Charles P. Pinney, et. al.. "Velocity Measurement."

Velocity Measurement

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16.1 Introduction

The *linear velocity* of an object, or more correctly a particle, is defined as the time rate of change of position of the object. It is a vector quantity, meaning it has a direction as well as a magnitude, and the direction is associated with the direction of the change in position. The magnitude of velocity is called the speed (or pace), and it quantifies how fast an object is moving. This is what the speedometer in a car tells you; thus, the speedometer is well named. Linear velocity is always measured in terms of, or from, some reference object. Thus, the speedometer of a car tells how fast one is moving relative to the earth. Usually, linear velocity is identified using only the term “velocity.” Common units for velocity include meters per second and miles per hour, but any similar combination of units of length per unit of time is correct.

The *rotational velocity* (or angular velocity) of an object is defined as the time rate of change of angular position, and it is a measure of how fast an object is turning. It is completely analogous to linear velocity, but for angular motion. Common units are revolutions per minute, but any angular unit of measurement per unit of time can be used. Rotational velocity is a vector quantity also, with the direction of the vector being the same as the direction of the axis about which object is turning. For example, with a car stopped at a stop light with the motor running, the rotational velocity of the crankshaft of the motor is given by a magnitude (rotational speed), say 800 rpm (rev/min), and a direction associated with the direction in which the crankshaft is pointing. The axis of rotation of the object may be moving, rather than fixed as when the car is turning a corner. The roll, yaw, or pitch velocity of an airplane would be given in terms of rotational speeds about each of the turning axes in the same manner as for a crankshaft.

Usually, the reference from which linear or rotational velocity is given is understood from the context of the problem. It is often not stated explicitly. The measurement method used defines the reference.

Applications for velocity measurement include:

1. Controlling the speed at which metal stock is fed into a machine tool. If the metal is fed too quickly the result could be premature tool wear or it could even lead to machine failure. Feeding the material too slowly will reduce the yield of the machine tool.
2. Measuring the approach speed of a robotic tool onto its target.
3. Monitoring the speed of a generator in an electric power station.
4. An airport radar system measuring the speed of an approaching aircraft using the Doppler effect.
5. Measuring an automobile’s wheel speed in order to provide feedback to an antilock brake system.

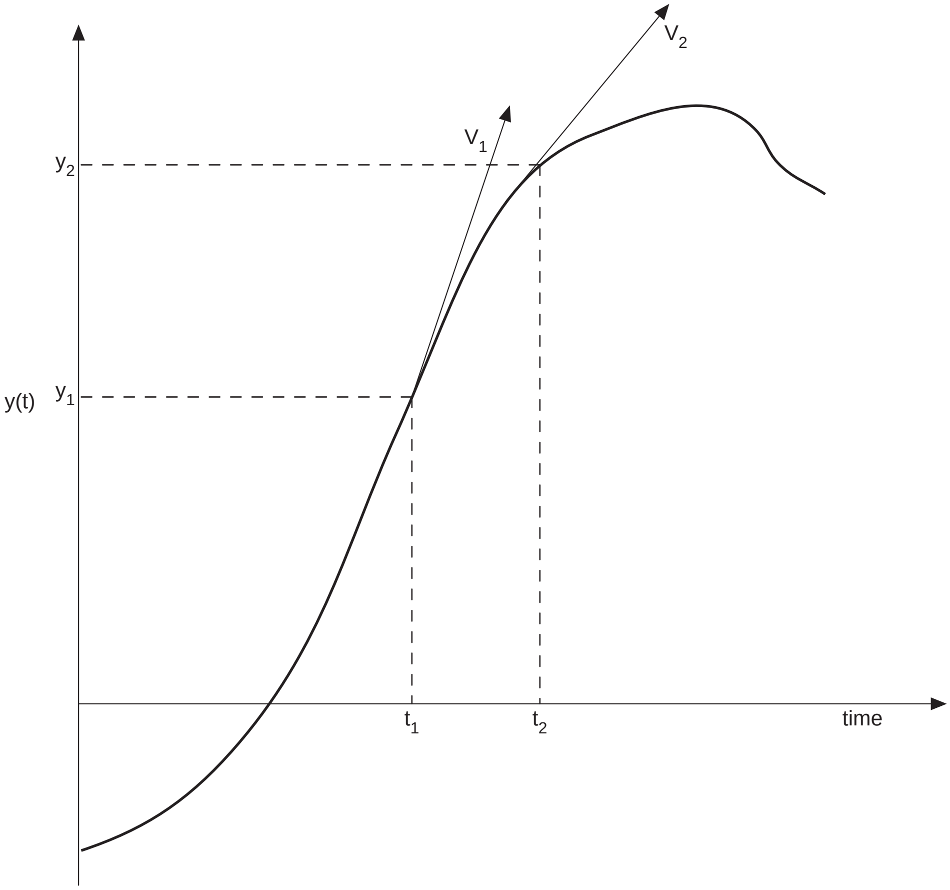


FIGURE 16.1 Position-time function for an object moving on a straight path.

16.2 Measurement of Linear Velocity

The problem of velocity measurement is somewhat different from that of measurement of other quantities in that there is not a large number of transducer types and transducer manufacturers from which to choose for a given problem. Frequently, the problem is such that the person must use his/her knowledge of measurement of other quantities and ingenuity to develop a velocity measurement method suitable for the problem at hand. Velocity is often obtained by differentiation of displacement or integration of acceleration. As background information for this, the necessary equations are given below.

Figure 16.1 shows a graph that represents the position of an object as a function of time as it moves along a straight, vertical path (y direction). The quantity to be measured could be an average velocity, and its magnitude would then be defined as follows:

$$\text{Average speed} = V_{\text{avg}} = \frac{y_2 - y_1}{t_2 - t_1} = \frac{\Delta y}{\Delta t} \tag{16.1}$$

for the time interval t_1 to t_2. As the time interval becomes small, the average speed becomes the instantaneous speed V_y, and the definition becomes:

$$V_y = \lim_{\Delta t \to 0} \frac{\Delta y}{\Delta t} = \frac{dy}{dt} \tag{16.2}$$

which is the slope of the position–time curve. The subscript indicates the *y* component. This speed, when associated with the known direction, becomes the velocity.

Since acceleration is defined as the time rate of change of velocity, the speed of an object may also be given by:

$$V_y(t) = V_i - \int_{t_i}^{t} a_y(t)\,dt \tag{16.3}$$

where $a_y(t)$ is the acceleration in the y direction (for Figure 16.1) and V_i is the speed at time t_i. Each of the above equations can be used as a basis for making a velocity measurement. Note that for motion in more than one dimension, there would be more than one component, and there would be corresponding equations for the other dimensions (*x* and *y*). However, velocity measurements are always done by individual component.

