

EVALUATION OF FREQUENCY SCANNING INTERFEROMETER PERFORMANCES FOR SURVEYING, ALIGNMENT AND MONITORING OF PHYSICS INSTRUMENTATION

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Abstract

During the last three years, the performance of Frequency Scanning Interferometry, accurate to a few micrometres, has been evaluated at CERN in the frame of the PACMAN project. Improvements have been studied and tested to make it better suited for typical alignment and survey conditions in accelerators and experiments. The results of these developments and tests, coupled with the multi-channel capability of the system, and its compactness that eases its integration in the area to be surveyed, offer a wide scope of possible applications for in-situ large-scale metrology for physics equipment and facility elements. Furthermore, the fact that the system electronics can be placed far away from the position to be measured, allows the system to be used in confined and hazardous spaces. This paper briefly describes the system and its improvements. It gives the precision obtained for distance measurements and for the 3D point reconstruction based on FSI observations in the case of CLIC component fiducialization.

INTRODUCTION

Particle accelerator alignment at CERN is synonymous with very demanding requirements. These range from micrometric accuracies, to extreme temperatures and high radiation. Often, traditional instrumentation cannot meet these demands and new alternatives have to be thought. In this paper, we describe Frequency Scanning Interferometry (FSI), a versatile absolute distance measurement technique for which interest at CERN is growing.

FSI

Theory and Origin

FSI was first developed to monitor shape changes of the Semi-Conductor Tracker (SCT) of the ATLAS detector [1] – its origin can therefore be traced to CERN. FSI relies on a frequency tuneable laser that is simultaneously coupled to a measurement interferometer and a reference interferometer – see Fig. 1.

As the laser is tuned over a frequency interval, it induces a phase change $\Delta\theta$ and $\Delta\Phi$ in the measurement and reference interferometers respectively as shown in Eqs. (1) and (2)

$$\Delta\theta = \frac{2\pi}{c} L_M \Delta\nu \quad (1)$$

$$\Delta\Phi = \frac{2\pi}{c} L_R \Delta\nu \quad (2)$$

where L_M and L_R are the lengths of the measurement and reference interferometers respectively, c is the speed of light and $\Delta\nu$ is the frequency interval of the laser during the

scan [1]. Combining Eq. (1) and Eq. (2) results in Eq. (3) from which the length of the measurement interferometer can be calculated if that of the reference interferometer is known.

$$L_M = L_R \frac{\Delta\theta}{\Delta\Phi} \quad (3)$$

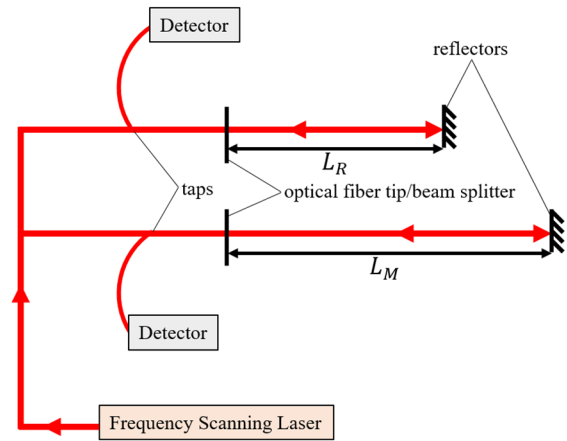


Figure 1: Illustration of a basic FSI implementation [2].

FSI, unlike traditional displacement interferometry can tolerate beam breaks, as it does not rely on counting the absolute order number of fringes. This is very useful in many measurement environments, where obstacles are common.

Absolute Multiline Technology

Basic implementations of FSI such as that shown in Fig. 1 are sensitive to drift. Any drift that occurs during the measurement is magnified by a factor m as shown in Eq. (4) where ν is the average scan frequency and $\Delta\nu$ is the frequency-tuning interval [1].

$$m = \frac{\nu}{\Delta\nu} \quad (4)$$

For a typical tuning interval of 1520 to 1590 nm, m would be equal to 22 – therefore, even sub micrometric drift would become significant.

Absolute Multiline Technology (AMT) is a commercial FSI system (Fig. 2) manufactured by Etalon AG [3]. This system incorporates two frequency tuneable lasers scanning simultaneously in opposite directions. This has the effect of cancelling the drift that occurs in the measurement process. This system has a measurement uncertainty of $0.5 \mu\text{m.m}^{-1}$ ($k=2$) and can measure distances of up to 30 m.

