optic sensors into different AM structural materials allows for the measurement and analysis of deformation, fatigue damage, and evaluation of structural integrity [55, 56].

According to recent scientific literature, the use of AM with integrated optics opens new possibilities for sensor production and has accelerated and improved the development of analytical technology [57]. Analytical procedures can be rapidly prototyped and improved thanks to 3D printing, which allows fabrication that is simply specified in software. As a result, there is great potential for the creation of new integrated systems in photonics and optoelectronics [57].

Concerning the use of AM for the manufacturing of cylindrical layouts, it has been demonstrated that fiber optic sensing is well suited for diameter measurement of these structures. An example of this is reported by Cardoso *et al* [58–60]. The authors proposed and compared two sensing configurations, one based on a single FBG, another combining an FBG and a fiber taper. The sensors were embedded in a composite material structure (figure 10). Varying the diameter of this 3D generated structure will induce a corresponding response from the sensor. Its characterization shown that both sensing heads can be used to monitor diameter variation. The one with an FBG in series with a tapered fiber demonstrated a sensitivity of 0.54 nm mm^{-1} and a dynamic range of 7 mm, while the configuration with the FBG alone provided a sensitivity of 0.65 nm mm^{-1} and a dynamic range of 6 mm.

In another work the same authors proposed an alternative fiber sensing approach for diameter measurement [61]. It is based on the concept of fiber modal interference. The sensor structure consists of a cylindrical component fabricated using AM techniques, specifically a 3D printer, and a modal Mach–Zehnder interferometer. To mitigate the polarization effects resulting from the sensor curvature two additional rods were incorporated, therefore the sensing device solely experiences the effects of tension on the fiber. The configuration can be observed in figure 11.

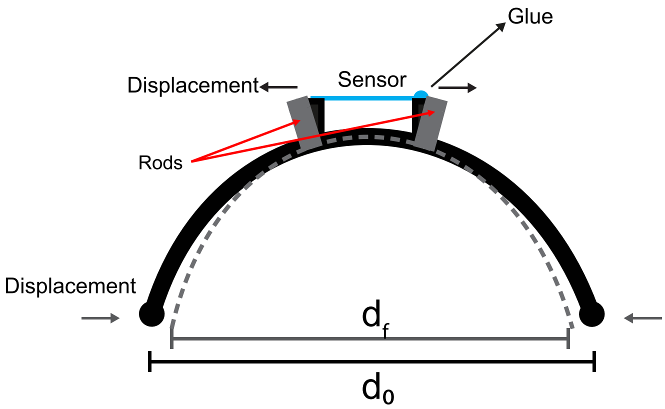


Figure 11. Schematic of the sensor superimpose on 3D piece with rods were incorporated. Reproduced from [59]. CC BY 4.0.

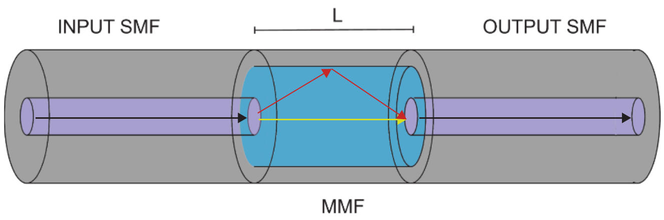


Figure 12. Schematic of the SMS sensor.

The fiber modal interferometer is a single mode–multimode–single mode (SMS) sequence, i.e. it consists of two sections of SMFs and one section of multimode fiber (MMF) [62–65]. The three segments were fused spliced together (figure 12). The presence of the core mismatch between the fibers results in the excitation of multiple modes in the MMF [66–71]. In the multimode section, the longitudinal propagation constants, β_m and β_n, for the m and n order modes are related as [72]:

$$\beta_m - \beta_n = \frac{u_m^2 - {}_n^2}{2k_0 a^2 n_{\text{core}}} \tag{2}$$

where a is the core radius of the MMF, n_{core} is the core refractive index of the MMF, while u_m and u_n are the normalized transverse propagation constants. When the phase difference between two modes is a multiple of 2π the following condition appears [70–72]:

$$(\beta_m - \beta_n) L = 2\pi N. \tag{3}$$

When this happens it comes out [68, 73]:

$$\Delta\lambda = \lambda_N - \lambda_{N-1} = \frac{16 n_{\text{core}} a^2}{(m-n)\left[2(m+n)-1\right]L}. \tag{4}$$

