3D Optical Spectroscopic Methods in Astronomy
ASP Conference Series, Vol. 71, 1995
G. Comte, M. Marcelin, eds.

The Scanning Fabry-Perot Spectrometer

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Abstract. In this review the development of the Scanning Fabry-Perot for use in Astronomy, from its invention to the present day is described. The limitation of angle scanning and pressure scanning led to the development of piezo scanned etalons incorporating capacitance micrometers to form a servo-controlled system.

1. Introduction

It was in 1831 that George Airy first described mathematically the coherent addition of multiple reflections between two plane surfaces. However it was more than 60 years later that the interesting case where both surfaces are high reflectors was first explored in detail by Fabry and Perot. Not only did they solve extreme practical difficulties to build a working instrument, but they were also the first to realise the range of potential applications. For a period of more than 30 years Fabry, Perot, Buisson and others used this new interferometer in a wide variety of applications, developing the art of the method of exact fractions to increase the precision of fundamental length measurements, the wavelength of atomic lines, and the study of emission lines from gaseous nebulae.

Fabry and Perots' first scanning interferometer used a modified theodolite for adjusting the angle of one of the plates, whilst the other was mounted on a flexure stage which allowed the plate spacing to be changed through the change in the water level in a rubber balloon in physical contact with it. This allowed a smooth change in spacing, so the FP rings could be scanned. An engineered version of this FP was produced by Jobin in 1899 and described by Fabry (1923). In fact this instrument still exists at the Observatoire de Marseille, having narrowly missed destruction during the Second World War.

The use of Fabry-Perots' in Astronomy in the years following Fabry's death continued mainly in France. It was not until 1954, when Jacquinot (1954), and his student Chabbal (1958), realised that for a given resolving power the FP had an enormous advantage in light gathering power over gratings or prisms of similar size, that there was a resurgence in interest in the FP.

At this time the main mode of operation of the FP in astronomy was photographic. With the FP in the pupil of a focal reducer an image of an object was formed on a photographic plate, with the Fabry Perot fringes superimposed upon it. The fringe system for a reference line would also be recorded, and the difference analysed in terms of the velocity field of the object (Carranza, 1968).

This is essentially a form of angle scanning. With the FP in the pupil, different parts of the image pass through the FP at different angles, and hence at different wavelengths. Typically a fixed gap FP is used, sometimes referred to as an etalon.

2. Scanning Fabry-Perots

With the advent of high quantum efficiency photomultiplier tubes in the mid 1960s, single point measurements of high efficiency could be made. Although the photographic use of the FP gave a large spatial multiplex gain, it was at relatively low quantum efficiency (typically less than 1%). However photomultiplier tubes reached a peak quantum efficiency of 20% in the blue. This was of most use in studying point sources at high resolution, for example the study of interstellar absorption lines in the spectra of bright stars (Mack et al, 1963, Hicks at al, 1975). In this case it was necessary to scan the FP either by tilting it or by changing its spacing, or by changing the index of refraction.

Tilting the FP causes the line profile to vary during the scan, which complicates data analysis. This is because as one moves a finite aperture off the central spot of the FP ring system, so the luminosity is reduced and the line profile broadens and becomes asymmetric. Pressure scanning and gap scanning were much more successful techniques for producing high quality data.

2.1 Pressure Scanning

Pressure scanning was popular for about 20 years, from the mid 50's to the mid 70's, and some pressure scanned systems are still in use today, most notably the highly productive PEPSIOS system (Mack et al 1963; Roesler et al, 1974).

Changing the index μ by changing the air pressure is fairly straightforward. However the scan range is limited by $d\mu/dP$ for air. Other gases, notably propane and butane (although not the most fragrant) have higher $d\mu/dp$ allowing scan ranges of up to about 5 Angstroms to be achieved.

Once the limitations of range speed and finesse inherent in these techniques became clear a number of workers began using piezos to fine-tune their etalons.