A key advantage of FSI in general is the fact that it can measure multiple distance simultaneously. CERN has recently acquired a couple of AMT systems that measure

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eight distances simultaneously. However, it is possible to upgrade these systems to measure up to 124 distances simultaneously. By attaching optical switches to the individual measurement channels, a single AMT system has the potential to measure several hundred distances. However, in this case the distance measurements related to the different channels will not be simultaneous. A measurement time of several seconds should be considered.

The AMT measurement arm consists of optical fibres that are typically 10-20 m long but can be up to a few kilometres long. This capability brings a number of advantages. Firstly, one central unit can perform measurements in a number of spatially separated measurement locations without having to move it. Secondly, very large assemblies can be measured by a single AMT system in an instant.

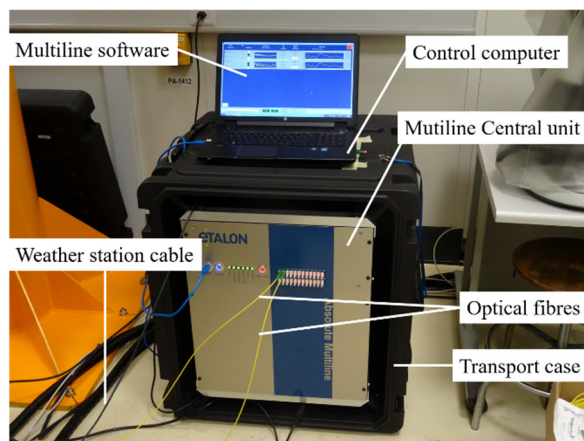


Figure 2: Absolute Multiline Technology control unit.

The AMT measurement head is an optical fibre tip attached to a collimator that collimates light to a retroreflector (Fig. 3) and focuses the retroreflected light back into the optical fibre. The commonly used F280FC Thorlabs collimator is lightweight (30 g) and small (11 mm diameter and 27 mm length) - this means that they can be installed easily even in tight spaces.

AMT, unlike earlier FSI implementations, incorporates a gas cell reference that acts as a reference from which FSI distances are measured. By measuring $\Delta\Phi$ and $\Delta\nu$, the length L_R , of the reference interferometer, which is simply an optical fibre, can be determined using Eq. (1) [2]. Since L_R is determined during each scan, bulky evacuated references with long-term stability are not needed. Because of this, AMT is portable.

The system is equipped with a weather station that measures temperature, pressure and humidity. The impact of these environmental factors on the refractive index of air is corrected and the 0.5 μm ($k=2$) AMT distance uncertainty includes the uncertainty with which the refractive index of air is determined. Therefore, this system can measure with micrometric accuracy even in environments where the temperature is fluctuating.

The AMT measurement beam is infrared and cannot be seen by the naked eye. The system incorporates a red guide laser that makes alignment easier.

As an off the shelf product, AMT cannot measure distances in different directions from the same point. This restricts AMT measurement channels to one dimensional distance measurements. Consequently, the usefulness of AMT is somewhat restricted. For example, it cannot be used to determine 3D coordinates of points.

Particle Accelerator Component's Metrology and Alignment to the Nanometre scale (PACMAN), was an EU funded project hosted at CERN. PACMAN was geared towards the development and improvement of a number of metrology tools that were directly applicable to the Compact Linear Collider (CLIC) project but with potential to be extrapolated to other research and industrial projects. One of the subjects tackled within the PACMAN projects relates to developments that address some of the limitations of the AMT and thus increases its usefulness and is the subject of an ETH Zurich PhD study.

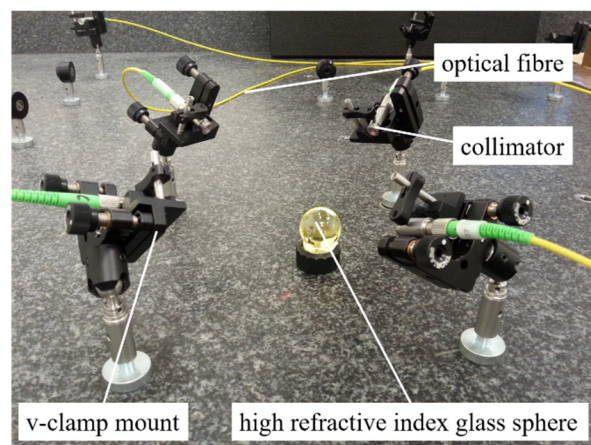


Figure 3: Four FSI channels mounted on kinematic V-clamp mounts measuring to a high refractive index glass sphere used as retroreflector.