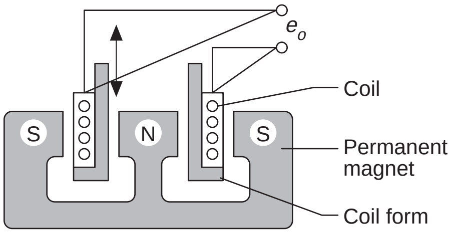
It is convenient in the discussion of techniques of measuring velocity to divide the methods into two categories: one will be called "referenced-based methods" and the other "seismic or inertial referenced transducers." Referenced-based methods refer to measurements made for which the instrumentation has component(s) on both the moving object and the reference frame for the measurement. The seismic transducers do not require contact with the reference frame. However, they give a speed relative to the transducer speed at the start of the test. The initial motion must be determined from other considerations in the test setup and added to the relative speed.

Reference-Based Measurement

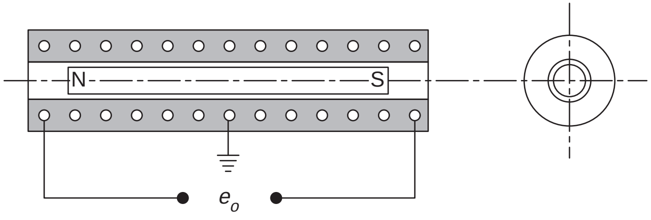
Using Equation 16.1, one value of the average speed in a given direction of an object can be determined from the distance traveled in that direction and the time required. Determining the muzzle speed of a projectile is an example. Having two pickups spaced a known distance apart, and recording the time for the projectile edge to pass between them is a common way of doing this. Typical pickups would include proximity transducers (see displacement measurement), laser or collimated light beams with diode sensors, and electric contacts closed (or opened) by the moving object. Measuring the time interval can be done with an electronic counter or displaying the output of the pickups on an oscilloscope. In designing such a system, care must be exercised to minimize or eliminate the effect to the object passing through the window on the positions of the sensors and their response. For example, pressure from a muzzle blast can move the sensors on their supports. This could distort the distance between them during the measurement; but afterwards, the appearance of the setup could be unchanged, so the experimenter would be unaware of the error.

Using a series of equally spaced pickups can determine the average speed for a sequence of positions. For some applications, illumination of the path of motion of the object with a stroboscope flashing at a known rate and use of time exposure photography can give a single picture of the object at a sequence of positions. With knowledge of the length scale and the flash rate, the average speed at a sequence of positions can be calculated. If the plane of motion is the same as the plane of the photograph, then two components of the velocity can be determined. A variation of this method is to use video recording of the motion and the time base of the video for measurement of time increments. Availability of high-speed video cameras, to 12,000 frames per second, extends the range of applicable velocities, and digital recording can enhance the ease and accuracy of making the distance measurements.

Another variation of this method is to use some type of position transducer to record the position–time function of the moving object and then differentiate this function to get speed–time. Displacement



Moving Coil Type



Moving Magnet Type

FIGURE 16.2 Velocity transducers (LVT).

transducers were discussed in an earlier chapter, and the selection of an acceptable transducer is important. Range, resolution, and mass loading are important parameters. Because differentiation of experimental data is a noise-generating process, particular care must be exercised to reduce the electric noise in the displacement data to a minimum. Also, the calculated speed–time function might require some smoothing to reduce the numerically introduced noise.

One type of velocity transducer is based on a linear generator. When a coil cuts the magnetic field lines around a magnet, a voltage is induced in the coil, and this voltage is dependent on the following relation:

$$e_i \propto BLV \tag{16.4}$$

where e_i = induced voltage
B = magnetic field strength
L = length of wire in the coil
V = speed of the coil relative to the magnet.

This relation is used as the basis for linear velocity transducers, called LVTs, and a schematic is shown in Figure 16.2. Manufacturers of these transducers include Trans-Tek Inc. of Ellington, CN; Robinson-Halpern Products of Valley Forge, PA; and the Macro Sensors, Div. of Howard A. Schaevitz Technologies, Inc. of Pennsauken, NJ. The working displacement ranges are from 0.5 in. to 24 in., and typical sensitivities are from 40 mV/ips (inches per second) to 600 mV/ips.

Conversion of Linear to Rotational Velocity

A rotational dc generator (discussed in the next section) can also be used to measure linear velocities by placing a rack on the moving object and having the rack drive the generator through a pinion gear. This is the same principle by which a speedometer converts the linear velocity of an automobile to an angular velocity gage on the dashboard of a car.

Doppler Shift

The Doppler shift is an apparent change in the frequency of waves occurring when the source and observer are in motion relative to each other. This phenomenon is applicable to waves in general; for example, sound, light, microwaves, etc. It was first observed for sound waves, and it is named after the Austrian mathematician and physicist Christian Doppler (1803–1853) who first published a paper on it for light waves in 1842. The frequency will increase when the source and observer approach each other (red shift) and decrease when they move apart (blue shift). This phenomenon was illustrated by having people listen to the pitch of an oncoming train. The high-pitched whistle would transition to a lower pitch as the train passed the observer.

Radar, which is named for radio detection and ranging, is another technique for detecting the position, motion, and nature of a remote object by means of radio waves reflected from its surface. Pulse radar systems use a single directional antenna to transmit and receive the waves. They transmit pulses of electromagnetic waves (usually microwaves), some of which are reflected by objects in the path of the beam. Reflections are received by the radar unit, processed electronically, and converted into images on a cathode-ray tube. The antenna must be connected only to the transmitter when sending and only to the receiver while receiving; this is accomplished by switching from one to the other and back again in the fraction of a microsecond between pulses. The distance of the object from the radar source is determined by measuring the time required for the radar signal to reach the target and return. The direction of the object with respect to the radar unit is determined from the direction in which the pulses were transmitted. In most units, the beam of pulses is continuously rotated at a constant speed, or it is scanned (swung back and forth) over a sector at a constant rate. Pulse radar is used primarily for aircraft and naval navigation and for military applications. In Doppler radar, or continuous-wave radar, two antennas are used — one to transmit and the other to receive. Because the time a continuous-wave signal takes to reach the target and return cannot be measured, Doppler radar cannot determine distance. The velocity of the object is determined using the Doppler effect. If the object is approaching the radar unit, the frequency of the returned signal is greater than the frequency of the transmitted signal. If the object is receding, the returned frequency is less; and if the object is not moving relative to the radar unit, the frequency of the returned signal is the same as the frequency of the transmitted signal.