2.2 Piezo Scanned FP's

By the mid 1960's most pressure scanned etalons were of the optically contacted design, with the plates and spacers 'wrung' together. The optical contact bond relies on the surfaces being sufficiently clean and smooth that the intermolecular forces will hold the parts together. Such designs are very stable, and free from the sensitivity to vibration which plagues mechanically mounted FP plates. However, because of the difficulty in manufacturing the spacers to exactly the right length, it is difficult to get very high finesse except over a small area, unless the spacers could be adjusted. Usually this was achieved by applying a spring force above the spacer in order to change its length by compressing it slightly. In this way finesses up to 30, over a 6 inch diameter became feasible. From here it was but a small step to include piezos in the spacer (Bates et al, 1966), to allow fine tuning of the cavity spacing and parallelism. At this point however the characteristics of the piezos become important, in particular hysteresis, non-linearity and creep.

2.3.1 Piezo-Electric Translators

The piezo electric effect is a well known phenomenon in which a voltage is generated across two faces of a crystal when it is subjected to a stress. In the inverse piezo-electric effect a voltage applied between two faces of a crystal or ceramic will cause the material to change its shape. For most natural materials this effect is very small. However ceramics (most notably Lead Zirconate Titanate) have been developed in which the effect reaches a maximum dimensional change of about 0.1% with a field strength of 1kV/mm. So to get an extension of 5μm requires about 5mm of material. In order to reduce the field from 5kV, a stack of ceramic disc is used, interleaved with electrodes.

In practice piezo translators of this form have effectively infinite positional resolution. Tests at Queensgate show that the minimum resolvable step is certainly below 1 picometer. In practice this resolution is limited by the voltage noise, which produces a noise equivalent motion in the FP cavity. Electrically piezos appear as capacitors, and so need to be charged up to produce a change in dimension. The current limit of the drive amplifier thus limits the maximum speed of any large change. For small movements the characteristic response time of piezos is about 5μsecs.

Piezos are also extremely stiff and can generate very high forces, so the Fabry Perot construction is also very stiff, leading to vibration immunity and high resonant frequencies for the etalon (up to 40kHz).

2.3.2 Hysteresis

The main disadvantage of the piezo translator is the phenomenon of hysteresis. The relationship between voltage and position is not linear or single valued.

In effect the position depends upon where the piezo was before. Figure 1 shows a typical hysteresis curve for a piezo translator. Note that the response is non-linear. Furthermore the piezo tends to creep slowly, continuing to expand or contract, even when the voltage has stopped changing.

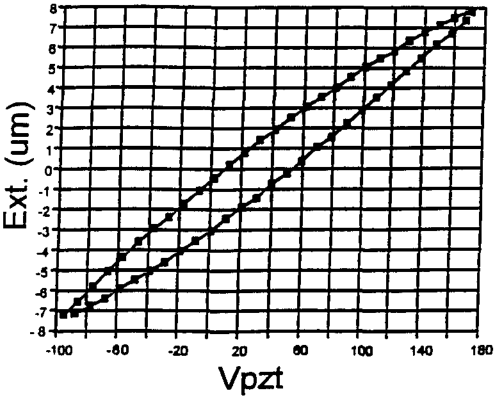


Figure 1. Hysteresis behaviour of a piezo-electric translator

For laboratory applications, some workers have overcome these difficulties, correcting the linearity in hardware, and using rate and bias adjustments on the electronic controllers to ensure the plates start parallel and also scan parallel. Systems of this kind have been used productively in astronomy, but usually at the coude focus, in a temperature controlled environment, and requiring frequent attention (Smith et al 1976).

Operation at the coude focus is acceptable for the study of bright point sources. But for imaging faint extended sources, for which the use of the FP is most advantageous because of its luminosity and efficiency, the cassegrain focus is essential. Here the efficiency is higher and the image does not rotate.

However operation at the Cassegrain focus of a large telescope is another matter entirely. Here there are vibrations from motors and pumps, rapidly changing temperatures, and changes in orientation which cause mechanical structures to flex by tens of microns, far more than can be tolerated by a mechanically tuned FP.

