The Advances & Technologies Of Galvanometer-based Optical Scanners

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ABSTRACT

The technology of closed loop galvanometer-based optical scanners continues to be advanced, enabling a broader range of laser system applications and uses. Advances in the technology have provided major improvements in galvo positioning speed, accuracy, size and cost. Galvanometers are designed with a variety of positioning actuator and detection technologies to provide the system integrator with a flexible range of price/performance options. As an example, Cambridge Technology offers 13 different models of galvanometers with several different configurations of actuator and position detector technology to allow the optimization of positioning speed, accuracy, cost and size.

This paper will introduce the benefits, operating ranges and recent advances in galvanometer technology for scanning applications. Several different actuator and position detector technologies and designs will be presented. This will include moving iron, moving coil and moving magnet actuators along with several capacitive and optical position detector designs that offer positioning speeds as fast as 150 micro-seconds and positioning repeatability/resolution to a single microradian. The performance and system design trade-offs that one should consider during the selection of the appropriate galvanometer technology and the optical systems design will be discussed along with a performance comparison of the galvanometer to other optical scanning technologies.

Keywords: Galvanometer, Optical Scanner, Moving Coil, Moving Magnet, Positioning, Beam Steering, Laser

1. INTRODUCTION

Closed Loop Galvanometer-based Optical Scanners have been used in laser-based system applications for many years. The continued advances in this technology have broadened their integration into a increasing range of beam steered system applications and optical system designs. The popularity of the closed loop galvanometers stems from its unique combination of positioning accuracy, speed, control flexibility, ease of integration and cost for optical scanning applications. This paper will cover the basics of the Galvanometer-based Optical Scanner technology along with the options, advances and performance levels that are achievable with closed loop galvanometer technology. Also included is a performance comparison with other optical scanning technologies.

2. GALVANOMETER BASICS AND TECHNOLOGY OPTIONS

There are three main elements to a closed loop galvanometer system – the positioning actuator, the position detector and the closed loop servo control electronics. For each of the main system elements, there are several different design topologies and technologies that provide unique levels of positioning accuracy, speed, size and cost.

2.1 The Actuator

Most modern galvanometer actuators function on the basic principles of a permanent magnet motor where the interaction of a permanent magnet and the magnetic field created by a current in a wire coil result in a rotary torque on the actuator's rotor. The galvanometer actuator's rotor is suspended on a set of bearings and is designed specifically for precision high speed motion over a limited angular range. Galvanometers are available in three different actuator configurations – the original moving iron actuator design and the more advanced style moving coil and moving magnet actuators.

The key performance criteria of a galvanometer actuator are its torque/inertia ratio, its maximum peak and RMS torque capability, its mechanical resonant frequency, its positioning repeatability characteristics and its bearing technology lifetimes. The response time of the galvanometer is defined by the torque constant and peak current capability, its inertia and its mechanical resonant frequency. The galvanometer's maximum repetitive frequency is defined by its maximum power capability and ability to dissipate its operating heat. The positioning precision of the actuator is defined by its bearing

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suspension, its design sensitivity to manufacturing tolerances and its method of integrating a position detector technology into its design.

In all three actuator styles, the actual performance is defined not only by the style of actuator chosen but also by the design implementation details that vary from vendor to vendor. The performance comparisons presented, while general in nature with respect to each position detector style and configuration, represent details and conclusions that may be very specific to Cambridge Technology proprietary designs and product offerings.

The original galvanometer Moving Iron Actuator design (as shown in Figure 1) offered a relatively high positioning torque constant capability but was limited in its high speed performance due to the magnetic saturation properties of the Iron rotor. This actuator design was also often only available with older position detector technology that required a torsion bar spring and provided reduced levels of positioning accuracy, stability and reliability over time.