One value of this Doppler technology is shown on the evening weather broadcast. Radar can measure wind rotation inside a thunderstorm and identify possible tornadoes. The VORAD system by Eaton is an on-board system for vehicle safety. It detects when a dangerous approach to another vehicle is taking place. It will automatically apply the brakes in an emergency situation.

Light Interference Methods

Velocity measurements can be made using light interference principles. Figure 16.3 shows the setup used by Michelson in the 1890s to demonstrate light interference. A beam of monochromatic light is split into two beams. One beam is directed onto a stationary mirror. The other beam is directed onto a moving target. The observer sees the superposition of the two beams. As the mirror moves in one direction, summation of the waves of the two beams will alternately reinforce and cancel each other. The amount of motion for one cycle of light intensity variation is the wavelength of the light being used. The frequency of these light-to-dark transitions is proportional to the velocity of the moving target. Highly accurate measurements are available with interferometer techniques. For example 1 m is 1,650,763.73 fringe counts for the orange light emitted by krypton-86.

Refinements of this principle are needed for convenience of use. Lasers are used as the light source, for example. One commercial supplier of this type of device, commonly called a Laser Doppler Vibrometer, is Polytec PI, Inc. of Costa Mesa, CA. The basic principle gives velocity parallel to the laser beam, but Polytec PI also has a unit that utilizes scattered laser light which permits measurement of the in-plane velocity. It is called a laser surface velocimeter.

VISAR System

Another application of interferometry to the measurement of velocity–time profiles is a device called VISAR, for "velocity interference system for any reflector." Earlier interferometer systems had required that the target have a highly polished reflecting surface and that there be very little surface tilt during a test. The VISAR system functions with either specularly or diffusely reflecting surfaces, and is quite insensitive to tilting of the target. It was developed for shock wave research work, and is useful for measurement of very high speeds. Reference [3] gives a detailed description of the principles of operation.

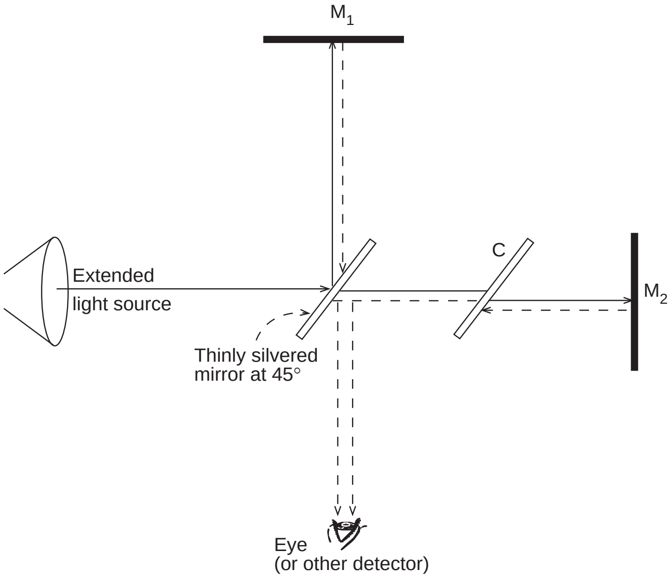


FIGURE 16.3 The basic components of a Michelson interferometer. The clear glass slab C is called a compensating plate. It has the same dimensions and orientation as the 45° mirror in order to make the light paths in glass equal along the two arms, a condition necessary when a white-light source is used.

The signal from the VISAR is generated with a photodiode or other light-sensitive device, and is basically a measure of the rate of fringe variation. Additional data reduction is required to obtain speeds. The sensitivities of the devices are specified in "fringes per meter/second." Typical sensitivities are in the range of 100 m/s to 4000 m/s per fringe.

The first VISARs were laboratory devices, individually assembled from the needed optical components. Commercial units are now available. Valyn International of Albuquerque, NM, makes VISARs and components. Figure 16.4 shows a schematic of a test setup. This unit can measure speeds from 100 m s^{-1} to 10 km s^{-1} or more. The standard measurement range, given as depth of field, of the VISAR is 12 mm, but systems measuring over 10 m have been used. Applications for the VISAR include:

In-bore projectile velocity
Flyer plate velocity
Flying foil velocity
Hugoniot equation of state
Structural response to shock loading

Seismic Devices

The devices discussed in the previous section required a link of some type between the reference and the moving object. Seismic devices do not have this requirement. A seismic device refers to a transducer, which is based on a mass attached to the transducer base, usually with a linear spring. The base is attached to the surface whose motion is desired, and the motion of the seismic mass relative to the base is recorded with a motion transducer. Figure 16.5 shows the principal components of this transducer type. Use of the governing equation of motion for the seismic mass permits the determination of the motion of the base from the relative motion function.

If the motion transducer in the seismic instrument measures the displacement of the mass relative to the base, the output of the transducer is proportional to the acceleration of the transducer base for a specific frequency range and the device is called an *accelerometer.* Acceleration measurement using this