For successful operation in this environment some kind of position sensor is required to correct for the hysteresis of the piezos and the mechanical deformations of the structure.

3. The Imperial College Servo Stabilised FP

In 1970, at the Astronomy Group of Imperial College London, Reay, Hicks and Scaddan began the development of a piezo-tuned FP system using capacitance sensors to servo stabilise the cavity. Capacitance sensors were preferred to laser interferometers or white-light fringe systems (eg. Ramsey 1966) because of problems of scattered light and fringe hopping.

3.1 Capacitance Micrometry

Capacitance micrometry is an extraordinarily sensitive technique for measuring relative motions. A typical capacitance sensor might consist of two conductive pads, 12 mm in diameter, separated by a spacing of 50μm, producing a capacitance of approximately 20pF. A change in the sensor spacing of 1 nm will produce a change in capacitance of 0.4 femtoFarads. Surprisingly this can be measured with a capacitance bridge. In fact, using sophisticated electronics, a sensitivity of about 1 picometer can be achieved in about 1 second averaging time. Such sensors can be configured to produce high linearity (<0.1%) zero hysteresis (<5 pm) and can be fabricated from high stability materials such as Zerodur and Fused Silica.

In fact with long enough integration times the resolution of these sensors can reach about the size of an electron (10^{-14}). Commercially available systems can easily resolve the diameter of a Hydrogen atom (0.1 nm), or the separation of atoms in the Silicon lattice (~0.3 nm).

For the purposes of controlling a Fabry Perot Interferometer in the mid-visible such sensitivity is clearly good enough, $\lambda/1000$ being equivalent to 0.5nm. At a finesse of 50 the change in plate spacing required to tune over one passband is about 5nm. So a noise level of 0.1nm in the cavity is about 2% of a passband width.

3.2 CasFPer

Affectionately known as CasFPer (for obvious reasons) the first prototype servo-stabilised FP was first tested at the 2.5 meter Isaac Newton Telescope at Herstmonceux, Sussex, and used to study the [OIII] lines of planetary nebulae.

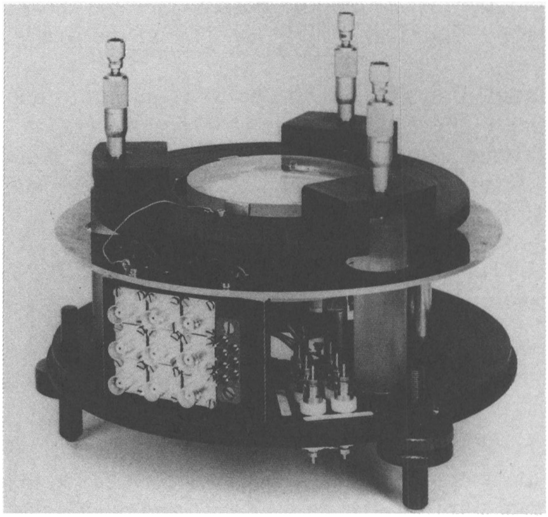


Figure 2: The CasFPer servo-stabilised FP, Mark I

This first generation device was piezo-tuned, capacitatively stabilised, and mechanically aligned, using micrometers. Several limitations were immediately apparent:

- mechanical drift in the micrometers would quickly use up the range of the piezos, requiring readjustment of the FP every few hours;
- the scans, while repeatable and free of drift, were not linear
- the plates while parallel at the beginning of a scan were not perfectly parallel at the end. This effect was christened 'dynamic parallelism'.

This led first to schemes for correcting the linearity and dynamic parallelism. However we soon realised that these corrections would be etalon specific, in that they relied upon the capacitance sensors having specific orientations and overlaps.

4. The Queensgate Servo Stabilised FP

In 1978 the Astronomy Group moved out of 10 Prince's Gardens, a large Regency terraced House, off Prince's Gate, to a new building on Queen's Gate, a road leading from the Queen's gate of Hyde Park in London. It was here, in the basement of the Physics Department of Imperial College, that Queensgate Instruments was born, in November 1979.

