Laser scanning and chopping methods using mechanical resonant devices

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ABSTRACT

Resonant optical scanners are electromechanically driven oscillating devices which deflect a light beam with a sinusoidal motion. While their frequency is fixed, scan amplitude can be controlled. Resonant optical modulators (tuning fork choppers) are oscillating devices which modulate a light beam at a fixed frequency. A wide selection of vanes, mirrors, prisms, lenses, gratings, and other peripheral components can be attached to these devices. The low power, compact sized, and lightweight scanners and tuning fork choppers can easily be incorporated in small size and portable instruments. Since no lubrication is needed and the construction is bearing free, they provide long life and high reliability. Resonant scanners and choppers are capable of operating in high vacuum and under a large temperature range, making them excellent candidates for use in various industrial, scientific, medical, aerospace, and military disciplines.

This paper outlines the benefits and limitations of oscillating device methodologies, including tuning fork, taut band, and torsion rod designs. Issues relating to drive electronics, such as locking a resonant device to an external clock are also addressed. Design applications are exemplified and discussed.

Keywords: resonant, scanner, chopper, modulator, torsion rod, taut band, tuning fork

1. INTRODUCTION

This paper discusses some of the benefits and limitations of resonant optical scanners and modulators. The goal of this paper is to provide the reader with enough understanding so that he or she can determine if a mechanically resonant device is best suited for the optical application at hand. Although resonant scanners and resonant modulators perform two very different and distinct tasks, both are discussed in this paper because they share similar advantages and disadvantages inherent in mechanically resonant designs.

Methods for scanning an optical beam have been developing since the first light house was built. As the need to achieve optical scanning rates at ever faster speeds has grown, many scanning mechanisms have evolved over time. Among the scanning devices in modern day use are rotating polygons, galvanometers, and resonant scanners. Each of these device groups has benefits and drawbacks which makes it suitable in some applications but not others. Selecting the appropriate scanner for a given application is an important first step, since modifying a design to incorporate a different scanning device group after manufacturing has begun is generally a costly undertaking.

Similarly, the variety of devices used to modulate optical beams are abundant, including rotating disk, electro-optic (E-O), and resonant modulators. Much like scanning equipment, each of these device groups has operational strengths and weaknesses which must be taken into account before selecting the modulator best suited for a particular application.

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2. RESONANT SCANNERS

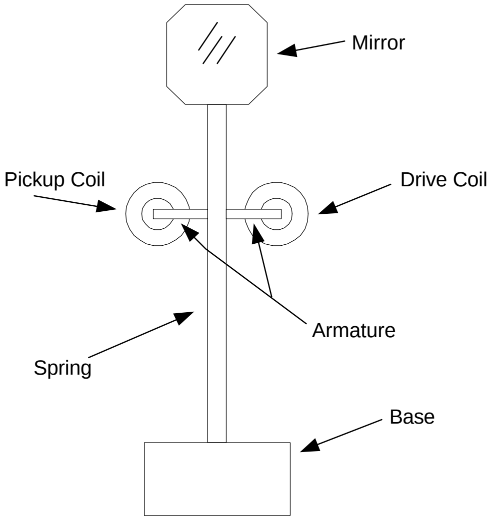

Figure 1: The basic structure of resonant optical scanners.

In Figure 1, a representation of the basic structure of a resonant scanner is shown. The resonant scanner includes a mirror fixed to a spring, with the spring anchored to a scanner base. An iron or magnetic armature attached to the spring passes through the magnetic field of a drive coil. To achieve motion, the drive coil is modulated, causing the armature, spring, and mirror assembly (referred to as the rotor assembly) to swing back and forth. At frequencies other than the rotor assembly's natural resonant frequency, the motion produced by the drive coil is negligible. At the resonant frequency, however, the rotor assembly oscillates back and forth at a substantially greater amplitude which is large enough to produce a useful scan angle. A resonant scanner typically includes a pickup coil in order to determine the mirror's position and to provide feedback to the scanner's driving circuit.