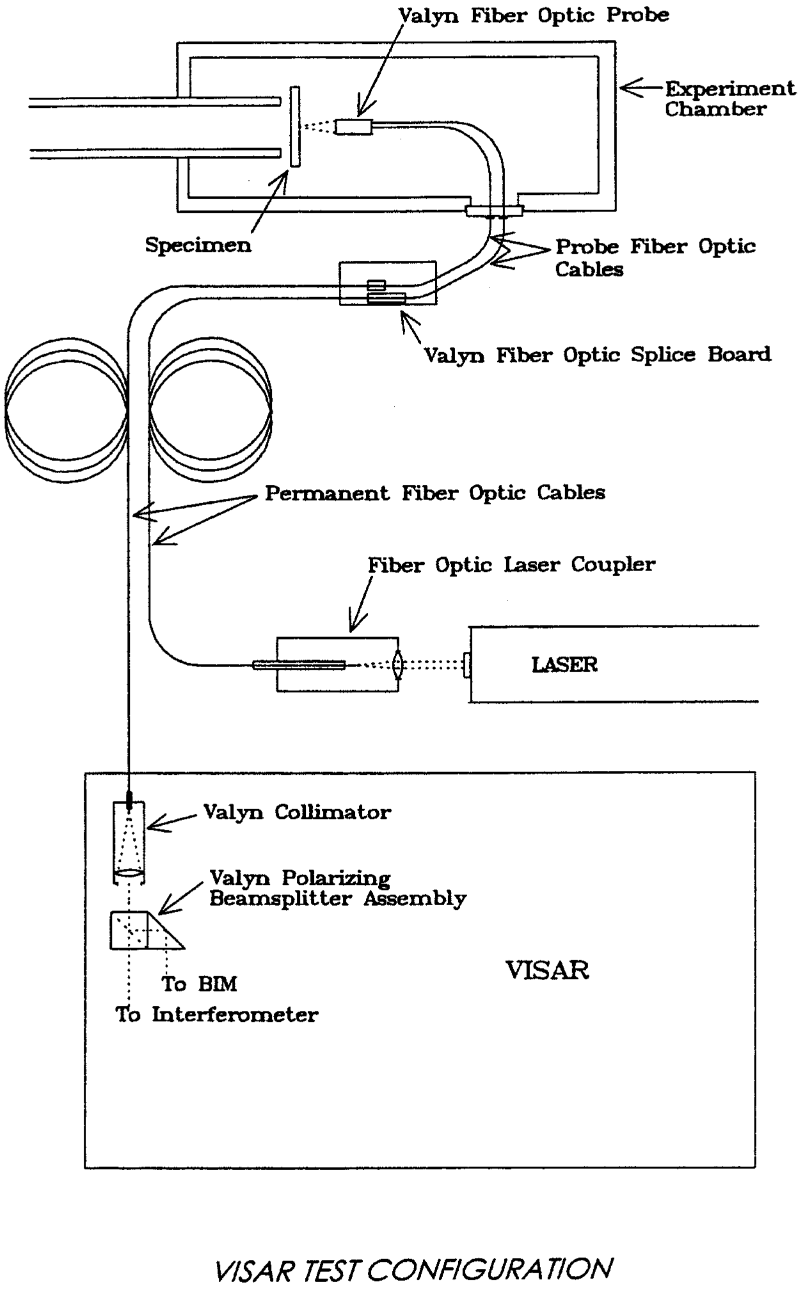


FIGURE 16.4 Schematic diagram showing how fiber optic components, available from Valyn, can transport laser light to and from a shock experiment, minimizing any laser light beam hazards. (Courtesy: Valyn International, Albuquerque, NM.)

type of device (or with other types of accelerometers) permits the determination of the velocity–time function by integration through the application of Equation 16.3. In this equation, $a_y(t)$ would be determined from the output of the accelerometer.

The simplicity of this concept is evident and, because integration is a smoothing process, the numerically introduced noise encountered with a "differentiation of displacement" method of speed measurement does not occur. However, other errors can be introduced. First, any error in the acceleration

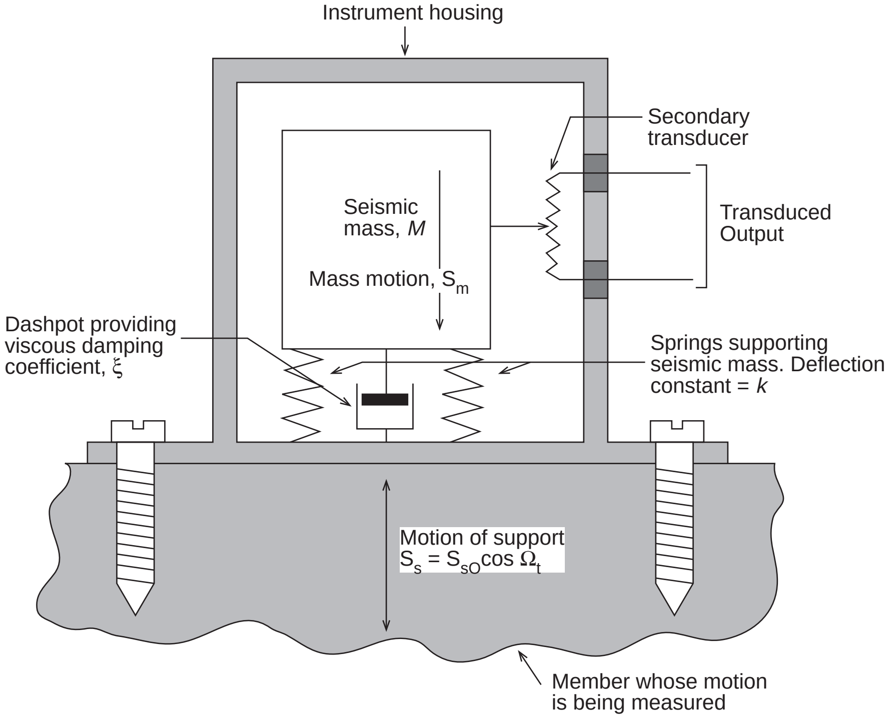


FIGURE 16.5 Seismic type of motion-measuring instrument.

measurement will be carried over. However, additional precautions are necessary to obtain good results for speed measurement. The problem areas include the following:

- The initial speed, V_i, must be known at the beginning of the time of interest. Because this quantity is added to the change in speed, an error in it will be a constant on each value.
- A bias, or zero shift, in the accelerometer signal will be included as a constant acceleration, and thus introduce a linearly increasing error in the calculated values throughout the time interval of interest. This bias may be introduced from electrical or thermal characteristics of the circuit, or, in the case of measurement of accelerations during impact after a free fall, by the 1 *g* acceleration of gravity.
- If the frequency content of the acceleration falls outside the usable bandwidth of the accelerometer and recording circuit, errors in acceleration occur. The low-frequency cutoff depends on the recording equipment and circuit, and the high frequency cutoff depends on the natural frequency and damping of the accelerometer, as well as the bandwidth of each piece of equipment in the recording circuit.
- Accelerometer theory is based on harmonic excitation of the system. For many velocity measurement applications, the input is a transient. Combination of these two factors can result in inaccurate accelerometer data; for example, ringing may occur, and cause errors in the calculated speeds. This problem is accentuated for lightly damped accelerometers.

When this method of speed measurement must be used, a series of check tests should be conducted to evaluate the accuracy of the method for that particular system.

A variation of the above method is to put an integrating circuit in the accelerometer and perform the integration with an analog circuit. Then, the output of the "velocity" transducer is proportional to the change in speed. This type of device is subject to all of the potential error sources discussed above. A manufacturer of this type of transducer is Wilcoxon Research of Gaithersburg, MD.