Based upon several years of experience we designed a second generation system as part of the Taurus Imaging FP system, a collaborative program between Imperial College and the Royal Greenwich Observatory (Atherton et al, 1982). This design used several new techniques, including optically contacted piezo-tuned etalons, and a much more sophisticated control system. The advantages were improved linearity, elimination of dynamic parallelism, improved stability, reduced noise and the ability to control a wide range of etalons designed for different tasks.

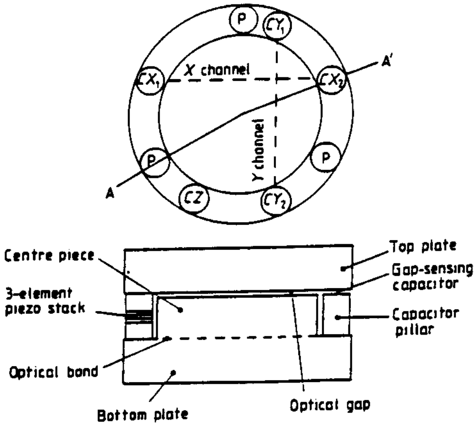


Figure 3: The Queensgate servo-stabilised Fabry-Perot

Parallel plate capacitance sensors are formed around the edge of the Fabry Perot cavity. The etalon plates themselves are held apart by three pzt actuators A,B,C. CX_1, CX_2, CY_1, CY_2 and CZ are five parallel plate capacitors formed by evaporating gold pads onto fused silica pillars fixed to one of the plates. The optical gap is set at the time of manufacture by adjusting the thickness of the fused silica centre piece.

In operation parallelism information is obtained by comparing CX_1 with CX_2, CY_1 with CY_2, while the spacing is controlled by comparing CZ with a fixed external reference. CREF.

Figure 4 shows schematically the bridge circuit used for comparison of the capacitors, and the way in which the error signals are combined and applied to the piezo-electric transducers to form three closed servo loops.

The three capacitance bridges are driven by four AC Bridge drive voltages Vx, Vy, Vz and Vcom.

Vx, Vy and Vz are nominally equal to each other and of nominally equal amplitude to Vcom, but of opposite phase. Thus taking the X channel as an example, if CX_1 is the same as CX_2 then no current will flow into the current amplifier, and the bridge is balanced. If now the etalon parallelism changes such that CX_1 does not equal CX_2, then a current will flow into AX. This will be 90 degrees in advance of Vcom if $CX_2<CX_1$ and 90 degrees retarded if $CX_1>CX_2$. The Phase Sensitive Detector will thus generate a voltage which is proportional to the error in both magnitude and sense. This voltage is ampified by the B channel HV amplifier and applied to the PZTs in such a way as to reduce the error, forming a servo-control loop.

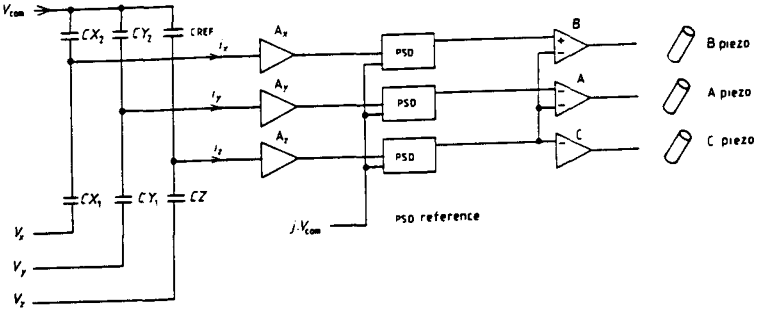


Figure 4: Schematic of the servo-loop

In practice it is necessary to use a simple coordinate transformation to correct for the fact that the piezos are situated at 120 degree intervals, so as to separate the motions required for the three different servo-loops : X,Y and Z.

In practice when the interferometer plates are parallel then CX_1 will not equal CX_2 because of manufacturing tolerances. Hence it is necessary to provide for a means of balancing the channels through external offsets, to allow adjustment of parallelism and spacing.