The resonant scanner's principle of operation points out some limitations and advantages associated with its use. First, since the scanner's motion is governed by the resonant frequency of the rotor assembly, it operates at a *single sinusoidal* frequency determined at the time of manufacture. Unlike polygon and galvanometric scanners, resonant scanners cannot be frequency modulated. In addition, resonant scanners cannot be steered to a desired position as can galvanometric scanners.

The resonant frequency of the rotor assembly is generally described by the equation

$$f_R = \frac{1}{2p}\sqrt{\frac{k}{J}} \ , \qquad (1)$$

where f_R is the resonant frequency, k is the spring constant, and J is the inertial momentum of the rotor assembly. From this equation, it is evident that the scanner's operating frequency is inversely proportional to the mirror size, since the mirror is part of the rotor assembly. Thus, as the mirror size increases, the frequency of the scanner decreases. This is an important fact to consider in applications requiring a large beam diameter to be scanned, or in applications using high energy lasers where large heat dissipating mirrors are needed.

Unlike polygon scanners, the scan amplitude of resonant scanners can be controlled. Scan angle control is often useful in inspection and quality control applications where a region covered by a maximum scan angle sweep needs to be magnified by zooming with a reduced scan angle sweep. By adjusting the drive signal amplitude at the drive coil, the torsional force applied to the rotor assembly changes and the scanner's rotational scan angle amplitude is controlled. The resonant scanner's rotational angle f is calculated by the equation

$$f = \frac{T}{k} \ , \qquad (2)$$

where T is the peak rotation torque and k is the spring constant. As the current is modulated at the drive coil, the torque induced to the armature is also modulated, thus adjusting the scan angle.

Combining equations (1) and (2), results in the equation

$$f_R = \frac{1}{2p}\sqrt{\frac{T}{J \cdot f}} \quad . \qquad (3)$$

This equation establishes that the resonant scanner's scan angle is inversely proportional to its resonant frequency. Thus, a higher frequency scanner typically has a smaller scan angle than a similar lower frequency scanner. In order to keep scan angles constant at higher operating frequencies, it is necessary to reduce inertial momentum of the rotor assembly by reducing the scanner's mirror size.

One of the most attractive features of resonant scanners is the simple, low power drive circuitry needed to operate them. Typically, a resonant scanner driver is an oscillator circuit such as the one shown in Figure 2. An amplifier energizes the drive coil at the scanner's resonant frequency. The resonant frequency is maintained by feed back from the pickup coil which is passed to the drive coil amplifier. Generally, the startup time needed to achieve resonant frequency is less than a few seconds due to the small inertia of the rotor assembly, unlike polygon scanners which require substantially longer to reach their scanning velocity. The signal from the pickup coil can also be used as a mirror position signal (monitor) output. An automatic gain control circuit (AGC) can be utilized to ensure amplitude stability with respect to a DC reference voltage set by the user.

Since resonant scanners operate at their natural resonance frequency, very little power is needed to drive them. Typically, resonant scanners require only 10 to 200 mW of power to operate. This is a direct result of their high "Q" factor, which is commonly in the order of 100 to 1000. The low power requirements of resonant scanners make them ideal candidates for use in portable scanning applications.

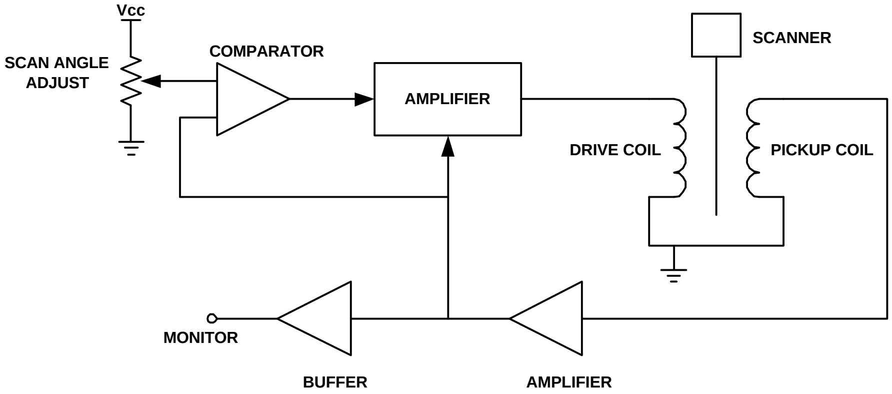

Figure 2: The basic driver circuit for resonant optical scanners.