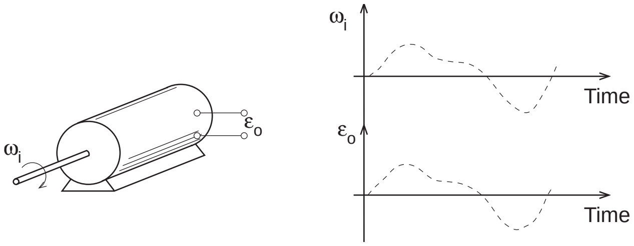


FIGURE 16.6 Permanent-magnet dc tach-generator.

It can be shown that if the electromechanical transducer in a seismic instrument gives an output which is proportional to the speed on one end relative to the other end, then the output of the seismic transducer is proportional to the speed of the transducer in an inertial reference frame, i.e., relative to the earth, for input motion frequencies well above the natural period of the seismic mass. Thus, use of a linear velocity transducer as the motion measurement transducer in a seismic instrument makes it a "seismic velocity transducer." This type of device is called several different names, including seismometer, geophone, and vibrometer, as well as velocity transducer.

The natural frequency and damping in these instruments are selected to match the application. As with an accelerometer, the usable bandwidth depends on these two characteristics. The low-frequency limit for this type of transducer is dependent on the accuracy required in the measurement. The governing equation is given in Doebelin [3]. As an example, it can be used to show that if an accuracy of 5% is required, the lowest data frequency must be 4.6 times the natural frequency of the transducer, and that the upper data frequency is not limited. In fact, the higher the upper frequency, the more accurate the results.

Seismometers are used for recording and studying motion from earthquakes, and these devices can be quite large. Natural periods can be in the range of 10 s to 50 s, and damping is normally selected as 0.7 of critical to extend the frequency range as much as possible. Geophones are commonly used for oil well logging and related work. Their natural periods are in the vicinity of 10 s. Manufacturers of these devices include Teledyne Brown Engineering and GeoSpace Corporation of Houston, TX.

16.3 Velocity: Angular

Measurement of angular velocity is often applied to rotating machinery such as pumps, engines, and generators. The most familiar unit of measurement in rotating machinery applications is revolutions per minute (rpm). In most cases, the measurement of rpm involves the generation of a pulse train or sine wave whose frequency is proportional to angular velocity. The measuring technologies using pulse trains and waves include ac and dc generator tachometers, optical sensors, variable reluctance sensors, rotating magnet sensors, Wiegand effect sensors, stroboscopy, etc.

These types of measurements are taken with respect to the base of the item being measured. They are relative measurements because one is measuring the motion between two bodies.

Another class of measurement problem is that of moving or inertial bodies. In this case, a measurement of absolute motion is performed. Some fixed reference must be stated or implied. This reference is often the Earth. A universal reference is sometimes required for celestial measurements. These inertial measurements are typically taken with gyroscope-type devices.

Relative: Tachometer

Electrical (dc and ac) Tachometer Generator

A rotating generator produces a voltage signal proportional to the rotational velocity of the input shaft. A dc generator produces a voltage level proportional to speed, as in Figure 16.6. The ac generator produces

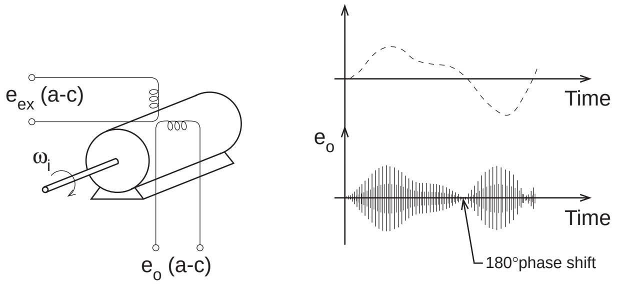


FIGURE 16.7 Ac tach-generator.

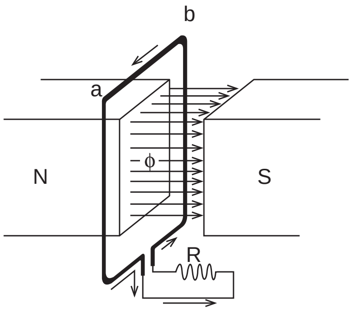


FIGURE 16.8 Generated electromotive force. Moving conductor.

an ac voltage output with a frequency proportional to rotational speed, as shown in Figure 16.7. In a simple two-phase motor, the ac voltage is applied to one phase of the motor and the measurement is taken off the other. Typical operating frequencies are 60 Hz and 400 Hz. This carrier frequency should be 5 to 10 times the required frequency response of the ac generator tachometer. The direction of travel is determined by the phase of the signal with opposite directions being 180° out of phase. The basic dc generator is shown in Figure 16.8.

Sources of tachometer generators include the GE Company of Fairfield, CT; Kollmorgen Motion Technologies Group of Radford, VA; Sierracin/Magnedyne of Vista, CA; and Micro Mo Electronics of Clearwater, FL.

Counter Types

An entire class of angular velocity measuring techniques exists that uses pulses generated by electromechanical interaction. The common thread is a pulse-to-voltage converter giving a voltage output proportional to velocity.

Rotating Magnet Sensors: Passive speed sensors convert mechanical motion to ac voltage without an external power source. These self-contained magnetic sensors produce a magnetic field that, when in the proximity of ferrous objects in motion, generates a voltage.

When a magnetic sensor is mounted in the proximity of a ferrous target, such as gear teeth on a rotating shaft, the voltage output frequency is directly proportional to the rotational speed of the target. A frequency-to-voltage converter can then convert the signal to a voltage. An engineering unit conversion from voltage to velocity then provides an actual velocity measurement.

Typical applications for these types of sensors include:

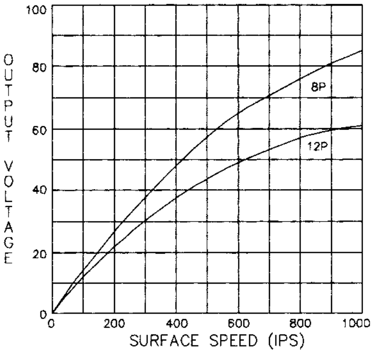


FIGURE 16.9 Magnetic speed sensor output voltage vs. speed. (Courtesy: Smith Systems, Inc., Brevard, NC.)