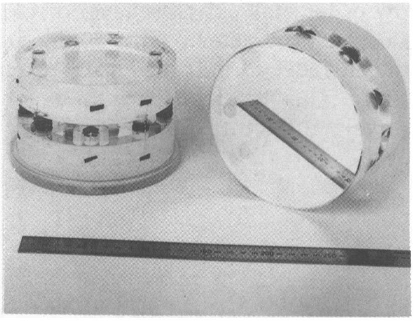
5. Performance

We have tested the stability of this servo-controlled Fabry Perot by monitoring the intensity change occurring when the passband is positioned at the half intensity point of the 6438.7 A Cadmium line from a high pressure lamp, selected because of its wavelength stability, linewidth and intensity stability. The drifts measured were less than 0.1nm in the cavity over a period of an hour. This experiment is reported in detail by Hicks et al (1984). Righini (1992) reported a stability in the cavity of 0.08nm over 16 hours using a sealed cell and controlling the etalon temperature to 0.01k and the electronics to 0.1k.

6. Present and Future Developments

So far we have delivered about 100 of these systems to astronomers and aeronomers around the world. Systems are in operation at the South Pole, Northern Alaska, Russia, China, India, Chile, Japan and all over Europe and the United States. There is even a system in orbit on the Upper Atmosphere Research Satellite as part of the Wind Imaging Interferometer. The highest population density is probably on Mauna Kea, Hawaii.

Fabry-Perot technology continues to evolve rapidly. Nowadays a major application of this technology is in telecommunications. Queensgate has recently developed the MicroFilter, a miniature single-mode fiber-coupled, piezo-tuned FP which is used to isolate one of 256 lasers propagating down a single optical fiber.



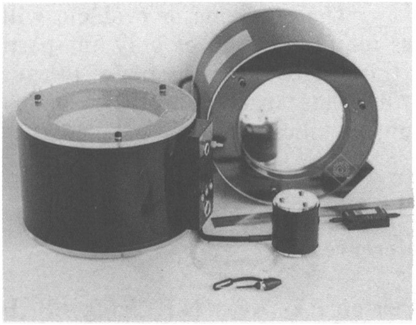


Figure 5a: two 120mm diameter etalons (ET116). The piezo stacks and capacitance sensors can be clearly seen around the edge of the etalon.
Figure 5b: a MicroFilter compared with two ET116s and an ED25.

Acknowledgements

The development of the Queensgate Fabry-Perot system involved primarily Tom Hicks, Ken Reay, Jim Ring, Martyn Wells and myself, with contributions from Terry Dines and Harry Yates of I C Optical Systems and the support of many technicians and craftsmen. For a detailed review of Fabry-Perot theory see for example Atherton et al (1981). For a fascinating review of the history of the development of the Fabry-Perot see Vaughan (1989).

Discussion

J. Bland-Hawthorn: It is widely recognized that Queensgate Instruments are the world leaders in gap scanning optics. It is not so clear that the development of interference coatings is keeping pace with your achievements. How does one apply high quality coatings for gap spacings of order 1 micron.

P.D.Atherton: There have been huge strides in coating development over the past few years. Ion-beam sputtered coatings are much denser amd more reproducible, while crystal monitoring and real-time spectroscopic monitoring of the coatings during deposition allows much higher accuracy to be achieved in the coating process. Ellipsometric techniques allow the actual multilayer complex refractive indices to be determined as a function of wavelength, and fed back into computer models to increase the accuracy of the modelling process.

We have recently produced coatings optimised for two, separate wavelength windows, and also coatings which increase their refelctivity with wavelength.

The next step is to control the phase on reflection as a function of wavelength. This is a major limitation on the effectiveness of low-order FPs, since the FSR achieved is usually much smaller than predicted because of this effect.

The other major problem with low order etalons is the level of cleanliness required. It takes only one particle of 2μm diameter over a 50mm area to be trapped between the plates to cause the surfaces to deform locally around it as the plate spacing decreases below 2μm. This level of cleanliness is only found in silicon fabrication plants, and is very difficult to achieve.

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