As previously mentioned, a resonant scanner driver enables the scanner's mirror position to be monitored. This feature is another advantage of resonant scanners over conventional polygon scanners. Although polygon scanners can provide a velocity monitor signal, the driving circuitry cannot determine mirror position with a high degree of certainty. Closely related to this point, a resonant scanner is able to both frequency lock and phase lock the mirror's motion to a clock input signal. While polygon scanners can lock their rotational velocity to a clock signal's frequency, they cannot lock the polygon scan phase to the clock phase. Small changes due to friction, air resistance, or the like can cause the mirror facets to drift out of phase with a clock signal, even though frequency lock is still maintained.

Another important feature of resonant scanners is their virtually unlimited operating life. Generally, the most dominant factor determining the operational life of a mechanical scanner is the occurrence of frictional contact within the scanner assembly. Resonant scanners have no parts which come in frictional contact of each other since, unlike most galvanometers and polygon scanners, resonant scanners do not require ball bearings to support movement. In addition, resonant scanners provide excellent performance when exposed to vibration and shock conditions. Vibration and shock are the main factors which cause the precision shape of ball bearings to deform. Over time, the deformation of bearings causes these scanners to lose their smooth motion and begin to lose scan repeatability. Because resonant scanners are not susceptible to the wear and tear of other types of mechanical scanners which require ball bearings, they are useful in applications such as military and deep space, where field service is difficult or impossible.

Along similar lines, resonant scanners are well suited for applications requiring operation in extreme pressure and temperature conditions. Resonant scanners do not need any lubrication to achieve rotational motion as do most galvanometers and polygon scanners. This allows resonant scanners to be incorporated in applications where out-gassing prohibits the use of other types of scanners. For example, resonant scanners are frequently used in clean room applications and aerospace applications due to their lack of environment contaminating/out-gassing construction. Moreover, resonant scanners perform well in applications which require scanning at very high or very low temperatures. This is again due to their simple non-frictional and no lubrication construction.

Unlike most polygon scanners, resonant scanners are less likely to incur wobble and jitter errors during scanning. Slight and unavoidable deviations in facet to facet angles of polygon scanners typically cause scan wobble to occur. Since resonant scanners use a single facet, their wobble error is minimal. Slight variations in a polygon scanner's motor speed due to periodic frictional disturbances manifest themselves as scan jitter errors. Resonant scanners are relatively free of these errors due to their inherently frictionless operation.

How a resonant scanner is actually constructed depends on the type of spring used. Nevertheless, most design configurations share the properties inherent to resonant scanners as described above. In general, commercially available scanner designs employ either a torsion rod or taut band spring. Both design methodologies are presented in greater detail below.

2.1. Torsion Rod Scanners

A typical torsion rod scanner is depicted in Figure 3. The torsion rod scanner utilizes a torsion rod spring coupled to a mirror to achieve sinusoidal scan motion. Since the torsion rod is fixed to the scanner's base at only one end, a relatively rigid torsion rod must be used to minimize scanner wobble. As a consequence, a torsion rod scanner is not well suited for low frequency scanning applications. However, because of their ability to scan at high frequencies, torsion rod scanners are an excellent choice for high speed scan applications. In Table 1, exemplary ranges of torsion rod scan frequencies as a function of scan angle and mirror size are given.