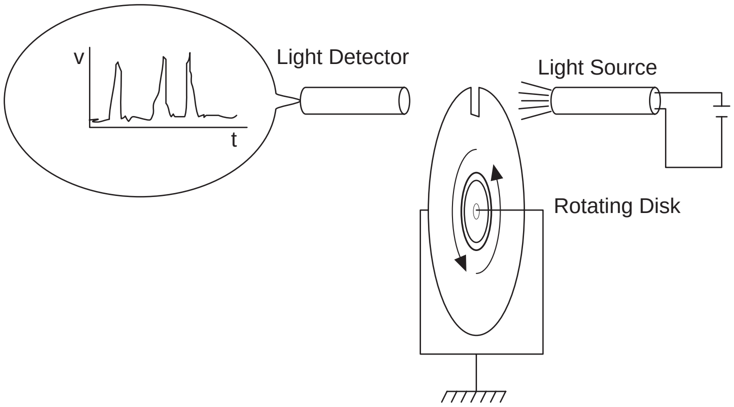


FIGURE 16.10 A slotted disk provides one pulse output for each rotation.

Transmission speed
Engine rpm
Over/under speed
Wheel speed
Pump shaft speed
Multiple engine synchronization
Feedback for speed control
Crankshaft position/engine timing
Computer peripheral speeds

The typical specifications for magnetic speed sensors are given by a graph of output voltage versus surface speed in inches per second, as in Figure 16.9.

Sources for magnetic sensors include Smith Systems of Brevard, NC; Optek Technology of Carrolton, TX; Allied-Signal of Morristown, NJ; and Baluff of Florence, KY.

Optical Sensors

Optical methods of angular velocity detection employ a light emitter and a light detector. A light-emitting diode (LED) paired with a light-sensitive diode is the most common arrangement.

A slotted disk is placed in the axis of a rotating shaft. Each slot or slit will allow the light to pass through the disk. Figure 16.10 shows a typical arrangement. The detector will generate a pulse train with a rate proportional to the angular velocity.

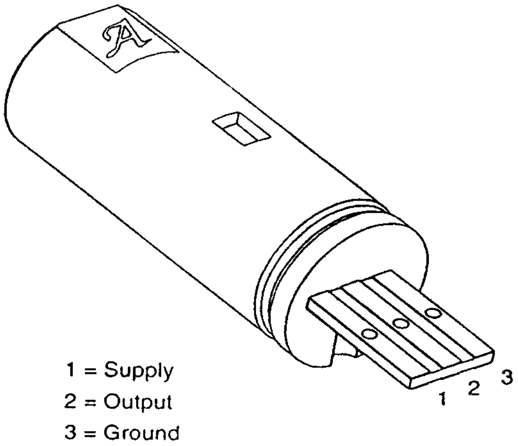


FIGURE 16.11 Hall-effect gear tooth sensor. (Courtesy: Allegro Microsystems, Inc., Worcester, MA.)

The effects of external light sources must be considered in the application of optical sensors.

Sources of optical sensor systems include Scientific Technologies of Fremont, CA; Banner Engineering Corp. of Minneapolis, MN; and Aromat Corp. of New Providence, NJ.

Hall Effect

The Hall effect describes the potential difference that develops across the width of a current-carrying conductor. E.H. Hall first used this effect in 1879 to determine the sign of current carriers in conductors. Hall effect devices are finding their way into many sensing applications. A typical Hall effect sensor application is the wheel speed sensor for antilock braking systems in automobiles. The Allegro ATS632LSC gear-tooth sensor, shown in Figure 16.11, is an optimized Hall-effect IC/magnet combination. The sensor consists of a high-temperature plastic shell that holds together a compound samarium–cobalt magnet, a single-element self-calibrating Hall effect IC, and a voltage regulator. The operation of this circuit is shown in Figure 16.12.

Wiegand Effect

The Wiegand effect is useful for proximity sensing, tachometry, rotary shaft encoding, and speed sensing in applications such as:

Electronic indexing for water, gas, and electric meters and remote metering systems
Measuring shaft speed in engines and other machinery
Tachometers, speedometers, and other rotational counting devices

Wiegand effect technology employs unique magnetic properties of specially processed, small-diameter ferromagnetic wire. By causing the magnetic field of this wire to suddenly reverse, a sharp, uniform voltage pulse is generated. This pulse is referred to as a Wiegand pulse. Sensors utilizing this effect require only a few simple components to produce sharply defined voltage pulses in response to changes in the applied magnetic field. These sensors consist of a short length of Wiegand wire, a sensing coil, and alternating magnetic fields that generally are derived from small permanent magnets.

The major advantages of the Wiegand effect based sensors are:

No external power requirement
Two-wire operation
Noncontact with no wear
20 kHz pulse rate
High-level voltage output pulse
Wide operating temperature range (e.g., –40°C to +125°C)

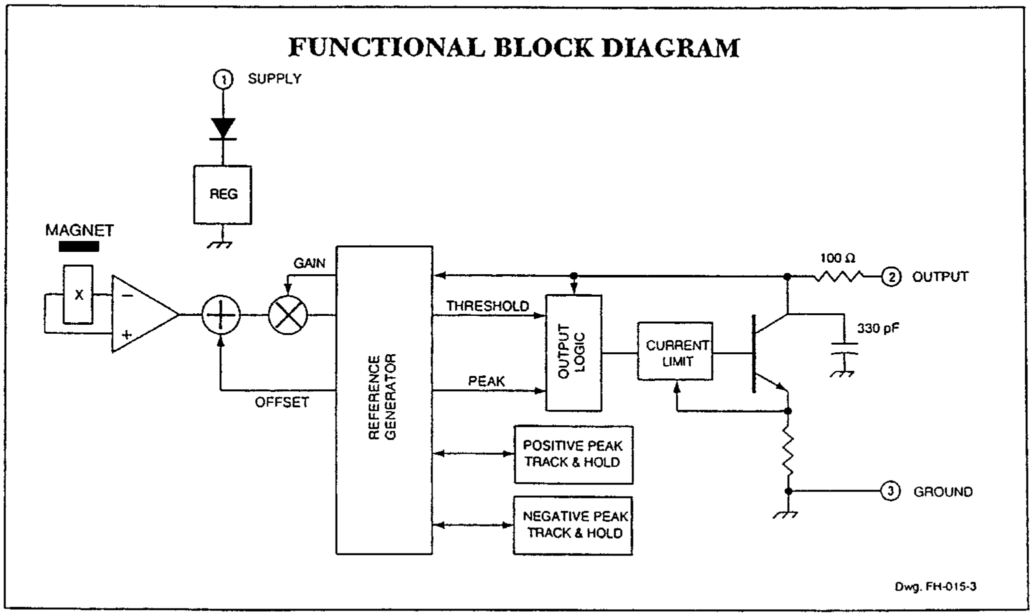


FIGURE 16.12 Hall-effect gear tooth sensor circuit. (Courtesy: Allegro Microsystems, Inc., Worcester, MA.)