DEVELOPMENTS

Localization of FSI Optical Fibre Tip

The first development concerns the localization of the optical fibre tip. The approach used involves inserting the FSI collimator, which is attached to the fibre tip, into a 38.1 mm diameter ceramic reference sphere [4]. The goal is to reference the fibre tip to the centre of the reference spheres. However, no attempt is made to position the fibre tip exactly at the centre of the sphere, as this would be difficult and costly. Therefore, there is an offset between the tip of the fibre and the centre of the sphere. This offset is split into two components; a y offset perpendicular to the direction of the FSI beam propagation and an x offset along the beam. The y offset has a small impact on the measured distance that reduces with distance. If the FSI beam is properly centred on a retroreflector, a considerably large 0.5 mm y offset introduces a distance error of only 0.25 μm at a distance of 0.5 m reducing to 0.05 μm at 2.5 m. The x offset can easily be calibrated.

Another development is a three-ball base support for the repeatable positioning of the reference sphere [4]. This

support is also suitable for Spherically Mounted Retroreflectors (SMR) – see Fig. 4.

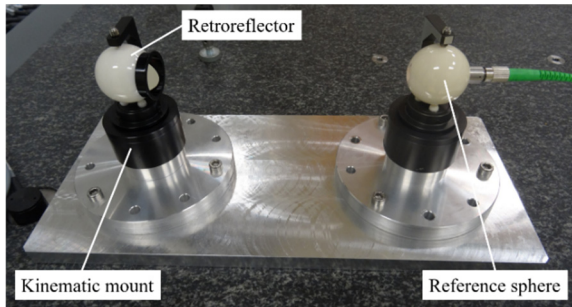


Figure 4: SMR (left) and reference sphere (right) mounted on three ball supports

The distance standard deviation of positioning a sphere on the support is $0.2 \mu\text{m}$ while the distance repeatability due to point the beam emanating from the reference sphere is $0.6 \mu\text{m}$.

The reference sphere placed on top of a three-ball kinematic mount enables the AMT laser beam alignment from a same point to different directions and then distance measurement to different retroreflectors. Therefore, AMT can be used for coordinate measurement via multilateration [5].

High Refractive Index Glass Spheres

One disadvantage of commercial SMRs is their limited acceptance angle of about $\pm 30^\circ$ which somewhat limits the region within which measurement instruments can be placed. To overcome this, the SMR has to be physically oriented towards the instruments, a fact that increases the measurement time and is an additional source of uncertainty. In many applications, it is not physically possible to orient the SMRs since they are not accessible.

High refractive index glass spheres can act as retroreflectors [6] with an unlimited acceptance angle. However, they have low efficiency – the retroreflected beam has only about 8% of intensity of the incident beam.

We have developed and validated high refractive index glass spheres that are compatible with AMT. These 12.7 mm spheres are made of TAFD55 glass to which a steel disc has been added to allow mounting on magnetic supports. A 100 nm thick layer of aluminium is placed between the sphere and the steel disc and the reference sphere to prevent undesirable reflections from the steel disc.

Results

The distance repeatability due to pointing the FSI beam in the reference sphere to the TAFD55 glass targets is $0.6 \mu\text{m}$.

The prototypes developed, i.e., the reference sphere, kinematic mount and TAFD55 targets were used to build a multilateration network for the fiducialization of a CLIC main beam quadrupole magnet and beam position monitor [5]. The coordinate uncertainties achieved were $< 3 \mu\text{m}$. The total combined fiducialization uncertainty was $4.4 \mu\text{m}$, which is below the $5 \mu\text{m}$ stipulated uncertainty for CLIC components with the tightest uncertainties.

We compared the coordinates determined by our network with those measured with a Leitz Infinity Coordinate Measuring Machine (CMM), which has a Maximum Permissible Error of $0.3 \mu\text{m} + 1 \text{ ppm}$. The Root Mean Square Error (RMS) was found to be $5.1 \mu\text{m}$ showing close agreement between our solution and this high-accuracy CMM.

Other Applications and Perspectives

The FSI reference sphere in combination with and SMR can enable AMT to provide an accurate active scale – for example for QDaedalus, a micro-triangulation system that can measure white ceramic target spheres.

AMT will be used in the High Luminosity Large Hadron Collider (HL LHC) to monitor position changes of crab cavities whose role is to reduce the crossing angles of beams in order to increase luminosity [7]. AMT has been chosen for this project because the collimators can withstand radiation levels of up to 10 MGy and a temperature gradient of between 2K and room temperature.

CONCLUSION

FSI is a very exciting technology that has a lot of potential for particle accelerator alignment. We have presented improvements to AMT, a commercial FSI system that allow it to perform 3D coordinate measurement, a fact that has been exploited for the fiducialization of CLIC components. We have also presented other CERN applications for the LHC.

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