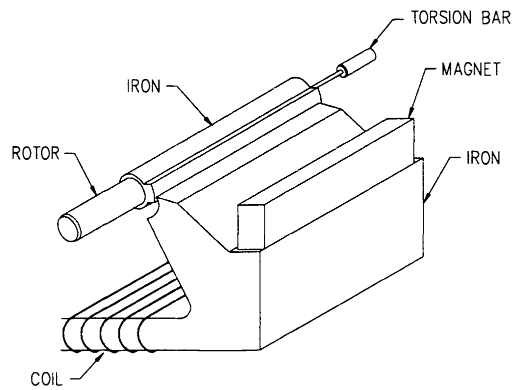

Figure 1. A Moving Iron Actuator

The Moving Coil design of actuator (as shown in Figure 2) offers high torque/inertia ratios, high peak/RMS torque and resonant frequency characteristics due to its high flux/low inertia rotor design and the use of high energy density neodymium iron boron magnets. The moving coil actuator coupled with a front end moving butterfly position detector offers the highest level of positioning accuracy available in galvanometer technology with extremely high levels of short term and long term repeatability and stability.

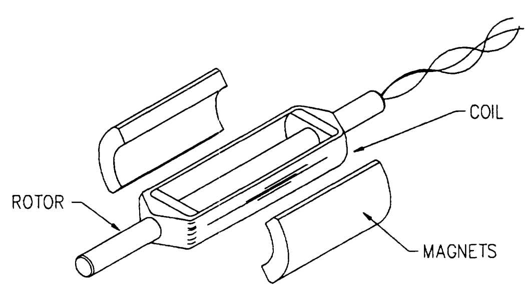

Figure 2. A Moving Coil Actuator

The Moving Magnet Actuator (as shown in Figure 3) offers the highest mechanical resonance, high torque constant and torque/inertia ratios and very good positioning repeatability characteristics. The Moving Magnet galvanometers are also typically designed with high energy density neodymium iron boron magnets. They offer the highest positioning speeds due to the higher resonant frequency characteristics of the solid moving magnet rotor design.

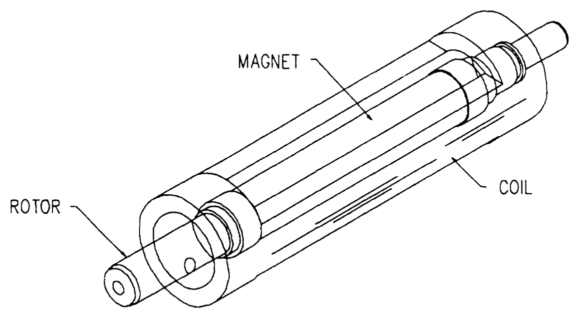

Figure 3. A Moving Magnet Actuator

2.2 The Position Detector

The key to positioning accuracy and precision in a closed loop optical scanner is the Position Detector which senses and reports the actual position of the actuator for the closed loop servo system. Several electronic and optical design configurations and patented techniques are used in commercially available galvanometers. Position Detector technology is one of the key areas where there has been continued innovation in the last several years to broaden the galvanometer price/performance levels that are available to the optical system designer. When integrated with a high speed actuator and used in conjunction with the appropriate position demodulation and closed loop servo control electronics, very high levels of positioning accuracy and stability can be achieved, down to the single micro-radian level of positioning resolution.

The key performance criteria of a galvanometer's position detector are Positioning Repeatability, Linearity, Time and Temperature Drift. The complete set of system requirements often add both size and cost to the system designers list of position detector and galvanometer requirements. At least two different types and several different configurations of each type of position detector technology are used in currently available closed loop galvanometers. Once again, the actual positioning performance is defined not only by the position detection configuration chosen but also by the actual implementation details that do vary from vendor to vendor. The performance comparisons presented, while general in nature with respect to each position detector style and configuration, do represent details and conclusions that may be very specific to Cambridge Technology proprietary designs and product offerings.

2.2.1 Capacitive Position Detection

The typical Capacitive Position detection method works on the principle of a differential capacitor which changes values with the rotation of the galvanometer actuator. The change in capacitance provides the indication of angular galvanometer position. The typical capacitance position detector electronics employs a high voltage, high frequency AC source and position demodulation circuits to measure the change in capacitance and report the actual actuator position. The output signal is typically with two differential currents whose difference is proportional to the actuator's angular position.

2.2.1.1 The Radial Capacitance Method:

The Radial Capacitance Detection method was used in the original Moving Iron galvanometers. It detected the change in capacitance between the iron housing of the stator and radial plates integrated into the actuator rotor. This design configuration (shown in Figure 4) did offer reasonable positioning control but was limited in its absolute positioning accuracy, long term stability and reliability due to the placement of the capacitive plates and their dependence on very precise and stable manufacturing tolerances and materials.