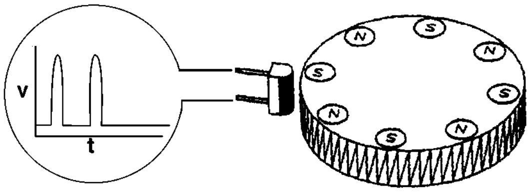


FIGURE 16.13 Small magnets cause sudden reversal in the ferromagnetic wire in a Wiegand sensor. (Courtesy: HID Corporation, North Haven, CT.)

When an alternating magnetic field of proper strength is applied to the Wiegand wire, the magnetic field of the core switches polarity and then reverses, causing the Wiegand pulse to be generated, as shown in Figure 16.13. The magnetic switching action of the Wiegand wire induces a voltage across the pickup coil of approximately 10 µs duration. These alternating magnetic fields are typically produced by magnets that are affixed to the rotating or moving equipment, by a stationary read head and moving Wiegand wires, or by an alternating current generated field.

Absolute: Angular Rate Sensors

Gyroscopes

Many absolute angular rate-measuring devices fall under the designation of gyroscope. A mechanical gyroscope is a device consisting of a spinning mass, typically a disk or wheel, mounted on a base so that its axis can turn freely in one or more directions and thereby maintain its orientation regardless of any movement of the base. It is important to make an initial distinction between angular velocity gyros and rate-integrating gyros. Angular velocity gyros are used to measure motion and as signal inputs to stabilization systems. Rate-integrating gyros are used as the basis for highly accurate inertial navigation systems. They allow a stable platform to maintain a fixed attitude with reference. These devices can be very complex. Three gyros are often teamed with three double-integrated accelerometers to provide an accurate measurement of absolute vehicle motion.

Ricardo Dao of Humphrey Inc. provided an excellent comparison of angular rate sensors in an article in *Measurements & Control* [14]. The five different technologies are summarized below.

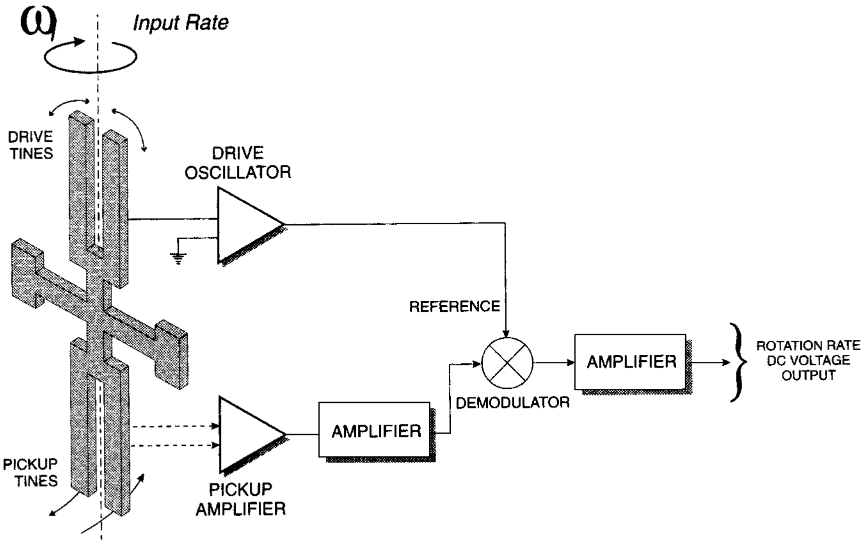


FIGURE 16.14 A vibrating quartz tuning fork uses the Coriolis effect to sense angular velocity. (Courtesy: BEI Sensors and Systems Co., Concord, CA.)

Spinning mass: The traditional gyro consists of a spinning wheel in a gimbaled frame. The principle of conservation of angular momentum provides the measurement tool.

Fluidic: A stream of helium gas flows past two thin tungsten wires [14]. The tungsten wires act as two arms of a Wheatstone bridge. At rest, the gas flow cools the sensing wires equally and the transducer bridge is balanced with zero output. When angular motion is applied to the sensor, one sensor wire will be subjected to increased flow while the other will see less flow. The resistance of the two wires will change and the bridge will be unbalanced. The sensor will produce a voltage output proportional to the angular velocity.

A pump is used to circulate the helium gas. This pump is a piezoelectric crystal circular disk that is excited with an external circuit. The pump produces a laminar flow of relatively high-velocity gas across the two parallel sensing wires.

Piezoelectric vibration: A number of angular velocity sensors have been developed that use micromachined quartz elements. A number of shapes are used, but the operating principle is similar for each. The quartz element vibrates at its natural frequency. Angular motion causes a secondary vibration that, when demodulated, is proportional to angular vibration. A description of one design follows.

The QRS and GyroChip™ family of products uses a vibrating quartz tuning fork to sense angular velocity [15, 16]. Using the Coriolis effect, a rotational motion about the sensor's longitudinal axis produces a dc voltage proportional to the rate of rotation. Figure 16.14 shows that the sensor consists of a microminiature double-ended quartz tuning fork and supporting structure, all fabricated chemically from a single wafer of monocrystalline piezoelectric quartz (similar to quartz watch crystals).

Use of piezoelectric quartz material simplifies the active element, resulting in exceptional stability over temperature and time. The drive tines, being the active portion of the sensor, are driven by an oscillator circuit at a precise amplitude, causing the tines to move toward and away from each other at a high frequency.

Each tine will have a Coriolis force acting on it of: $\{F = 2m\ W_i \times V_r\}$ where the tine mass is m, the instantaneous radial velocity is V_r, and the input rate is W_i. This force is perpendicular to both the input rate and the instantaneous radial velocity.

The two drive tines move in opposite directions, and the resultant forces are perpendicular to the plane of the fork assembly and in opposite directions. This produces a torque that is proportional to the

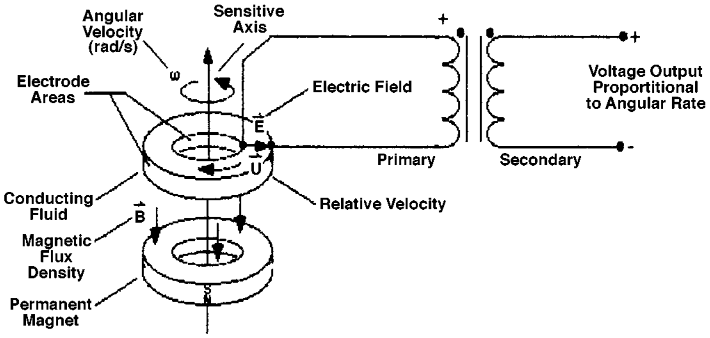


FIGURE 16.15 Magnetohydrodynamic angular rate sensor. (Courtesy: ATA Sensors, Albuquerque, NM.)

input rotational rate. Since the radial velocity is sinusoidal, the torque produced is also sinusoidal at the same frequency of the drive tines, and in-phase with the radial velocity of the tine.