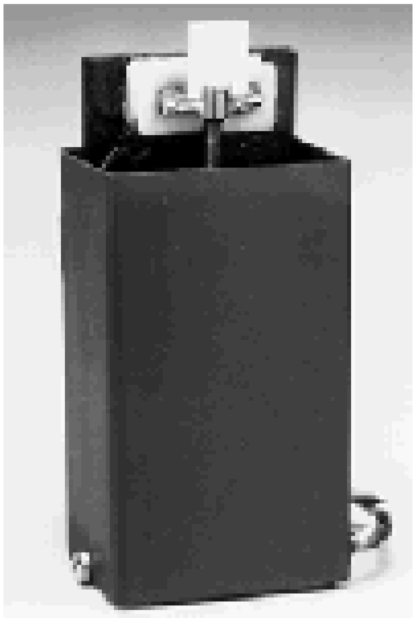

Figure 3: A typical torsion rod resonant scanner. *Photograph courtesy of Electro-Optical Products, Corp.*

FREQUENCY Hz	SCAN ANGLE P-P Degrees Optical	MIRROR SIZE mm
200-750	30°	25×25
750-4000	20°	10×10
4000-6000	16°	8×9
6000-8000	12°	7×8
8000-10000	12°	5×6
10000-16000	6°	4×5
16000	5°	3×4

Table 1: Typical torsion rod scan frequencies as a function of scan angle and mirror size.

The torsion rod scanner's resonance frequency f_R is described by the equation

$$f_R = \sqrt{\frac{k \cdot d^4}{l \cdot J}} \quad , \tag{4}$$

where k is a constant dependent on the rod material used, d is the diameter of the rod, l is the rod length, and J is the inertial momentum of the rotor assembly. In addition to meeting the frequency requirements of the intended application, the dimensions of the rod must not exceed material stress levels during operation. To ensure that the torsion rod does not fatigue and eventually fail over time, the rod diameter d must satisfy the equation

$$d \leq \frac{l}{S \cdot f} \ , \qquad (5)$$

where l is the rod length, S is the rod material's torsional stress coefficient, and f is the maximum rotational scan angle. Once equation (5) is satisfied, the torsion rod scanner can run for virtually an unlimited number of cycles.

2.2. Taut Band Scanners

Figure 4 depicts a typical commercially available taut band scanner. Unlike the torsion rod scanner, the spring is fastened to the frame at both ends, making the scanner much less susceptible to wobbling at low frequencies. Generally, the taut band spring is flat, allowing for easy attachment to the base and mirror. Temperature compensating rods can also be incorporated in the scanner design as shown in Figure 4. These rods help maintain constant tension on the taut band spring over a large temperature range by stretching and contracting the frame sides. By maintaining constant tension across the spring, resonant frequency drift due to variations in temperature is minimized.

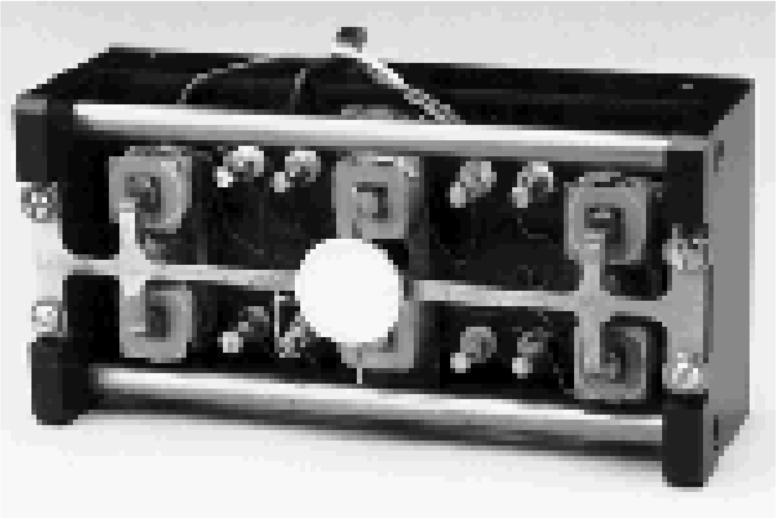

Figure 4: A typical taut band resonant scanner. *Photograph courtesy of Electro-Optical Products, Corp.*

Since taut band scanners secure the spring at both ends, these devices are better suited to scan at lower frequencies. Table 2 gives exemplary scan frequency ranges as a function of scan angle and mirror size.