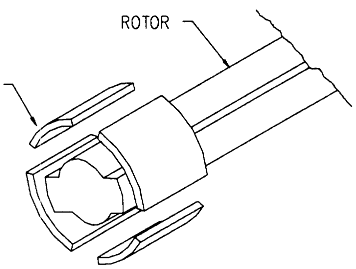

Figure 4. Radial Capacitive Position Detector

2.2.1.2 The Moving Dielectric Butterfly Capacitive Method

The Moving Dielectric Butterfly Capacitive Method (shown in Figure 5) uses a low inertia dielectic "butterfly" mounted axially to the actuator's rotor and positioned between four cross-coupled circuit board "plates" to form the Position Detector's "variable capacitors". The capacitive plates are cross-coupled to provide error cancellation of manufacturing tolerances and any non-radial actuator motion. This patented capacitive position detection method when used in conjunction with position demodulation that includes this error cancellation and automatic gain control provides positioning repeatability down to the single micro-radian level (i.e.1mm resolution at 1Km).

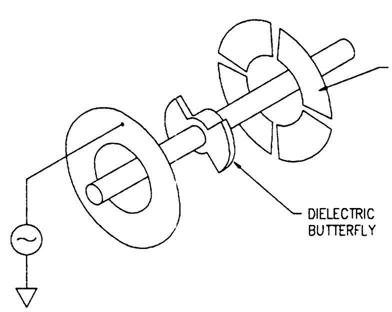

Figure 5. Moving Dielectric Butterfly Capacitive Position Detector (Cambridge Technology US patent # 4864295)

2.2.2 Optical Position Detection

The most common Optical Position detection technology works on the principle of a light source or sources, a blocking element secured to the rotor of the actuator and the photocell measurement/detection of the transmitted light. The amount and location of the measured light is a measure of the galvanometer's angular position. Much like the capacitive position detector, the output of the optical position detector is typically two differential output currents whose difference is proportional to the actuator's position. The key advantages of the Optical Position Detector are size and cost.

2.2.2.1 The Radial Optical Position Detector

Cambridge Technology's first patented Optical Position Detector significantly reduced the size and cost of galvanometer position detector technology. This position detector employed two LED light sources, an actuator vane and four "cross-coupled" photocells to measure position. This class of Position detector does not offer the same level of positioning accuracy as the capacitive type but it offers reduced size/cost, good position accuracy and increased speed for those applications with less demanding accuracy requirements.

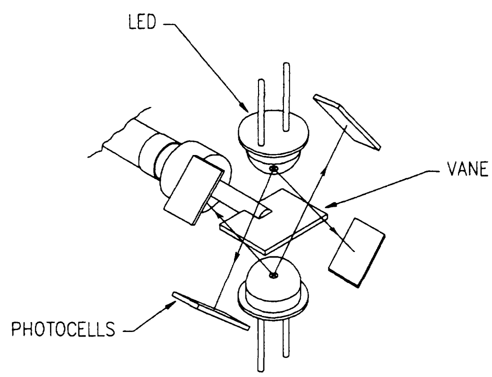

Figure 6. Radial Optical Position Detector (Cambridge Technology US patent # 5671043)

2.2.2.2 The Advanced Optical Position Detector

Cambridge Technology's newest innovation and patented Advanced Optical Position Detector technology (employed in the recently introduced Model 6200 and 6210 galvos) has significantly advanced the accuracy, stability, size, and cost that can be achieved with optical position detector technology. This position detector uses a new optical configuration with one LED light source, a blocking butterfly and a cross-coupled array of photocells to achieve the size reduction along with improved linearity, repeatability and drift specifications.