The pickup tines, being the sensing portion of the sensor, respond to the oscillating torque by moving in and out of plane, producing a signal at the pickup amplifier. After amplification, those signals are demodulated into a dc signal that is proportional to the rotation of the sensor.

The output signal of the GyroChip™ reverses sign with the reversal of the input rate since the oscillating torque produced by the Coriolis effect reverses phase when the direction of rotation reverses. The GyroChip™ will generate a signal only with rotation about the axis of symmetry of the fork; that is, the only motion that will, by Coriolis sensing, produce an oscillating torque at the frequency of the drive tines. This also means that the GyroChip™ can truly sense a zero rate input.

MHD effect: The magnetohydrodynamic angular rate sensor is used to measure angular vibrations in the frequency range of 1 Hz to 1000 Hz. It is used where there is a high shock environment and a high rate of angular motion such as 10 to 250 rad s^{-1}. It does not measure a constant or dc velocity. It is used to measure impacts shorter than 1 s duration and vibrations between 1 Hz and 1000 Hz.

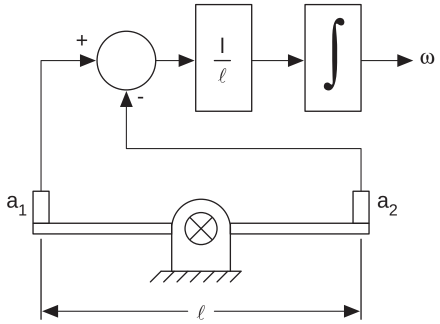
The principle of operation is illustrated in Figure 16.15 [17, 18]. A permanent magnet is attached to the outer case of the sensor. When the case turns, a moving magnetic field is produced (B). There is also a conductive fluid inside the sensor. When the sensor case turns, the fluid tends to stay in one place, according to Newton's first law. This produces a relative motion (U) between a magnetic field and conductor. This motion will produce a voltage (E) across the conductor proportional to relative velocity according to Faraday's law.

Since the fluid is constrained to move in an angular path, the voltage signal will be proportional to angular velocity about the center axis of the sensor. Due to this constraint, the sensor is insensitive to linear motion. The voltage signal is amplified through a transformer or an amplifier for output to a measuring device.

Fiber optic/laser: A beam of light is directed around the axis of rotation. A phase shift of the optical or laser beam is detected to measure angular velocity. The principle of operation is similar to the Doppler shift.

Differenced and integrated accelerometers: An array of accelerometers can be used to measure angular motion. The output of the accelerometers is differenced when they are aligned, or summed when they are mounted in opposite directions. This differencing will eliminate the linear component of motion. As shown in Figure 16.16, the magnitude of the differenced signals, a_1 and a_2, is divided by the distance between the two sensors, l. This gives a measure of angular acceleration. The angular acceleration is integrated over time to give angular velocity. It is important to address the same concerns in this process as when integration was discussed in the linear section. It is assumed that there is a rigid mounting structure between the two accelerometers.

This technique is commonly applied to crash testing of anthropomorphic test devices (ATDs). The ATDs are used in automotive crash testing and aerospace egress system testing.



$$\omega = \int \frac{a_1 - a_2}{\ell}\,dt$$

FIGURE 16.16 Angular acceleration by differencing accelerometers and integration.

16.4 Conclusion

But alas, as Poincaré [20] stated, there is no way to determine absolute velocity.

References

1. J. W. Dally, W. F. Riley, and K. G. McConnell, *Instrumentation for Engineering Measurements*, New York: John Wiley & Sons, 1984.
2. A. Hudson and R. Nelson, *University Physics*, New York: Harcourt Brace Jovanovitch, 1982.
3. E. O. Doebelin, *Measurement Systems, 4th ed.,* New York: McGraw-Hill, 1990.
4. Trans-Tek, Inc., [Online], 1998. Available *http://transtekinc.com/lvt.htm*
5. L. M. Barker and R. E. Hollenbach, Laser interferometer for measuring high velocities of any reflecting surface, *J. Appl. Phys.,* 43(11), 1972.
6. Valyn International, [Online], 1998. Available *www.valynvisar.com*
7. L. C. Rodman, J. H. Bell, and R. D. Mehta, A 3-component laser-doppler velocimeter data acquisition and reduction system, NASA contractor report; NASA CR-177390.
8. E. A. Loew, *Direct and Alternating Currents, 3rd edition,* New York: McGraw-Hill, 1946.
9. P. Emerald, Low duty cycle operation of hall effect sensors for circuit power conservation, *Sensors*, 15(3), 1998.
10. Allegro MicroSystems, Inc., [Online], 1998. Available *http://www.allegromicro.com/*
11. The Hall effect sensor: basic principles of operation and application, *Sensors*, May 1988.
12. J. B. Scarborough, *The Gyroscope: Theory and Applications,* New York: Interscience, 1958.
13. R. F. Deimel, *Mechanics of the Gyroscope: The Dynamics of Rotation,* New York: Dover Publications, 1950.
14. E. Dao, Fluidic angular rate sensors, *Measurements & Control*, February 1994, 126-131.
15. Systron Donner Inertial Division, [Online], 1998. Available *http://www.systron.com*
16. S. Orloski and B. Zimmerman, Dead reckoning in an emergency vehicle location system using a quartz rotation sensor and GPS, *Proc. Sensor Expo,* Chicago, IL, September 1995, Peterborough, NH: Helmers Publishing, 1995.
17. G. Kulikovskiy and G. A. Lyubimov, *Magnetohydrodynamics*, Reading, MA: Addison-Wesley, 1965.
18. Applied Technology Associates, [Online], 1998. Available *http://www.aptec.com/bus-opp.html*
19. G. Unger et al., NASA's first in-space optical gyroscope: a technology experiment on the X-ray timing Explorer spacecraft, NASA technical memorandum; 109242.
20. R.P. Feynman, R.B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, Reading, MA: Addison-Wesley, 1963, 15-5.