FREQUENCY	SCAN ANGLE	MIRROR SIZE
Hz	P-P Degrees Optical	mm
5-200	70°	30×30
200-300	70°	20×20
300-400	60°	10×10
300-400	40°	15×15
400-1000	40°	10×10
400-1000	30°	12×12
1000-1500	30°	10×10
1500-2000	24°	8×8

Table 2: Typical taut band scan frequencies as a function of scan angle and mirror size.

Unlike torsion rod scanners, the resonant frequency of taut band scanners is dependent on the spring thickness rather than the diameter. The relationship between the spring thickness t and resonant frequency is given by the equation

$$f_R = \sqrt{\frac{k \cdot t^4}{l \cdot J}} \quad . \tag{6}$$

As was the case with torsion rod scanners, the spring dimensions must not exceed material stress levels during operation. Thus the taut band spring construction must also satisfy the equation

$$t \le \frac{l}{S \cdot f} \, . \tag{7}$$

3. RESONANT MODULATORS

As noted at the beginning of this paper, resonant modulators exhibit much of the same properties that resonant scanners do. Therefore, this discussion of resonant modulators is much more concise, with frequent references back to the discussion of resonant scanners.

Resonant modulators, like resonant scanners, operate at a single sinusoidal frequency selected at the time of manufacture. This limitation is not shared by most other modulating methods. For example, rotating choppers utilize a spinning disk blade with openings cut radially throughout the disk. As the disk is rotated, a beam passing through one of the openings is modulated, and the rate of disk rotation determines the modulation frequency.

Unlike rotating choppers, however, resonant choppers are not susceptible to blade phase jitter and motor speed jitter. With rotating choppers, slight defects between the size of each blade opening causes blade phase jitter to occur. This type of jitter manifests itself in the frequency domain as fractional components of the chopping frequency. Motor speed jitter, due to motor speed instability, manifests itself as random frequency shifting of the entire modulated signal. Jitter introduces signal detection errors and can lead to inaccurate signal measurements. Resonant choppers, on the other hand, use only one aperture opening and are therefore essentially free of jitter problems.

Because of their simple frictionless design, resonant choppers share the same beneficial operating attributes that resonant scanners do. Specifically, resonant choppers can withstand shock and vibration, are virtually maintenance free, and have an extremely long operating life. In addition, resonant choppers are well suited to operate in vacuum environments and environments of very high or very low temperatures.

Resonant choppers can use the same drive circuitry as resonant scanners. As such, they enjoy the same benefits previously discussed regarding resonant device drivers. These advantages include simple circuit design, automatic gain control, and the ability to lock in both frequency and phase to an external clock signal. In addition, resonant choppers require very little power to operate, unlike other modulating devices.

Commercially available resonant choppers are generally constructed with either a tuning fork spring or a taut band spring. It is important to note however that some applications utilize torsion rod scanners as modulators when high frequency modulation is required. Modulation using torsion rod scanners is accomplished by placing a detector in line with only a segment of the scan sweep. This configuration effectively chops the signal at the scanning frequency. Discussed below are specific design considerations relating to tuning fork choppers and taut band choppers.