In the structure that includes the rods, the sensor is submitted only to stress, so the wavelength shift depends on the change in the axial strain [61, 74]:

$$\Delta\lambda = -\left(1 + 2\nu + \frac{\rho_e}{n_{\text{core}}}\right)\varepsilon \times \lambda \tag{5}$$

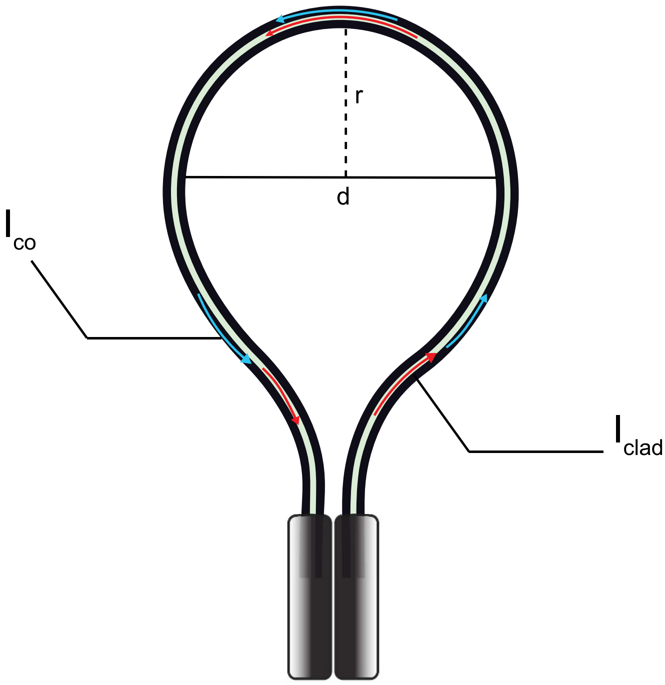


Figure 13. Schematic of the balloon-like interferometer. Reproduced from [59]. CC BY 4.0.

where, ν is the Poisson ratio of the fiber, ρ_e is the effective strain-optic coefficient, n_{core} is the refractive index and ε is the applied strain.

To finish this section shall be mentioned the so called balloon-like interferometric configuration which has been proposed to measure several parameters, in particular diameter variations following the setup illustrated in figure 13.

The interferometer has a d bending diameter and a r bending radius. As light travels through this balloon-like structure, the SMF fiber's curvature causes modal interference between the core and cladding modes. With this setting, the radius and diameter can be modified to suit the requirements of each application. The modal interference pattern shifts when displacement is applied to the interferometer as a result of measurand variations [75–77]. The detection of these shifts combined with proper modeling allows to obtain information about the changes [59, 78, 79].

7. Conclusion

Based on this centenary review article, it can be concluded that the work of Anderson and Barr remains relevant and influential within the context of diameter measurement of transparent tubes and other cylindrical structures. Their two innovative methods, which were ahead of their time, have been a source of inspiration in the last century for the development of other techniques oriented to the same objective. In a first stage these techniques were essentially upgrades of the methods proposed by Anderson and Barr, then evolved to novel approaches but yet supported a similar technological background, and later become possible to revisit most of these sensing configurations with the edge and flexibility provided by new technological developments, most notably the laser and the optical fiber. On this line, the outcome of fiber optics sensing triggered disruptive advances on the field of optical measurement, in particular in optical sensing, opening new perspectives to tackle with high performance the problem of diameter measurement addressed by Anderson and Barr.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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