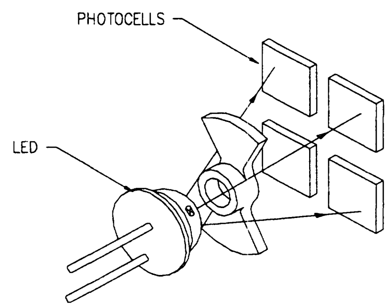

Figure 7. Advanced Optical Position Detector (Cambridge Technology US patent # 5844673)

2.3 The Servo Control

Equally critical to a closed loop optical scanning system for positioning speed, accuracy and system integration is the servo control electronics. Much like the actuator and position detection technology associated with the galvanometer, there have been significant advance in the design and feature sets of servo electronics over the last two years. New Servo topologies and electronics support higher speeds, improved accuracy, more system integration features and the reduced size of surface mount technology. As there are a number of options in the selection of the most appropriate type of galvanometer for an application, there are also options in the selection of proper servo configuration and features for an optical system application. There are two basic types of galvanometer servo, the Integrating and Non-Integrating servo, and there are many servo features that should be considered in the integration, control and cost of a galvo-based scanning system.

2.3.1.1 The Integrating Servo

The Integrating Servo architecture employs not only position and velocity terms in its closed loop system control but also an error integration factor to minimize positioning error and provide the highest level of positioning accuracy and resolution. This type of servo is used in applications which require the maximum positioning accuracy of the galvanometer being used.

2.3.1.2 The Non-Integrating Servo

The Non-Integrating Servo architecture does not employ error integration and is used in applications with less demanding positioning accuracy requirements and maximum speed requirements.

2.3.1.3 Servo Feature Sets

Beyond the basic style of servo chosen, there are also many advanced servo features, which can be critical to the integration of a closed loop galvanometer into a system design. Some of those features that should be considered in servo selection include:

- Low Frequency and High Frequency Damping to reduce noise and improve resolution.
- Bandwidth Enhancement Modules to maximize system speed.
- Signal Conditioning for control of small and large angle moves.
- Scan Field Sizing to application requirements.
- Power-on/off control features for reliable system protection and operation.
- Positioning status signals such as position, error, velocity and fault for ease of system integration.

3.0 SYSTEM OPTICAL SCANNING TECHNOLOGIES

In the development of an optical application, there are not only several galvanometer options to choose from but there are also a number of other optical scanning technologies for the optical designer to consider. Each technology has some specific strengths (and usually associated weaknesses) and application/market segments that they serve. At the same time, there are often different scanning technologies employed within some markets to cover the complete price/performance needs of that market so the optical system designer should be familiar with all of the scanning options available to them. In order of increasing scanning frequency, Table 1 provides an overview of the different technologies and their most notable strengths and weaknesses for system integration.

Scanner Type	Max Frequency	Strengths	Weaknesses
Open Loop Galvo	hundreds of Hz	Lowest Cost	Low accuracy
Closed Loop Galvo	1.5 kHz	Highest Accuracy/Resolution Waveform Control Flexibility High Frequency	Max Speed/Frequency
Resonant	up to 8 kHz	Higher Frequency	Fixed Scan Waveform
Rotating Polygon	tens of kHz	Higher Frequency	Fixed Scan Waveform Scan Discontinuities High Cost
Acousto-Optic	Single MHz	Highest Frequency	Limited Angle/Resolution Laser Attenuation High cost

Table 1. Optical Scanning Technology Comparison

4.0 GALVANOMETER-BASED OPTICAL SCANNING PERFORMANCE SUMMARY

The closed loop galvanometer offers a unique combination of speed, accuracy, cost and control system design flexibility. These attributes meet the scanning requirements of a broad range of applications and the advances in this technology (along with the advances in laser technology) continues to broaden the galvanometer's application range and enable new applications and markets.

Those galvanometer advances have broadened their positioning performance to include the following range of positioning and beam steering capabilities and requirements:

- Apertures from 1mm to >50mm
- +/- 80 degree range of Optical deflection
- Broad Range of Options to optimize Speed, Accuracy, Size and Cost
- Full scanning waveform flexibility within bandwidth, RMS power and angular range of scanner.
- Maximum torque capabilities from 6.5×10^4 to 9×10^7 Dyne-cm^2
- Small Angle Step Response Times as small as 150 usec
- System Bandwidths up to 5.5 kHz
- Max Sinusoidal Frequency > 1 KHz
- Positioning repeatability/resolution to 1 urad
- Operating Lifetime of Billions of cycles
- Galvanometer sizes from 1 to 12.5 inches in length

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