3.1. Tuning Fork Choppers

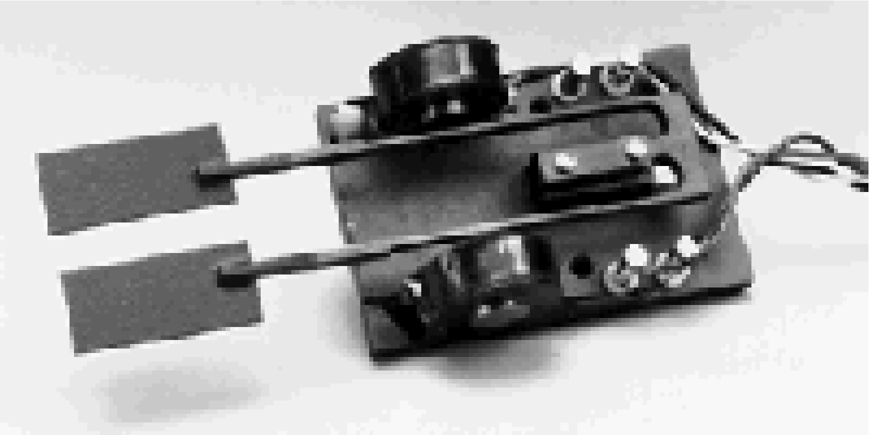

Figure 5: A typical tuning fork resonant chopper. *Photograph courtesy of Electro-Optical Products, Corp.*

Figure 5 shows a typical commercially available tuning fork chopper. The modulator comprises a tuning fork spring with vanes mounted at each end of the tuning fork's tines. A drive coil is located on one side of the tuning fork, and a pickup coil is located on the other side. When a drive signal is applied to the drive coil and matched to the resonant frequency of the fork, the resulting magnetic force causes the tines of the fork to vibrate back and forth sinusoidally with time in opposing directions. As the chopper vanes oscillate and overlap each other, any beam passing between the vane gap is modulated. Since the chopper blades move inwardly and outwardly in unison, the aperture area is functionally doubled during operation. The pickup coil is used to generate a feedback signal to the driver, and is also used as input to a lock-in-amplifier circuit for signal filtering.

Tuning fork choppers are called "balanced" units because the fork tines move in opposite directions from one other, effectively canceling out most vibrations that would otherwise be transmitted through the chopper base. Since the chopper is balanced, there is very little energy loss during its operation. Tuning fork choppers typically require between 10 to 100 mW of drive power, with exact power consumption dependent on the resonant frequency. A balanced tuning fork chopper also has a high Q, in the range of 5000 (close to that of a quartz crystal), which gives the chopper high frequency stability.

As with other resonant devices, the resonant frequency of the tuning fork chopper is directly related to its spring geometry. The relationship between the tuning fork dimensions and the resonant frequency f_R is given by

$$f_R = \frac{k \cdot l}{(h-b)^2} \ , \tag{8}$$

where k is the spring constant, l is the tine length, h is the tine height, and b is the height of the tuning fork base. Table 3 gives typical tuning fork modulating frequency ranges as a function of aperture size.

FREQUENCY	FULL APERTURE
Hz	mm
10-150	10.2
400	4.8
700	2.0
1000	1.2
2000	0.6
3000	0.3

Table 3: Typical tuning fork modulating frequencies as a function of aperture size.

3.2. Taut Band Modulators

A taut band chopper is depicted in Figure 6. The chopper is identical in design to the taut band scanner, except a vane is mounted perpendicular to the spring instead of the mirror. As the spring rotates at the resonant frequency, the vane rocks back and forth sinusoidally with time. A beam passing alongside one of the vane edges is modulated as the vane swings in front of the beam path.

Taut band choppers are often used in applications which require modulation of a large beam diameter, or when low frequency modulation is needed. Table 4 gives exemplary taut band modulating frequency ranges as a function of the maximum modulated beam diameter.

FREQUENCY Hz	BEAM DIAMETER inches
5-15	0.6
25	0.6
40	0.4
100	0.3

Table 4: Typical taut band modulating frequencies as a function of the maximum modulated beam diameter.

Figure 6: A typical taut band chopper. *Photograph courtesy of Electro-Optical Products, Corp.*

4. CONCLUSION

Although mechanical resonant devices are limited to a single fixed sinusoidal operating frequency, there are many applications where such a limitation is not prohibitive. In such applications, the use of resonant optical scanners and choppers should be carefully considered. Resonant scanning and modulating units have many advantageous properties which separate them from other scanning and modulating methodologies in current use.